The Fundamentals of Aircraft Combat Survivability Analysis and Design

Second Edition

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Foreword

The second edition of the authoritative text *The Fundamentals of Aircraft Combat Survivability Analysis and Design* by Dr. Robert E. Ball provides a wealth of new information for the design of combat aircraft. The first edition of this book was published in 1985 as the fourth book in the newly established AIAA Education Series of textbooks for which I served as its editor-in-chief for some 20 years. This unique text provided invaluable materials for the military planners and aerospace industry designers to improve the survivability of future U. S. military aircraft. The great testimony to this improvement in survivability of the new generation of combat aircraft is the superb combat performance of U. S. aircraft in the recent Operation Iraqi Freedom. Throughout his academic career Professor Ball has established himself unquestionably as the foremost authority on the subject. As a member of the Joint Technical Coordinating Group on Aircraft Survivability sponsored by the U. S. Department of Defense, he was able to incorporate the latest concepts into his revised text that will have an impact on the design of new military aircraft for the 21st century.

As in the first edition, the text is organized into chapters on 1) Introduction to the Aircraft Combat Survivability Discipline, 2) Aircraft Anatomy, 3) Missions, Threats, and Threat Effects, 4) Susceptibility (P_H and P_F), 5) Vulnerability ($P_{K|H}$ and $P_{K|F}$), and 6) Survivability (P_S and P_K). Appendix A provides survivability features of several aircraft used in World War II and Appendix B summarizes probability theory and its application to survivability assessment. Also a useful list of acronyms is provided. Thus the new edition, like the old one, will continue to be the world's leading source of information for the design of survivable combat aircraft.

It should be noted that the AIAA Education Series of textbooks and monographs, inaugurated in 1984, embraces a broad spectrum of theory and application of not only different disciplines in aeronautics and astronautics, including aerospace design practice, but also texts, such as the present one, on defense science, engineering, and management.

J. S. Przemieniecki
Former Editor-in-Chief
AIAA Education Series

Foreword to the Previous Edition

The Fundamentals of Aircraft Combat Survivability Analysis and Design by Robert E. Ball—a comprehensive treatise on survivability concepts in the design of military aircraft—presents the fundamentals of the newly emerging design discipline of survivability engineering applied to tactical and strategic aircraft: both theoretical background for this new discipline and, just as important, lessons of survivability from the past military operations with various types of aircraft, both fixed- and rotary-wing.

Professor Ball developed this text from lecture notes prepared for a survivability course at the U. S. Naval Postgraduate School; he also used his notes in a similar course at the Air Force Institute of Technology. Both courses provided Dept. of Defense engineers and technical managers with the opportunity to learn the fundamentals of survivability engineering and their application in aircraft design.

Publication of *The Fundamentals of Aircraft Combat Survivability Analysis and Design,* as a formal text in the AIAA Education Series, will allow for much broader dissemination of this important material to scientists and engineers in the aerospace industry concerned with survivability of the next generation of military aircraft. Likewise, the text should also be of a great value to military analysts who plan combat operations with the objective of maximizing the survivability of the aircraft.

J. S. Przemieniecki
Editor-in-Chief
AIAA Education Series
1985

Preface

The concept of designing and operating military aircraft to survive in combat originated early in the 20th century when the pilots of World War I aircraft flew above the maximum altitude of the enemy's ground-based guns, sat on stove lids for additional protection, and carried guns to defend themselves from the enemy fighters. However, it was not until the early 1970s, as the conflict in Southeast Asia (SEA) drew to a close, that combat survivability began to emerge as a formal design discipline for military aircraft. In 1985 AIAA (http://www.aiaa.org) published the first survivability textbook entitled *The Fundamentals of Aircraft Combat Survivability Analysis and Design* as part of their new Education Series. I was the author. That textbook presents the fundamentals of the aircraft combat survivability design discipline as I understood them in 1985. It provides the reader with the history, concepts, terminology, facts, procedures, requirements, measures, methodology, and the technology for the nonnuclear combat survivability analysis and design of both fixed-wing and rotary-wing aircraft. It is also applicable to unmanned aerial vehicles (UAVs) and guided/cruise missiles. Approximately 10,000 copies of the first edition have been sold in five printings.

Why this second edition of the textbook? There are many reasons, and some of them are given in the following paragraphs.

What Has Happened to Survivability Since 1985?

The aircraft combat survivability discipline has come a long way since the first textbook was published in 1985. It is now an established design discipline for U. S. military aircraft. New 'stealth' aircraft have been developed with survivability as one of the highest design priorities. The public appearance of the U. S. Air Force F-117 fighter and B-2 bomber in 1988 brought out of the black perhaps the most significant design revolution since the development of the jet engine in WWII. The latest aircraft in development or production today, such as the F/A-18E/F, F/A-22, V-22, RAH-66, and Joint Strike Fighter (JSF), are designed to survive while operating in their projected threat environment.

Designing U. S. aircraft for survivability during the 1970s and 1980s paid off in Operation Desert Storm in 1991 when survivability played a major role in the success of the U. S. air operations. According to the data,* Air Force F-117s conducted nearly 1800 strikes at night (defined in the Gulf War Air Power Survey as the delivery of a weapon or weapons against a specific target) and were credited with destroying a significant percentage of the strategic targets attacked by the coalition forces without a single loss or damage incident as a result of the

***Gulf War Air Power Survey, Vol. V, A Statistical Compendium and Chronology*, U. S. Government Printing Office, Washington, DC, 1993.

combination of stealth, electronic attack, and the darkness of night. The A-10, designed in the early 1970s to survive the extremely hostile close air support mission, conducted over 6800 strikes in Desert Storm. Approximately one-half of these strikes were against military troop installations, material and storage depots, and fortifications and defense systems. Although 20 A-10/OA-10s were hit while on daytime combat or combat support missions, 14 of the 20 survived because of the aircraft's rugged design, and the six aircraft that were killed were downed by infrared (IR) surface-to-air missiles (SAMs). Three other A-10s survived similar IR missile hits. According to Air Force Capt. Paul Johnson, who flew home from a mission over Kuwait with a gaping hole in his A-10's right wing, "The guys developed a great affection for the airplane and a very healthy respect for what it could absorb."* Other aircraft developed since the end of the SEA conflict, such as the UH-60 and AH-64 helicopters and the F-15, F-16, and F/A-18, relied heavily on their survivability features as they operated in one of the world's most hostile air defense environments. Particularly noteworthy was the survival of the seven F/A-18s and two F-16s originally thought to be hit by IR SAMs.

The accomplishments of these survivable aircraft were unprecedented in the annals of air warfare. According to Les Aspin, former U. S. Secretary of Defense, and U. S. Congressman William Dickinson, "The second key component of the air campaign enhanced by high technology is aircraft survivability. The remarkable survivability record in Operation Desert Storm allowed consistently high sortie rates, which in turn allowed the devastating momentum of the campaign to build."†

The hostile environment military aircraft must operate in has changed since 1985. The continued improvement of antiaircraft weapons was to be expected. What was not expected in 1985 was the large array of weapons that are now available to any country—large or small; friend, neutral, or foe. The threats to U. S. military aircraft today are not just the "red" threats developed by the former Soviet Union, but now include French, Chinese, British, and U. S. weapons, as well as weapons from many other smaller countries, such as Israel, Sweden, and South Africa. "Rainbow" weapons, which are weapons built by one country and modified by another country, are another proliferating threat. Of particular concern are the relatively inexpensive and potentially lethal man-portable air defense systems (MANPADS).

In addition to the traditional threat posed by guns and guided missiles, antiaircraft weapons that use directed electromagnetic energy to temporarily blind, permanently damage, or physically destroy critical aircraft sensors have been developed. Accompanying these relatively new, but conventional, radiation threats are the unconventional chemical, biological, and nuclear weapons that were not perceived as realistic threats in the past but have now become threats that cannot be ignored.

The concern for personnel safety and survivability has significantly increased in the U. S. military during the past two decades. According to the U. S. Navy Guiding

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*"Air Force Pilot Tests A-10's Toughness in Battle," *Aviation Week and Space Technology*, 5 Aug. 1991.

†Aspin, L., and Dickinson, W., *Defense for a New Era*, Brassey's (U. S.), Inc., Washington, DC, 1992, p. 18.

Principles presented in the *1992 Navy Policy Book*, "The purpose of the Department of the Navy support establishment is to provide our sailors and Marines with the ability to go anywhere, anytime, to defend the nation's interests successfully and survive." (http://www.chinfo.navy.mil/navpalib/policy/navpolbk/navpolbk.txt) One example of this concern is the raid, known as Diablo Canyon, by Navy and Air Force aircraft on Libya in April 1986. The force package and tactics for the raid were designed to minimize losses. The military did not want a repeat of the incident in Lebanon in December 1983, when U. S. citizens watched on television as a downed U. S. pilot was dragged through the streets by an angry crowd. Consequently, a relatively large number of aircraft were dedicated to enhancing the survivability of the strike aircraft, serving as fighter escorts, antiradiation missile shooters, and electronic warfare aircraft. Nevertheless, one F-111 was lost, and not all of the mission objectives were achieved.

The importance of survivability in combat has become so dominant that the Air Force general in charge of the Tactical Air Command in 1992 said that the B-2 bomber will not be used where the probability of survival is not virtually 100%. A retired vice admiral who once was the Deputy Chief of Naval Operations for Air Warfare wrote in the *Naval Institute Proceedings* in 1994,* "Unless the U. S. carrier force can conduct precision strikes with a high level of assurance of no losses, naval aviation could be drifting into ineffectiveness in the significant first-strike mission." A recent example of the U. S. military's desire to not lose aircraft in combat was their decision to not send AH-64 attack helicopters into combat in Kosovo during Operation Allied Force in the spring of 1999.

One of the most important changes since the appearance of the 1985 textbook is the fact that survivability is now an essential part of the U. S. Department of Defense (DoD) acquisition process. In 1991 the DoD 5000 Series of Directives and Instructions for the acquisition of weapon systems defined survivability as a critical system characteristic, that is, a characteristic of the system that has a critical role in the effectiveness of the system. According to the 2001 version of DoD Regulation 5000.2-R, "Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs,"

> C5.2.3.5.12 Survivability. Unless waived by the MDA (Major Decision Authority), mission-critical systems, including crew, regardless of the ACAT (Acquisition Category), shall be survivable to the threat levels anticipated in their projected operating environment as portrayed in the System Threat Assessment Report. Design and testing shall ensure that the system and crew can withstand man-made hostile environments without the crew suffering acute chronic illness, disability, or death.
>
> C5.2.3.5.12.1 The PM (Program Manager) shall fully assess system and crew survivability against all anticipated threats at all levels of conflict, early in the program, but in no case later than entering system demonstration or equivalent. This assessment shall also consider fratricide and detection.

Another example of the recent integration of survivability into the acquisition process is the Live Fire Test (LFT) law. This law was passed in fiscal year

*Dec. 1994, p. 28.

1987, when the U. S. Congress amended Title 10, U. S. Code, by adding Section 2366, "*Major Systems and Munitions Programs: Survivability and Lethality Testing; Operational Testing.*" The LFT law requires that the Secretary of Defense conduct realistic survivability, lethality, and initial operational testing and evaluation (IOT&E) on covered weapons systems before they proceed beyond low rate initial production. This program is currently under the direction of the Deputy Director, Operational Test and Evaluation/Live Fire Test and Evaluation. (http://www.dote.osd.mil/lfte/INDEX.HTML). Realistic survivability testing (referred to as full-up, system-level testing) means testing for the vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the operational requirements and combat performance of the system. Configured for combat means loading or equipping the system with all dangerous materials (including all flammables and explosives) that would normally be onboard.

The Secretary of Defense can waive the full-up, system-level tests if the Secretary certifies to Congress, before the system enters full-scale development, that such testing would be unreasonably expensive and impractical. An alternate program for evaluating the vulnerability of the system must accompany the waiver request. A study of the LFT law by the National Research Council's Committee on Weapons Effects on Airborne Systems came to the conclusion that "the law is a valuable contribution to vulnerability assessment and to the design of survivable aircraft."*

The emphasis by the U. S. Department of Defense on aircraft survivability is revealed in several recent major weapons acquisition programs. The DoD, when announcing the winning team for the RAH-66 Comanche Lightweight Helicopter (LH) program, stated, "The LH is a fully integrated combat system designed for world-wide combat effectiveness. It will be lethal, survivable, and deployable, yet maintainable in a field environment." From a recent Operational Requirements Document for an upgrade to an existing aircraft: "The following shortfalls severely limit mission accomplishment: inadequate payload, range, speed, and survivability." The F-22 Raptor candidate for the new U. S. Air Force advanced tactical fighter (ATF) had the motto, 'First look, first shot, first kill.' The most recent example of the importance of survivability to U. S. military aircraft is the Joint Strike Fighter program, now the F-35. The four 'pillars' of the JSF program are affordability, lethality, supportability, and survivability.

The U. S. is not the only country that now considers survivability to be a critical attribute of combat aircraft. The U. K. Ministry of Defence refers to system requirements as either cardinal points or key characteristics. The cardinal points are the essential attributes required of the system; the key characteristics are very important but not mandatory. The cardinal points identified for an attack helicopter include lethality, survivability, payload/range, mission management, night/adverse weather battlefield operations, and supportability. Key characteristics include

*Committee on Weapons Effects on Airborne Systems, *Vulnerability Assessment of Aircraft, A Review of The Department of Defense Live Fire Test and Evaluation Program*, National Research Council, National Academies Press, Washington, DC, 1993.

deployability (air/sea), manpower and personnel integration (MANPRINT), growth capability and interoperability.*

As a consequence of this increased emphasis by the military on survivability in combat, the American Defense Preparedness Association (ADPA), now part of the National Defense Industrial Association (NDIA), established the Combat Survivability Division in 1988 (http://www. ndia.org/committees/combat/index.cfm); and in 1989 AIAA added survivability to its list of technical committees (http://www. aiaa.org/tc/sur). Companies that compete for the award of a new aircraft development program, or seek approval to go into full-rate production, or are looking for foreign sales routinely run full-page ads in *Aviation Week and Space Technology* proclaiming the survivability of their product.

The military is not the only community that has recently emphasized survivability. The attitude in the U. S. with regard to public health, safety, and survivability has changed over the past few decades, and society's tolerance for careless loss of life and property has diminished significantly. Government organizations have taken the lead in establishing requirements, and industry has jumped on the bandwagon. How many cities had 'no smoking' ordinances in 1985, and how many television commercials for automobiles in 1985 emphasized airbags and promoted the ability of their product to withstand a crash? Automobile seat belts, car seats for children, and motorcycle and bicycle helmets are the law now.

Improving commercial aviation safety has become a major goal of the Federal Aviation Administration as the number of passengers escalates exponentially each year. According to an article in the 4 November, 1996 issue of *Aviation Week and Space Technology* entitled "Aviation Safety Takes Center Stage Worldwide," there were 12 aircraft accidents by U. S. major scheduled airlines that resulted in one or more fatalities in 3.8 million departures in 1960. This equates to one fatal accident per 317,000 departures or to 0.316 fatal accidents per 100,000 departures. In the 1990s the fatal accident rate fell to less than 0.01 per 100,000 departures as the number of flights nearly tripled. Although this significantly reduced rate appears to be very low, there could be a major hull loss once a week in the year 2015 if the increase in passenger traffic continues to grow at the historical rate and the accident rate remains constant.

In addition to the normal hazards that accompany day-to-day flying in a world generally at peace, the air transport safety and security community must now contend with an increasing terrorist threat in the form of MANPADS that can be launched at an aircraft as it takes off or lands and explosives that are surreptitiously placed onboard an aircraft. Inspection equipment that can quickly detect explosive devices in passenger baggage is being developed, and baggage containers and aircraft cargo bay structures are being designed to withstand internal bomb blasts. A major experimental program using retired large-body aircraft is being conducted jointly by British and U. S. aviation security specialists to determine the ability of new hardening concepts to prevent catastrophic structural failure. Many of the physical phenomena associated with terrorist weapons are the same as those associated with military antiaircraft weapons, and many of the safety problems associated with mechanical failures and other hazards in peacetime, such as the

*Hughes, D., "Interview," *Defence Helicopter*, June–July 1993, p. 3.

explosion of the centerline fuel tank on TWA 800 in July 1996, are the same problems faced by the survivability engineer when protecting a military aircraft from the weapons that can be fired by a hostile air defense.

What is New About This Second Edition?

This second edition is more than just an expansion of the 1985 textbook. It is now, truly, a student's textbook. It should also be more useful to the person who wants to learn what the discipline is all about. It has been rewritten into a form that should be useful to those who want to know only the essentials of the discipline (read Chapter 1), as well as to those who want to know all of the details (read the rest of the textbook). Large amounts of new material have been added throughout the textbook, and a new appendix on probability theory and its application to survivability assessment has been introduced. Learning objectives have been added at the beginning of each major section, and problems are now at the end of each section for those who are serious about learning the material.

This second edition also provides the author with an opportunity to present information on the survivability features of several current U. S. military aircraft and some of the combat data from the SEA conflict and Operation Desert Storm. This information has only recently been released to the public.

People Who Have Made This Second Edition Possible

As with the 1985 textbook, my students at the Naval Postgraduate School (NPS) have been a source of motivation, information, and assistance, and I thank them all. I especially want to recognize the contributions of Christopher Adams, Steven Barrie, Sean Brennan, Douglas Dickman, David Dunaway, Brian Flachsbart, Christopher Keane, James Knight, Michael Novak, Robert Novak, Carlos Rippe, Victor See, Jr., and Nigel Sutton to this second edition.

I also want to thank the many individuals who have contributed to this edition either intentionally, by providing me with information and ideas, or unintentionally, by publishing documents that I could not reference because of classification restrictions. In particular, I want to express my deep appreciation to the dedicated survivability specialists in the U. S. DoD, Army, Navy, and Air Force, and the U. S. aircraft industry for their invaluable help and support. Special thanks goes to Kevin Crosthwaite, the director of the Survivability/Vulnerability Information Analysis Center (SURVIAC), for providing me with the information I needed when I needed it.

I want to thank at least some of the people responsible for the financial support and technical advice for this second edition. They include James O'Bryon, the previous deputy director, Operational Test and Evaluation (Live Fire Testing and Evaluation), Office of the Secretary of Defense, who was a lecturer in my survivability course and the sponsor of the textbook; Larry Miller, the current deputy director; Lt. Col. Tony Dedmond; Cmdr. Kenneth Nelson; John Over; Lt. Col. John Lawless; Raymond Flores and Joseph Jolley, previous directors of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS); with particular thanks to the two most recent directors, Lt. Col. Charles R. Schwarz Jr., who made sure the text was finished on his watch, and Cmdr. Andrew Cibula, the current director (and a graduate of my survivability course at the Naval Postgraduate School); Kenneth Goff, head of the Survivability Division 4.1.8, Naval Air Systems Command, Patuxent River, Maryland; Richard "Tim" Horton, head of the Survivability Division 4.1.8, Naval Air Systems Command, China Lake, California, and the current Navy principal member of the JTCG/AS Principal Member Steering Group (PMSG); Ralph Lauzze, 46th Test Wing, Wright-Patterson Air Force Base, Ohio, the Air Force principal member for many years; Steven Messervy, Army Aviation and Missile Command, the current Army principal member and chairman of the PMSG; and all of the previous principal members of the JTCG/AS PMSG over the last 17 years. I am indebted to Allan Wearner, Leo Budd, David Hall (retired), and their colleagues in the systems vulnerability and systems susceptibility/survivability branches of the Survivability Division 4.1.8, Naval Air Systems Command, China Lake, California; Kristina Langer, 46th Test Wing, Wright-Patterson Air Force Base, Ohio; and the technical review team headed by Philip Weinberg, the Navy civilian representative to the JTCG/AS Central Office, for providing valuable information and good advice.

I want to thank Cmdr. Mark Couch, the military instructor in the Department of Aeronautics and Astronautics, NPS, for taking over my survivability course when I retired, his students, for reviewing the many rough drafts, and Professor David Jenn, NPS, for reviewing the material on radar cross sections and radar cross-section reduction.

And finally, I want to thank the person who introduced me to survivability and has been a continual source of inspiration, ideas, information, advice, and support—Dale B. Atkinson.

The Internet, My Survivability Web Site, and a Disclaimer

The Internet has become an invaluable source of information, and there are many links throughout the textbook to relevant sites. I used the following sites for many of the definitions and acronyms given in the textbook:

"DoD Dictionary of Military and Associated Terms," Joint Publication 1-02, Joint Chiefs of Staff, U. S. Department of Defense, at http://www.dtic.mil.doctrine/jel/doddict/ and at http://www.dtic.mil/doctrine/jel/new_pubs/jp1_02.pdf.

Department of Defense Joint Program Office for Test and Evaluation [JPO (T&E)] Acronyms and Glossaries, at http://tecnet0.jcte.jcs.mil/htdocs/dodinfo/acronyms/index.html.

"Space and Electronic Warfare Lexicon," at http://www.sew-lexicon.com/.

"Glossary of Defense Acquisition Acronyms and Terms (2001)," Defense Systems Management College, at http://www.dau.mil/pubs/glossary/preface.asp.

"Terms/Abreviations/Acronyms," Federation of American Scientists, at http://www.fas.org/news/reference/terms/acronym.html.

"Scientific and Technical Information Network (STINET)," Defense and Technical Information Center, at http://stinet.dtic.mil/.

For the student who would like to go to the Internet and learn more about the survivability discipline, the author plans to maintain the "Aircraft Combat Survivability Education Web Site" at http://www.aircraft-survivability.com. Please stop by and say hello.

Finally, just like the 1985 textbook, this second edition is not to be interpreted as reflecting the official opinion or policy of any U. S. government agency. The text has been written about the survivability discipline as I see it, and the views expressed are my own.

Robert E. Ball, Ph.D.
May 2003

Preface to the Previous Edition

"The survival of a military aircraft operating in a hostile environment depends upon many diverse factors, such as the design of the aircraft, the skill and experience of the crew, the armament carried, the onboard countermeasures equipment, the offboard supporting systems, and the tactics employed. The cost of modern aircraft weapon systems, coupled with the requirement that the system be *effective*, makes imperative the consideration of the aircraft's survivability throughout the life cycle of the system."

Anonymous

In blossom today, then scattered;
Life is so like a delicate flower.
How can one expect the fragrance
To last forever.

Vice-Admiral Takijiro Onishi
Kamikaze Special Attack Squad

In the book *Zero!*, by Masatake Okumiya and Jiro Horikoshi (the designer of the Zero), with Martin Caidin (E. P. Dutton & Co., New York, 1956), Mitsusa Kofukuda, commander of the 6th Japanese Air Force during World War II, states that the ruggedness, firepower, and aggressive employment of the U. S. B-17 and B-24 presented a serious problem to the Japanese and that the ability of these bombers to carry out their mission despite fighter opposition was the deciding factor in the final outcome of Japan's war with the United States. He further states that Japanese naval and aeronautical engineers made their greatest technical blunder by concentrating their efforts on increasing aircraft ranges and completely neglecting any attempt to improve an aircraft's ability to survive enemy firepower. According to Commander Kofukuda, this opinion was shared by many senior Japanese officers.

The U. S. 8th Air Force, operating over Germany in daylight and without fighter escort, suffered a 24% attrition rate in October 1943 in raids against the ball bearing factories in Schweinfurt. This heavy loss of aircraft led to the termination of the Air Force's daytime unescorted, deep penetrations into Germany.

During the Korean War, U. S. Air Force B-29s suffered a 20% loss rate during a series of daylight missions, causing the Bomber Command to cancel the daylight raids and to operate only at night.

The heavy losses of Israeli A-4 aircraft on the first day of the Yom Kippur War in 1973 resulted in cancellation of the close air support missions over the Golan Heights. When the ground situation absolutely required resumption of the close air missions, the tactics were changed so that A-4s operated at the outer fringes of the battle zone and were not faced with the intense Syrian air defenses.

All of the above examples, both strategic and tactical, illustrate the overwhelming requirement for the consideration of survivability in the design and utilization of military aircraft. As a result of this requirement, a technology for enhancing survivability and a methodology for assessing survivability has evolved over the past 70 years. However, because the importance of survivability is sometimes either forgotten or neglected in the design and development of military aircraft during periods of peace, aircraft designers, program managers, and operators must be reminded that survivability considerations must be neither overlooked nor ignored. They need to be informed about the current technology for increasing survivability and about the methodology for assessing the payoffs and the penalties associated with survivability enhancement features. This text is devoted to that end. It presents the fundamentals of the maturing aircraft combat survivability design discipline. It provides the reader with the history, concepts, terminology, facts, procedures, requirements, measures, methodology, and the current technology for the nonnuclear combat survivability analysis and design of both fixed-wing and rotary-wing aircraft. It is also applicable to guided missiles. The text should be helpful to anyone involved in airborne weapons effectiveness studies or in the development of antiaircraft weapon systems for defense against hostile manned aircraft and guided missiles. Knowledge of aircraft survivability fundamentals should also be beneficial to anyone faced with the prospect of flying in a hostile environment.

This text could not have been written without the participation of several of my thesis students at the Naval Postgraduate School. In particular, R. G. Nosco and K. O. Krumbholz were early contributors to the threat and susceptibility and the vulnerability areas, respectively, and M. A. Boies contributed much of the material on the evolution of the survivability technology. Other thesis students who helped with various portions of the text were M. R. Etheridge Jr., P. F. Coste, J. E. Parr, C. K. Fair, and D. R. Ferrell; P. Cox assisted me in the task of putting it all together. I also want to express my deep appreciation to Dale B. Atkinson, Naval Air Systems Command, who provided continuous intellectual encouragement and financial support, and to John Morrow, Naval Weapons Center, for his tutelage. Other people I am indebted to are Capt. P. van R. Schoeffel, USN, retired, Maj. Tim Horton, USA, retired, Lieut. Col. Jim Sebolka, USAF, and John Aldridge, Vince Di Rito, George Ducker, Don Voyls, and the rest of the JTCG/AS Design Criteria and Industry Interface Sub-group for their encouragement and financial support of this effort. I especially want to thank Don Jacobs for preparing the artwork, Regina Stewart and Jo Ann Schmalz for interpreting my handwriting and typing the text, and Jim Buckner for tackling the very difficult job of editing the text.

This text is not to be interpreted as reflecting the official opinion or policy of any Government agency. The text has been written about the survivability discipline as I see it, and the views expressed are my own.

Robert E. Ball
Naval Postgraduate School
Monterey, California
1985

Acknowledgment

On behalf of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), I would like to extend our continued support for Professor Ball and this second edition of the comprehensive text on aircraft survivability. This book will provide the reference material for aircraft combat survivability as a design discipline.

The JTCG/AS is chartered by the Joint Aeronautical Commanders Group (JACG) and serves as the focal point for common aviation cooperation and issues across the services, NASA, Federal Aviation Administration, and the Coast Guard. The JACG has been supportive of our efforts over the years to further the discipline of aircraft survivability within the U. S. Department of Defense aviation community. Our OSD sponsor, the Director for Operational Test and Evaluation, has likewise continued to be an advocate and supporter of our efforts to increase awareness and research on aircraft survivability. The JTCG/AS implements efforts to complement each service's survivability programs. We are charged with coordinating information across the JACG member organizations and conducting research and methodologies in order to maintain survivability as a design discipline. Sponsoring this work by Professor Ball is one way that we can achieve our objectives.

Professor Bob Ball's name is synonymous with the field of aircraft survivability. Through his research, writing, and teaching, he codified the body of knowledge that has been, and now continues to be, used by aircraft designers, pilots, leaders, and aircraft subsystem engineers worldwide. This second edition, with its expanded coverage of the discipline, will continue to provide practitioners the material and educational content necessary to carry the discipline forward for many years.

Steven L. Messervy
Chairman, Joint Technical Coordinating Group
on Aircraft Survivability
December 2002

Acknowledgment to the Previous Edition

The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) is chartered under the Joint Army Material Development and Research Command/ Naval Material Command/Air Force Logistics Command/Air Force Systems Command Commanders to conduct a Joint Survivability Program and to coordinate the individual Service survivability programs. The mission of the JTCG/AS includes a long-range goal to "establish survivability as a design discipline." Professor Ball has been a leader in helping the JTCG/AS reach this goal.

In 1977, Professor Ball introduced a graduate level survivability course that has since been offered as part of the Naval Postgraduate School (NPS) Aeronautical Engineering curriculum. Professor Ball and his thesis students have made major technical contributions toward establishing survivability as a design discipline over the years. Professor Ball also developed an NPS short course on Aircraft Combat Survivability. This course has provided Department of Defense and industry engineers and managers with the opportunity to learn the fundamentals of survivability engineering and their application to actual aircraft. Both courses have gained an outstanding reputation due to Professor Ball's lecturing skills and his continuing efforts to update and improve the course material.

This book continues and extends Professor Ball's high-quality work in this field. Professor Ball has done an outstanding job of providing a comprehensive, well-written, and technically accurate book that will be useful to engineers and managers involved in all phases of aircraft design and development, as well as those involved in training engineers and program managers.

Dale B. Atkinson, Chairman
Joint Technical Coordinating
Group on Aircraft Survivability
1985

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Prologue—A Sense of Perspective

MNS, MOPs, MOEs, and Aircraft Attributes

U. S. military aircraft are designed, developed, and operated to fill a need initially expressed in a DoD Mission Need Statement (MNS).* They are special purpose aircraft that must operate efficiently in peacetime and effectively in wartime. As a result of this dual peacetime–wartime environment, they have more requirements imposed upon them during the acquisition process than those imposed upon civilian aircraft. Here is a list of some of the characteristics, capabilities, or attributes that must be considered when developing or acquiring a military aircraft:

Affordable
Safe to operate and maintain
Fast and high (enough) flight
Carries a large/heavy payload over a long distance
Multimission capability
Long lived
Stealthy
Nighttime capability
Low crew workload
Easy to modernize
Easily maintained
Easy to produce and repair
Secure communications
Delivers effective weapons accurately from long range or high altitude
Terrain following capability
Few logistics requirements
Heavy weapons bringback capability
Dirty environment capability
All weather capability
Crew situational awareness
Reliable
Good handling qualities
Deployable
Good target acquisition capability
Short field capability
Maneuverable and agile
Long endurance
Low number of crew members
Precise navigation
Carrier suitable

and of course, survivable—and easy to repair when damaged in combat.†

*The MNS is a brief, nonsystem specific statement that succinctly defines a mission deficiency or technological opportunity in broad operational terms. It identifies potential materiel alternatives and describes the required operational capabilities and constraints to be studied. Information on the MNS and other aspects of the U.S. Department of Defense acquisition program is provided by the *Defense Acquisition Deskbook* available online at http://deskbook.dau.mil/jsp/default.jsp

†The 10 established performance attributes for the F/A-22 are radar cross section from the front sector of the aircraft, supercruise, acceleration, maneuverability, payload, combat radius, radar detection range, airlift support, sortie generation rate, and mean time between maintenance. Two additional attributes, situational awareness and low observability, are considered by the U.S. Air Force to be critical system characteristics that do not lend themselves well to measurement and reporting. (http://www.fas.org/man/gao/nsiad98137.htm).

Some of them, such as carries a large payload over a long distance, are operationally related; others, such as easy to modernize, are not. Many of them, such as stealthy and delivers lethal weapons accurately, are unique to military aircraft. Of interest here is the relatively recent aircraft attribute known as survivability.

Note that survivability is but one of many important attributes. However, also note that many of the attributes listed in the preceding paragraph, such as stealth, fast flight, and terrain-following capability, are important attributes because they enhance survivability, which is also an attribute. Thus, survivability is an upper-level attribute that is affected by many of the other attributes listed, as well as many other design and performance features not listed. Survivability is now referred to as a critical system characteristic because it has a critical role in the effectiveness of an aircraft as a weapons system.

All of the attributes listed are desirable characteristics and capabilities of a final product that is being designed to fill a need expressed in the MNS. A simple example of a MNS is the need to destroy small formations of enemy armored vehicles in close proximity to friendly forces and within 400 km of a coastline. One alternative that could satisfy this need is the use of manned, carrier-based aircraft to conduct the close air support (CAS) mission. Most of the attributes listed earlier will be important for this particular mission (and any other missions the aircraft might be called upon to perform) and therefore must be considered in the design of the aircraft.

Each attribute has one or more measures of performance (MOPs) or performance parameters. A MOP is a quantitative measure of the physical performance associated with the attribute. Early in the aircraft acquisition program, a minimum acceptable performance requirement, known as a threshold, is assigned to each of the performance parameters associated with the required attributes. In addition to the threshold, a desired objective might also be assigned. For example, the attribute long life could have the performance parameter of total flight hours before retirement. The threshold for this MOP could be the requirement that the fatigue life of the aircraft have a minimum value of 8000 flight hours, and an objective could be 10,000 flight hours. The measure of performance for the range-payload attribute could be pounds of payload carried over miles traveled without refueling. A threshold would be the requirement the aircraft carry 4000 lb of a particular type of ordnance at least 1000 km using only internal fuel, and an accompanying objective would be 4000 lb and 1500 km. The performance parameters associated with the most important attributes of an aircraft are referred to as the key performance parameters (KPPs).

The system performance specifications are contractual, operational, and technical requirements selected to satisfy the thresholds. For example, a performance specification associated with the fatigue life threshold could be the requirement that the maximum stress under the design limit load be less than 67% of the ultimate stress. A performance specification for the range-payload threshold is a maximum engine fuel flow rate of 20 lb/min. Another range-payload performance specification is the requirement that the internal bomb bay be sized to carry four joint direct attack munitions (JDAMs). The performance specifications just described are engineering—or technically—based, that is, they are not directly related to the operational performance of the aircraft as a weapon system, such as its ability to destroy targets on the ground. Of current interest in the development and acquisition of military aircraft is the increased use of commercial specifications and standards, of which there are none for survivability, and performance specifications that are related to military operations. These specifications are referred to as performance-based specifications or functional-performance requirements. In this context performance means those operational and support characteristics of the system that allow it to perform its assigned mission effectively and efficiently over time.

The MOP thresholds and objectives, and the associated performance specifications, for those attributes required to satisfy the mission needs identified in the MNS are contained in the operational requirements document (ORD). The ORD states how the system will be operated, deployed, employed, and supported using operationally oriented parameters. As the system is developed, the requirements in the ORD can conflict with one another, forcing the acquisition team to reduce the threshold and associated specifications for one attribute in order to attain a desired threshold for another attribute. For example, having a two-member crew can reduce the crew's workload and increase their situational awareness, but will also increase both the flyaway cost of the aircraft and the annual cost of the aircraft's operations. Using only one engine rather than two will reduce the acquisition, operational, and logistics costs of the aircraft, but can also degrade survivability and safety; and the threshold required for stealth might conflict with those for speed, payload, and affordability.

All of the attributes listed earlier are important, but they all cannot be achieved at their highest level if the aircraft is to be affordable. Something has to give. Each operational requirement imposed by the user, and the corresponding system specification imposed by the developer, has an impact upon the design, the operations, and the life-cycle cost of the aircraft. The analysis of alternatives (AoA) is the procedure that is currently used to determine the particular set of values for the thresholds and objectives of each attribute which result in the most cost-effective system that satisfies the mission need.* The selection of the attributes and their numerical thresholds and objectives is based upon their contribution to the measures of effectiveness (MOEs) of the system.

Measures of effectiveness are related to mission or battle outcomes, such as the number of enemy surface targets killed per mission and the number of enemy aircraft killed per mission. The relationships between the attribute MOPs and the military MOEs are determined and used to develop the optimum combination of thresholds for one or more selected mission scenarios. For example, consider the connection between the survivability attribute and the large payload over a long-range attribute for the CAS mission just described. The two MOEs considered are the number of friendly aircraft lost and the number of enemy tanks killed in a campaign. The two MOPs considered are the radar cross section (RCS) of the aircraft, which affects the aircraft's survivability, and the amount of antitank ordnance carried, which affects the number of tanks killed. In a stealthy design the ordnance must be carried internally to achieve a low RCS, and consequently only a limited amount can be carried. In a campaign the stealthy aircraft kills X number of tanks, and Y aircraft are killed by the enemy air defense. In a more lethal

*The AOA was preceded by the cost and operational effectiveness analysis (COEA).

design additional antitank ordnance is mounted on the wings of the aircraft. This additional ordnance provides an opportunity for the aircraft to kill more tanks per campaign; however, it also increases the radar cross section of the aircraft, which may result in more than Y aircraft downed by the air defense. Which is the better (more cost-effective) solution?

Survivability as a Design Requirement

One of the most difficult attributes for which to establish the operational and technical requirements and the measures of performance is survivability. Survivability is achieved in so many ways, some of which are associated with the aircraft's design and some of which are associated with the aircraft's operations. Here is a partial list of the many design and operational features that can enhance the survivability of an aircraft:

- Speed and altitude
- Fire/explosion protection
- Self-repairing flight controls
- Redundant and separated hydraulics
- Night-time capability
- More than one engine-separated
- Low signatures
- Tactics
- Onboard electronic attack equipment
- Maneuverability/agility
- Terrain following
- No fuel adjacent to air inlets
- Self defense missiles and guns
- Crew situational awareness
- Hydrodynamic ram protection
- Crew training & proficiency
- Nonflammable hydraulic fluid
- Lethal launch-and-leave or stand-off weapons
- Chaff and flares
- Fighter escort
- Rugged structure
- Good target acquisition capability
- Threat warning system
- Mission planning system
- Antiradiation weapons
- Armor
- Standoff electronic attack equipment

Note the extreme diversity of the features just listed. For some of these features, it is relatively easy to identify the MOP. For example, speed and altitude have traditionally been specified in the design of an aircraft; the aircraft shall have a maximum speed of Mach 0.9 at sea level and Mach 1.2 at the maximum altitude of 40,000 ft. Recently, aircraft signatures and the ability of the aircraft to withstand a hit have been added to the list of required performance parameters. A MOP for an aircraft's radar signature is the radar cross section. A MOP for an aircraft's ability to withstand a hit is its vulnerable area A_V or its probability of (being) kill given a hit $P_{K|H}$.

Some of the other attributes that contribute to survivability, such as crew situational awareness and threat warning, traditionally have not been an explicit part of the operational requirements. Quantifying their contribution to survivability and setting operational thresholds is difficult at best. Nevertheless, because survivability is essential to effectiveness and because it must be incorporated early into the design of military aircraft in order to maximize effectiveness and minimize design impact, survivability must be a major consideration beginning with program inception and continuing throughout the acquisition process. All of the design and operational attributes that have the potential to enhance survivability should be identified early, the performance parameters for these features should be determined and evaluated for their contribution to effectiveness and cost, and the appropriate thresholds set for the 'right amount' of survivability.*

One of the major barriers to designing the right amount of survivability into an aircraft is the perception that survivability might be too expensive, particularly those features that make the aircraft tougher or less vulnerable, such as two, separated engines and hydrodynamic ram protection for the fuel tanks. Some believe that a hit aircraft is a downed aircraft, and nothing can be done about it. There is also the perception that the benefits from survivability will never be realized if the aircraft is never used in combat; and if it is used in combat, a return on investment might not be achieved until late in the life cycle of the aircraft. Based upon these gut feelings, a program manager, faced with the daunting task of keeping the program on schedule and under budget, might be tempted to forego serious consideration of survivability, or to soften the survivability requirements, until it is too late to optimize its contribution to weapon system effectiveness.

These beliefs and perceptions are not correct, and they must be eliminated using realistic cost-effectiveness analyses. These analyses will show that designing for survivability pays off, an aircraft that is both mission capable and survivable in combat will achieve its mission objectives and return home more often, it will be used more aggressively in high risk combat scenarios, and it will win battles. The fact that certain aircraft are designed to be survivable might actually eliminate the requirement to use them in battle if the enemy decides not to go to war because these aircraft will easily win that war.

The Survivability Discipline

To accomplish the goal of designing the right amount of combat survivability into military aircraft early in the life of the aircraft, all of the contributors to survivability, such as the tactics developers, signature specialists, electronic combat old crows, and the vulnerability assessment/reduction engineers, should be gathered together into a common survivability discipline. The people who work the engineering issues of combat survivability should be called survivability engineers, and the discipline should be treated as a unified discipline in the system engineering process, in the same manner as the traditional disciplines of structures, flight controls, aerodynamics, and propulsion are treated.

However, there is a difference between the survivability discipline and the traditional aeronautical engineering disciplines. Because the survivability discipline includes all of the disparate features listed in the preceding section (plus many others), it is affected by all of the other engineering disciplines, such as structures (rugged structure), flight controls (self-repairing flight controls), aerodynamics (maneuverability/agility), and propulsion (stealthy), as well as the operational

*How much survivability is enough? is a difficult question to answer. Setting the survivability performance thresholds too high can be fatal to an acquisition program; setting them too low can be fatal to the aircraft in combat.

employment of the aircraft (tactics). Consequently, the fundamentals of the survivability discipline, including the technology for enhancing survivability and the assessment methodology for quantifying survivability, should be familiar to not just the survivability engineers, but also to the system developers, designers, engineers, and users. This text is intended to provide the material these people need as they design, build, maintain, and operate survivable aircraft.

Although the text is written specifically for aircraft, including fixed-wing aircraft, helicopters, unmanned aerial vehicles, and cruise missiles, the survivability concepts, terminology, enhancement technology, and assessment methodology are applicable to other military vehicles, such as tanks, ships,* and spacecraft.†

Some Survivability Issues

Given here is a list of some important, and perhaps controversial, issues that involve survivability:

1) How survivable should an aircraft be, and how should this survivability be obtained?

2) Aircraft under development or in production today, such as the F/A-22, F/A-18E/F, V-22, and RAH-66 are considerably more expensive than the aircraft they are replacing. They are also designed to be more survivable. Are these more survivable aircraft worth the additional cost?

3) How much does survivability add to the cost of these aircraft?

4) Can the aircraft in development or production today take back the low-altitude arena that has been lost as a result of the presence of the MANPADS and other low-altitude guns and missiles?

5) Should an aircraft that was designed for missions with a relatively light enemy air defense be assigned missions with a more intense air defense?

6) How important are onboard electronic countermeasures to survivability, particularly for stealthy aircraft?

7) What tests should the aircraft program manager conduct to satisfy the congressionally mandated Live Fire Test Law?

8) How can the survivability of an aircraft be determined? What realistic tests should be performed? What is the role of modeling and simulation in the test and evaluation of survivability?

9) How important is survivability to you?

The author does not have the answers to these questions. These questions are posed here to illustrate the impact the survivability discipline has upon the development, cost, and operational effectiveness of military aircraft.

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*Ball, R. E., and Calvano, C. N., "Establishing the Fundamentals of a Surface Ship Survivability Design Discipline," *Journal of the American Society of Naval Engineers*, Vol. 106, No. 1, 1994, pp. 71–74.

†Ball, R. E., and Kolleck, M. L., "Survivability: It's Not Just for Aircraft Anymore," *JTCG/AS Newsletter*, Winter 2000, pp. 10, 11 (http://bahdayton.com/surviac/asnews.htm).

Acronyms

AA	=	aircraft availability
AA	=	air-to-air
AAA	=	antiaircraft artillery
AAC	=	Air Armament Center
AAH	=	Advanced Attack Helicopter
AAM	=	air-to-air missile
A/B	=	afterburner
ABDR	=	aircraft battle damage repair
ACAT	=	acquisition category
ACETEF	=	Air Combat Environment Test and Evaluation Facility
ACLOS	=	automatic command-to-line-of-sight
ACS	=	aircraft combat survivability
AD	=	air defense
ADA	=	air defense artillery
AEC	=	Army Evaluation Center
AEN	=	aircraft engine nacelle
AESA	=	active electronically scanning array
AEW	=	airborne early warning
AF	=	Air Force
AFB	=	Air Force base
AFCS	=	automatic flight control system
AFDTC	=	Air Force Development Test Center
AFEWES	=	Air Force Electronic Warfare Evaluation Simulator
AFFTC	=	Air Force Flight Test Center
AFMC	=	Air Force Material Command
AFMSS	=	Air Force Mission Support System
AFOTEC	=	Air Force Operational Test and Evaluation Center
AFSARC	=	Air Force Systems Acquisition Review Council
AFSOC	=	Air Force Special Operations Command
AGC	=	automatic gain control
AGL	=	above ground level
AI	=	air interceptor (aircraft)
AI	=	air interdiction (mission)
AKSS	=	acquisition knowledge sharing system
AMAD	=	airframe-mounted accessory drive
AMC	=	Army Materiel Command
AMRAAM	=	advanced medium range air-to-air missile
AMSAA	=	Army Material Systems Analysis Activity
AoA	=	analysis of alternatives
AOC	=	air officer commanding (Royal Air Force)

AOC	=	Association of Old Crows
AOTD	=	active optical target detector
AP	=	armor piercing
APB	=	acquisition program baseline
APG	=	Aberdeen Proving Ground
AP-I	=	armor-piercing incendiary
APU	=	auxiliary power unit
ARL	=	Army Research Laboratory
ARM	=	antiradiation missile
ASE	=	aircraft survivability equipment
ASPJ	=	airborne self-protection jammer
ASST	=	antiship surveillance and targeting
ASW	=	antisubmarine warfare
ATBM	=	antitactical ballistic missile
ATC	=	air traffic control
ATD	=	advanced technology development demonstration
ATEC	=	Army Test and Evaluation Command
ATF	=	advanced tactical fighter
ATIRCM	=	advanced threat infrared countermeasures
ATO	=	air tasking order
ATS	=	air traffic services
AVSF	=	Aerospace Vehicle Survivability Facility
AWACS	=	airborne warning and control system
BAD	=	behind armor debris/damage
BAI	=	battlefield air interdiction
BARCAP	=	barrier combat air patrol
BDA	=	battle damage assessment
BDR	=	battle damage repair
BN	=	bombardier/navigator
BUFCS	=	backup flight control system
BVR	=	beyond visual range
CAP	=	combat air patrol
CAS	=	close air support
CAS	=	control augmentation subsystem
CB	=	chemical and biological
CBIAC	=	Chemical and Biological Defense Information Analysis Center
CBR	=	chemical-biological-radiological
CBTDEV	=	combat developer
CBU	=	cluster bomb unit
CC	=	critical component
CDC	=	Combat Direction Center
CEP	=	circular error probable
CFC	=	chlorofluorocarbon
CIC	=	Combat Information Center
CIFS	=	close-in fire support
CIWS	=	close-in weapon system
CLOS	=	command-to-line-of-sight
CMWS	=	common missile warning system

CNA = Center for Naval Analyses
CNM = Chief of Naval Materiel
COEA = cost and operational effectiveness analysis
COI = critical operational issue
CP = control point
CPA = closest point of approach
CPE = circular probable error
CPS = computerized planning system
CRT = cathode-ray tube
CSAR = combat search and rescue
CVAA = Component Vulnerability Analysis Archive
CW = continuous wave
CWE = conventional weapons effects
C2 = command and control
C3 = command, control, and communications
C3I = command, control, communications, and intelligence
C4I = command, control, communications, computers, and intelligence
DAB = Defense Acquisition Board
DACM = defensive air combat maneuvering
DAD = Defense Acquisition Deskbook
DASIAC = Defense Special Weapons Agency Nuclear Information Analysis Center
DCA = defensive counter-air
DEAD = destruction of enemy air defenses
DECM = defensive electronic countermeasures
DE = directed energy
DEW = directed energy weapons/warfare
DF = direction-finding
DIADS = digital integrated air defense system
DIRCM = directional infrared countermeasures
DIS = distributed interactive system
DLA = Defense Logistics Agency
DLI = deck-launched interceptor
DMA = Defense Mapping Agency [now the National Imagery and Mapping Agency, (NIMA)]
DMEA = damage mode and effects analysis
DMSO = Defense Modeling and Simulation Office
DNA = Defense Nuclear Agency
DoD = Department of Defense
DoDD = DoD Directive
DoDI = DoD Instruction
DOT&E = Director, Operational Test and Evaluation
DS = Desert Storm
DSWA = Defense Special Weapons Agency
DT&E = developmental test and evaluation
DTC = Developmental Test Command
DTIC = Defense Technical Information Center
DTRA = Defense Threat Reduction Agency

E3A	=	essential events and elements analysis
EA	=	electronic attack
EAC	=	Evaluation Analysis Center
EC	=	electronic combat
ECCM	=	electronic counter-countermeasures
ECM	=	electronic countermeasures
ECR	=	Electronic Combat Range
ECS	=	environmental control system
EFP	=	explosively formed projectile/penetrator
EHA	=	electrohydraulic or -hydrostatic actuator
EM	=	electromagnetic
EMA	=	electromechanical actuator
EMAD	=	engine-mounted accessory drive
EMCC	=	Electromagnetic Code Consortium
EMI	=	electromagnetic interference
EMP	=	electromagnetic pulse
EMTE	=	electromagnetic test environment
EO	=	electro-optics
EOB	=	enemy order of battle or electronic order of battle
EP	=	electronic protection
EPA	=	electronically phased array
EPA	=	Environmental Protection Agency
EPP	=	emergency power package
ERP	=	effective radiated power
ES	=	electronic warfare support (previously ESM)
ESA	=	electronically scanning array
ESM	=	electronic support measures
ESR	=	electronically scanning radar
EW	=	early warning
EW	=	electronic warfare
EWO	=	electronic warfare officer
FAA	=	Federal Aviation Agency
FAC	=	forward air controller
FAC(A)	=	forward air controller (airborne)
FAD	=	fleet air defense
FALT	=	failure analysis logic tree
FATEPEN	=	fast air target encounter penetration model
FE	=	fighter escort
FEBA	=	forward edge of the battle area
FEZ	=	fighter engagement zone
FHA	=	functional hazard assessment
FLIR	=	forward looking infrared
FLOT	=	forward line of own troops
FMEA	=	failure mode and effects analysis
FMECA	=	failure mode, effects, and criticality analysis
FOD	=	foreign object damage
FOV	=	field of view
FPA	=	focal plane array

FRY	=	Federal Republic of Yugoslavia
FTA	=	fault tree analysis
GAO	=	General Accounting Office
GCI	=	ground control intercept
GO	=	geometrical/geometric optics
GPS	=	global positioning system
GTD	=	geometrical theory of diffraction
HARM	=	high-speed antiradiation missile
HE	=	high explosive
HE-I	=	high explosive incendiary
HEL	=	high-energy laser
HEMP	=	high-altitude electromagnetic pulse
HIMAD	=	high- to medium-altitude air defense
HITL	=	hardware-in-the-loop
HIVAS	=	high-velocity airflow system
HLA	=	high-level architecture
HPM	=	high-power microwave
HTS	=	HARM targeting system
HWIL	=	hardware-in-the-loop
IADS	=	integrated air defense system
ICS	=	internal communication system
IDECM	=	integrated defensive electronic countermeasures
IEEE	=	Institute of Electrical and Electronic Engineers
IFF	=	identification, friend or foe
IFFN	=	identification, friend, foe, or neutral
IFOV	=	instantaneous field of view
ILSP	=	integrated logistics support plan
INT	=	interdiction
IOC	=	initial operational capability
IOT&E	=	initial operational testing and evaluation
IP	=	initial point
IR	=	infrared
IRAP	=	infrared absorbent paint
IRCM	=	infrared countermeasures
IRIA	=	Infrared Information Analysis Center
IRST	=	infrared search and track
IW	=	information warfare
JACG	=	Joint Aeronautical Commanders Group
JASA	=	Joint Accreditation Support Activity
JCVP	=	Joint Component Vulnerability Program
JDAM	=	Joint Direct Attack Munition
JDL	=	Joint Directors of Laboratories
JERP	=	jammer effective radiated power
JETDS	=	Joint Electronics Type Designation System
JLC	=	Joint Logistics Commanders
JLF	=	joint live fire
JMASS	=	joint modeling and simulation system
JMEM	=	Joint Munitions Effectiveness Manual

JPO	=	Joint Project Office
JSB	=	joint synthetic battlespace
JSF	=	Joint Strike Fighter
JSTARS	=	Joint Surveillance Target Attack Radar System
JTCG/AS	=	Joint Technical Coordinating Group on Aircraft Survivability (now the Joint Aircraft Survivability Program)
JTCG/ME	=	Joint Technical Coordinating Group for Munitions Effectiveness
KPP	=	key performance parameter
KOB	=	keep out boundary
LANTIRN	=	low-altitude navigation and targeting infrared for night
LAR	=	launch acceptable/acceptability region
LC	=	life cycle
LCC	=	life cycle cost
LEL	=	low-energy laser
LFT	=	live fire test/live fire testing
LFT& E	=	live fire test and evaluation
LGB	=	laser-guided bomb
LH	=	lightweight helicopter
LO	=	low observables
LOC	=	lines of communication
LOMAD	=	low- to medium-altitude air defense
LORO	=	lobe on receive only
LOS	=	line-of-sight
LOS	=	lines of supply
LOX	=	liquid oxygen
LRF	=	laser range finder
LRIP	=	low-rate initial production
LTD	=	laser target designator
LV	=	low vulnerability
LWIR	=	longwave IR
MAAP	=	master air attack plan
MAIS	=	major automated information system
MALD	=	miniature air-launched decoy
MAM	=	mission attainment measure
MANPADS	=	man-portable air defense system
MANPRINT	=	manpower and personnel integration
MATDEV	=	materiel developer
MAWS	=	missile approach warning system
MCLOS	=	manual command-to-line-of-sight
MDA	=	Major/Milestone Decision Authority
MDAPS	=	major defense acquisition programs
MEDVAC	=	medical evacuation
MEL	=	medium-energy laser
MESA	=	Missile Engagement Simulation Arena
MEU(SOC)	=	Maritime Expeditionary Unit (Special Operations Capable)
MEWS	=	mission essential weapons systems

MEWS	=	missile early warning system
MEZ	=	missile engagement zone
MIG	=	Russian Aircraft Corporation "MiG"
MIGCAP	=	MIG combat air patrol
MLM	=	mission-level model
MM	=	method of moments
MNS	=	mission need statement
MOE	=	measure of effectiveness
MOME	=	measure of mission effectiveness
MOMS	=	measure of mission success
MOP	=	measure of performance
MPS	=	mission planning system
MRTFB	=	major range and test facility bases
M/S	=	maintenance/surveillance
MSIAC	=	Modeling and Simulation Information Analysis Center
MTI	=	moving target indicator/indication
MWIR	=	midwave infrared
MWS	=	missile warning system
M&S	=	modeling and simulation
NACSP	=	Naval Air Combat Survivability Program
NAIC	=	National Air Intelligence Center
NASA	=	National Aeronautics and Space Administration
NAVAIR	=	Naval Air Systems Command
NAWCADPAX	=	Naval Air Warfare Center—Aircraft Division, Patuxent River
NAWCWDCL	=	Naval Air Warfare Center—Weapons Division, China Lake
NBC	=	nuclear, biological, and chemical
NBCC	=	nuclear, biological, and chemical contamination
NCID	=	noncooperative target identification
NDIA	=	National Defense Industrial Association
NEA	=	nitrogen-enriched air
NEFD	=	noise equivalent flux density
NEI	=	noise equivalent irradiance
NGFS	=	naval gunfire support
NIMA	=	National Imagery and Mapping Agency
NOE	=	nap-of-the-Earth
NRTF	=	National Radar Test Facility
NSWC	=	Naval Surface Warfare Center
NTIS	=	National Technical Information Service
OAB	=	outer air battle
OAR	=	open air range
OBIGGS	=	onboard inert gas generating system
OBOGS	=	onboard oxygen generating system
OCA	=	offensive counter air
OHT	=	over-the-horizon targeting
OMB	=	Office of Management and Budget
OPNAV	=	Office of the Chief of Naval Operations

OPR	=	Office of Primary Responsibility
OPTEC	=	Operational Test and Evaluation Command
OR	=	operational requirement
ORD	=	operational requirements document
PBL	=	protection ballistic limit
PBW	=	particle beam weapon
PBW	=	power-by-wire
PC	=	power control
PD	=	point detonating
PD	=	pulse-doppler
PDF	=	Panamanian Defense Forces
PDF	=	probability density function
PEO	=	program executive officer
PGM	=	precision-guided munition
PM	=	program manager
PMF	=	probability mass function
PMSG	=	Principal Member Steering Group
POET	=	prime oscillator expendable transponder
POL	=	petroleum, oil, and lubrication
PPI	=	plan position indicator
PPS	=	pulses per second
PRF	=	pulse repetition frequency
PRI	=	pulse repetition interval
PSSA	=	preliminary system safety assessment
PSYOP	=	psychological operations
PTD	=	physical theory of diffraction
QA	=	quality assurance
RAF	=	Royal Air Force
RAM	=	radar absorbing/absorbent material
RAMS	=	RATSCAT Advanced Measurement System
RAS	=	radar absorbing/absorbent structure
RAT	=	ram air turbine
RATSCAT	=	Radar Target Scatter Division/National Radar Test Facility
RCS	=	radar cross section
RDEC	=	Research, Development, and Engineering Center
REDCAP	=	real-time electromagnetic digitally controlled analyzer processor
RF	=	radio frequency or radar frequency
RFCM	=	RF countermeasures
RGPO	=	range gate pull-off
RHAW	=	radar homing and warning
RIO	=	radar intercept officer
RLS	=	reservoir level sensor
ROC	=	required operational capability
ROE	=	rules of engagement
RPG	=	rocket propelled grenade
RPM	=	revolutions per minute
RRL	=	Radar Reflectivity Laboratory

RWR	=	radar warning receiver
R&D	=	research and development
SA	=	small arms
SACLOS	=	semiautomatic command-to-line-of-sight
SAE	=	Society of Automotive Engineers
SAH	=	semiactive homing
SAM	=	surface-to-air missile
SAR	=	search and rescue
SAS	=	stability augmentation subsystem
SBF	=	support by fire
SDD	=	systems development and demonstration
SEA	=	Southeast Asia
SEAD	=	suppression of enemy air defenses
SEKE	=	spherical earth/knife edge
SEMA	=	special electronic mission aircraft
SER	=	system evaluation report
SGR	=	sortie generation rate
SHORAD	=	short-range air defense
SIGINT	=	signal intelligence
SL	=	sea level
SLAD	=	Survivability and Lethality Analysis Division
SLV	=	survivability/lethality and vulnerability
SOA	=	Special Operations Aviation
SOAR	=	Special Operations Aviation Regiment
SOCOM	=	Special Operations Command
SOF	=	Special Operations Force
SOJ	=	stand-off jamming/jammer
SON	=	statement of need
SORO	=	scan-on-receive-only
SPEX	=	simple passive extinguisher
SR	=	susceptibility reduction
SR	=	survival rate
SSA	=	system safety assessment
STAMPS	=	strategic/tactical automated mission planning system
STAR	=	system threat assessment report
STEP	=	simulation, test, and evaluation process
STOVL	=	short takeoff and vertical landing
SuBEC	=	survivability biased engine control
SUBSAM	=	subsurface-to-air missile/submarine surface-to-air missile
SURVIAC	=	Survivability/Vulnerability Information Analysis Center
SWIR	=	shortwave infrared
S&A	=	safety and arming
TALD	=	tactical air-launched decoy
TAMPS	=	tactical mission planning system
TAR	=	target acquisition radar
TARCAP	=	target area combat air patrol
TARPS	=	tactical air reconnaissance pod system
TBM	=	tactical ballistic missile

TBM	=	theater ballistic missile
TDD	=	target detection/detecting device
TECOM	=	Test and Evaluation Command
TEL	=	transporter-erector-launcher
TEMP	=	test and evaluation master plan
TEMS	=	test and evaluation modeling and simulation
TI	=	thermal imaging
TLAM	=	Tomahawk Land Attack Missile
TMD	=	theater missile defense
TOGW	=	takeoff gross weight
TOT	=	time on target
TOW	=	tube-launched, optically tracked, and wire guided
TRAP	=	tactical recovery of aircraft and personnel
TREE	=	transient radiation effects on electronics
TTR	=	target tracking radar
TVM	=	track via missile
TWS	=	track-while-scan
T&E	=	test and evaluation
UAV	=	unmanned aerial vehicle
UCAV	=	unmanned combat aerial vehicle
UHF	=	ultra high frequency
UTTAS	=	utility tactical transport aircraft system
UV	=	ultraviolet
UWB	=	ultrawideband
VERTREP	=	vertical replenishment
V/L	=	vulnerability/lethality
VR	=	vulnerability reduction
V/STOL	=	vertical/short takeoff and landing
VT	=	variable time (implied)
VTOL	=	vertical takeoff and landing
VV&A	=	verification, validation, and accreditation
WEZ	=	weapon engagement zone
WMD	=	weapons of mass destruction
WSL	=	Weapons Survivability Laboratory
WSMR	=	White Sands Missile Range
WW	=	Wild Weasel

Chapter 1
Introduction to the Aircraft Combat Survivability Discipline

1.1 Overview of the Fundamentals

1.1.1 What Is Aircraft Combat Survivability?

Learning Objective	**1.1.1**	**Describe the aircraft attributes of combat survivability, susceptibility, vulnerability, and killability.**

Aircraft combat survivability (ACS) is defined here as the capability of an aircraft to avoid or withstand a man-made hostile environment.

The inability of an aircraft to avoid the guns, approaching missiles, exploding warheads, air interceptors, radars, and all of the other elements of an enemy's air defense that make up the man-made hostile mission environment is referred to as the susceptibility of the aircraft. The more likely an aircraft on a mission is physically impacted or hit by one or more damage (causing) mechanisms generated by the warhead on a threat weapon, the more susceptible is the aircraft. The susceptibility of an aircraft is influenced by the following:

- the location, number, and capabilities of the enemy air defense weapons (e.g., the location of large numbers of surface-to-air guided missile systems (SAMs), with excellent detection, tracking, guidance, and intercept capabilities, along the aircraft's flight path increases the aircraft's susceptibility)
- the aircraft's basic design (e.g., the use of smokeless engines and low radar and infrared signatures to degrade the enemy's detection capabilities and speed and agility to avoid any approaching enemy aircraft or missiles reduces susceptibility)
- the ordnance, survivability equipment, and self-defense weapons the aircraft carries to avoid the hostile environment (e.g., the use of long range stand-off weapons to attack the enemy, onboard electronic attack equipment to degrade enemy tracking and missile guidance systems, and missiles and guns to destroy attacking enemy aircraft reduces susceptibility)
- the aircraft tactics that are employed (e.g., the use of terrain masking to avoid detection, high altitude flight to avoid the surface-based guns and small SAMs, and fighter escorts to suppress or destroy the enemy air interceptors reduces susceptibility)

The inability of an aircraft to withstand the man-made hostile environment is referred to as the vulnerability of the aircraft. The more likely an aircraft is killed by the hits by the damage mechanisms from the warhead on a threat weapon (for example, the high velocity metal fragments and blast from an exploding warhead), the more vulnerable is the aircraft. The vulnerability of an aircraft is influenced by the following:

- the size, type, and number of the enemy's warheads that hit the aircraft (e.g., increasing the size of a ballistic projectile and increasing the number of direct hits by the projectiles increase the aircraft's vulnerability)
- the aircraft's basic design (e.g., fuel tanks separated from engine air inlets to prevent fuel ingestion by an engine due to a hit on a fuel tank and two engines widely separated so that a single hit will not kill both engines reduce vulnerability)
- the survivability equipment that reduces the amount and the effects of damage when the aircraft takes one or more hits (e.g., reticulated foam inside the fuel tanks to suppress explosions when hit and a flight control system that automatically compensates for any control degradation due to combat damage reduce vulnerability)

Note that both susceptibility and vulnerability are negative attributes of an aircraft; they refer to the inability of the aircraft to avoid and to withstand the man-made hostile environment, respectively.

The inability of the aircraft to both avoid and withstand the man-made hostile environment, that is, the ease with which the aircraft is killed by the enemy air defense, is referred to here as the aircraft's killability. Thus, the killability of an aircraft is reduced, and hence the survivability of the aircraft is increased, when susceptibility or vulnerability are reduced (Note 1).

Go to Problems 1.1.1 to 1.1.14.

1.1.2 How Do We Measure Survivability?

Learning Objective	**1.1.2**	**Describe how survivability, susceptibility, vulnerability, and killability are measured for both contact and proximity warheads.**

When an aircraft takes off on a combat mission, no a priori prediction regarding the survival of the aircraft can be made with certainty. Perhaps the aircraft will survive the mission, and perhaps it will not. Perhaps a gunner will pick your aircraft to shoot at, and perhaps he or she will not. Perhaps a fire will start when your aircraft is hit by the gunner's bullet, and perhaps it will not. If there is a fire, perhaps it will result in the loss of the aircraft, and perhaps it will not.

In any mission scenario there are many random variables similar to those just described that will influence an aircraft's survivability. As a consequence of these uncertainties, an aircraft's survival in combat is not a deterministic outcome that can be predicted with certainty; it is instead a random outcome: perhaps the aircraft will survive, and perhaps it will not.

As a consequence of the random nature of combat, aircraft survivability is measured by a probability. This probability is denoted as P_S, the probability the aircraft will survive. The probability of survival varies from 0 to 1; the closer the value is to 1, then the more survivable is the aircraft. The meaning and specific value of P_S will depend upon the particular scenario of interest. For example, P_S might refer to the probability the aircraft survives a mission, or it might refer to the probability the aircraft survives an encounter with a SAM (Note 2).

If the aircraft does not survive the mission or the encounter, it is said to be killed. The word kill is used here in the general sense. It could refer to an attrition kill, in which the aircraft is destroyed or downed by the air defense. Or it could refer to a mission abort kill, in which the damage inflicted on the aircraft by the air defense compels the pilot to return to base prior to achieving the mission objectives. The attrition kill is time dependent. For example, an aircraft might be destroyed immediately when hit by a large SAM, defined as a KK-level attrition kill; or it may fall out of control within 30 min after a nearby detonation of a proximity-fuzed high-explosive (HE) shell from an antiaircraft artillery (AAA) piece, defined as a B-level attrition kill (Note 3).

Aircraft killability is measured by the probability the aircraft is killed P_K (Note 4). Aircraft survivability and aircraft killability are said to be mutually exclusive and exhaustive outcomes, that is, the aircraft either survives or is killed and there are no other outcomes considered. Hence, the probability P_S is the complement of P_K. Thus,

$$P_S = 1 - P_K \tag{1.1}$$

or

$$\text{Survivability} = 1 - \text{Killability}$$

Aircraft killability is dependent upon both the susceptibility of the aircraft (the aircraft must be hit to be killed) and the vulnerability of the aircraft (the hit must cause sufficient damage to kill the aircraft). The measures of susceptibility and vulnerability depend upon the type of warhead on the threat weapon. Warheads come in two basic types: those that must hit the aircraft to kill it, and those that can kill the aircraft from a distance.

The first type of warhead is referred to as a hit-to-kill or contact warhead. Examples of contact warheads are ballistic penetrators, such as the 7.62- and 12.7-mm armor piercing (AP) projectiles fired from guns, contact-fuzed HE shells fired from guns, such as the 23- and 30-mm high explosive incendiary (HE-I) projectiles, and SAMs with contact-fuzed HE warheads, such as a man-portable air defense system (MANPADS). The second type of warhead is an HE warhead with a proximity fuze. The target detection device (TDD) used by the proximity fuze detects the presence of the nearby aircraft, and the fuze detonates the high explosive material at the right time. The HE detonation creates a blast wave and high-velocity metal fragments from the warhead case that propagate from the detonation point outward toward the aircraft in a relatively narrow fragment spray zone. If a part of this fragment spray zone hits the aircraft, the fragment impacts might result in a kill of the aircraft. This type of warhead will be referred to as a proximity warhead. Most of the medium and large ballistic projectiles and SAMs have an HE warhead with both a contact fuze and a proximity fuze.

An aircraft's susceptibility to a direct hit by a contact warhead can be measured by P_H, the probability the aircraft is hit by the warhead. Aircraft susceptibility to proximity warheads can be measured by P_F, the probability of successful proximity fuzing.

An aircraft's vulnerability to contact warheads can be measured by $P_{K|H}$, the conditional probability that the aircraft is killed given that it is hit by a warhead. Aircraft vulnerability to proximity warheads can be measured by $P_{K|F}$, the conditional probability that the aircraft is killed given successful proximity fuzing.

An aircraft will be killed when it is hit by a contact warhead, or a proximity warhead fuzes, and the hit, or fuzing, causes sufficient damage to the aircraft to kill it. Thus, the probability of kill of the aircraft (the aircraft's killability) P_K is the joint probability of the probability of hit or fuzing (the aircraft's susceptibility) P_H or P_F and the conditional probability of kill given a hit or fuzing (the aircraft's vulnerability) $P_{K|H}$ or $P_{K|F}$ (Note 5). Thus,

$$P_K = P_H P_{K|H} \quad \text{or} \quad P_K = P_F P_{K|F} \tag{1.2}$$

or

$$\text{Killability} = \text{Susceptibility} \cdot \text{Vulnerability}$$

Substituting P_K given by Eq. (1.2) into Eq. (1.1) for P_S gives

$$P_S = 1 - P_K = 1 - P_H P_{K|H} \quad \text{or} \quad P_S = 1 - P_K = 1 - P_F P_{K|F} \tag{1.3}$$

or

$$\text{Survivability} = 1 - \text{Killability} = 1 - \text{Susceptibility} \cdot \text{Vulnerability}$$

Equation (1.3) can be derived from a different point of view. According to the definition of aircraft combat survivability, an aircraft will survive if it avoids or withstands the man-made hostile environment. Considering weapons that use contact warheads, the inability of the aircraft to avoid the hostile environment is measured by P_H. Thus, the ability of the aircraft to avoid the hostile environment is the complement of P_H or NOT P_H and is denoted by P_H^c. The inability of the aircraft to withstand the contact warhead hostile environment is measured by $P_{K|H}$. Consequently, the capability of the aircraft to withstand the hostile environment is the complement of $P_{K|H}$ or NOT $P_{K|H}$ and is denoted by $P_{K|H}^c$. Thus, the definition of survivability can be written as

$$P_S = P_H^c + P_H P_{K|H}^c \tag{1.4a}$$

Note that $P_H + P_H^c = 1$ and $P_{K|H} + P_{K|H}^c = 1$. Using these two relationships in

Eq. (1.4a) results in

$$P_S = (1 - P_H) + P_H(1 - P_{\mathrm{K|H}}) = 1 - P_H P_{K|H} \tag{1.4b}$$

which is identical to Eq. (1.3) for the contact warhead. The same conclusion holds for the proximity warhead.

In simple words, if you want to survive, don't get hit; but if you do get hit, don't die. The battle damage repair community adds and if you don't die, get repaired quickly.

Go to Problems 1.1.15 to 1.1.18.

1.1.3 Why Do We Need Survivability? Because of Threats! What Are Those Threats?

Learning Objectives	**1.1.3**	**Describe the two major categories of threat weapons, list some of the current gun and missile threats to aircraft, and describe the weapon envelope.**
	1.1.4	**Describe the STAR.**

Combat survivability is a critical system characteristic of military aircraft because of the man-made hostile environment in which they operate. Consequently, the estimated effectiveness or lethality of the anticipated enemy air defense plays a primary role in the emphasis placed upon the survivability design and operation of military aircraft. When the enemy has effective weapons, aircraft must be designed and operated to reduce the effectiveness of those weapons to an acceptable level (Note 6).

1.1.3.1 Threat weapons: conventional and unconventional. The man-made threats to aircraft are divided into two categories: conventional weapons and unconventional weapons. Conventional weapons consist of all weapons that are neither nuclear, biological, nor chemical.[1] The nuclear, chemical, and biological weapons are known as unconventional weapons. One distinction between the two categories of weapons is the number of people that can be killed by one weapon. Guns, guided missiles, and the directed energy weapons typically attack one relatively small target at a time, whereas a nuclear, chemical, or biological weapon has the capability to kill many targets and people. The unconventional weapons are also referred to as weapons of mass destruction (WMD).[1]

The most common conventional threats today to U. S. military aircraft, as illustrated by the F/A-18 Hornet in Fig. 1.1c, are the guns and air-to-air missiles carried by aircraft, such as the one shown in Fig. 1.1a, the surface-to-air guns, such as the ones shown in Fig. 1.1b, and the surface-to-air guided missiles, such as the man–portable SAM and the vehicle–mounted SAM system shown in Fig. 1.1d and 1.1e, respectively. These threats are the "traditional" threats to aircraft and are the threats that are covered in this textbook. Table 1.1 lists some of the current antiaircraft

a) b) c) d) e)

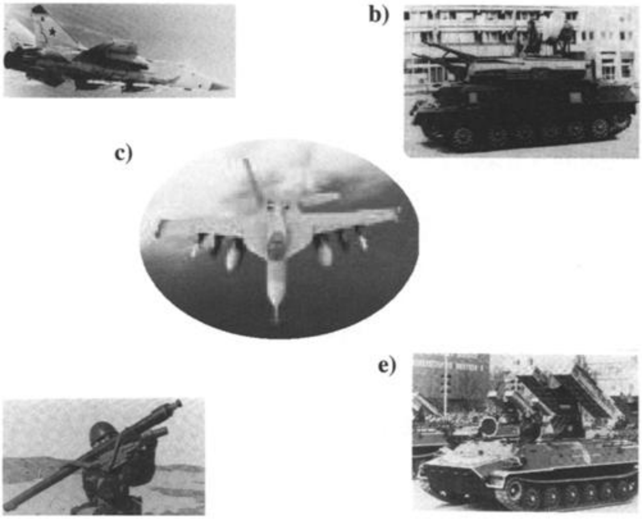


Fig. 1.1 Gun and missile threats to aircraft.

guns and missiles that could be a threat to U. S. aircraft (Note 7). These weapons can operate autonomously, or in small groups, or they can be part of a large-scale, integrated air defense system (IADS) with surveillance sensors, data filter centers, command centers, and weapon-firing platforms, all linked together as illustrated in Fig. 1.2.

In any of these situations, each weapon is assigned a specific volume or surface area to protect from attacking aircraft. The extent of the volume or area a weapon can successfully defend is defined by the weapon's envelope. For surface-based weapons this envelope is a three-dimensional envelope that extends around the weapon, typically in an irregular fashion because of line-of-sight restrictions and other limitations associated with the aircraft's flight path. For simplicity, a surface-based weapon's envelope can be idealized as a hemisphere located above the surface with the weapon at the center. The circumference of the hemisphere defines the extent of the surface area defended by the weapon, as illustrated by the circle around the SAM site A in Fig. 1.2. Aircraft that are inside this envelope can be detected, engaged, and killed by the weapon with a P_K that is at or above a certain value, such as 0.8 or 0.5. Aircraft that are outside of the weapon envelope have a P_S that is greater than 0.2 or 0.5, respectively. The maximum extent of the overlapping SAM envelopes forms the SAM ring around the targets as depicted in Fig. 1.2. Similarly, the radar ring indicated in the figure is the maximum extent the early warning radars can detect incoming aircraft.

For enemy aircraft with air-to-air missiles, the extent of the weapon's effectiveness is referred to as the launch acceptable region (LAR). In the case of air-launched weapons, the shooter aircraft is relatively free to move around the target aircraft. Consequently, the effectiveness envelope for air-to-air weapons is drawn around the target aircraft rather than around the launching aircraft. When the shooter is

Table 1.1 Some current antiaircraft weapons

Country	Surface-to-air gun system	Surface-to-air missile system/missile	Air-to-air gun system	Air-to-air missile system/missile
France	——	Roland[a]	——	R.550 Magic[b]
Italy	——	Aspide[c]	——	——
Israel	——	——	——	Shafrir[d]
Japan	——	Keiko[e]	——	——
People's Republic of China	——	HQ-2[f]	——	——
Russian Federation	ZSU-23-4 Shilka, 4 × 23 mm[g]	SA-2 Guideline[f]	Gsh-23, 2 × 23 mm[h]	AA-10/Alamo[i]
	AK-630, 6 × 30 mm (naval)[j]	SA-6 Gainful[k]		AA-11/Archer[i]
		SA-10/S-300 Grumble[m]		AA-12/Adder[i]
	Tunguska 2S6, 2×30 mm[l]	SA-13 Gopher[n]		
	S-60, 57 mm[o]	SA-16 Gimlet[p]		
	KS-19, 100 mm[q]	SA-N-4 Gecko(naval)[r]		
Sweden	——	RBS 70/Rayrider[s]	——	——
Switzerland	Oerlikon Contraves,[t] 2×25 mm, 2×35 mm	——	——	——

(Continued)

Table 1.1 Some current antiaircraft weapons (Continued)

Country	Surface-to-air gun system	Surface-to-air missile system/missile	Air-to-air gun system	Air-to-air missile systems/missile
United Kingdom	—	Rapier[u] Sea Wolf (naval)[w]	—	Sky Flash[v]
United States	—	Stinger/FIM-92[x]	Vulcan M61,[y] 6×20 mm	—

[a] Data online at http://www.wsmr.army.mil/paopage/Pages/Roland.htm.
[b] Data online at http://www.fas.org/man/dod-101/sys/missile/row/magic.htm.
[c] Data online at http://www.analisidifesa.it/image7/aspide.htm.
[d] Data online at http://danshistory.com/arms.shtml.
[e] Data online at http://jmr.janes.com/samples/sample5/html.
[f] Data online at http://www.fas.org/nuke/guide/russia/airdef/v-75.htm.
[g] Data online at http://www.fas.org/man/dod-101/sys/land/row/zsu-23-4.htm.
[h] Data online at http://www.zid.ru/en/products/military/gsh23.html and http://www.canit.se/~griffon/aviation/text/akandata.htm.
[i] Data online at http://www.wonderland.org.nz/raa.htm.
[j] Data online at http://www.fas.org/man/dod-101/sys/ship/row/rus/1144.htm.
[k] Data online at http://www.fas.org/man/dod-101/sys/missile/row/sa-6.htm.
[l] Data online at http://www.aeronautics.ru/tunguskaphotos.htm.
[m] Data online at http://www.cdiss.org/mos_as1.htm.
[n] Data online at http://www.army.mil/cmh-pg/books/www/289b.htm.
[o] Data online at http://www.army.mil/cmh-pg/books/www/286c.htm.
[p] Data online at http://hometown.aol.com/threatmstr/airdef.htm.
[q] Data online at http://www.fas.org/man/dod-101/sys/land/row/ks-19.htm.
[r] Data online at http://www.wonderland.org.nz/rnsa.htm.
[s] Data online at http://www.periscope1.com/demo/weapons/missrock/antiair/.
[t] Data online at http://www.oerlikoncontraves.com/ and http://translate.google.com/translate?hl=en&sl=it&u=http://www.oerlikoncontraves.it/&prev=/search%3Fq%3Doerlikon%2BContraves%26hl%3Den%265a%3DG.
[u] Data online at http://www.singaporerapier.com/member.html.
[v] Data online at http://www.raf.mod.uk/airpower/airtoair.html.
[w] Data online at http://web.ukonline.co.uk/aj.cashmore/.weapons/sam.html.
[x] Data online at http://www.janes.com/defence/air_forces/news/jlad/jlad001013_2_n.shtml and http://www.fas.org/man/dod-101/sys/land/stinger.htm.
[y] Data online at http://www.wpafb.af.mil/museum/arm/arm8.htm.

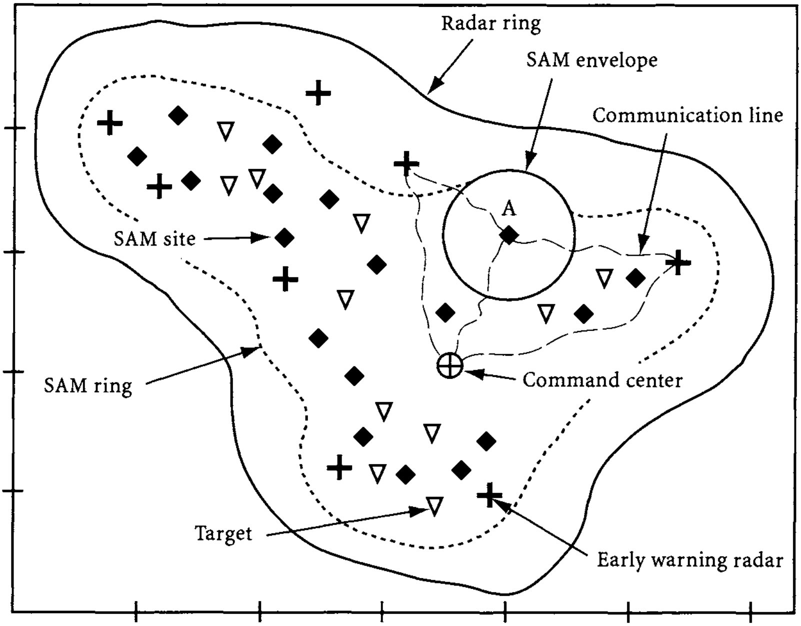


Fig. 1.2 Notional integrated air defense system (adapted from Ref. 2, reprinted with permission).

inside the LAR, the P_K associated with a shot is at or above a selected value, such as 0.8 or 0.5.

Other potential threats to aircraft now, or in the near future, include the conventional directed energy (DE) weapons (DEW), such as the low-, medium-, and high-power laser weapons and the high-power microwaves (HPM), and the unconventional chemical and biological (CB) and nuclear weapons. The combination of the chem-bio weapons and the residual radiation associated with the nuclear weapons is referred to as the nuclear, biological, and chemical (NBC) threat or the chemical, biological, and radiation threat (CBR). These weapons are briefly described later in this section.

1.1.3.2 Threat assessment. Perhaps one of the most important tasks in any aircraft development program is the prediction of the threats the aircraft could encounter over its operational lifetime. It is extremely important that the type of threats and the threat capabilities not be overestimated, leading to an aircraft that is overly expensive for its role. Neither should they be underestimated, leading to a killable aircraft that will not be effective in the role for which it was designed. This guidance is easier to write than to follow (Note 8). The life span of an aircraft from program inception to removal from service can exceed 50 years. Consequently, an aircraft that begins life in 2002, when the threats are primarily guns and missiles, can still be in operation, in one form or another, in 2052, when the threats could include the DE weapons, CB agents, and nuclear threats, in addition to significantly improved guns and missiles (Note 9).

Combining the difficulty in predicting the future threats with the uncertain future political environment and the additional roles and missions the aircraft might be called upon to perform leads one to the conclusion that the design threats should not be just the threats of the day, but must include the threats of the future. The U. S. Department of Defense's mission need statement that precedes the start of any new aircraft acquisition program must specifically state the threats to be countered by the proposed system. The document that defines the threats to the system is known as the system threat assessment report (STAR). The analysis that identifies the predicted encounter conditions between the aircraft and the threats identified in the STAR is known as the mission-threat analysis. This analysis is described in Chapter 3, Sec. 3.9.

Go to Problems 1.1.19 to 1.1.24.

Note: The material in the following three sections (Sections 1.1.4, 1.1.5, and 1.1.6) contains a relatively detailed presentation of the various probabilities used in survivability assessment. The reader who is not interested in this level of detail and is tempted to skip these sections is encouraged to study Fig. 1.3 and Examples 1.1–1.5 before proceeding to Sec. 1.1.7, How Is Survivability Enhanced?

1.1.4 One-on-One or Engagement-Level Survivability Assessment

Learning Objective	**1.1.5**	**Describe the tree diagram for the one-on-one scenario, including the terminology and the probabilities for the various portions of the tree.**

When an aircraft flies into a geographical area, or volume of air space, defended by one threat weapon, or is assigned as a target to only one weapon out of several weapons, the scenario is referred to as a one-on-one scenario or encounter between the aircraft and the threat weapon. The assessment of the survivability of the aircraft in the one-on-one scenario is referred to as an engagement-level survivability assessment. A simple procedure for estimating the aircraft's survivability is described next. This procedure is not intended to be a detailed assessment; instead, its purpose is to illustrate the major phases and outcomes that occur in the one-on-one scenario and to define the terminology and the probability associated with each of the phase outcomes.

1.1.4.1 Scenario phases. The one-on-one scenario can be divided into two portions: the susceptibility portion and the vulnerability portion. The susceptibility portion can be divided into five sequential phases. Within each phase there are one or more operational functions that must be performed by the various elements of the air defense. To hit the aircraft, the threat weapon must perform the following:

1) Search for the aircraft.
2) Detect the aircraft.
3) Engage the aircraft by firing a gun or launching a missile at the aircraft.

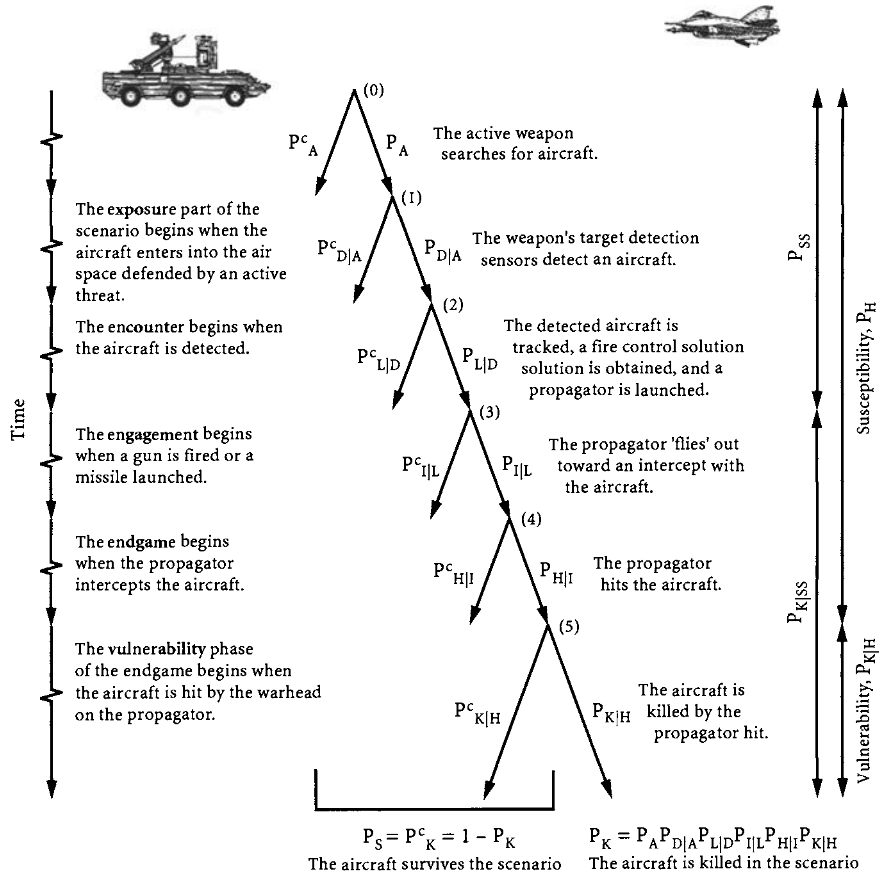


Fig. 1.3 Tree diagram for the one-on-one scenario (single shot).

4) The gun-fired ballistic projectile or the guided missile, both known as the threat propagator, must 'fly out' and intercept the aircraft.

5) The damage mechanisms carried by the warhead on the propagator must hit the intercepted aircraft, either by a direct hit or by proximity fuzing.

The final phase of the one-on-one scenario is the vulnerability phase. To kill the impacted aircraft, the following must occur:

6) The damage mechanisms that hit the aircraft must kill one or more of the aircraft's critical components, resulting in the loss of an essential function for flight or mission completion.

In every one-on-one scenario each of these phases will end with either a successful outcome (from the enemy's point of view) at some point in time during the scenario or an unsuccessful outcome during the entire phase. For example, suppose an aircraft enters into an area defended by a gunner with a shoulder-mounted, infrared-guided SAM. If the gunner is scanning the defended area looking for aircraft, the threat is said to be active, which is defined as a successful outcome for phase 1. If this active threat, the gunner with the infrared (IR) SAM, subsequently detects the aircraft at some particular time during the scenario, known as the detection event on the time line, the outcome of phase 2 is deemed successful, and the scenario proceeds to phase 3. On the other hand, if either the gunner or the IR SAM does not detect the aircraft as it passes through the defended area, the outcome of phase 2 is deemed unsuccessful (detection does not occur), and the one-on-one scenario ends.

1.1.4.2 Scenario tree diagram and the outcome probabilities. The successful and unsuccessful outcomes of each of the six sequential phases of the one-on-one scenario just described can be illustrated using the tree diagram shown in Fig. 1.3 (Note 10). In the tree diagram each downward arrow is a branch of the tree. From the enemy's point of view, each tree branch to the right represents a successful outcome of a particular phase at some time during the scenario, and each branch to the left (a NOT branch) represents an unsuccessful outcome for that phase. Associated with each branch is the outcome probability. The sum of the two outcome probabilities for each phase is unity.

An aircraft will be killed only when each of the six phases has a successful outcome. If a large number of similar scenarios are examined, the likelihood or probability that each phase will have a successful outcome sometime during the scenario, given that the preceding phases were successful, can be estimated with a conditional probability. The likelihood of a successful outcome for each of the five susceptibility phases can be measured by the following probabilities:

1) P_A is the probability that a threat weapon in the vicinity of the aircraft is active, that is, the weapon is searching, actively or passively, and ready to encounter and engage aircraft flying within its defended area.

2) $P_{D|A}$ is the conditional probability that the aircraft is detected, given that the threat is active.

3) $P_{L|D}$ is the conditional probability that the aircraft is tracked, a fire control solution is obtained, and a missile is launched or a gun is fired at the aircraft, given that the threat was active and detected the aircraft.

4) $P_{I|L}$ is the conditional probability that the threat propagator approaches or intercepts the aircraft, given that the propagator was launched or fired at the aircraft.

5) $P_{H|I}$ (or $P_{F|I}$) is the conditional probability that the propagator hits the aircraft (or a proximity warhead fuzes), given that the propagator has intercepted the aircraft.

The final phase of the one-on-one scenario is the vulnerability phase. The probability of a successful outcome for the air defense in this phase is $P_{K|H}$ (or $P_{K|F}$), where the following applies:

6) $P_{K|H}$ (or $P_{K|F}$) is the conditional probability that the aircraft is killed, given a direct hit by the propagator (or given a proximity-fuzed warhead detonation).

Each path down one or more sequential branches of the tree diagram is referred to as an event. The probability any particular path down the tree (an event) occurs in the scenario is the joint probability, also known as the logical product or intersection, of the outcome probabilities associated with each of the sequential branches along the path.

1.1.4.3 Example scenario. The example scenario takes place at night. The threat weapon is a radio-frequency (RF) or radar-directed guided missile system with an HE contact warhead on the missile. The scenario begins at the top of the tree at node (0) when the aircraft flies into the area defended by the threat weapon. The aircraft is exposed to an active, searching threat with the probability P_A. The term exposure refers to the situation where the aircraft is within the area defended by the active threat. The aircraft is not exposed to an active threat with the probability P_A^c, where $P_A^c = 1 - P_A$.

If the aircraft is not exposed to an active threat, it has survived the scenario. For example, if the night attack is a surprise and the missile crew is not ready to begin searching as the aircraft flies through the defended area, the threat is inactive and therefore incapable of killing the aircraft. Another example of an inactive threat occurs when the enemy's search radar or missile launching platform is destroyed by either the attacking aircraft or the friendly supporting forces. The probability that either of these situations occurs is P_A^c. When the aircraft's flight path is routed around the area defended by the weapon, or when the use of long-range or stand-off precision-guided munitions (PGMs) allows the aircraft to remain outside of the defended area, $P_A = 0$ (Note 11).

If the aircraft is exposed to an active threat, the scenario proceeds down the right branch of the tree from node (0) to (1). At node (1) detection of the aircraft by the active threat occurs with the probability $P_{D|A}$ and does not occur with the probability $P_{D|A}^c$. Detection can occur when the exposed aircraft's radar signature is sufficiently large to be seen by the enemy's radar. Because detection is dependent upon the relative location of the aircraft to the active threat radar, the specific value of $P_{D|A}$ depends upon the aircraft location at the scenario time of interest. In general, the closer the aircraft is to the radar, the more likely that it will be detected. The probability the event where the active threat detects the aircraft occurs is given by the joint probability of the two outcomes $P_A P_{D|A}$. If the aircraft is exposed to the scanning radar as it proceeds on its mission, but is never detected by the radar because its echo is below the threshold value for detection or because the noise from a friendly standoff electronic jamming (SOJ) aircraft has obscured the echo, it has survived the scenario (Note 12). The probability of this survival event where the active threat does not detect the aircraft is given by $P_A P_{D|A}^c$.

If the aircraft is eventually detected, the scenario proceeds down the right branch from node (1) to (2), and the encounter begins. At node (2) the aircraft is tracked for a sufficient period of time to obtain a firing solution, and the missile is launched with the probability $P_{L|D}$. The probability the missile is not launched at the detected aircraft is $P_{L|D}^c$. The probability the event where the active threat detects the aircraft and launches a missile occurs is given by $P_A P_{D|A} P_{L|D}$, and the probability the event where the active threat detects the aircraft but does not launch a missile occurs is given by $P_A P_{D|A} P_{L|D}^c$.

If the SAM installation launches a missile, the scenario proceeds down the right branch from node (2) to (3), and the engagement begins. In this example scenario only one missile is fired at the aircraft. If the launched missile comes sufficiently close to the target so that the warhead on the missile has a possibility of killing the approaching target, a successful intercept is said to occur. At node (3) a successful intercept occurs with the probability $P_{I|L}$, and a successful intercept does not occur with the probability $P_{I|L}^c$.

If an intercept occurs, the scenario proceeds down the right branch from node (3) to (4) where the endgame begins. At node (4) the missile either hits the intercepted aircraft with the probability $P_{H|I}$, or the intercepted aircraft is not hit with the probability $P^c_{H|I}$.

If the aircraft is hit, the vulnerability phase of the endgame begins, and the process proceeds from node (5) down the right branch to the final outcome where the aircraft is killed by the hit with the probability $P_{K|H}$ or down the left branch where it is not killed with the probability $P^c_{K|H}$.

If the warhead on the missile was a proximity warhead instead of a contact warhead, the probability of hit given an intercept $P_{H|I}$ is replaced with the probability of warhead proximity fuzing given an intercept $P_{F|I}$, and the probability of kill given a hit $P_{K|H}$ is replaced with the probability of kill given fuzing $P_{K|F}$.

Go to Problems 1.1.25 to 1.1.30.

1.1.4.4 Scenario event probabilities for a single shot.

Learning Objectives	**1.1.6**	**Compute P_H, P_F, P_K, $P_{E|A}$, P_E, P_{SS}, $P_{H|SS}$, $P_{F|SS}$, and $P_{K|SS}$ for a single shot in a one-on-one scenario.**
	1.1.7	**Compute P_S for a single shot in a one-on-one scenario.**

Each of the five sequential phases of the susceptibility portion of the scenario just described must have a successful outcome to achieve a hit or proximity fuzing on the aircraft. Thus, the probability the aircraft is hit, or proximity fuzing occurs, is the joint probability that these five phases were successful. This joint probability is given by the logical product of the five individual probabilities of success along the path down the right side of the tree from node (0) to (5). Thus, the probability the aircraft is hit by a single shot as it flies through the area assigned to the weapon is given by

$$P_H = P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I} \tag{1.5a}$$

Similarly, the probability of fuzing is given by

$$P_F = P_A P_{D|A} P_{L|D} P_{I|L} P_{F|I} \tag{1.5b}$$

The aircraft can be killed in this one-on-one scenario only by proceeding down all six branches on the right side of the tree diagram shown in Fig. 1.3. The path down the six branches is sometimes referred to as the kill chain. Thus, the probability the aircraft is killed by a threat with a contact warhead is given by

$$P_K = (P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I}) P_{K|H} = P_H P_{K|H} \tag{1.5c}$$

Similarly, the probability the aircraft is killed by a threat with a proximity warhead is given by

$$P_K = (P_A P_{D|A} P_{L|D} P_{I|L} P_{F|I}) P_{K|F} = P_F P_{K|F} \tag{1.5d}$$

Several of the probabilities shown in Fig. 1.3 and given in Eqs. (1.5a–1.5d) can be combined to give other probabilities of interest. For example, the logical product of $P_{D|A}$ and $P_{L|D}$ has been referred to as the engageability of the aircraft given an active weapon $P_{E|A}$ (Ref. 3). Thus (Note 13),

$$P_{E|A} = P_{D|A} P_{L|D} \tag{1.5e}$$

The probability the aircraft is engaged in the scenario P_E is the joint probability that the threat weapon is active P_A and the conditional probability that the aircraft is engaged given the weapon is active $P_{E|A}$. Thus,

$$P_E = P_A P_{E|A} = P_A(P_{D|A} P_{L|D}) \tag{1.5f}$$

When the engagement consists of a single shot, P_E can be replaced with P_{SS}, the probability a single shot is taken in the scenario. Consequently,

$$P_E \text{ (single shot)} = P_{SS} \tag{1.5g}$$

The logical product of $P_{\mathrm{I|L}}$ and $P_{\mathrm{H|I}}$ for the single shot has been referred to as the hitability of the engaged aircraft $P_{H|SS}$ (Ref. 3). Therefore,

$$P_{H|SS} = P_{I|L} P_{H|I} \quad \text{or} \quad P_{F|SS} = P_{I|L} P_{F|I} \tag{1.5h}$$

Jointly combining the probabilities $P_{H|SS}$ and $P_{K|H}$ and the probabilities $P_{F|SS}$ and $P_{K|F}$ gives the probability of kill given an engagement by a single shot $P_{K|SS}$, also denoted as P_{SSK}, the probability of a single-shot kill. Thus,

$$P_{K|SS} = P_{H|SS} P_{K|H} \quad \text{or} \quad P_{K|SS} = P_{F|SS} P_{K|F} \tag{1.5i}$$

Jointly combining the probability that the aircraft is engaged in the scenario with a single shot P_{SS} and the probability that the aircraft is killed given the single-shot engagement $P_{K|SS}$ results in another general equation for the weapon's ability to kill the aircraft in the single-shot scenario

$$P_K = P_{SS} P_{K|SS} \tag{1.5j}$$

From the point of view of the enemy air defense, P_K is the (measure of the) effectiveness of their weapon system, $P_{K|SS}$ is the weapon's lethality or the effectiveness of the weapon in flight, and $P_{K|H}$ or $P_{K|F}$ is the lethality of the munition or the warhead on the weapon.

1.1.4.5 Aircraft survival in the single-shot scenario. Aircraft survival in this one-on-one, single-shot scenario is achieved by going down a path containing any one of the NOT branches on the left side of the tree shown in Fig. 1.3. Each NOT branch represents a failure of the enemy weapon to complete a particular phase in the scenario successfully, and hence each failure is a break in the kill chain. For example, the aircraft survives the scenario if a weapon is active, detects the aircraft, and engages the aircraft, but the threat propagator does not intercept the aircraft. The probability this particular event occurs is given by the product of the probabilities of the four branches along that particular path or $P_A P_{D|A} P_{L|D} P^c_{I|L}$.

The probability the aircraft survives the one-on-one scenario is given by the logical sum or union of all of the paths down the tree that eventually end in a NOT branch. The union of all of these NOT paths is the complement of the joint combination of right side branches that lead to the kill of the aircraft P_K. Thus, for the contact warhead weapon

$$\begin{aligned} P_S = P^c_K &= 1 - P_K = 1 - P_H P_{K|H} \\ &= 1 - (P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I}) P_{K|H} \end{aligned} \tag{1.5k}$$

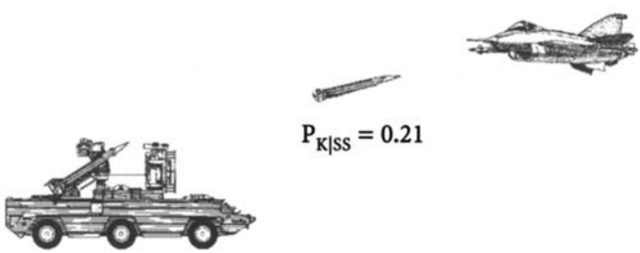
according to Eq. (1.5c). If the warhead contains a proximity warhead,

$$\begin{aligned} P_S = P^c_K &= 1 - P_K = 1 - P_F P_{K|F} \\ &= 1 - (P_A P_{D|A} P_{L|D} P_{I|L} P_{F|I}) P_{K|F} \end{aligned} \tag{1.5l}$$

according to Eq. (1.5d).

Example 1.1 illustrates the assessment of engagement-level survivability for the single-shot scenario.

Example 1.1 One-on-One Survivability (Single Shot)



Suppose 10 aircraft are sent on an interdiction mission to a target defended by several gun and RF SAM installations. Suppose one of the mission aircraft enters into the area defended by one of the SAM firing units. The SAM has a contact-fuzed HE warhead, and the firing doctrine is to fire one missile at the target aircraft. Assume the following probabilities for the susceptibility portion of the scenario:

$$P_A = 1.0 \quad P_{D|A} = 0.8 \quad P_{L|D} = 0.9 \quad P_{I|L} = 0.6 \quad P_{H|I} = 0.7$$

Hence, according to Eqs. (1.5f), (1.5g), (1.5h), and (1.5a),

$$P_E = P_{SS} = 1.0 \cdot 0.8 \cdot 0.9 = 0.72$$

$$P_{H|SS} = 0.6 \cdot 0.7 = 0.42$$

$$P_H = 1.0 \cdot 0.8 \cdot 0.9 \cdot 0.6 \cdot 0.7 = 0.72 \cdot 0.42 = 0.3024 \approx 0.30$$

Thus, the firing unit has a 0.72 probability of launching the missile at the aircraft, the launched missile has a probability of 0.42 of hitting the aircraft, and the aircraft has a 0.30 probability of being hit in the scenario.

Suppose the aircraft's vulnerability to the missile is

$$P_{K|H} = 0.5$$

Thus, according to Eq. (1.5i), the single-shot probability of kill is

$$P_{K|SS} = 0.42 \cdot 0.5 = 0.6 \cdot 0.7 \cdot 0.5 = 0.21$$

and the aircraft's killability and survivability in this one-on-one scenario are

$$P_K = 0.30 \cdot 0.5 = 0.72 \cdot 0.21 = 0.15$$
$$P_S = 1 - 0.15 = 0.85$$

according to Eqs. (1.5b), (1.5j), and (1.5k).

Note: The value for each of the probabilities in this, and in all other examples and problems in this textbook, are assumed values and are not related to any actual weapon, aircraft, or scenario. The scenario and the specific probability values have been chosen to both illustrate the concepts and simplify the reader's task in understanding the example.

Go to Problems 1.1.31 to 1.1.32.

1.1.4.6 Survivability against multiple shots by one weapon.

Learning Objective	**1.1.8**	**Compute $P_{K\|E}$, $P_{S\|E}$, P_K, and P_S for multiple shots in a one-on-one scenario.**

The one-on-one scenario illustrated in Fig. 1.3 considers one weapon that fires one propagator toward the aircraft. In many combat situations an aircraft might be shot at several times by one weapon. For example, rapid-firing guns might fire from 20 to 60 rounds in a burst, and several bursts might be fired at the aircraft as it passes through the area defended by the weapon. Missiles might be fired at an aircraft in a shoot-look-shoot or shoot-shoot-look sequence, depending upon the fire control doctrine and tactical situation. In the shoot-look-shoot situation a second missile is fired if the look reveals that the aircraft was not killed by the first missile. In the shoot-shoot-look situation two missiles are fired to increase the probability the aircraft is killed, and then a look is taken to determine if the aircraft was killed by either of the two shots. More missiles might be fired if the aircraft has survived the first two shots and is still within the area defended by the weapon. The total number of missiles fired at a particular aircraft depends upon the number of aircraft that are assigned to the weapon, the priority of the targeted aircraft, the fire control doctrine, and the location of the target within the weapon envelope.

Equation (1.5j) for the P_K of the single shot, one-on-one scenario must be modified for the multiple-shot situation. The probability the aircraft is engaged by a single shot P_{SS} is replaced with the more general probability the aircraft is engaged by one or more shots P_E. In addition, the probability the aircraft is killed given an engagement consisting of a single shot $P_{K|SS}$ is replaced with the more general probability the aircraft is killed given an engagement consisting of one or more shots $P_{K|E}$. Thus, in the general one-on-one scenario

$$P_K = P_E P_{K|E} \tag{1.6a}$$

The probability the aircraft is killed as a result of multiple shots $P_{K|E}$ will be affected by the outcomes of each of the individual shots. There are two possible situations to consider: either the outcomes of later shots are affected by the outcomes of the earlier shots, or they are unaffected. If they are affected, they are referred to as dependent outcomes, and the individual shot kill probability depends upon, or is conditional upon, the outcomes of all preceding shots. If the later shot outcomes are unaffected by the earlier shot outcomes, they are referred to as independent outcomes or events, and their kill probabilities are not conditional.

Dependent shot outcome probabilities. As an example of a conditional, multiple-shot situation, consider a two-engine aircraft, designed so that one hit cannot kill both engines and the aircraft can fly with one engine inoperative. Suppose the left engine is killed by the first shot. The aircraft is not killed by the first shot because the thrust required for flight is provided by the right engine. However, although the aircraft survived the first shot, its $P_{K|H}$ will be larger when the second shot is fired because it is more vulnerable with only one operating engine. If the remaining engine is killed by the second shot, the aircraft is killed. If the first shot had not killed one engine, the second shot could not kill the aircraft by killing both engines; the aircraft was designed to prevent this particular event from occurring. Thus, the aircraft kill outcome of the second shot is conditional upon the outcome of the first shot. Furthermore, because the aircraft has only one engine remaining after the first shot its susceptibility might also be higher for the second shot. This shot outcome dependence is denoted by the conditional kill probability $P_{K2|S1}$, which is the probability the aircraft is killed by the second shot given that it survived the first shot. If a third shot is fired, the probability the aircraft is killed by the third shot given that it survived the first two shots is denoted by $P_{K3|(S1 \text{ AND } S2)}$.

The procedure for determining $P_{K|E}$ when the shot outcomes are dependent is relatively complex. Consequently, the assumption of independent shot outcomes is usually made when assessing multiple-shot survivability because of the difficulty in determining the likelihood of dependent outcomes. There are just too many possible outcomes and events to consider, and the numerical value for the probability that each particular outcome or event will occur is usually unknown. Whether or not this is a good assumption depends upon the scenario. The reader who is interested in learning how to determine $P_{K|E}$ for the multiple, dependent shot scenario should read Appendix B, Sec. B.4.2.

Independent shot outcome probabilities. The probability an aircraft is killed in a multiple-shot, independent outcome engagement can be determined using a tree

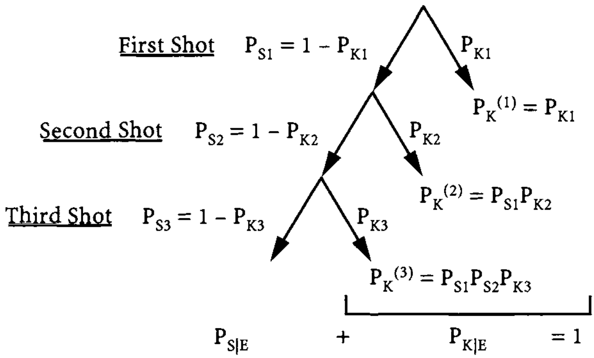


Fig. 1.4 Tree diagram for three independent shots.

diagram. Consider the tree diagram for the independent three-shot engagement shown in Fig. 1.4. There are two mutually exclusive outcomes considered for each shot; the aircraft is killed by the shot, and the aircraft survives the shot. The outcome of surviving a shot is represented by a branch down the left-hand side of the tree. A kill by any shot is represented by a right branch.

Because the two outcomes of a given shot (kill and survive) are assumed to be independent of the outcomes of all previous shots, the two outcomes of each shot are simply denoted by the shot subscript on the outcome probability. For example, the outcomes P_{K2} and P_{S2} are the probabilities the aircraft is killed by the second shot and survives the second shot, respectively, given that it survived the first shot. The condition that the aircraft survived the first shot is implied. Hence,

$$P_{S2|S1} = P_{S2} = 1 - P_{K2|S1} = 1 - P_{K2}$$

Each of the three shots has a probability of actually killing the aircraft in the multiple-shot engagement. The probability the first shot is the one that kills the aircraft is denoted by $P_K^{(1)}$ and is given by the first right branch in the tree. Thus,

$$P_K^{(1)} = P_{K1} \tag{1.6b}$$

The probability the second shot is the one that kills the aircraft in the engagement, denoted by $P_K^{(2)}$, is given by the path down the tree where the aircraft survives the first shot P_{S1}, and the surviving aircraft is killed by the second shot P_{K2}. Thus,

$$P_K^{(2)} = P_{S1}P_{K2} = (1 - P_{K1})P_{K2} \tag{1.6c}$$

Similarly, the probability the third shot is the one that kills the aircraft is given by

$$P_K^{(3)} = P_{S1}P_{S2}P_{K3} = (1 - P_{K1})(1 - P_{K2})P_{K3} \tag{1.6d}$$

The aircraft survives the engagement when it survives all three shots. Thus, $P_{S|E}$ can be determined using any of the following relationships:

$$P_{S|E} = P_{S1}P_{S2}P_{S3} = (1 - P_{K1})(1 - P_{K2})(1 - P_{K3}) \\ = 1 - \left[P_K^{(1)} + P_K^{(2)} + P_K^{(3)}\right] = 1 - P_{K|E} \tag{1.6e}$$

according to the tree diagram illustrated in Fig. 1.4. When the engagement consists of N independent shots, the probability the aircraft survives the engagement is given by

$$P_{S|E} = P_{S1}P_{S2}\ldots P_{SN} = (1 - P_{K1})(1 - P_{K2})\ldots(1 - P_{KN}) \\ = 1 - \left[P_K^{(1)} + P_K^{(2)}\ldots + P_K^{(N)}\right] = 1 - P_{K|E} \tag{1.6f}$$

Rearranging Eq. (1.6f) to solve for $P_{K|E}$ leads to

$$P_{K|E} = 1 - P_{S1}P_{S2}\ldots P_{SN} = 1 - (1 - P_{K1})(1 - P_{K2})\ldots(1 - P_{KN}) \\ = \left[P_K^{(1)} + P_K^{(2)}\ldots + P_K^{(N)}\right] = 1 - P_{S|E} \tag{1.6g}$$

When the individual shot P_K are identical and equal to $P_{K|SS}$ for all N shots, Eqs. (1.6e) and (1.6f) become

$$P_{S|E} = (1 - P_{K|SS})^N = 1 - P_{K|E} \tag{1.6h}$$

$$P_{K|E} = 1 - (1 - P_{K|SS})^N = 1 - P_{S|E} \tag{1.6i}$$

The probability the aircraft survives the multiple-shot scenario is given by

$$P_S = 1 - P_K = 1 - P_E P_{K|E} \tag{1.6j}$$

where $P_{K|E}$ is determined using Eq. (1.6g) or (1.6i).

Example 1.2 illustrates the assessment of the survivability of an aircraft in an independent multiple-shot scenario (Note 14).

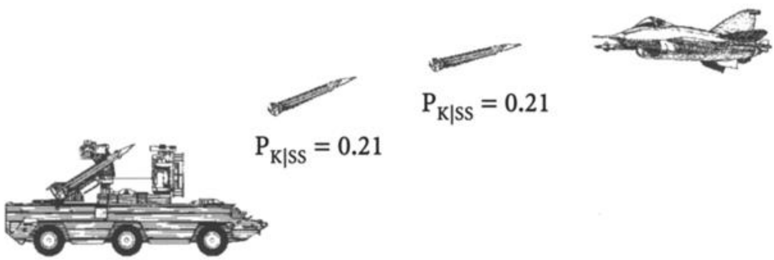
Go to Problems 1.1.33 to 1.1.35.

1.1.5 Many-on-Many or Mission-Level Survivability Assessment

Learning Objectives	**1.1.9**	**Compute the loss rate based upon combat data from one or more missions.**
	1.1.10	**Compute the expected number of aircraft killed and the survival and loss rates predicted for a mission.**

The one-on-one scenario described in the preceding section considers the situation where one aircraft on a mission is encountered and engaged by one threat weapon that fires one or more propagators at the aircraft. Of interest here is the general scenario where more than one aircraft are on a mission into a hostile territory defended by more than one threat weapon. This scenario is generally known as a many-on-many scenario, and survivability assessment at this level is referred to as a mission-level survivability assessment. The measures of interest in the mission-level survivability assessment typically are the loss and survival rates for the mission and the expected number of mission aircraft killed.

Example 1.2 One-on-One Survivability (Two Independent Shots)



Consider the one-on-one scenario examined in Example 1.1. In that scenario the probability the aircraft was engaged by a single shot was

$$P_E = P_{SS} = 0.72$$

For that shot

$$P_{K|SS} = 0.21$$

Suppose the SAM fire unit engages the aircraft with the same probability, but fires two missiles at the aircraft in a shoot-shoot-look mode. Assume the two shot outcome probabilities are independent, and the $P_{K|SS}$ of both missiles is

$$P_{K|SS} = 0.21$$

According to Eq. (1.6b), the probability the aircraft is killed by the first shot is

$$P_K^{(1)} = P_{K1} = P_{K|SS} = 0.21$$

According to Eq. (1.6c), the probability the aircraft is not killed by the first shot and then is killed by the second shot is

$$P_K^{(2)} = P_{S1}P_{K2} = (1 - P_{K1})P_{K2} = (1 - 0.21) \cdot 0.21 = 0.1659$$

The probability the aircraft is killed in the two-shot engagement is

$$P_{K|E} = 0.21 + 0.1659 = 0.3759 \qquad \text{(vs 0.21 for the single shot)}$$

according to Eq. (1.6g). The probability the aircraft is not killed by either shot is

$$P_{S|E} = (1 - 0.21)^2 = 0.6241 \qquad \text{(vs 0.79 for the single shot)}$$

according to Eq. (1.6h). Therefore, the probability the aircraft survives the two-shot encounter is

$$P_S = 1 - 0.72 \cdot 0.3759 = 0.73 \qquad \text{(vs 0.85 for the single-shot scenario)}$$

according to Eq. (1.6j).

1.1.5.1 Mission/sortie loss and survival rates. A mission is the dispatching of one or more aircraft to accomplish one particular task or objective, and a sortie is an operational flight by one aircraft.[1] For example, if a force package consisting of 24 aircraft is sent on an air interdiction mission to destroy a major line of supply deep within enemy territory, each of the 24 aircraft flies one sortie, and a total of 24 sorties are flown on this one mission. The 16 attack aircraft that are assigned to destroy the enemy forces, equipment, and infrastructure fly 16 combat sorties, and the four fighters that escort the attack aircraft also fly four combat sorties. The 20 attack and fighter aircraft are referred to as combat or shooter aircraft, where a shooter aircraft is defined as one that can deliver any kind of munitions from bullets to bombs.[4] The four aircraft that provide supporting services to the shooter aircraft, such as air refueling, standoff electronic attack, and strike and traffic control, fly four combat support sorties (Note 15).

The survivability measures of interest for each of the aircraft on a mission are the loss or attrition rate (LR) and the survival rate (SR), where

$$\mathrm{SR} = 1 - \mathrm{LR} \tag{1.7a}$$

These measures can be obtained from actual combat data, or they can be predicted by a mission-level survivability assessment.

1.1.5.2 Loss rate for one or more missions based upon combat data. When the LR is based upon actual combat data from one or more missions,

$$\text{Combat Loss Rate} = \frac{\text{number of mission aircraft killed}}{\text{total number of sorties flown}} \tag{1.7b}$$

which has the units of the number of aircraft killed per aircraft sortie flown. Many published combat loss rates do not specify the type of aircraft sorties. If the interest is in the likelihood any of the aircraft on the mission are killed, then the sorties of all mission aircraft are included. If the interest is in the likelihood that a shooter aircraft is killed, then the total number of sorties flown in Eq. (1.7b) consists of the sorties flown by the shooter aircraft; the sorties flown by the combat support aircraft are not included in the equation. The combat loss rate is usually expressed as a percentage or as the number of aircraft killed per 1000 sorties. The rules of thumb for loss rates are the following:

1) 1 percent or 10 (per 1000 sorties) in WW II.
2) 0.1 percent or 1 (per 1000 sorties) for the 1962–1973 conflict in Southeast Asia (SEA).
3) 0.04 percent or 0.4 (per 1000 sorties) in Desert Storm (DS) in 1991.

Example 1.3 illustrates the procedure for computing the combat loss rate.

Example 1.3 Combat Loss Rate[5]

On 4 December 1983, 26 U. S. Navy attack aircraft conducted a raid on targets near Beirut, Lebanon. The Lebanese air defense launched more than 40 SAMs and fired about 150 guns at the attacking aircraft. According to eyewitnesses, SA-7s and SA-9s (SAMs) were coming up all over the place, and the explosions of the AAA shells appeared as thick as a carpet. Two aircraft were killed, one A-6E Intruder and one A-7E Corsair II. The pilot of the Intruder, Lt. Mark Lange, and the bombardier/navigator (BN), Lt. Robert Goodman, Jr., ejected from their aircraft while over land. Lange died of injuries incurred during the ejection. Goodman survived the ejection and descent, but was captured and imprisoned. He was released on 4 January 1984, and subsequently attended the Naval Postgraduate School, graduating in 1987 with a Master of Science degree in Systems Technology, Space Systems Operations (Note 16).

The pilot of the Corsair, Cmdr. Edward Andrews, was able to fly his damaged aircraft back to the beach, where he ejected and was eventually rescued. (This was his third ejection from a damaged aircraft.) The following is his recollection of the event. When it happens (your aircraft is hit), you set up a series of objectives. First, check that the aircraft is still flyable; his was, but only barely. Second, try to get over water (referred to as feet wet), where chances of survival and rescue are better. Working on this second objective, he had just crossed the shoreline of a small bay heading out to sea, when the entire tail section of his A-7E came off. As the aircraft rolled about 90 degs. out of control, he pulled the ejection handle and eventually hit the water yards from a small fishing boat carrying an old man and a very young, frightened boy. They insisted he get in the boat. He did. Some time later he was returned to friendly territory.

In addition to the two aircraft killed, one A-7E was severely damaged by an explosion near the tail of the aircraft, shredding the rudder and parts of the horizontal stabilizer surfaces and damaging the engine. Despite the damage, the pilot, Cmdr. Les Kappel, was able to return to the carrier and land. The mechanics who repaired the damage said that, considering the hits to the engine, Kappel was lucky it all stayed together.

The combat loss rate for the attack aircraft on this mission was

$$\text{Combat Loss Rate} = (2 \text{ aircraft killed})/(26 \text{ sorties}) = 0.077$$

or 7.7% or 77 (aircraft killed in 1000 sorties).

1.1.5.3 Predicted loss rate for a mission and expected number of aircraft killed. When the loss rate is predicted based upon an assumed mission scenario, the following assumptions can apply. Typically, there are A aircraft on the mission, and these A aircraft fly into a hostile territory defended by W active weapons. An aircraft that is encountered and eventually selected for engagement by a weapon, or is assigned to a weapon, is said to be targeted. When an active weapon has the potential to encounter and engage several aircraft, the assumption is made that the weapon is composed of several individual weapons, and each of these weapons can engage only one aircraft.

There are two situations to consider when predicting loss rates; there may be as many or more active weapons than aircraft ($W \geq A$), or there may be fewer ($W < A$).

As many or more weapons than aircraft ($W \geq A$). For this situation assume that the number of active weapons W is NA, where N is an integer, and each of the A aircraft is encountered and engaged by N weapons in N one-on-one scenarios. For example, suppose there are 10 aircraft on a close air support mission ($A = 10$), and the target is defended by 30 weapons ($W = 30$). Thus, each of the 10 aircraft will be encountered and engaged by three weapons ($N = 3$), and each of the three encounters is considered to be a one-on-one scenario.

The multiple one-on-one scenario situation for each mission aircraft is analogous to the one-on-one, multiple-shot scenario just described. An encounter is analogous to a shot, and each aircraft will survive the mission only when it survives each of the N encounters during the mission. The outcome probabilities of each weapon encounter can be dependent or independent. Assuming they are independent, the multiple-shot tree diagram illustrated in Fig. 1.4 and expressed by Eqs. (1.6a–1.6g) apply, where P_{Si} and P_{Ki} now refer to the probability the aircraft survives the ith encounter or is killed in the ith encounter (assuming it survived all previous encounters), respectively, and $P_{S|E}$ and $P_{K|E}$ are replaced with P_S and P_K, the probability each aircraft survives all N encounters or is killed in one of the encounters, respectively. The probability $P_K^{(i)}$ now refers to the probability the aircraft survives the previous $i - 1$ encounters and is killed on the ith encounter. When the probability the aircraft is killed by a weapon is the same for all weapons encountered, Eqs. (1.6h) and (1.6i) apply. The single-shot probability of kill $P_{K|SS}$ is replaced with P_{Ki}, the probability the aircraft is killed by the ith weapon, which is the same numerical value for all N weapons. Note that Eq. (1.6j) is not applicable in the multiple one-on-one scenario.

The mission SR is equal to P_S (or $P_{S|E}$) given by Eq. (1.6f) or (1.6h), and the LR is equal to P_K (or $P_{K|E}$) given by Eq. (1.6g) or (1.6i). Thus,

$$\mathrm{SR} = P_{S1} P_{S2} \ldots P_{Sn} = (1 - P_{K1})(1 - P_{K2}) \ldots (1 - P_{KN}) = 1 - \mathrm{LR} \tag{1.7c}$$

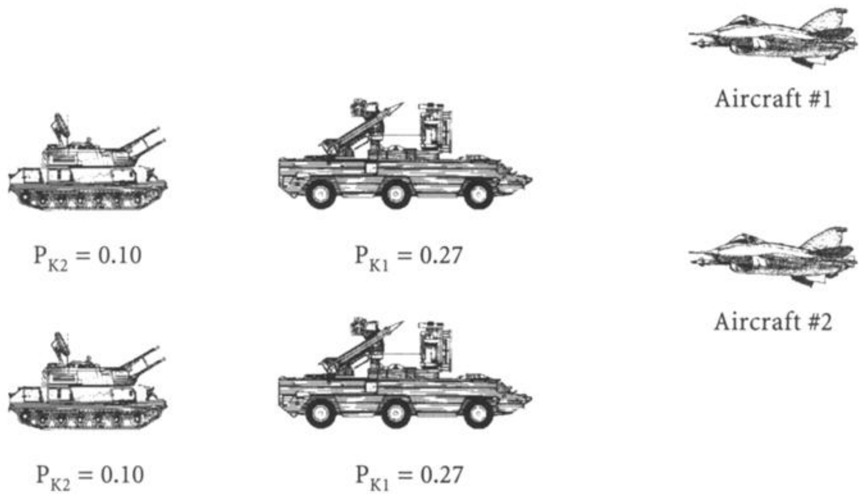
In a real-world mission scenario the actual number of aircraft that could be killed by the W weapons can vary from zero to A. Of interest here is the expected number of mission aircraft killed. Based upon the assumption that each of the A aircraft has an encounter with N weapons, the expected number of mission aircraft killed

E_K is given by (Note 17)

$$E_K = A \cdot \mathrm{LR} = A(1 - \mathrm{SR}) \tag{1.7d}$$

Example 1.4a presents the procedure for computing the loss and survival rates and the expected number of aircraft killed when there are more weapons than aircraft.

Example 1.4a Mission Loss and Survival Rates and Expected Number of Mission Aircraft Killed: More Weapons than Aircraft



Suppose two aircraft are sent on an interdiction mission to a target defended by two gun and two SAM fire units. Assume each aircraft is encountered and engaged first by a SAM and then by a gun.

In Example 1.2 the aircraft is killed in the one-on-one, two independent shot encounter with the SAM with the probability

$$P_{K1} = P_K^{(1)} = 0.27$$

The aircraft survives the SAM encounter with the probability

$$P_{S1} = 1 - 0.27 = 0.73$$

In this example the surviving aircraft is targeted by a gun shortly after the SAM encounter, with $P_E = 1$. Suppose the gun fires 35 rounds at the aircraft, and each round has a probability of killing the aircraft of 0.003. The probability the surviving aircraft is killed by the gun is

$$P_{K2} = 1 - (1 - 0.003)^{35} = 0.10$$

according to Eq. (1.6i). Hence,

$$P_{S2} = 1 - 0.10 = 0.90$$

The probability that the gun is the weapon that kills the aircraft during this mission is

$$P_K^{(2)} = 0.73 \cdot 0.10 = 0.073$$

according to Eq. (1.6c).

The joint probability the aircraft survives both the SAM encounter and the gun encounter on this mission is

$$P_S = \mathrm{SR} = 0.73 \cdot 0.90 = 0.657$$

according to Eq. (1.7c). The probability the aircraft is killed by either the SAM or the gun is

$$\mathrm{LR} = 0.27 + 0.073 = 1 - 0.657 = 0.343$$

according to Eq. (1.6g) and (1.7a).

The expected number of aircraft killed on the two aircraft mission is

$$E_K = 2 \cdot 0.343 = 0.686$$

according to Eq. (1.7d). Thus, if this two-aircraft mission was flown 100 times, 68.6 aircraft are expected to be killed in the 200 sorties.

Fewer weapons than aircraft (W < A). Now consider the situation where there are fewer active weapons than mission aircraft. For example, suppose there are seven active weapons defending an interdiction target ($W = 7$) against 10 attacking aircraft ($A = 10$). Assume that although each weapon can encounter several aircraft, it can engage only one aircraft and that no aircraft is engaged by more than one weapon. Thus, there will be seven one-on-one identical encounters (between seven aircraft and seven active weapons) that can result in an engagement. All 10 aircraft might be exposed to the seven weapons, but only seven of the 10 aircraft can be designated as a target and subsequently engaged by an active, assigned weapon with the probability $P_{E|A}$. For the three aircraft not targeted, $P_E = 0$.

The expected number of the W aircraft killed in the W identical encounters is the product of the expected number of engagements $WP_{E|A}$ and the probability the aircraft is killed by the assigned weapon in the engagement $P_{K|E}$. Thus,

$$E_K = WP_{E|A}P_{K|E} = WP_{K|A} \tag{1.7e}$$

where $P_{K|A}$ is the probability an aircraft is killed given that an encounter with an assigned, active weapon occurs.

The equation for the predicted loss rate is similar to the combat loss rate [Eq. (1.7b)], with the actual number of mission aircraft killed in combat replaced by the expected number of mission aircraft killed E_K given by Eq. (1.7e). Thus,

$$\mathrm{LR} = \frac{\text{expected number of mission aircraft killed}}{\text{number of aircraft on the mission}} = \frac{WP_{K|A}}{A} \tag{1.7f}$$

The ratio (W/A) in Eq. (1.7f) can be considered as the equally likely probability that any one of the A aircraft will be assigned to one of the W active threats, which is P_A for all of the mission aircraft. Thus,

$$P_A = W/A \tag{1.7g}$$

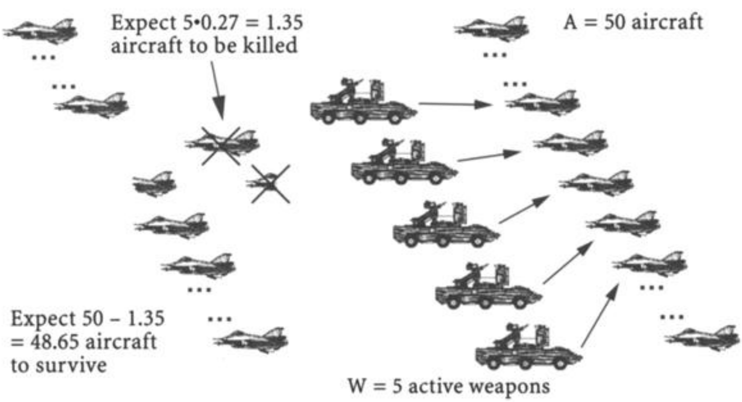
Consequently, the mission loss rate can also be given in the form

$$\mathrm{LR} = P_A P_{K|A} \tag{1.7h}$$

Example 1.4b presents the procedure for computing the expected number of aircraft killed and the loss rate when there are fewer weapons than aircraft.

Go to Problems 1.1.36 to 1.1.39.

Example 1.1.4b Mission Loss and Survival Rates and Expected Number of Mission Aircraft Killed: Fewer Weapons than Aircraft



Suppose 50 aircraft are on a mission to a target area defended by five of the SAM fire units described in Examples 1.1 and 1.2. Assume each SAM fire unit can encounter several aircraft, but can engage only one aircraft. Assume each aircraft has a $P_{K|A} = 0.27$ when encountered and engaged with two shots by an assigned SAM fire unit.

The equally likely probability that each of the 50 aircraft is targeted by a SAM fire unit is

$$P_A = 5/50 = 0.1$$

Thus, the expected number of mission aircraft killed in the five one-on-one encounters is

$$E_K = 5 \cdot 0.27 = 50 \cdot 0.1 \cdot 0.27 = 1.35$$

according to Eqs. (1.7d) and (1.7e).

The predicted mission loss and survivability rates are

$$\text{LR} = 1.35/50 = 0.1 \cdot 0.27 = 0.027$$

or 2.7% or 27 aircraft killed out of 1000 sorties and

$$\text{SR} = 1 - 0.027 = 0.973$$

or 97.3% or 973 aircraft survive out of 1000 sorties, according to Eqs. (1.7f) and (1.7h), and Eq. (1.7a), respectively.

If this 50 sortie mission is to be conducted 200 times, $200 \cdot 50 \cdot 0.027 = 270$ aircraft are expected to be killed out of the 1000 targeted aircraft in the 10,000 sorties, according to Eq. (1.7d).

1.1.6 Campaign-Level Survivability

Learning Objectives	**1.1.11**	**Compute the campaign survivability for a campaign consisting of N missions.**
	1.1.12	**Compute the number of aircraft remaining after a campaign.**
	1.1.13	**Determine the number of missions for an acceptable tour of duty.**

Campaign-level survivability refers to the probability that an aircraft will survive a campaign consisting of N missions and is denoted here by CS. When the mission survival rate SR is different for each mission and the individual mission outcomes are independent, the survivability equation for multiple independent shots and for multiple independent encounters given by Eq. (1.6e) applies. Thus,

$$\text{CS} = P_{SI} P_{S2} \ldots P_{Si} \ldots P_{SN} = (1 - P_{KI})(1 - P_{K2}) \ldots (1 - P_{Ki}) \ldots (1 - P_{KN}) \tag{1.8a}$$

where P_{Si} and P_{Ki} refer to the aircraft's mission survivability or SR and killability or LR on the ith mission, respectively. When the mission survivability is constant and identical for each mission, $P_{Si} = P_S$ and $P_{Ki} = P_K$, and Eq. (1.8a) becomes

$$\mathrm{CS} = P_S^N = \mathrm{SR}^N = (1 - P_K)^N = (1 - \mathrm{LR})^N \tag{1.8b}$$

Example 1.5a illustrates the assessment of an aircraft's campaign survivability for several different campaigns.

Example 1.5a Campaign Survivability

In World War II a B-17 crew member had to fly on 25 missions before he could return home. The mission loss rate of the B-17 in 1943 was approximately 8% or 80 per 1000 sorties. Thus, the crew member had a probability of completing his 25 mission tour of duty of

$$\mathrm{CS} = (1 - 0.08)^{25} = 0.12$$

according to Eq. (1.8b). With this very high attrition rate only about 12% of the crews could expect to survive their tour of duty in 1943 (Note 18).

The overall loss rate for U. S. heavy bombers in WWII was approximately 1.5% or 1.5 per 1000 sorties. Thus, the overall CS of bomber crews who flew 25 missions in WWII was

$$\mathrm{CS} = (1 - 0.015)^{25} = 0.69$$

In the SEA conflict the combat loss rate for many of the U. S. tactical aircraft was approximately 0.1% or 1 per 1000 sorties, and many aircrews flew more than 80 combat sorties. Their expected probability of surviving 80 sorties was

$$\mathrm{CS} = (1 - 0.001)^{80} = 0.923$$

1.1.6.1 Number of aircraft remaining after a campaign. The LR can have a substantial impact upon the ability of an air force to sustain operations over a long campaign in terms of both equipment and morale. Assume there are A aircraft available at the beginning of a campaign. If every surviving aircraft flies on every mission and if the downed aircraft are not replaced, then the number of the original A aircraft that is expected to survive the N mission campaign is $A \cdot$ CS, which can be computed from

Number of aircraft remaining (without replacement)

$$= A \cdot \mathrm{CS} = A \cdot P_S^N = A \cdot \mathrm{SR}^N = A(1 - P_K)^N = A(1 - \mathrm{LR})^N \tag{1.8c}$$

according to Eq. (1.8b). This assumes the air defense is also attrited so that the LR remains the same for all missions.

The surviving fraction of the original A aircraft is equal to CS, the campaign survivability given by Eq. (1.8b). CS and the surviving fraction of aircraft are

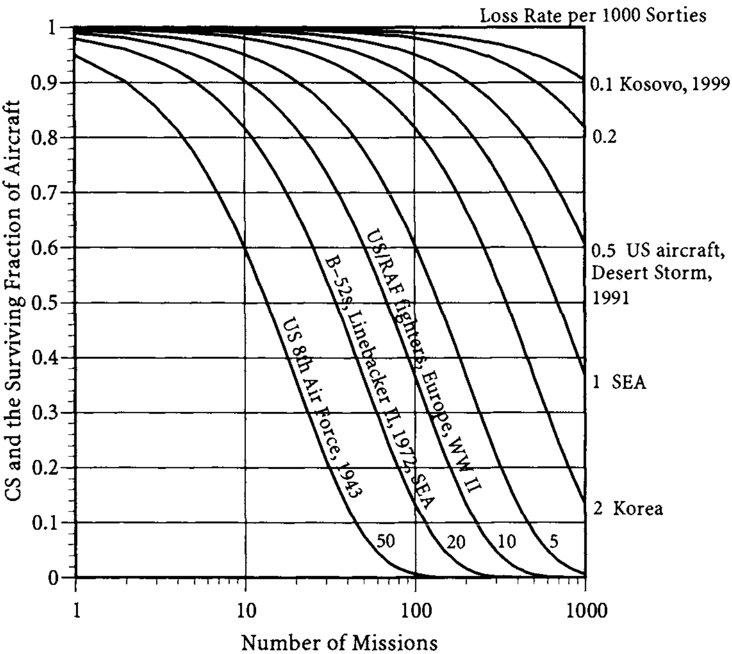


Fig. 1.5 CS and the surviving fraction of A aircraft after N missions.

plotted in Fig. 1.5 as a function of the number of missions for several values of the loss rate. An historical example (an approximate value) is given for most of the loss rates in the figure. This figure can be used to determine both the probability an aircraft will survive a campaign (CS) and the expected number of aircraft remaining after the campaign ($A \cdot \mathrm{CS}$).

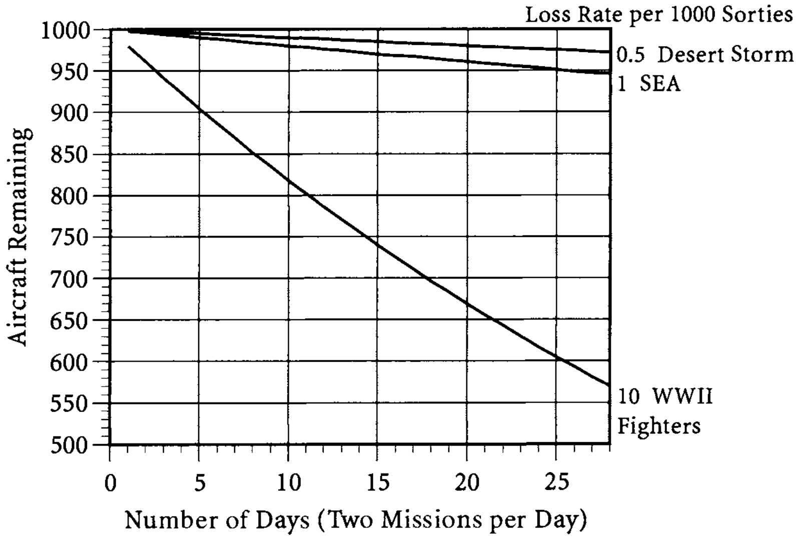
The values for CS and the surviving fraction of aircraft given in Fig. 1.5 assume that downed aircraft are not replaced. On the other hand, if every aircraft that is killed by the air defense is immediately replaced by a new aircraft, then A aircraft fly on every mission, and the expected number of aircraft killed in the campaign is

$$\text{Number of aircraft killed (with replacement)} = N \cdot A \cdot \mathrm{LR} \tag{1.8d}$$

For large numbers of missions, the reduction in the number of surviving aircraft is drastic, even for what appears to be a low loss rate. Example 1.5b illustrates the effect of attrition on the number of aircraft remaining after a 28-day, 56-mission campaign for several historical loss rates, both with and without replacement aircraft.

Example 1.5b Effect of Attrition

In Operation Downfall the allies expect to bring 1000 combat aircraft into the theater. The operation is planned to last 28 days, and two missions are to be flown every day by all available aircraft. No new aircraft will be brought into the theater to replace those killed by the enemy air defense. The remaining number of aircraft at the end of each day of the campaign is shown in the figure below as a function of the approximate loss rate (per 1000 sorties) for DS (0.5), SEA (1), and WWII fighters (10).



At the end of the 56-mission campaign, the number of aircraft remaining is expected to be 972.4 using the Desert Storm LR, 945.5 using the SEA LR, and 570 using the WWII LR. Accordingly, the number of killed aircraft is 22.6, 54.5, and 430, respectively.

If a new aircraft is brought into the theater to replace every downed aircraft after every mission and if the assumption is made that all 1000 aircraft will be available for every mission, then the number of aircraft expected to be killed in the 28-day, 56,000-sortie operation is 28 using the Desert Storm LR, 56 using the SEA LR, and 560 using the WWII LR.

1.1.6.2 Tour of duty. The relationship between the loss rate and the probability of surviving N missions given by Eq. (1.8b) can be used to determine the number of missions that represent an acceptable tour of duty for a military aviator. For example, suppose the person responsible for deciding how many missions is enough selects 0.90 as the acceptable probability for surviving a tour of duty or CS. The number of missions that result in that particular value of CS can be determined by rearranging Eq. (1.8b) to solve for N. Thus,

$$\text{Tour of Duty} = N \text{ missions} = \frac{\log_{10} \text{CS}}{\log_{10} \text{SR}} = \frac{\log_{10} \text{CS}}{\log_{10}(1 - \text{LR})} \tag{1.8e}$$

A sample calculation for an acceptable tour of duty is given in Example 1.5c.

Example 1.5c Tour of Duty

If an acceptable probability of surviving a tour of duty is 0.90 and the loss rate is 2 (per 1000 sorties), the corresponding tour of duty is 52.6 missions according to Eq. (1.8e). Figure 1.5 also can be used to determine the tour of duty. Select 0.90 for the campaign survivability, and proceed horizontally across the chart to the loss rate of 2. Dropping down to the number of missions results in approximately 50 missions. For a campaign survivability of 0.99 and a loss rate of 0.4, the tour of duty is 25 missions.

Go to Problems 1.1.40 to 1.1.42.

1.1.7 Summary of the Survivability Equations

The definitions and equations for the various probabilities of an aircraft kill and survival in a one-on-one scenario, a mission, and a campaign are summarized in Table 1.2 and in the following subsections.

1.1.7.1 Mission-level survivability assessment.

$$\text{Combat Loss Rate} = \frac{\text{number of mission aircraft killed}}{\text{total number of sorties flown}}$$

SR is the probability that each of the aircraft on a mission survives the mission. LR is the probability that each of the aircraft on the mission is killed:

$$\text{SR} = 1 - \text{LR}$$

A is the number of aircraft on the mission; W is the number of active weapons, and each active weapon can engage only one of the A aircraft; and E_K is the expected number of aircraft killed on the mission.

Same *or* more *weapons than aircraft.*

$$W \geq NA$$

where N is an integer.

$$\text{SR} = P_S = P_{S1} P_{S2} \ldots P_{SN} = (1 - P_{K1})(1 - P_{K2}) \ldots (1 - P_{KN}) = 1 - \text{LR}$$

where P_{Si} and P_{Ki} are the independent probabilities that each aircraft survives and is killed by the ith encounter while on the mission, respectively. E_K is the expected number of mission aircraft killed $= N \cdot \text{LR}$.

Fewer *weapons than aircraft.*

$$W < A$$

Table 1.2 Survivability equations

Equation	Description of probability
	Aircraft survival in a single-shot scenario
$P_H = P_A P_{D\|A} P_{L\|D} P_{I\|L} P_{H\|I}$ [a–e]	Prob. the aircraft is hit in the scenario
$P_K = P_H P_{K\|H}$ [f]	Prob. the aircraft is killed in the scenario (by a hit)
$P_F = P_A P_{D\|A} P_{L\|D} P_{I\|L} P_{F\|I}$ [g]	Prob. the HE warhead on the propagator fuzes in the scenario
$P_K = P_F P_{K\|F}$ [h]	Prob. the aircraft is killed in the scenario (by a proximity-fuzed detonation)
$P_{E\|A} = P_{D\|A} P_{L\|D}$	Prob. the aircraft is engaged by an active weapon
$P_E = P_A P_{E\|A}$	Prob. the aircraft is engaged in the scenario
$P_{E(\text{single shot})} = P_{SS} = P_A P_{E\|A}$	Prob. a single shot is fired at the aircraft in the scenario
$P_{H\|SS} = P_{I\|L} P_{H\|I}$	Prob. the aircraft is hit, given a single shot
$P_{F\|SS} = P_{I\|L} P_{F\|I}$	Prob. of fuzing, given a single shot
$P_{K\|SS} = P_{SSK} = P_{H\|SS} P_{K\|H}$	Prob. the aircraft is killed (by a hit), given a single shot
$P_{K\|SS} = P_{SSK} = P_{F\|SS} P_{K\|F}$	Prob. the aircraft is killed (by a prox-fuzed det.), given a single shot
$P_K = P_{SS} P_{K\|SS}$	Prob. the aircraft is killed in a single-shot scenario
$P_S = 1 - P_K$	Prob. the aircraft survives the single-shot scenario
	Aircraft survival in a multiple, independent-shot scenario
P_E	Prob. the aircraft is engaged in the scenario with one or more shots
P_{Ki}	Prob. the *i*th shot kills the aircraft, given a shot at a live aircraft
P_{Si}	Prob. the *i*th shot does not kill the aircraft, given a shot at a live aircraft
$P_K^{(i)} = P_{SI} P_{S2} \ldots P_{Si-1} P_{Ki}$	Prob. the aircraft is killed by the *i*th shot in the scenario
$P_{K\|E} = P_K^{(1)} + P_K^{(2)} \ldots + P_K^{(n)}$	Prob. the aircraft is killed in the engagement consisting of *N* shots
$P_{S\|E} = P_{SI} P_{S2} \ldots P_{SN} = (1 - P_{KI}) \times (1 - P_{K2}) \ldots (1 - P_{KN})$	Prob. the aircraft survives the *N* (different) shot engagements
$P_{S\|E} = (1 - P_{K\|SS})^N = 1 - P_{K\|E}$	Prob. the aircraft survives the *N* (identical) shot engagements

[a] P_A is the probability that a threat weapon is active, searching, and ready to encounter the aircraft that enter into its defended area.
[b] $P_{D|A}$ is the conditional probability that the aircraft is detected, given that the threat is active.
[c] $P_{L|D}$ is the conditional probability that the aircraft is tracked, a fire control solution is obtained, and a missile is launched or a gun is fired at the aircraft, given that the threat was active and detected the aircraft.
[d] $P_{I|L}$ is the conditional probability that the threat propagator intercepts the aircraft, given that the propagator was launched or fired at the aircraft.
[e] $P_{H|I}$ is the conditional probability that the propagator hits the aircraft, given that the propagator has intercepted the aircraft.
[f] $P_{K|H}$ is the conditional probability that the aircraft is killed, given a hit by the propagator.
[g] $P_{F|I}$ is the conditional probability that the proximity fuze on the propagator detonates an HE warhead, given that the propagator has intercepted the aircraft.
[h] $P_{K|F}$ is the conditional probability that the aircraft is killed, given a proximity-fuzed warhead detonation.

$P_{K|A}$ is the probability an aircraft is killed, given an active, assigned weapon.

$$\mathrm{LR} = (\mathrm{W}/A)P_{K|A}$$

E_K is the expected number of mission aircraft killed $= WP_E P_{K|E} = AP_A P_E P_{K|E} = AP_A P_{K|A}$ where $P_A = W/A$.

1.1.7.2 Campaign-level survivability assessment. CS is the probability that an aircraft will survive a campaign consisting of N missions.

$$\mathrm{CS} = P_{S1} P_{S2} \ldots P_{Si} \ldots P_{SN} = (1 - P_{K1})(1 - P_{K2}) \ldots (1 - P_{Ki}) \ldots (1 - P_{KN})$$

where P_{Si} and P_{Ki} refer to the aircraft's mission survivability, or survival rate, and killability, or loss rate, on the ith mission, respectively. When the mission survivability P_S and killability P_K are the same for each mission,

$$\mathrm{CS} = (P_S)^N = (1 - P_K)^N$$

1.1.8 How Is Survivability Enhanced?

Learning Objective	1.1.14	Describe how survivability can be enhanced, and define a survivability enhancement feature.

In general, the survivability of an aircraft can be increased or enhanced by 1) a good design that does not cause significant weight, cost, or performance impacts; 2) the addition of extra elements to the design that do involve weight, cost, or performance impacts; and 3) the proper utilization of the aircraft.

Any particular characteristic of the aircraft, specific piece of equipment, design technique, armament, or tactic that reduces either the susceptibility P_H, or the vulnerability $P_{K|H}$, of the aircraft has the potential for increasing survivability and is referred to as a survivability enhancement feature. Some typical survivability enhancement features are listed here:

Speed and altitude
Fire/explosion protection
Self-repairing flight controls
Redundant and separated hydraulics
Night-time capability
More than one engine-separated
Low signatures
Tactics
Onboard electronic attack equipment
Maneuverability/agility
Terrain following
No fuel adjacent to air inlets
Self defense missiles and guns
Crew situational awareness
Hydrodynamic ram protection
Crew training & proficiency
Nonflammable hydraulic fluid
Lethal launch-and-leave or stand-off weapons
Chaff and flares
Fighter escort
Rugged structure
Good target acquisition capability
Threat warning system
Mission planning system
Antiradiation weapons
Armor
Standoff electronic attack equipment

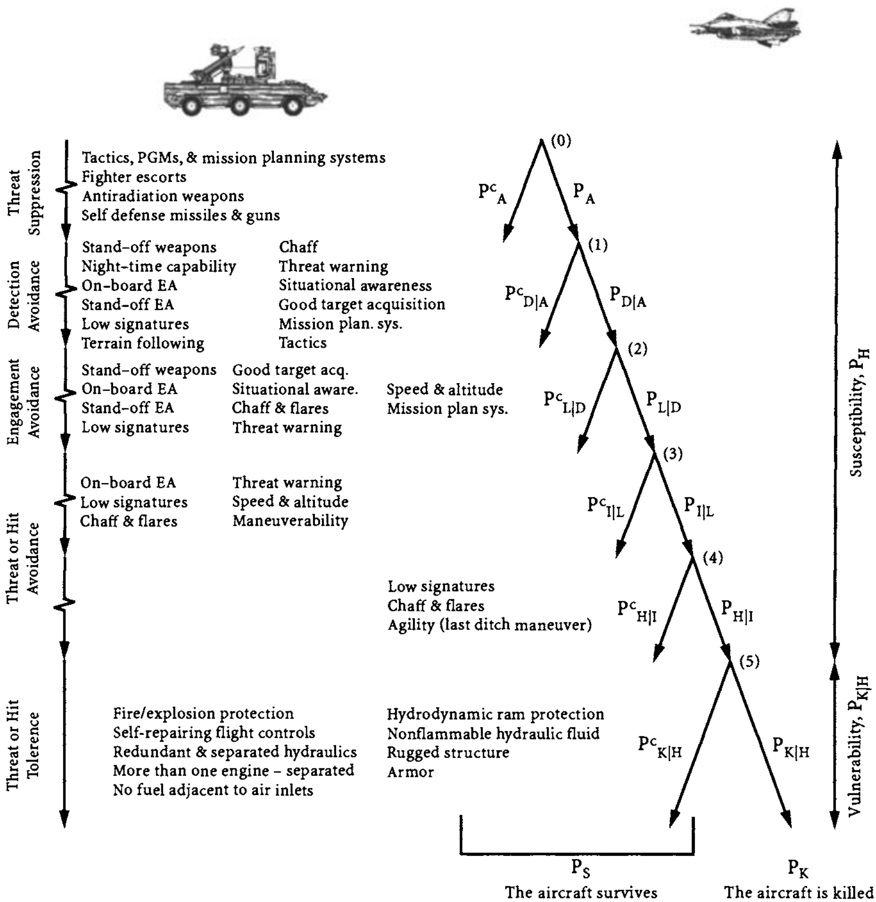


Fig. 1.6 Tree diagram for a one-on-one scenario with some susceptibility and vulnerability reduction features.

Each of the features listed reduces either the susceptibility or the vulnerability of the aircraft. Figure 1.6 is a copy of the one-on-one tree diagram shown in Fig. 1.3, with the survivability enhancement features listed next to the specific probabilities that the feature might affect. Each of these survivability enhancement features reduces the applicable right-branch probability and therefore increases the likelihood that the outcome of each of the sequential phases will branch to the left, thus breaking the kill chain.

Although the susceptibility and vulnerability reduction features just listed appear to be widely disparate, each one performs a certain function that reduces either susceptibility or vulnerability. There are 12 general functions or concepts fundamental to survivability enhancement, six for susceptibility reduction (SR) and six for vulnerability reduction (VR). These 12 survivability enhancement

Table 1.3 The twelve survivability enhancement concepts

Susceptibility reduction, P_H	Vulnerability reduction, $P_{K\|H}$
Threat warning	Component redundancy (with separation)
Noise jamming and deceiving	Component location
Signature reduction	Passive damage suppression
Expendables	Active damage suppression
Threat suppression	Component shielding
Weapons and tactics, flight performance, and crew training and proficiency	Component elimination or replacement

concepts are listed in Table 1.3. Each of the survivability enhancement features can be placed into one of the 12 concepts listed in Table 1.3.

1.1.8.1 Susceptibility reduction.

Learning Objective 1.1.15 Describe the six survivability enhancement concepts for susceptibility reduction, and give at least one example of a feature for each concept.

Reducing an aircraft's susceptibility increases its capability to avoid the man-made hostile environment. Susceptibility reduction, also known as threat avoidance, is achieved by reducing the probability the aircraft is detected, tracked, engaged, and hit. Many of the SR features are given in the encounter tree diagram in Fig. 1.6 next to the specific probability they reduce. According to this figure, reducing susceptibility can be accomplished by permanently or temporarily destroying one or more essential components of the air defense, delaying or denying detection of the aircraft, delaying or preventing a missile launch or gun firing, increasing the propagator closest point of approach (the miss distance), and avoiding a propagator hit or proximity fuzing. The six SR concepts described next can be used to degrade the capabilities of the air defense in each of these encounter phases.

As shown in Table 1.3, the susceptibility of an aircraft can be reduced by the use of a threat warning or situational awareness system, such as a radar warning receiver (RWR) or missile approach warning system (MAWS), that informs the crew of the type and location of tracking systems that are a threat to the aircraft or of a missile launch toward the aircraft. Electronic attack (EA) equipment in the form of electronic noise jammers and deceivers, previously known as electronic countermeasures (ECM) equipment or jammers, carried onboard or on supporting units can be used to prevent detection systems from detecting the aircraft or to send out deceiving signals or false target echoes that break the lock of a tracking system, thus preventing an engagement. Combinations of SR features (techniques or devices) which increase the probability that an aircraft ingressing hostile territory will penetrate the enemy's air defenses are known as penetration aids.

Signature reduction, or the reduction of the observables of the aircraft, makes the aircraft more difficult to detect and track. Aircraft whose signatures have been reduced to low levels are sometimes referred to as stealth or stealthy aircraft. Expendables, such as chaff and infrared flares, can provide a screen behind which the aircraft can hide, or they can be towed decoys that are more attractive targets than the aircraft. Threat suppression is accomplished by launching antiradiation missiles that home in on operating radar transmitters, by using self-defense missiles and guns against attacking enemy units, by friendly supporting fire from flying escorts or ground-based units, and by the use of dedicated aircraft whose mission is the suppression or destruction of the enemy air defense (SEAD or lethal SEAD, referred to as DEAD).

The tactics that are developed by the operational forces attempt to reduce susceptibility by minimizing the exposure of the aircraft to the threat air defense systems while achieving the mission objectives. This can be accomplished by flying as fast as possible (the "speed is life" philosophy), or as high as possible (the "fly high" philosophy), and by the use of a sophisticated mission planning system or on-the-spot planning that combines aircraft flight performance, terrain data, weather, time of day, and intelligence information regarding the estimated enemy weapon locations to develop routes that avoid or mask the enemy sensor and weapon envelopes. Exposure can also be reduced through the use of SEAD or DEAD to roll back the air defense and by the use of effective launch-and-leave or shoot-and-scoot weapons with good target acquisition capability that allow the aircraft to quickly locate the target, deliver its ordnance, and leave the defended area. The air defense can be avoided altogether by launching long-range or standoff precision-guided munitions outside of the defending weapon envelopes. Although the aircraft's flight performance capabilities (including its top speed and altitude, maneuverability, and agility), its handling qualities, and the crew workload and situational awareness have a major impact on the selection and effectiveness of the tactics employed, perhaps one of the most important survivability enhancement features is the crew's training and proficiency in this demanding and dangerous role.

The technology for reducing susceptibility is described in detail in Chapter 4, Sec. 4.4.

1.1.8.2 Vulnerability reduction.

Learning Objectives	**1.1.16**	**Define the essential functions for flight, the critical components on an aircraft, and the kill modes.**
	1.1.17	**Describe the six survivability enhancement concepts for vulnerability reduction, and give at least one example of a feature for each concept.**

Reducing the vulnerability of an aircraft increases its capability to withstand the man-made hostile environment. Vulnerability reduction, also known as threat or hit tolerance or aircraft hardening, is achieved by reducing the likelihood that the critical components on the aircraft are killed when the aircraft is hit.

Critical components and kill modes. An aircraft is composed of thousands of components. Each component provides or contributes to one or more functions that are essential for flight or mission completion. Sustained flight is only possible when the structure of the aircraft is intact and the forces of lift, thrust, and control are sufficient to maintain the desired altitude, speed, and attitude. Consequently, the essential functions for flight are structural integrity, and lift, thrust, and control.

Examples of components that contribute to one or more of these four flight essential functions are the pilot (control), the engines (thrust), the wings (lift), and fuselage longerons (structural integrity). An attrition kill of the aircraft occurs if one or more of the flight essential functions is lost. Mission essential functions include such elements as communication, navigation, weapons delivery, as well as many others. The radio, the global positioning system (GPS) receiver, and the weapons pylons are examples of mission essential components. A mission abort kill occurs if none of the flight essential functions are lost but one or more of the mission essential functions is lost as a result of the hit.

An aircraft's vulnerability is caused by the vulnerability of its components. Those components whose kill, either individually or jointly, result in an aircraft kill, such as an attrition kill or a mission abort kill, are referred to as the critical components. Critical components are either nonredundant or redundant. Nonredundant critical components are those components whose kill individually results in an aircraft kill. Examples of nonredundant critical components for an attrition kill are the single pilot on an aircraft, the single engine, and a wing fuel tank that can suffer a major explosion when hit, destroying the wing structural torque box. Redundant critical components are those components whose kill jointly results in a kill. Examples of redundant critical components for an attrition kill are the pilot and the copilot, both engines on a two-engine aircraft, and a hydraulically powered flight control system with multiple hydraulic power sources.

The inability of a component to provide the function it was designed to provide because of hits by one or more damage mechanisms is referred to variously as a component dysfunction, damage, failure, or kill, depending upon the type of analysis being performed and the performing organization. The ways in which a component can fail or be killed are referred to here as the component kill modes. Examples of a component kill mode are pilot death, engine fuel starvation, and an internal fuel tank explosion. System kill modes refer to the ways that essential functions provided by systems or subsystems can be lost. Examples of a system kill mode are the loss of thrust that occurs when one or more of the engines are killed and the loss of control that occurs when the sources of hydraulic power to the control surfaces are killed. Table 1.4 presents the component and system kill modes for the major systems of an aircraft. Kill modes are also referred to as damage modes.

Reducing vulnerability. An aircraft's vulnerability is reduced when the likelihood that one or more of the critical components will be killed if the aircraft is hit

Table 1.4 List of component and system kill modes

Component/system	Kill mode

Fuel	Fuel supply depletion
	Fire/explosion
	  In-tank/ullage
	  Void space
	Hydrodynamic ram

Structural	Fracture/removal Pressure overload Thermal weakening Delamination/fiber buckling Connection failure
Avionics	Mechanical damage Fire/overheat
Armament	Fire/explosion

Propulsion	Air inlet flow distortion
	Engine failure
	  Fuel ingestion
	  Foreign object damage
	  Fan/compressor damage
	  Combustor damage
	  Turbine damage
	  Exhaust duct or after-burner damage
	Engine fire
	Engine subsystem or control failure
	  Loss of lubrication
	  Engine controls and accessories failure

Power train and rotor blade/propeller	Mechanical/structural damage Loss of lubrication

Flight control	Disruption of the control signal path
	  Loss of pilot
	  Loss of control lines
	  Computer failure
	  Sensor damage
	Loss of control power
	  Hydraulic failure
	  Electrical failure
	  Actuator damage
	Damage to control surfaces/hinges
	Hydraulic fluid fire

Electrical power	Severing/grounding Mechanical damage Overheating
Crew	Injury/death Life support failure

is reduced. Each of the VR features listed in Fig. 1.6 either reduces the vulnerability of a nonredundant critical component by preventing a component kill mode from occurring or reduces the vulnerability of the aircraft by including redundant and separated critical components that prevent system kill modes from occurring. All of the component and system kill modes are described in detail in Chapter 5, Sec. 5.2.

The six VR concepts for an aircraft listed in Table 1.3 include critical component redundancy with separation. For example, adding a second flight control computer to an unstable aircraft has the potential to reduce vulnerability. However, the redundant components *must* be effectively separated in order to minimize the probability that they can be killed, jointly, by a single hit. Critical component location is the positioning of the aircraft's critical components to minimize the possibility and extent of damage. For example, fuel should not be located next to an air inlet duct where it could spew through a hit-caused hole and be ingested by the engine, possibly killing it; and an airframe-mounted accessory drive (AMAD) should be located behind noncritical components or structure, out of the direct line of fire.

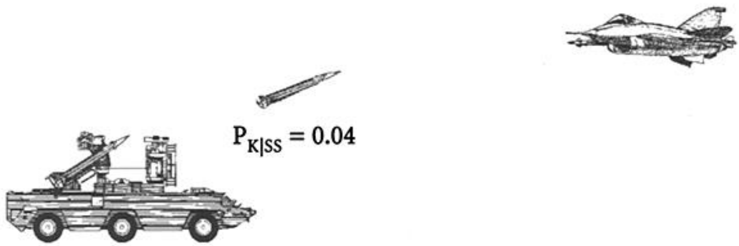
The passive and active damage suppression concepts reduce vulnerability either by containing or minimizing the damage or by reducing the effects of damage to the critical components. Vulnerability reduction features based upon the passive damage suppression concept have no damage-sensing capability. For example, placing explosion-suppression reticulated foam inside fuel tanks and designing the tank structure to resist the hydrodynamic ram pressure from the fuel on the tank walls when the fuel tank is penetrated by a penetrator or fragment are examples of the passive damage suppression concept. Vulnerability reduction features based upon the active damage suppression concept utilize a sensor or other device that senses when a hit or damage process occurs and activates a function that either contains the subsequent damage or reduces the effects of the damage. A self-repairing flight control system that senses when damage occurs to one or more control surfaces and automatically reconfigures the control system to ameliorate the damage effects and a fire detection and extinguishing system are two examples of the active damage suppression concept.

Critical component shielding is the placement of ballistically resistant materials, usually in the form of armor, in front of a critical component, such as a pilot, to prevent the damage mechanisms from hitting the component. A very lightweight example of component shielding is the use of laser-resistant goggles to prevent a laser beam from blinding a crew member. Critical component elimination or replacement is either the removal of a critical component, such as the pilot, or the replacement of a critical component with a less vulnerable one, such as the replacement of a flammable avionics coolant with a nonflammable coolant.

The technology for reducing vulnerability is described in Sec. 5.4.

1.1.8.3 Examples of the benefits of survivability enhancement. To illustrate the increase in an aircraft's survivability as a result of the addition of several survivability enhancement features, Examples 1.6, 1.7, and 1.8 reassess the one-on-one, mission, and campaign survivability for the scenarios described in Examples 1.1–1.5.

Example 1.6 One-on-One Survivability (Two Independent Shots) Revisited



Suppose an aircraft more survivable than the one considered in Examples 1.1 and 1.2 enters into the area defended by the SAM fire unit. Assume the following probabilities apply for this more survivable aircraft:

$$P_A = 1.0 \quad (\text{vs } 1.0) \quad \text{the threat is still active}$$

$$P_{D|A} = 0.3 \quad (\text{vs } 0.8) \quad \text{as a result of radar signature reduction}$$

$$P_{L|D} = 0.7 \quad (\text{vs } 0.9) \quad \text{as a result of radar threat warning and chaff}$$

The number of shots is reduced from two at the less survivable aircraft in Example 1.2 to one at the more survivable aircraft because of a delay in detection of the reduced-signature aircraft and onboard ECM. Thus, the aircraft is engaged by a single missile with the probability

$$P_{SS} = 1.0 \cdot 0.3 \cdot 0.7 = 0.21 \quad (\text{vs } 0.72)$$

The single-shot probability of kill is based upon

$$P_{I|L} = 0.4 \quad (\text{vs } 0.6) \quad \text{as a result of onboard ECM}$$

$$P_{H|I} = 0.5 \quad (\text{vs } 0.7) \quad \text{as a result of a last ditch maneuver provided by the MAWS}$$

The vulnerability of the more survivable aircraft is

$$P_{K|H} = 0.2 \quad (\text{vs } 0.5) \quad \text{as a result of fuel system protection and other VR features}$$

Thus,

$$P_{K|SS} = 0.4 \cdot 0.5 \cdot 0.2 = 0.04 \quad (\text{vs } 0.21)$$

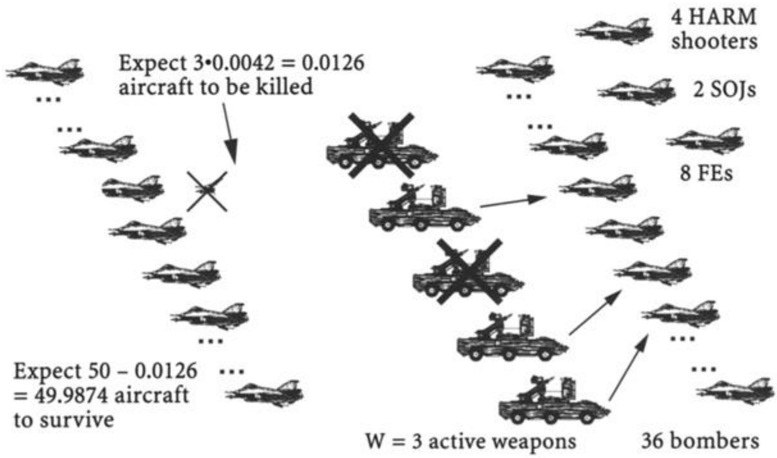
The more survivable aircraft's killability and survivability become

$$P_K = 0.21 \cdot 0.04 = 0.0084 \quad (\text{for one shot vs } 0.27 \text{ for two shots})$$

$$P_S = 1 - 0.0084 = 0.9916 \quad (\text{vs } 0.73)$$

This more survivable aircraft has a 0.9916 (vs 0.73) probability of surviving this one-on-one scenario. If this mission were to be flown 1000 times, 8.4 of the more survivable aircraft are expected to be killed vs an expected loss of 270 of the more killable aircraft.

Example 1.7 Mission Survivability (Fewer Weapons Than Aircraft) Revisited



Assume that the 50 mission aircraft described in Example 1.4b are replaced by the more survivable aircraft described in Example 1.6. Furthermore, assume that six of the 50 aircraft in the package are now assigned to the SEAD role and eight are assigned as fighter escorts (FEs). Two of the SEAD aircraft are stand-off jammers and four are High Speed Antiradiation Missile (HARM) shooters. The remaining 36 aircraft carry the bombs. Again, assume each of the active defending SAMs can engage only one aircraft. However, the lethal SEAD aircraft take out two of the five SAM fire units before they can engage any of the bombers.

According to Example 1.6, each of the more survivable aircraft has a $P_K =$ 0.0084 when assigned to an active SAM and engaged in a one-on-one scenario. However, in this many-on-many scenario the jamming from the SOJs reduces the P_K of the SAMs from 0.0084 to 0.0042 as a result of a 50% reduction in $P_{D|A}$. Thus, the number of bombers expected to be killed by the three remaining SAM fire units is

$$3 \cdot 0.0042 = 0.0126 \quad (\text{vs } 1.35)$$

Therefore, the expected loss rate for all of the mission aircraft is

$$\mathrm{LR} = 0.0126/50 = 0.000252,$$

or 0.025%, or 0.25 aircraft killed per 1000 sorties (vs 27.0). The mission survivability for all of the aircraft is

$$\mathrm{SR} = (50 - 0.0126)/50 = 0.999748 \quad (\text{vs } 0.973)$$

If this 50-sortie mission is to be conducted 200 times, $200 \cdot 50 \cdot 0.000252 = 2.52$ aircraft are expected to be killed in the 10,000 sorties (vs 270).

However, note that only 36 of the 50 aircraft in this force package drop bombs. Furthermore, each aircraft might carry less ordnance because of the more survivable design. For example, the ordnance might be carried internally to reduce the radar signature. Thus, the amount of damage to the target might be less if only conventional dumb bombs are dropped. However, the damage to the target might be greater if the 36 bombers employed smart or precision-guided munitions.

An alternate force package for this mission is one that consists of only five large stealth bombers loaded with PGMs. These air-to-surface weapons can be launched from the outer region of the area defended by the SAMs. Assume SR = 0.9999 for each aircraft for this scenario. Thus, the expected number of aircraft killed on the mission is

$$E_K = 5 \cdot (1 - 0.9999) = 0.0005$$

or 0.1 aircraft is expected be killed in 200 missions consisting of 1000 sorties.

Example 1.8 Campaign Survivability Revisited

In Desert Storm the air campaign lasted approximately 6 weeks. If a pilot had flown on two missions a day on each day of the campaign, that pilot would have flown approximately 80 sorties. The LR in DS was approximately 0.0004. Assuming 80 sorties were flown with a LR of 0.0004,

$$\mathrm{CS} = (1 - 0.0004)^{80} = 0.9685$$

(vs 0.78 for 25 missions in WWII and 0.923 for 80 missions in the SEA conflict).

If the pilot had flown on only 25 missions during Desert Storm,

$$\mathrm{CS} = (1 - 0.0004)^{25} = 0.9900$$

Which airplane would you rather fly: the B-17 Flying Fortress or the F-117 Nighthawk?

Go to Problems 1.1.43 to 1.1.54.

1.1.9 What Are the Goals of the Aircraft Combat Survivability Discipline?

Learning Objective 1.1.18 Describe the two goals of the survivability discipline.

The mission of the aircraft, the supporting friendly forces, and the density and effectiveness of the enemy air defense weapons significantly influence the relative importance of each survivability enhancement feature. Not all survivability enhancement features are either appropriate or necessary for any one particular aircraft on a specific mission. Furthermore, a reduction in vulnerability could lead to an increase in susceptibility (for example, adding heavy armor could slow the aircraft down and make it easier to hit, and adding a second engine can increase the IR signature) and vice versa (for example, adding a flare dispenser could increase vulnerability as a result of the flammability of the flares, and carrying ordnance internally to reduce the radar signature could increase vulnerability caused by the proximity of the ordnance to critical components). Consequently, the goals of the aircraft combat survivability discipline are as follows:

1) The early identification and successful incorporation of those specific survivability enhancement features that increase the combat cost effectiveness of the aircraft as a weapon system is the first goal.

2) In those situations where the damage will eventually lead to an aircraft kill, the survivability enhancement features should allow a graceful degradation of the system capabilities, giving the crew a chance to depart the aircraft over friendly territory.

When it comes to incorporating survivability features into the design of the aircraft, the earlier it is done the better. Adding a feature relatively late in the development or retrofitting a feature to an existing aircraft can impose penalties that could have been avoided if the feature had been incorporated in the beginning of the program. Often, the penalties associated with the addition of a feature late in the design cycle can be so severe that the feature is not incorporated.

Go to Problems 1.1.55 to 1.1.56.

1.1.10 What Is the Relationship Between Survivability and Effectiveness?

Learning Objectives

1.1.19 Describe the relationship between availability, offensive effectiveness, survivability, and effectiveness.

1.1.20 Describe the measures AA, MAM, SR, MOMS, and MOME, and use them to quantify the operational effectiveness of a particular design.

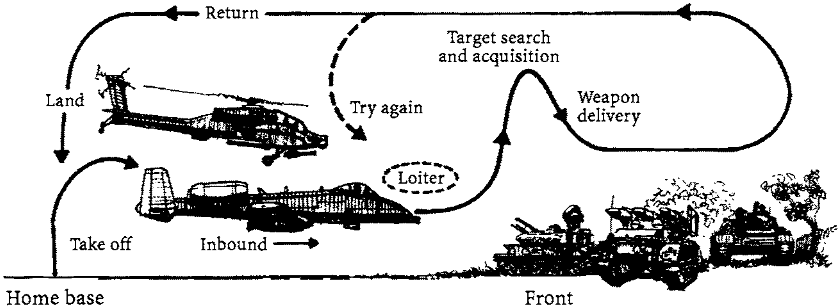


Fig. 1.7 Typical combat mission.

The effectiveness of a particular airborne weapon system on a specific mission is influenced by many factors. These factors are associated with the threat, the weapon system itself, and the operational environment. Figure 1.7 is an illustration of a typical combat mission. In this scenario a mission-capable aircraft takes off from home base and ingresses to the target area. Once in the target area, it locates the intended target, delivers one or more weapons that kill the target, and returns home. A study of this (or any other) scenario reveals that the ability of an aircraft weapon system to complete its assigned mission successfully is dependent upon three primary or top-level attributes. These attributes are 1) the availability of the aircraft for the mission, 2) the offensive capability of the aircraft to accomplish the assigned mission goals, and 3) the defensive survivability of the aircraft as it conducts its mission.

These three attributes are interdependent. For example, increasing offensive capability by releasing ordnance at a lower altitude and closer to the target to improve delivery accuracy will most likely increase susceptibility and decrease survivability, and locating critical components close to the aircraft skin for ease of maintenance and improved availability will increase vulnerability and decrease survivability. Designing an aircraft for low signatures will increase survivability but might also increase maintenance. The increase in the aircraft cost caused by an increase in capability and in survivability is most likely accompanied by a reduction in the number of aircraft purchased and hence in the number of aircraft available for the mission. The next few paragraphs describe these three attributes and the factors that influence them.

1.1.10.1 Availability. Availability, or readiness, influences effectiveness because the more likely a weapon system is available to send on the mission, the more likely the target will be killed, all other factors being the same. Availability is affected by the number of systems purchased, the deployability of the weapon system (the ability to quickly transport the aircraft and its supplies to the theater of operations), the reliability of the system, the availability of spare parts, and the required turnaround time between missions. Aircraft designed to be deployable and supportable with rapid turnaround times are more likely to be available than those not so designed. Availability is also affected by the flight safety and combat survivability of the aircraft. Safer aircraft with more survivability will return from a mission more often, and consequently more aircraft will be available for subsequent missions. The ability to rapidly repair the more survivable aircraft that return with battle damage can have a major impact on availability. Damage repair can be especially important for stealth aircraft where the damage and subsequent repair might adversely affect the aircraft's signatures.

1.1.10.2 Offensive capability and defensive survivability. Both the offensive capability of the aircraft as a weapon system and the aircraft's defensive survivability are affected by many factors, including 1) the aircraft flight performance capabilities and handling qualities; 2) the target acquisition capability; 3) the type, effectiveness, and number of weapons carried; 4) the command, control, and communications and other supporting systems available; and 5) the tactics used and the terrain and weather conditions.

Aircraft flight performance capabilities affect capability by limiting the combat radius, cruise speed, dash speed, payload, and loiter time on station. Undesirable handling qualities affect capability by increasing the pilot workload and by limiting the flight envelope (for example, flying close to the deck to avoid detection might be too difficult to accomplish). Performance capabilities, such as speed and maneuverability, can also have a strong influence on survivability (for example, the 'speed is life' and 'no sitting duck' philosophies).

The ability to acquire the target rapidly and precisely has a very strong influence on effectiveness, for it is in this phase that the aircraft could be the most susceptible. Target acquisition capability depends upon the navigation and targeting aids, the visual field of view from the cockpit, and assistance from any onboard radar or electro-optics, such as a forward-looking infrared (FLIR) sight. Flight vectoring information from a ground-based forward air controller (FAC), or an airborne forward air controller [FAC(A)], and the GPS can assist the crew in locating the target rapidly.

The type, effectiveness, and number of weapons carried influence weapon delivery tactics and the number of sorties required to kill the target. The more sorties required to get the job done, the more likely the loss of aircraft. The use of standoff, launch-and-leave, fire-and-forget, and shoot-and-scoot weapons can allow the aircraft to remain outside of the threat envelope or quickly exit the defended area. Any self-protection armament or antiradiation missiles carried by an aircraft to defend itself from enemy interceptors and radars reduce the payload carried.

Supporting systems, like command, control, and communications (C3), fighter escorts, SEAD threat-suppression aircraft, standoff jamming aircraft, escort or stand-in jamming, off-board target locators/designators, and electronic signal monitoring/missile launch warning aircraft, reduce the susceptibility of the aircraft and hence increase the likelihood that the aircraft will get to the target and return home. They can also increase offensive capability by improving target acquisition accuracy and reducing mission time.

The aircraft signatures and the onboard electronic equipment employed influence the probability that the aircraft is detected, tracked, and fired upon before it gets to the target to deliver its weapons and hence influence survivability. They can also affect the performance and payload capabilities of the aircraft because of special design requirements, such as the requirement to carry ordnance internally to reduce the radar signature. Furthermore, the requirements established for one of these two survivability enhancement features affect the required performance capabilities of the other, for example, the more powerful the capability of the onboard EA equipment, the higher the allowable signature levels for a given level of survivability.

The tactics used can significantly affect the susceptibility of the aircraft. Low-level, terrain following, or nap-of-the-Earth flight, terrain masking, bad weather, and nighttime operations are often used to reduce exposure to the threats. Jinking, a periodic, three-dimensional weaving flight path to degrade gun fire control accuracy and missile guidance routines, and a last ditch evasive maneuver to avoid approaching missiles, reduces susceptibility. When combat support aircraft are jumped by enemy fighters, the use of defensive air combat maneuvering (DACM) can prevent the fighter from taking an easy shot at the aircraft. The assignment of supporting friendly fighter or helicopter escorts is another approach to reducing the susceptibility of strike and support aircraft.

Note that all of the preceding factors strongly influence the susceptibility of the aircraft. Combining these factors with the aircraft's vulnerability leads to the inescapable conclusion that the operational effectiveness of an aircraft as a weapon system and the aircraft's survivability are neither incompatible nor exclusive, but instead are inextricably related, one to the other. A military aircraft cannot be effective if it is not survivable. However, a survivable aircraft is not necessarily an effective aircraft.

1.1.10.3 Mission availability, capability, and survivability measures. A measure of the availability of an aircraft for a particular mission, referred to as the readiness rate or mission capable rate, is AA, the likelihood the aircraft is available for the mission. The number of sorties an aircraft can fly per unit period of time, for example, two sorties per day, is known as the sortie generation rate (SGR) and is a measure of mission availability that can be used in campaign analyses (Note 19).

The measures for mission capability and survivability can be determined by considering the mission of the aircraft from two points of view: an offensive capability point of view in which the aircraft attempts to successfully conduct its mission (for example, destroy bridges, deliver troops, locate submarines, down enemy bombers) and a defensive survivability point of view in which the aircraft operates in a man-made hostile environment while conducting the mission (Note 20).

Consider a war-at-sea strike mission. The aircraft's assignment is to destroy a major surface combatant using a laser-guided, air-to-surface weapon. The ship can defend itself using SAMs and guns. Figure 1.8 illustrates a breakdown of the mission profile into a chain of events or mission elements from both the offensive and the defensive point of view. Although these two chains are separate, they are subtly intertwined. The demands of the offensive elements of the mission will affect survivability (for example, the necessity to ingress to a location near the ship, pop up into the ship's weapons envelopes in order to locate the target and deliver the ordnance will adversely affect survivability) and vice versa (for example, the crew workload required to operate a chaff and flare dispenser can degrade their operation of the weapon delivery system, and low-level, high-speed ingress to reduce the enemy's detection range, tracking accuracy, and engagement opportunities will adversely affect flight performance, such as range).

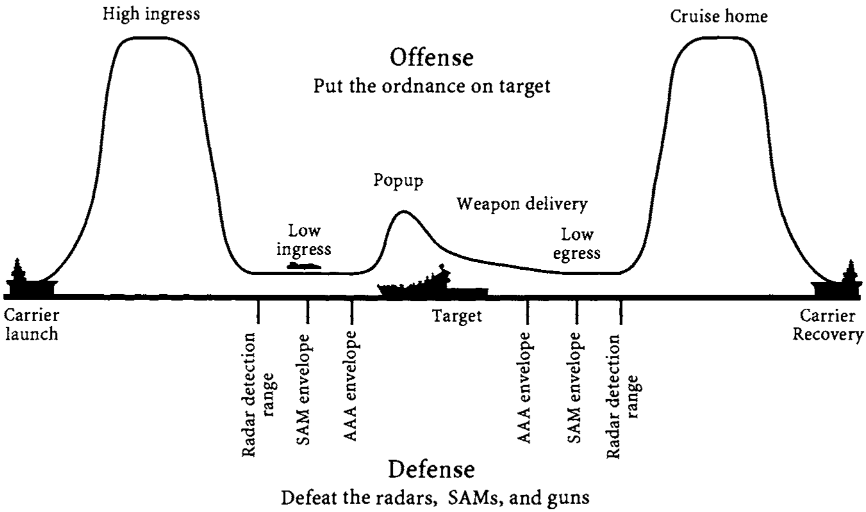


Fig. 1.8 Offensive and defensive views of a hypothetical mission profile for a single plane, daytime strike at sea.

The effectiveness of the available aircraft from the offensive capability point of view of the mission can be quantified by the mission attainment measure (MAM), which ranges from 0 to 1. When evaluating the MAM for a specific mission, the aircraft operates as if the threat were present (for example, appropriate tactics, flight paths, and electronic attack are employed), but the killing effects of the threat are not considered. Thus, the MAM is a conditional measure of the offensive capability of the aircraft to accomplish its objectives in the presence of the threat without the consideration of the threat effects. From a probability point of view, the MAM is the conditional probability the aircraft can successfully accomplish its mission goals, given that it survives.

The effectiveness of the aircraft from the defensive survivability point of view of the mission can be measured by the aircraft's mission SR. The more survivable the aircraft is, the closer SR is to unity.

1.1.10.4 Simple measures of effectiveness. As shown by the tree diagram in Fig. 1.9 for a mission, an available aircraft can successfully complete the assigned mission only when the available aircraft survives the mission (the SR) and accomplishes the mission's offensive objectives or goals (the MAM) (Note 21).

One simple measure of the effectiveness of an available aircraft in a particular scenario is the measure of mission success (MOMS), which is given by

$$\text{Measure of Mission Success} = \text{Survivability} \cdot \text{Offensive Capability}$$

$$\text{MOMS} = \text{SR} \cdot \text{MAM} \tag{1.9a}$$

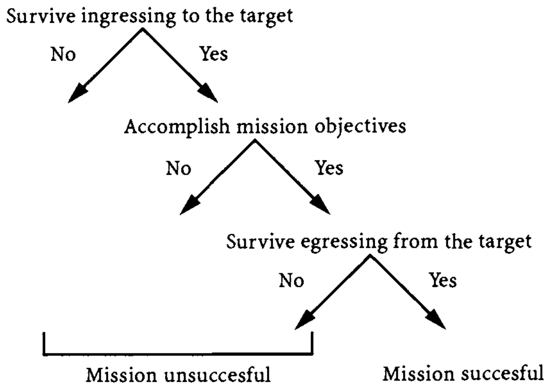


Fig. 1.9 Tree diagram for mission success.

Note that the MOMS is directly proportional to mission survivability. The aircraft must survive in order to accomplish its mission. Aircraft that are very effective from an offensive point of view will have a large MAM. If those same aircraft have a relatively low mission survival rate, the MAM will be reduced intentionally by the operational commanders to increase the SR using the concept of managed attrition described in Sec. 1.1.11.

When the availability of the aircraft for the mission (AA) is considered, one simple measure of effectiveness is the measure of mission effectiveness (MOME), which is given by

$$\text{Measure of Mission Effectiveness} = \text{Availability} \cdot \text{Survivability} \cdot \text{Capability}$$

$$\text{MOME} = \text{AA} \cdot \text{MOMS} = \text{AA} \cdot \text{SR} \cdot \text{MAM} \tag{1.9b}$$

When the effectiveness of a particular type of aircraft flying many sorties is considered, each aircraft has a readiness measure of AA for the mission, and each available aircraft has a mission success rate given by the MOMS. Given a total campaign goal of G successful sorties, then the number of available aircraft that must be launched to achieve that goal is given by

$$L = G/\text{MOMS} \tag{1.9c}$$

The number of aircraft killed in accomplishing this goal K is given by

$$K = L(1 - \text{SR}) \tag{1.9d}$$

In those situations where the MAM is reduced in order to increase the SR, the more survivable aircraft could possibly have a smaller MOMS. Consequently, more sorties will have to be flown by the more survivable aircraft in order to accomplish the total goal. However, there will most likely be more of the more survivable aircraft available to sustain the operations, and fewer replacement aircraft and aircrews will be needed. This reduced demand for replacements could be of paramount importance in an intense conflict because of the long times required to build aircraft and train aircrews.

The most desirable aircraft is the one that is available, offensively capable, survivable, and, perhaps most importantly, affordable. This aircraft is the one that wins battles and wars quickly. However, because of the inherent interconnections between these four attributes, selecting the right amount of each attribute, in a balanced design, is difficult. Example 1.9 illustrates the assessment of the effectiveness of two competing designs.

Example 1.9 Survivability and Effectiveness

Consider two competing aircraft designs and tactics. The campaign goal G is 10,000 successful sorties.

Design and tactic #1 has the measures

$$\mathrm{AA} = 0.96 \quad \mathrm{SR} = 0.99 \quad \mathrm{MAM} = 0.80$$

Therefore,

$$\mathrm{MOMS} = 0.99 \cdot 0.80 = 0.792 \qquad \mathrm{MOME} = 0.96 \cdot 0.792 = 0.760$$
$$\text{Aircraft Launched } (L) = 10,000/0.792 = 12,626$$
$$\text{Aircraft Killed } (K) = 12,626 \cdot (1 - 0.99) = 126$$

according to Eqs. (1.9a–1.9d).

Design and tactic #2 has the measures

$$\mathrm{AA} = 0.96 \quad \mathrm{SR} = 0.999 \quad \mathrm{MAM} = 0.78$$

Therefore,

$$\mathrm{MOMS} = 0.999 \cdot 0.78 = 0.779 \quad \mathrm{MOME} = 0.96 \cdot 0.779 = 0.748$$
$$\text{Aircraft Launched } (L) = 10,000/0.779 = 12,837$$
$$\text{Aircraft Killed } (K) = 0.001 \cdot 12,837 = 12.8$$

according to Eqs. (1.9a–1.9d).

Note that although option #1 has a slightly higher MAM and MOMS and fewer aircraft launches, aircraft #2 might be the preferred option because of the significantly fewer number of aircraft killed. The life-cycle costs of the competing designs and tactics must be considered before any final selection can be made.

Go to Problems 1.1.57 to 1.1.62.

1.1.11 What Are Managed Attrition and Virtual Attrition?

Learning Objective 1.1.21	**Describe and give some examples of managed attrition and virtual attrition.**

Aircraft survivability has been shown to play a major role in effectiveness. If heavy losses are expected on a particular mission or during a campaign, commanders will manage attrition, that is, they will reduce the MAM in order to increase the SR (for example, electronic jammer pods will replace ordnance on wing stations of attack aircraft, ordnance will be released from high altitude so that the launching aircraft can stay above the air defense's weapon envelopes, and many of the aircraft in the force package will be dedicated to enhancing the survivability of the other aircraft). The phrase managed attrition refers to the intentional reduction in the effectiveness of the air attack (the MAM is reduced) in order to reduce the attrition of the aircraft to an acceptable level (the SR is increased).

The air defense community refers to this intentional degradation in offensive effectiveness by the attacking air force as virtual attrition. Although relatively few of the aircraft are killed by the air defense, the attacking aircraft are less effective in accomplishing their offensive goal (the MAM is reduced), and hence they are virtually killed. Thus, virtual attrition is that situation in which most of the attacking aircraft are neither destroyed nor damaged by the air defense, but the offensive accomplishments of the aircraft are less than would be predicted based upon the aircraft capabilities because of the presence of the air defense. Several examples of managed attrition and virtual attrition are given next.

A classic example of managed attrition is the first major strike against a bridge in North Vietnam known as the Dragon's Jaw bridge during the SEA conflict.[6] This example is a vivid illustration of the vast amount of operational resources that have been dedicated in the past to enhancing the survivability of aircraft that were not originally designed to be survivable. Shortly after noon on 3 April 1965, 79 U. S. Air Force aircraft took off for Thanh Hoa in North Vietnam. Forty-six were F-105s, 21 were F-100 Super Sabres, two were RF-101s, and 10 were KC-135 air-refueling tankers. Of the 46 F-105s only 31 were specifically dedicated to the destruction of the bridge using Bullpup missiles and 750-lb bombs (Note 22). Because of the concern for the antiaircraft artillery defenses around the bridge, 15 of the F-105s and seven of the F-100s were to provide flak suppression, that is, they were to destroy the enemy's ground-based air defenses using 750-lb bombs and 2.75-in. rockets. Two F-100s were dedicated to weather reconnaissance, four F-100s were for fighter escort or MIGCAP, and eight were for combat search and rescue (CSAR), if required (Note 23).

Note that only 31 out of 69 tactical aircraft were assigned to the offensive portion of the mission—destroying the bridge. Twenty-six aircraft were dedicated to enhancing the survivability of the 31 bombers, and the eight CSAR aircraft were there to enhance the survivability of any downed aircrew. Thus, more aircraft were used to enhance the survivability portion of the mission (the SR) than were used to increase the mission attainment measure (the MAM). The strike was not totally successful in either aspect. The bridge was damaged, but not destroyed, and the antiaircraft fire was considerably more intense than anticipated. Two aircraft were lost, and several were damaged on this first of many strikes at the Dragon's Jaw bridge. The bridge was eventually put out of commission—temporarily—in 1972 by U. S. Air Force F-4s using laser-guided bombs.

Managed attrition occurred in 1986 in the Soviet–Afghanistan conflict when the U. S. Stinger infrared SAM was used by the Afghan rebels against Soviet strike aircraft. "The Stinger has forced high-performance Soviet strike aircraft pilots to deliver their weapons from high altitudes, seriously eroding accuracy. It also has forced pilots of Soviet helicopter gunships and tactical strike aircraft, such as the Sukhoi Su-25 Frogfoot, to fly nap-of-the-Earth missions and deliver their ordnance on the first pass, making them vulnerable (susceptible) to massed small arms fire and further eroding accuracy."[7]

In 1987, two Libyan bombers conducted a bombing raid on the capital of Chad. When one of the bombers was shot down by a U. S. Hawk SAM as it was approaching its target, the second bomber turned back without releasing its bombs, thus increasing its survivability but also decreasing its MAM to zero. The net result for the air defense was two bombers killed; one was a hard kill, the other was a virtual or soft kill—neither bomber dropped their bombs.[8]

Another example of managed attrition occurred during the planning of the first strikes of Operation Desert Storm in January 1991. "The Navy and Marine Corps also contributed planners to the original Checkmate effort and then to the Black Hole. At first Navy and Marine planners hoped to use their A-6 precision bombers against targets in the Baghdad area, but computer modeling of the threat persuaded them to leave that job to the F-117s and Tomahawks"[9] (Note 24). The decision to use the more survivable F-117s and Tomahawk cruise missiles in the strikes against Baghdad was based upon the premise that the increased ordnance that could be delivered by the A-6s (increasing the MAM) was not sufficient to risk losing them to the air defense (their SR was too small.).

The second Desert Storm example is a classic illustration of the degradation in offensive bombing capability to achieve an acceptable level of survivability. "Prior to the war, the planners anticipated using this tactic (bombing from medium altitude) only for attacks during daylight. However, after three days of actual combat and the loss of several aircraft (bombing at low altitude), commanders restricted all bombing missions to medium altitude. . . . Moving the bombing aircraft above this (low) altitude increased aircraft survivability, but it decreased the bombing accuracy. Given the conditions of this war and the need to minimize causalities, the move was a prudent trade-off."[10]

Another consequence of the medium-altitude requirement in Desert Storm was the additional requirement for high weather ceilings. The high weather ceiling allowed the aircrew to fly below the clouds, where they could visually locate the targets, and at a sufficiently high altitude where they could avoid the low-altitude threats. If the weather ceiling were low and they flew below the clouds to enhance target acquisition and bombing accuracy, they could easily be detected and engaged by the low-altitude air defense. If they flew above the low ceiling weather to avoid detection and engagement by the low-altitude weapons, they might have difficulty locating their target. Furthermore, flying above the weather could prevent the aircrew from spotting any missiles launched at them from the ground, which could decrease their survivability. Thus, many missions were canceled when the ceilings were too low.

One of the most recent examples of managed attrition was the situation in Kosovo during May of 1999 when the 24 AH-64 Apaches that were sent to Albania were not used because the mission apparently was considered by senior leaders to be too risky.

Tactical aircraft are not the only aircraft that manage attrition. In Bosnia in 1994, the U. S. Air Force used C-130s and C-141s to conduct air drops of supplies to refugees from above 10,000 ft. The normal altitude for an accurate drop is below 3000 ft. The transports made their drops from above 10,000 feet in order to avoid antiaircraft gun fire.

Go to Problem 1.1.63.

1.1.12 When and How Do We Assess Survivability?

Learning Objectives	**1.1.22**	**List the four broad applications of a survivability assessment.**
	1.1.23	**Briefly describe the survivability assessment methodology.**
	1.1.24	**Describe and compute the single hit vulnerable area of a component and an aircraft.**
	1.1.25	**Conduct a trade study.**

Most of the activities or tasks associated with the survivability program of an aircraft in development can be grouped into four broad applications: 1) establishing the requirements for survivability, 2) selecting and designing the specific survivability enhancement features that will meet the requirements, 3) supporting the evaluation that the final product meets the requirements, and 4) providing survivability and vulnerability data to mission and campaign models. The flow of the survivability assessment methodology used in any of these applications is illustrated in Fig. 1.10.

1.1.12.1 Mission-threat analysis. Because an aircraft's survivability is directly dependent upon the intensity and the effectiveness of the threat, the survivability program begins with a mission-threat analysis. This analysis consists of the definition of the mission, the aircraft operational mode throughout the mission, and the threats the aircraft might encounter on the mission. The aircraft operational mode includes the aircraft configuration factors, such as weight, fuel status, armament loading, etc., and the proposed operational concepts, such as mission profile and accompanying forces.

The threats to the aircraft, based on the aircraft operational mode, are estimated for the appropriate operational years and theaters and the predicted enemy order of

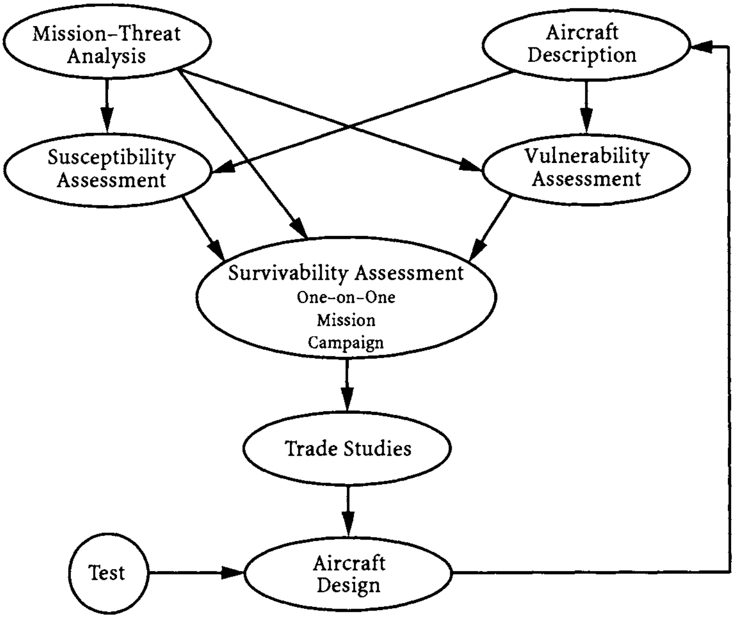


Fig. 1.10 Flow of the survivability assessment methodology.

battle (EOB), which includes the identification, strength, command structure, and disposition of the personnel, units, and equipment of the enemy force.[1] Included in the threat identification are the threat characteristics and modes of operation. Some of the important threat characteristics are the type of threat platform (for example, airborne interceptor) and propagator (for example, guided missile) and the type of ordnance package on the propagator (for example, a high-explosive warhead with fragmentation case and proximity fuze). Associated with the warhead are the damage mechanisms (for example, blast, fragments, and incendiary particles). The modes of operation include those functions associated with searching for hostile aircraft, known as targets, communicating with other elements of the air defense, detecting targets, tracking targets, and firing, or launching and guiding, a propagator.

The overlap between the threat coverage and the aircraft operational mode is analyzed to determine the scenario conditions for the threat and the aircraft. These conditions include the threat order of battle, with weapon types, numbers, locations, and command structure of the enemy's personnel, units, and equipment, and the aircraft's flight path and accompanying friendly forces. Environmental and terrain data for the scenarios of interest can be gathered at this stage.

The procedure for conducting a mission-threat analysis is described in Chapter 3, Sec. 3.9.

1.1.12.2 Aircraft description. Another required task in the assessment consists of obtaining the most detailed technical description of the aircraft that is available. This should include information on the location, construction, and operation of all of the systems, subsystems, and components of the aircraft. It will be used in both the susceptibility and vulnerability assessments. This information is particularly important in the early stages of the design, when many of the major decisions regarding the incorporation of survivability features are made.

A description of the major systems and subsystems of an aircraft is given in Chapter 2, Aircraft Anatomy, for the reader who is unfamiliar with an aircraft, its parts, and its operation.

1.1.12.3 Susceptibility assessment. The assessment of the susceptibility of the aircraft at this stage of the process usually begins with the determination of the essential operations and performance parameters associated with the air defense elements involved in the detection, acquisition, and tracking functions of the air defense and ends with predictions of P_H or P_F based upon an assumed aircraft flight path. The operations and parameters of any SR techniques that are under consideration, such as an onboard noise jammer or expendables package, are also identified. Some of the required surveillance and tracking sensor performance parameters are the radar wavelength, the gain pattern of the radar antenna, and the signal-to-noise ratio required for target detection. The magnitude of the signatures of the aircraft that are used by the threat sensors for detection and tracking, such as the radar signature and the infrared signature, are also determined here. The radar signature is referred to as the radar cross section (RCS) and has the units of square meters or of decibels referenced to one square meter (dBsm). A polar plot of the RCS of the A-7 Corsair II is shown in Fig. 1.11a. The IR signature is given as the radiant intensity, in watts/steradian, in the radiation bandwidth of the threat IR sensor. A plot of the IR signature of a nonstealthy generic aircraft at four locations around the aircraft is shown in Fig. 1.11b.

Most of the susceptibility portion of a survivability assessment of an encounter between a weapon and an aircraft is usually conducted using computer models or live-fire tests to determine the likelihood the aircraft is hit, or a proximity-fuzed HE warhead detonates, at a particular location. The use of modeling and simulation in a survivability assessment is described in Sec. 1.5 of this chapter, and the procedures for computing the signatures of an aircraft and the susceptibility probabilities P_H and P_F are described in Chapter 4.

1.1.12.4 Vulnerability assessment. The assessment of the vulnerability of an aircraft to the predicted threats consists of the following three tasks: 1) selection of the type of aircraft kill, such as an attrition kill at the B level or a mission abort kill; 2) identification of the critical components and their kill modes, using two analysis tools called fault tree analysis (FTA) and failure mode and effects analysis (FMEA); 3) computation of the numerical values for the measures of vulnerability of the aircraft for the selected threat, such as a ballistic projectile or fragment, a contact-fuzed HE warhead, and a proximity-fuzed HE warhead.

Vulnerable area. One measure of an aircraft's vulnerability to contact weapons is $P_{K|H}$. Another measure is vulnerable area. Vulnerable area is defined as an area

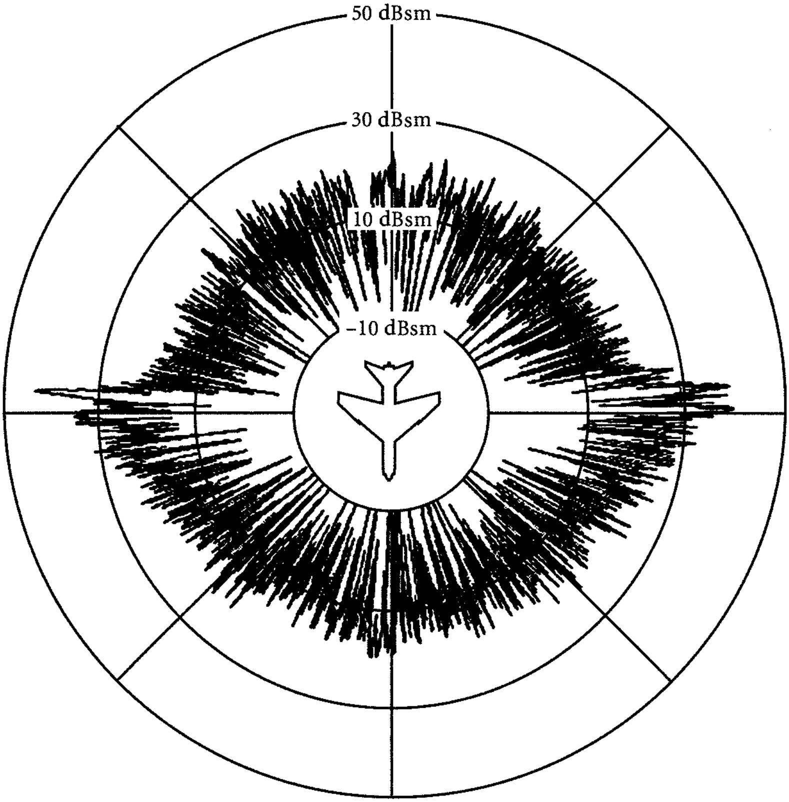


Fig. 1.11a Polar plot of the RCS of the A-7 Corsair II.[11]

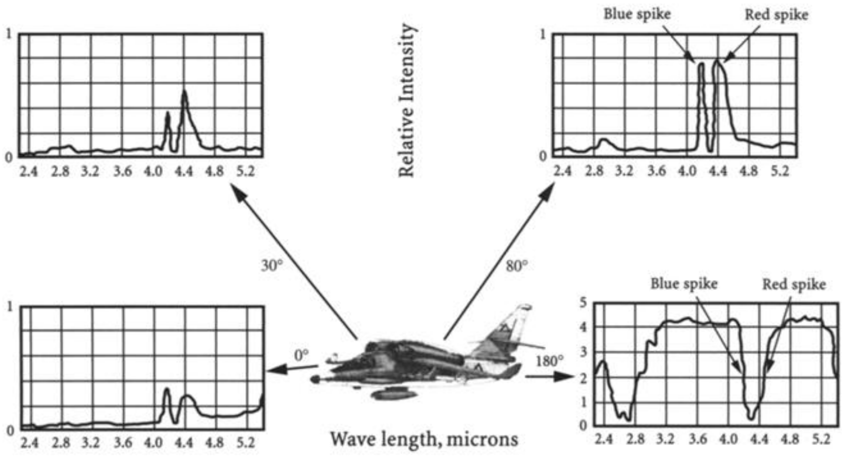


Fig. 1.11b IR signature around an aircraft.

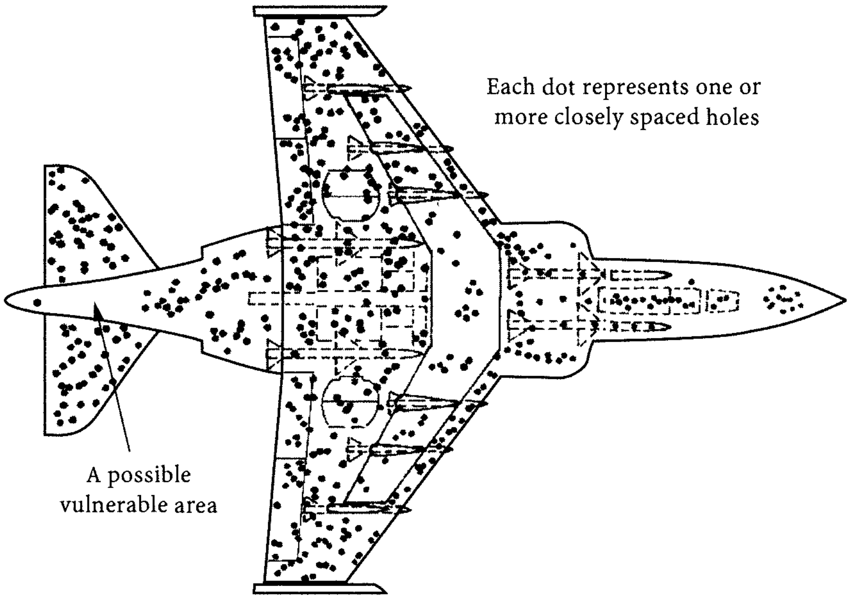


Fig. 1.12 Bottom hit plot.

on a component or the aircraft that if hit will result in a kill of the component or the aircraft. The concept of vulnerable area as a measure of an aircraft's vulnerability can be illustrated using combat data from aircraft that have returned from a mission with battle damage. Examination of the damage on aircraft that return to base can provide information on the vulnerability of the aircraft to the threats that caused the damage. A spatial plot of the location of all of the penetrating hits taken by aircraft of a particular type that returned to base with battle damage can be used to determine the vulnerable areas on that aircraft type. This plot is known as a hit plot.

A typical example of a hit plot on the bottom of an aircraft is illustrated in Fig. 1.12. Each dot on the plot represents one or more closely spaced holes in the aircraft's skin caused by one or more closely spaced hits by a damage mechanism, such as a bullet or fragment. When the number of hits from any one direction is sufficient to nearly cover the aircraft in a random distribution, as in Fig. 1.12, locations on the aircraft where few or no hits are recorded are locations that either were not hit, which is unlikely, or are locations of components that, when hit, lead to an aircraft kill.

Certain vulnerable areas and the critical components associated with those areas can be identified very quickly from these hit plots. For example, an area in Fig. 1.12 nearly devoid of hits is at the tail of the aircraft. Here, redundant hydraulic lines usually come together to provide two independent sources of power for the stabilator actuator. One hit here could damage both lines. If all hydraulic power is lost to the stabilator, the stabilator can go hard-over as a result of aerodynamic forces, causing the aircraft to become uncontrollable. This can happen so fast that the crew might not be able to eject (Note 25). Another area in Fig. 1.12 with few

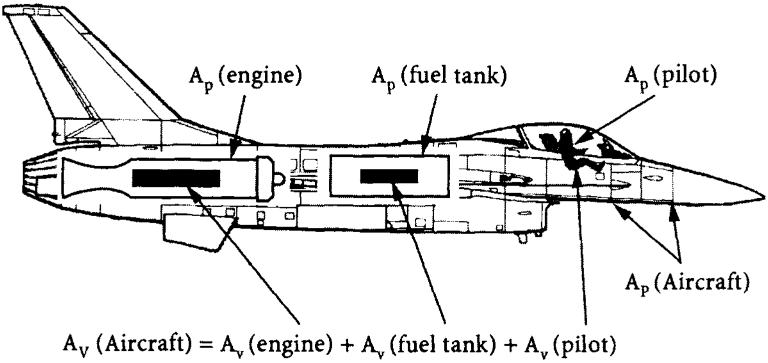


Fig. 1.13 Aircraft and component presented and vulnerable areas.

holes is that over the bottom of the wing. This particular area corresponds to the location of the wing fuel tanks. Most of the aircraft that were hit here might have been killed. However, another possible explanation for the lack of holes in this area could be the fact that the wing skin in this area is extremely thick, and the damage mechanisms could not penetrate the skin; hence, the absence of holes. A third possible vulnerable area is near the nose of the aircraft. Projectiles or fragments approaching the aircraft from in front and below could possibly kill the pilot, resulting in an aircraft kill.

Hit plots for the other directions around an aircraft can be examined to determine the direction of heaviest attack. For example, examination of the hit plots for many of the tactical aircraft used in the air-to-surface role in the SEA conflict reveals that most of the hits occurred on the bottom surface of the aircraft.

Computing an aircraft's single-hit vulnerability. The procedure for computing the vulnerability of an aircraft caused by a single hit by a nonexplosive ballistic projectile or fragment is briefly described next to illustrate the assessment process and the terminology.

Consider the single-pilot, single-engine aircraft shown in Fig. 1.13. The assumption is made that the attack direction of the ballistic projectile or fragment is perpendicular to the side of the aircraft. The type of kill selected is the A level attrition kill. (The aircraft falls out of control within five minutes of the hit.) Accordingly, three nonredundant critical components have been identified: the pilot, the engine, and the fuselage fuel tank. The kill modes of these three components are pilot death, engine loss of thrust, and a fuel tank explosion, respectively. A kill of one or more of these components will result in a kill of the aircraft. Note that none of the components overlap each other from the attack direction shown.

Aircraft are vulnerable because their critical components are vulnerable. Like the aircraft, the vulnerability of each of the critical components can be measured by $P_{k|h}$, the probability the component is killed given a hit by the projectile or fragment on the component. The magnitude $P_{k|h}$ for each component depends upon the size of ballistic projectile or fragment and the velocity of impact of the projectile or fragment upon the component (Note 26).

In the process of determining the $P_{K|H}$ of the aircraft, it is helpful to use the concept of a single-hit vulnerable area. Each critical component has a single-hit vulnerable area A_v, and each component's vulnerable area contributes to the vulnerable area of the aircraft A_V in some way. The single-hit vulnerable area of a component is defined to be that theoretical area on the component that if hit once would cause a kill of the component. When the assumptions that the hit is equally likely to occur at any location over the component's presented area in the attack direction A_p and that the $P_{k|h}$ is uniform over the component's presented area are made, the component A_v is computed using

$$A_v = A_p P_{k|h} \tag{1.10a}$$

The black area within each of the three critical components shown in Fig. 1.13 denotes the vulnerable area of the component.

The vulnerable areas of the components contribute to the single-hit vulnerable area of the aircraft A_V, that theoretical area on the aircraft which if hit once would cause a kill of the aircraft. In this simple example with only nonredundant and nonoverlapping critical components, the vulnerable area of the aircraft is the sum of the vulnerable area of the three critical components shown in Fig. 1.13. Thus,

$$A_V = A_v\,(\text{pilot}) + A_v(\text{fuel tank}) + A_v(\text{engine}) \tag{1.10b}$$

The probability the aircraft is killed given a random hit on the aircraft $P_{K|H}$ is given by

$$P_{K|H} = \frac{A_V}{A_P} \tag{1.10c}$$

where A_P is the presented area of the aircraft (Note 27).

The computer program usually used today to compute an aircraft's single hit A_V and $P_{K|H}$ is the Computation of Vulnerable Area and Repair Time (COVART) program. COVART might be replaced in the near future by the Advanced Joint Effectiveness Model (AJEM). Both programs are briefly described in Sec. 1.5.2. The analytical procedures for computing the vulnerability of a complex aircraft to both contact warheads and proximity warheads and the computer programs that carry out these procedures are described in Chapter 5.

1.1.12.5 Survivability assessment. In the survivability assessment the scenario conditions and threat capabilities identified in the mission-threat analysis are combined with the results of the susceptibility and vulnerability assessments to determine the probability of survival of the aircraft in a selected scenario. Of interest is the survivability of the aircraft when 1) one aircraft encounters one threat weapon (engagement-level survivability assessment), 2) many aircraft encounter many threat weapons (mission-level survivability assessment), and 3) many aircraft encounter many threat weapons on many missions (campaign-level survivability assessment).

The prediction of aircraft P_S in any of these scenarios can be accomplished through the use of digital computer programs that mathematically model the scenario. A typical one-on-one or many-on-many scenario includes 1) the terrain map and the threat weapons laydown; 2) the aircraft flight paths; 3) the physical and electromagnetic aspects of aircraft detection and tracking; 4) track data transfer and processing and target assignment; 5) missile launch, or gun firing, and propagator fly out; and 6) the endgame, which consists of the warhead impact or proximity detonation and the terminal effects.

The use of computer models to simulate the physical events in any scenario is described in more detail in this chapter in Sec. 1.5, and the procedures and equations for assessing survivability are described in Chapter 6.

1.1.12.6 Trade studies. A trade study is conducted to determine the payoffs (for example, the number of aircraft saved in a campaign or over the lifetime of the aircraft model as a result of a survivability enhancement feature) and the performance and cost impacts or burdens (for example, the various costs, both physical and financial) associated with each survivability feature considered. In this study the one-on-one P_S for the selected threats, the mission survival rate (SR), and the campaign survivability (CS) are determined for both the baseline design and the modified design for each survivability enhancement feature, or combination of features, considered. The impact of the feature(s) on the MAM, the aircraft weight, flight performance, reliability, maintainability, safety, repairability, and the other attributes of the aircraft is also evaluated. Any risk associated with the development of the feature must be identified and possibly quantified. The life-cycle (LC) dollar cost, including the cost associated with the research and development, production, and operations and support of the aircraft associated with the feature(s), is then estimated for a postulated lifetime (peacetime plus wartime) of the aircraft. This process is repeated at some level for all of the feature(s) initially considered. The final trade study should include all of the features selected for final consideration in order to account for any synergism between the features.

A campaign measure of cost effectiveness, or figure of merit, is then determined, such as the net LC cost savings caused by the feature or combination of features. The net savings is equal to the cost of replacing the aircraft and aircrews that are saved by the survivability features (money saved) minus the cost associated with incorporating the features on all of the aircraft (money spent). Associated with the net savings is a level of risk. A hypothetical trade study is given in Example 1.10.

Example 1.10 Hypothetical Trade Study

Consider a helicopter being designed to carry 11 troops into a forward area near enemy forces. In the mission-threat analysis for the helicopter, the primary threat environment is predicted to be low intensity, and 100,000 helicopter sorties are predicted to be flown by the helicopter in the low-intensity threat environment over the life of the helicopter. The results of the survivability assessment of the baseline helicopter in 100,000 helicopter sorties in the hostile environment predict that 280 helicopters would be hit and that 14 of these helicopters would be killed in the campaign by the air defense.

One of the survivability enhancement features being considered is the protection of the helicopter's fuel system using self-sealing fuel bladders and lines. The self-sealing material prevents small arms projectiles and fragments from HE rounds from causing fuel leaks in the bladders and lines that would allow the fuel to migrate into adjacent dry bays and possibly ignite. The onboard fire could result in the loss of the helicopter. Without the self-sealing material the probability a fire occurs as a result of a hit on the fuel tanks and lines $P_{k|h}$, is 0.6. With the material the $P_{k|h}$ is reduced to 0.0.

The gross weight of the helicopter is increased by 50 lb because of the self-sealing, and the level of developmental risk associated with this feature is low. The total LC dollar cost associated with the incorporation of the self-sealing feature and with all of the other performance impacts is estimated to be \$25M for the entire fleet of 500 helicopters.

The assessment results for the more survivable helicopter indicate that, because of the reduced vulnerability of the fuel system, only 10 of the more survivable helicopters are expected to be killed over the lifetime of the helicopter. Thus, $14 - 10 = 4$ helicopters and $4 \cdot$ (2 crew members plus 11 troops) = 52 people would be saved by this feature. The dollar value of the 4 saved helicopters is estimated to be \$70M. Placing a dollar value on the 52 people whose lives are saved by the self-sealing is more difficult. There are many costs associated with a downed aircraft and its crew and passengers, such as search and rescue costs, survivor benefits, and the cost of replacing the lost crew members and passengers. For this example the dollar value of the 52 people saved is assumed to be \$30M.

Thus, incorporating the self-sealing bladders and lines is predicted to save \$70M + \$30M − \$25M = \$75M and the lives of 52 people if 100,000 sorties are flown in combat under the conditions simulated in the survivability assessment. However, if no combat sorties are flown during the lifetime of the 500 helicopters, the survivability enhancement feature costs the program \$25M. But wait a minute, the system safety engineer points out that the self-sealing feature also enhances flight safety and crash worthiness, as well as combat survivability, and, along with the survivability engineer, strongly recommends that this feature be included in the design. What would you recommend?

1.1.12.7 Testing. The proposed design of the aircraft must be tested as the design progresses from the conceptual stage into full scale in order to verify the efficacy of the proposed survivability enhancement features and to identify any potential problems not considered or overlooked in the design. Much of the testing is done in the conceptual and developmental phases to select the appropriate type and level of survivability enhancement provided by the features. Early testing for susceptibility might involve the use of subscale models for signature and electronic attack equipment evaluations and a combination of laboratory and field equipment. Final susceptibility testing, such as signature measurement, is usually conducted using full-scale models. Testing for vulnerability usually involves the use of live ammunition. This type of testing is referred to as live-fire testing. For example, suppose reticulated foam is a candidate for the suppression of any combustion overpressure in the flammable ullage space of a fuel tank when the tank is hit (Note 28). The amount of foam required to suppress the overpressure to a level that can be contained by the tank can be determined by shooting at the actual tank or a tank simulator (or surrogate) containing foam. The test conditions should be as realistic as possible in order to provide the right answer. For example, in the ullage test the tank interior, oxygen content, amount of fuel vapor, and temperature should be similar to the conditions that would occur in combat.

A major test program for the vulnerability of any new or modified U. S. military aircraft is the congressionally mandated Live Fire Test program. This important program is described in Sec. 1.6.

Go to Problems 1.1.64 to 1.1.71.

1.1.13 What Is System Survivability?

Learning Objective	1.1.26	Describe the eight survivability strategies for system survivability.

In the preceding material the survivability of an aircraft has been the subject of interest. An aircraft, with its weapons and other equipment, materials, services, and personnel required for self-sufficiency, is referred to as a weapon(s) system. Here, in the phrase system survivability, the word system can refer to a collection of individual units, elements, or components that are physically separated, as opposed to an individual aircraft in which the components that affect survivability are essentially collocated. For example, a space system can be composed of one or more spacecraft or satellites, several ground-based communication installations and command headquarters, and the communication links between all of the elements (Note 29). An unmanned aerial vehicle (UAV) system can be composed of the UAV itself, which is an aircraft, the command installation that controls the UAV, and the communication link between the controlling installation and the UAV. A system can also refer to an operational force, or system of systems.

The phrase system survivability refers, as it does for aircraft, to the capability of the system to avoid or withstand a man-made hostile environment. According to Air Force Instruction 62-201, System Survivability (Ref. 51), the survivability of any system can be enhanced using one or more of the following eight survivability strategies: 1) avoidance, 2) deception, 3) active defense, 4) hardness, 5) redundancy, 6) threat-effect tolerance, 7) proliferation, and 8) reconstitution. The first three strategies relate to susceptibility reduction, and the last five reduce the vulnerability of the system. These eight strategies, and their relationship to the 12 survivability enhancement concepts for an aircraft given in Table 1.3, are described next.

Avoidance here refers to measures taken to prevent experiencing or meeting the man-made hostile environment and is achieved by locating and operating the system elements outside of the enemy's known fixed defenses (tactics), by the use of threat warning to avoid or deny the enemy's mobile forces and weapons access to the system elements, and by the use of noise jamming and signature reduction, making it difficult for the enemy sensors to locate the elements. Deception is accomplished using signature reduction, electronic deceiving, and expendable decoys, and active defense is the threat suppression concept for reducing susceptibility.

Hardness is the ability of the system to withstand the man-made hostile environment, which is the complement of vulnerability. Hardness can be achieved by using the VR concepts of component location, component shielding, and component elimination or replacement. The redundancy strategy, which is equivalent to the VR concept of component redundancy (with separation), is the use of multiple systems, system elements, communication links, or other means of accomplishing an essential function to maintain the function in the event of a loss of one or more of the multiple elements. Threat-effect tolerance refers to the ability of the system to tolerate the threat effects and is achieved primarily by the concepts of active and passive damage suppression. Proliferation refers to increasing the numbers of the individual units to account for losses that result from exposure to the hostile environments or to increasing the number of targets that must be killed to achieve a system kill. Thus, proliferation reduces system vulnerability through the use of significant redundancy (Note 30).

Reconstitution reduces system vulnerability through the repair, replacement, or resupply of killed or damaged elements of a system. From an aircraft perspective the repair aspect of reconstitution is a form of active damage suppression. From a system perspective the repair of any battle damage on a system element that enables the element to participate in system operations enhances the survivability of the system. The other two aspects of reconstitution, replacement and resupply, although viable for a system, are usually not an option for increasing the survivability of an individual aircraft. The reason for this is the fact that a kill of a flying aircraft is measured in seconds and minutes. On the other hand, a system kill can be measured in hours or days, that is, a system is said to have survived an attack if it is returned to operational readiness within 24 hours of the attack (Note 31).

Go to Problems 1.1.72 to 1.1.74.

1.1.14 Relationship Between ACS Discipline and DE Survivability, NBC Contamination Survivability, and Nuclear Survivability

Learning Objectives	**1.1.27**	**Describe the DE weapons, their important parameters, the aircraft components vulnerable to these weapons, and the techniques for the vulnerability reduction of those components.**
	1.1.28	**Describe the relationship between the NBC contamination survivability terminology and the aircraft combat survivability terminology using a chemical attack on an airbase as an example.**
	1.1.29	**Describe the primary damage mechanisms associated with a nuclear weapon.**

A considerable number of publications about directed energy, chem-bio, and nuclear weapons, their use, and their effects on people and equipment exist in both the open literature and the classified libraries, and many civilian and military personnel are engaged in survivability activities related to these weapons. Because of the distinct differences between these weapons and the more ubiquitous guns and missiles, a separate discipline has evolved for each weapon that is unrelated to any of the other threats to an aircraft and to the aircraft combat survivability discipline in general. As a consequence, the material covered and the terminology used for the other weapons is often different from that presented here for the conventional gun and guided missile weapons. For example, the word vulnerability has a significantly different meaning when used in the ACS discipline than it does when used in the chem-bio survivability discipline.

Because the design of a military aircraft must meet a large number of often conflicting survivability requirements based upon these different threats, it is essential that trade studies be conducted to determine the military worth of any proposed survivability enhancement feature for each threat. These studies should have a consistent terminology and methodology. This can only happen when all of the threats to the aircraft are considered within the framework of a general survivability discipline. Thus, a gathering of these individual disciplines into a single survivability discipline that also includes the electronic attack and system safety disciplines is very desirable. Consequently, a brief description of each of the other survivability disciplines and a translation between the different terminologies are provided here to facilitate communication between the disciplines.

1.1.14.1 DE survivability (Note 32). Beginning with the early years of the 20th century, when aircraft were first used in warfare, the threats to aircraft consisted of ground-based and airborne guns. Guided missiles were introduced as a threat to aircraft in the middle of the century. Now, a new threat known as the directed energy weapon has appeared. This new threat includes a broad class of weapons that use a beam or pulse of electromagnetic (EM) radiation or nuclear particles as the damage mechanism. Examples of the EM radiation weapon include the continuous wave (CW) and pulsed laser and the CW and high-power microwave. The electromagnetic pulse (EMP) created by a high-altitude nuclear burst is not a directed energy weapon by definition because the radiation is not directed at the target. However, its damage mechanism (the EM radiation) is the same as that of the other DE radiation weapons. Furthermore, an electromagnetic pulse can be generated and focused using explosively pumped power sources. Therefore, the EMP can be considered with the directed energy weapons, as well as with the nuclear weapons. The particle beam weapon (PBW) uses a stream of neutral or charged particles to inflict damage on an aircraft. Protection of U. S. personnel and equipment from damage by directed energy weapons is part of the electronic protection division of electronic warfare.

The directed energy radiation weapons of greatest tactical interest today are the low-energy lasers (LEL), medium-energy lasers (MEL), and high-power microwave systems. The LEL and MEL are currently used in laser range finders (LRF) and laser target designators (LTD). These lasers, although not specifically designed as such, can also be used as low-power weapons against human eyes and electro-optic (EO) or EM sensors. The HPM weapon will be used for both soft and hard kills of sensors and electronics (Note 33). The high-energy lasers (HEL) will be used primarily in the antiair warfare mission.

The DE radiation weapon is a line-of-sight weapon. The gunner points the weapon at the aircraft and fires a CW or pulse of EM radiation (a radiation bullet) that propagates toward the aircraft at the speed of light. The important parameters of the CW and the pulse are their power, frequency content, beam width, and duration for the CW, and pulse width, pulse repetition frequency (PRF), and the number of pulses for the pulsed weapon. Laser weapons typically fire a pulse of a single frequency or narrow bandwidth with a relatively short pulse width and relatively narrow beam width. The laser EM frequency can be in the ultraviolet, visible, or infrared region of the EM spectrum. The narrow width of the laser beam and the range to the target aircraft is such that the beam spot on the aircraft is relatively small. A slowly blinking flashlight is analogous to a laser weapon. However, a flashlight cannot damage EM sensors; the laser can. The HPM weapon fires either a narrow-band or a wide-band short-duration CW, or several pulses, in a relatively wide beam. The EMP pulse is ultra wide, relatively long, and relatively wide. The entire aircraft is impacted by the propagating pulse from HPM and EMP weapons. The impact of the laser beam on the aircraft, and the impact on and passage of the HPM beam or EMP wave across the aircraft, will induce alternating currents in the aircraft's conducting materials. This current, if sufficiently large, can disrupt, either temporarily or long term, or permanently damage sensitive sensors and electronics.

The major interests of those working in the DE survivability discipline are the vulnerability and vulnerability reduction of the aircraft's EM and EO sensors and of the flight and mission essential electronic equipment. The sensors consist of the eyes of the crew, as well as other sensor components sensitive to the incident EM radiation, such as the forward-looking infrared device. The EM radiation can impinge directly upon a sensor or electronic equipment (through the front door) or it can impinge on conducting surfaces near the sensor or equipment, indirectly causing currents to flow in the sensor or the electronics (through the back door). Either approach can temporarily disrupt or permanently damage the sensor or the electronics. The amount of sensor front door damage depends upon the wavelength of the EM radiation and the sensor bandwidth.

The primary technique to prevent sensor damage is to coat the sensor dome or pilot's goggles with a material that either reflects or absorbs the incident radiation, essentially shielding the sensor from the damage mechanism. The primary technique to prevent the induced flow of current in electronics is to surround the electronic boxes and cables with a conducting material, known as a Faraday shield. This prevents the EM radiation from entering the box or cable. The shield can be local (around the box) or global (around the aircraft). Protecting the aircraft from the effects of DE weapons can also reduce EM interference (EMI) problems caused by the EM radiation from radars, radio towers, and other EM generators encountered in peacetime. The susceptibility aspect of DE survivability has not received as much attention as the vulnerability aspect, primarily because of the fact that if the aircraft can be seen it most likely can be hit by the EM beam as a result of the light speed of the radiation from the DE weapon to the aircraft.

The reader interested in learning more about DE weapons should visit the Directed Energy Weapons Bibliography online at http://web.nps.navy.mil/~library/bibs/dewtoc.htm.

1.1.14.2 NBC contamination survivability (Note 34). The nuclear, biological, and chemical weapons are weapons of mass destruction. Consequently, U. S. the Department of Defense (DoD) has established the Defense Threat Reduction Agency (DTRA) to reduce the threat to the U. S. and its allies from the nuclear, chemical, biological, conventional, and special weapons. The Internet address of the DTRA is http://www.dtra.mil/. This quote from the "About DTRA" page (29 June 2001) describes the Agency's mission:

> In the post-Cold War environment, a unified, consistent approach to deterring, reducing and countering weapons of mass destruction is essential to maintaining our national security. Under DTRA, Department of Defense resources, expertise and capabilities are combined to ensure the United States remains ready and able to address the present and future WMD threat. We perform four essential functions to accomplish our mission: combat support, technology development, threat control and threat reduction. These functions form the basis for how we are organized and our daily activities. Together, they enable us to reduce the physical and psychological terror of weapons of mass destruction, thereby enhancing the security of the world's citizens. At the dawn of the 21st century, no other task is as challenging or demanding. We've established this site to provide you with the latest and most accurate information about what we do and why we do it. I hope you'll make use of this resource and all that it offers.

Before proceeding to the body of this section, two commonly used expressions in this field must be explained. These two expressions are nuclear, biological, and chemical (NBC) and chemical, biological, and radiological (CBR). NBC is the earliest of the pair and is used almost exclusively in the literature with regard to unconventional warfare, for example, NBC warfare. CBR, on the other hand, is of relatively recent origin and is used almost exclusively with defense, for example, CBR defense. The current survivability phrase is NBC contamination survivability. Another important point to note regarding NBC and CBR is the fact that the N in NBC and the R in CBR stand for the radiation from the residual radioactive material resulting from a nuclear burst, as opposed to the initial nuclear effects of the blast wave and the prompt radiation in the form of thermal and other EM radiation from the burst, which are treated in the nuclear survivability discipline.

A major milestone in the development of aircraft that are survivable in NBC warfare was the June 1987 publication of Department of Defense Instruction 4245.13, Design and Acquisition of Nuclear, Biological, and Chemical (NBC) Contamination-Survivable Systems (Note 35). The purpose of this instruction was to provide general management and documentation requirements for the survivability of systems designed and acquired to perform mission essential functions in an NBC contaminated environment. It contains the following important definitions:

> *1) NBC Contamination:* The deposit and/or absorption of residual radioactive material or biological, or chemical agents on or by structures, areas, personnel, or objects.
>
> a) *Nuclear (N) Contamination:* Residual radioactive material resulting from fallout, rainout, or irradiation produced by a nuclear explosion and persisting longer than one minute after burst.
> b) *Biological (B) Contamination:* Microorganisms and toxins that cause disease in man, plants, or animals or cause the deterioration of material.
> c) *Chemical (C) Contamination:* Chemical substances intended for use in military operations to kill, seriously injure, incapacitate, or temporarily irritate or disable man through their physiological effects.
>
> 2) *NBC Contamination Survivability:* The capability of a system and its crew to withstand an NBC-contaminated environment, including decontamination,

without losing the ability to accomplish the assigned mission. An NBC contamination survivable system is hardened against NBC contamination and decontaminants; it can be decontaminated and is compatible with individual protective equipment.

a) *Hardness:* The capability of materiel to withstand the materiel damaging effects of NBC contamination and decontamination agents and the procedures required to carry out the decontamination process.
b) *Decontamination:* The process of making personnel and materiel safe by absorbing, destroying, neutralizing, making harmless, or removing chemical or biological agents, or by removing radioactive material clinging to or around it.
c) *Compatibility:* The capability of a system to be operated, maintained, and resupplied by persons wearing a full complement of individual protective equipment, in all climates for which the system is designed, and for the period specified in the requirements document.

3) *Negligible Contamination Level:* That level of NBC contamination that would not produce militarily significant effects in previously unexposed and unprotected persons operating or maintaining the system.

The individual military services also have specific regulations that deal with NBC/CBR issues. For example, Army Regulation 70–75, Survivability of Army Personnel and Materiel,[12] establishes policy and procedures for the research, development, and acquisition of NBC contamination survivable materiel, and Navy OPNAV Instruction S3400.10F, Chemical, Biological and Radiological (CBR) Defense Requirements Supporting Naval Fleet Readiness,[13] deals with CBR defense.

The DoD, through its Defense Technical Information Center (DTIC), also established the Chemical and Biological Defense Information Analysis Center (CBIAC). United States government agencies and private companies under contract to the DoD can contact the CBIAC for information and services. The CBIAC serves as the center for the acquisition, compilation, analysis, and dissemination of information relevant to chemical warfare and chemical and biological defense technology. The current address and phone number of CBIAC is P.O. Box 196, Gunpowder Branch, Aberdeen Proving Ground, MD 21010-0196; telephone: (410) 676-9030; FAX (410) 676-9703; and e-mail:cbiac@battelle.org. Further information on CBIAC and its products can be obtained by contacting them at any of the preceding numbers or by accessing them online at http://www.cbiac.apgea.army.mil.

In general, NBC survivability can be divided into two broad fields. They are the operational aspects of NBC warfare, including weapon categories and employment, and the equipment or materiel survivability against the CBR weapons. Some of the survivability concepts and terminology that are presently used in the NBC survivability literature are described next. The terms, and the concepts and functions they refer to, are relatively unique and specific to NBC warfare environments. However, some of them can be translated into the terms used in the conventional ACS discipline.

Weapon categories and employment. The current chemical agents used in chemical and biological weapons can be classified into five general categories with respect to their physiologic effects: nerve, blood, choking, blister, and harassing (incapacitant/irritant) agents. The nerve, blood, and choking agents are very lethal to personnel. The blister and harassing agents are generally nonfatal at expected encounter doses. All agents can significantly degrade mission effectiveness. Furthermore, the compounds and techniques used to render them harmless, that is, decontamination, can have considerable antimaterial effects.

The biologic threats are classified into two broad categories: germs (pathogens) and toxins. Germ agents are living organisms, for example, viruses, bacteria, and fungi, that cause disease or death in man, animals, and plants. Their effects depend on their ability to multiply and spread, that is, to cause infection. Toxins are extremely poisonous substances usually produced by living organisms. Examples of toxins include mycotoxins produced by fungi, botulinum type A and anthrax produced by bacteria, snake venom, and poisonous substances produced by shellfish.

Chemical and biological weapons are often categorized as area weapons because their employment requires relatively few delivery platforms while producing many casualties over broad areas. They are readily incorporated into the warhead of most conventional types of delivery vehicles or threat propagators. These include artillery shells, rockets, mines, guided missiles, bombs, and sprayers. Biological agents can also be delivered using vectors. This refers to vermin (insects, rodents, etc.) that are infected with agents and then released into the intended environment in order to spread disease.

Upon detonation of the chemical warhead, an agent is typically expelled as some form of aerosol, vapor, or liquid. Aerosols are suspensions of finely divided solid or liquid particles, such as smoke, fog, or mist. By their nature most aerosols contain significant amounts of vapor as a result of evaporation. Likewise, liquids produce vapor compounds as the liquid substance evaporates. In an air burst of a chemical warhead, the dissemination is assisted by the local meteorological conditions that can produce a rapidly spreading chemical gas cloud or a rain attack that spreads the agent over exposed surfaces. In general, the content of an incoming warhead, be it high-explosive or chemical, is unknown until it functions in the manner for which it was designed. Thus, the use of CB weapons is very insidious (Note 36).

Material survivability. Four major terms used in materiel survivability are hazards, susceptibility, accessibility, and vulnerability. These terms are used primarily in the areas concerned with the interaction between the CB agent and the component material. The relationships between these four expressions and the terminology used in the conventional survivability discipline are provided next.

The hazards associated with the NBC weapons are the threats to the survivability of the aircraft and its components and are equivalent to the damage mechanisms in conventional ACS terminology, that is, they are the physical entities that can damage or kill components. Hazards are grouped into three primary categories with which the aircraft must contend: the chemical agent itself, the decontamination agent, and the decomposition products of the agents.

Accessibility refers to the ability of the agent to gain access to the reactive material in a component. In conventional ACS this can be related to component susceptibility, that is, the likelihood the damage mechanism hits the reactive material in the component.

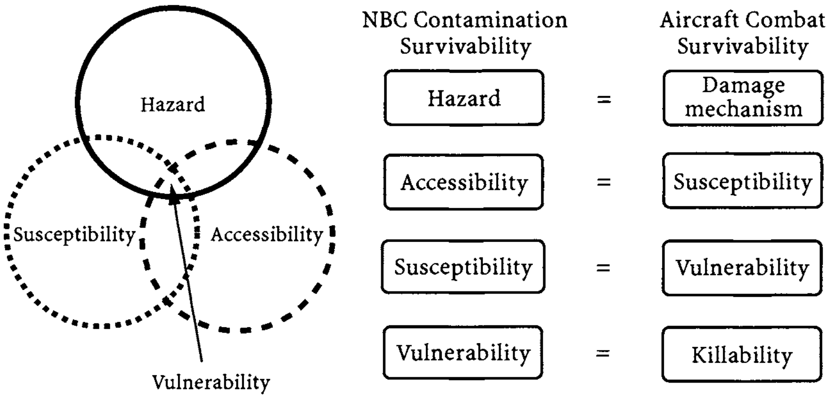


Fig. 1.14 Translator for NBC contamination survivability and aircraft combat survivability terminology.

Susceptibility refers to the actual effects of agents on various materials or the reactiveness of the material to specific agents. In other words, susceptibility refers to those events that occur when a component is contaminated (hit) with an agent (damage mechanism), which is component vulnerability in the conventional ACS discipline.

Vulnerability refers to the combined effects of hazard, accessibility, and susceptibility on specific components. In other words, the chemical vulnerability of the component to CB agents refers to its inability to avoid or withstand the hostile chemical environment, that is, the component's killability in the conventional ACS sense.

Figure 1.14 contains the three-ring CBR vulnerability diagram and the translation between the major CBR and ACS terms. The intersection of the three rings represents the conditions required for the vulnerability of a component, that is, a component is vulnerable when a hazard is present, it has access to the component, and the component is susceptible to it.

Chemical attack. The example of a chemical attack on an airbase is used to clarify the NBC contamination survivability terms just introduced and to demonstrate the applicability of the conventional ACS terminology to the NBC terms. Figure 1.15 contains the descriptions of the major events during the attack and the terminology used in the two disciplines. In the example described next, the conventional ACS terminology will be indicated in parentheses following the chemical descriptor, as appropriate.

Suppose early warning sensors and intelligence sources have detected an imminent cruise missile attack on the airbase. The enemy has employed CB weapons in the past, but the nature of these incoming warheads is unknown. They could be any combination of CB, incendiary, high-explosive, nuclear, or specialized submunitions. Personnel are well trained in defensive countermeasures (tactics) for any of these threat types and are well equipped for decontamination (battle damage repair)

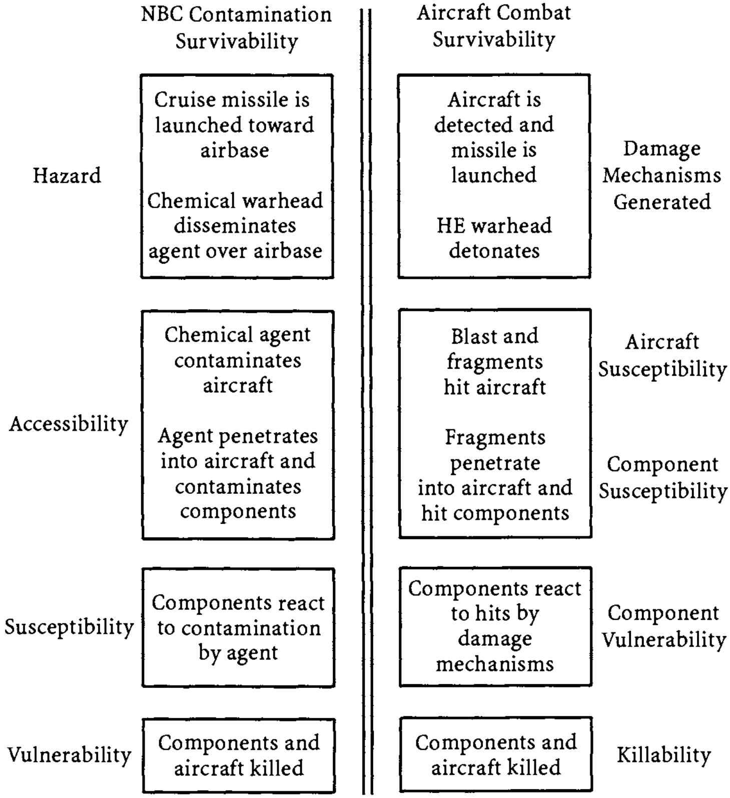


Fig. 1.15 Chemical attack on an airbase.

in order to sustain operations. CB defensive measures are begun as a precaution against this particular threat. These measures involve personnel donning individual protective ensembles and activating the overpressure systems in the operations and maintenance spaces (vulnerability and susceptibility reduction). Several missiles overfly the aircraft parking areas and explode, disseminating droplets of some type of hazardous substance (damage mechanism) that settles on and contaminates a broad area (susceptibility). Detection devices indicate that the substance is a nerve agent, which is a known hazard (damage mechanism) to exposed personnel and certain equipment.

Aircraft operations continue while the contaminated area is being decontaminated (battle damage repair). Aircraft taxiing through contaminated areas splash agent into their wheel wells and ingest agent through their intakes. There are susceptible (vulnerable) components and materials that the agent has access to (susceptible) from these locations. Two of these accessible (susceptible) components are hydraulic actuator seals in the wheel wells and the pilot via the environmental control system, which uses bleed air from engine intake air. The liquid agent (damage mechanism) reacts with the susceptible (vulnerable) seal material causing it to deteriorate to such an extent that the hydraulic cylinders leak fluid and hydraulic pressure is lost. The agent vapor (damage mechanism) causes vision problems for the susceptible (vulnerable) pilot so that he can no longer control the aircraft (an aircraft kill). Thus, these components are vulnerable (killable) in this scenario.

The combination of the presence of the nerve agent (damage mechanism), the agent's accessibility to the components (component susceptibility), and the susceptibility (vulnerability), or reactiveness, of these components when exposed to this particular agent makes them vulnerable (killable) to this hazard (damage mechanism) because they are easily killed by it. In conventional ACS terminology this example could be stated as follows. The components are susceptible to this threat because they are readily contaminated with the agent in a CB attack. Once contact is made, they are easily killed or damaged, which indicates their high degree of vulnerability. Because they are susceptible and vulnerable, they are killable.

1.1.14.3 Nuclear survivability. DoD Directive 4245.4, Acquisition of Nuclear Survivable Systems, 28 July 1988, established the requirement that nuclear survivability be incorporated into the development of major and nonmajor systems that perform critical missions. This Directive provided guidelines for the involvement of the Defense Acquisition Board, the Assistant to the Secretary of Defense (Atomic Energy), and the head of each DoD component in the acquisition of nuclear survivable systems. The current (2002) organization within the DoD responsible for nuclear survivability is the Defense Threat Reduction Agency (DTRA), which was formed in 1998 by consolidating elements of the Office of the Secretary of Defense staff, the Defense Technology Security Administration, the Defense Special Weapons Agency (DSWA), and the On-Site Inspection Agency. The DTRA sponsors the Defense Threat Reduction Information Analysis Center (DTRIAC). The DTRIAC is the key DoD source of information and analysis on nuclear and conventional weapons-related topics. "DTRIAC has major reference collections of documents and photographic data and can search, retrieve, and perform analyses on internal and community-wide nuclear/conventional weapons phenomena, effects and technology matters, and related nuclear/conventional technology transfer applications." (DTRIAC is online at http://www.dtra.mil/td/dtriac/td_dtriac_index.html).

The individual military services are responsible for achieving and verifying a system's nuclear survivability and hardness and create and maintain procedures and provisions ensuring that nuclear survivability is retained over the life of the system. Army Regulation 70–75, Survivability of Army Personnel and Materiel,[12] OPNAV Instruction 3401.3A, Nuclear Survivability of Navy and Marine Corps Systems,[14] and Air Force Instruction 62-201, System Survivability,[15] contain the individual service policy and procedures for nuclear survivability programs.

Weapon effects. The products from a nuclear detonation depend upon the location of the warhead. The location is usually divided into underground and underwater bursts, surface and near-surface bursts, air bursts, and high-altitude bursts above 30 km. The air burst produces nuclear radiation in the form of neutrons and gamma rays and a large fireball at an extremely high temperature. The very hot fireball radiates EM radiation in the form of heat, and the rapid expansion of the fireball creates an air blast. The nuclear radiation from an air burst can create an electromagnetic pulse. At high altitudes the most important products are x-ray radiation, nuclear radiation, and high-altitude EMP (HEMP). The nuclear radiation from the burst is referred to as prompt or initial radiation and is included with the nuclear weapon effects. The transient effect of this radiation on electronics is referred to as TREE. The residual radioactive material created by the prompt radiation is included with the NBC survivability discipline. The EMP problem has already been described with the DE weapons. Thus, the primary damage mechanisms associated with a nuclear weapon include the blast wave, thermal radiation, and the prompt nuclear radiation.

Enhancing nuclear survivability. Some of the approaches to increasing the nuclear survivability of a system include threat avoidance, proliferation, reconstitution, and nuclear hardening. These approaches have been described as they relate to a total system in What is System Survivability? (Sec.1.1.13). Only threat avoidance and nuclear hardening are applicable to an individual aircraft. Threat avoidance consists of those measures taken to evade the products of a nuclear burst. If avoidance fails, then the aircraft must be designed to withstand the hostile nuclear environment, that is, its vulnerability to the nuclear damage mechanisms must be reduced. In essence, this requires hardening the aircraft against the air blast, thermal radiation, initial nuclear radiation, and EMP created by the nuclear detonation. The major tasks in any nuclear survivability program are the development of the nuclear survivability criteria and system specifications, the validation of nuclear survivability using analyses and appropriate tests, and hardness assurance to verify that the production process and operational usage does not degrade the designed-in hardness.

Go to Problems 1.1.75 to 1.1.82.

1.1.15 Relationship Between the Combat Survivability Discipline, the Survivability Discipline, and the System Safety Discipline for Military and Civilian Aircraft

Learning Objectives	**1.1.30**	**Describe the relationships between the system safety, survivability, and combat survivability disciplines.**
	1.1.31	**Describe a hazard and a mishap, and conduct a hazard analysis and a mishap risk assessment.**
	1.1.32	**Describe the relationship between the system safety terms and the aircraft vulnerability terms.**
	1.1.33	**Compute the probability an aircraft will fly safely (without a class A mishap) for a specified time.**

Aircraft combat survivability is defined here as the capability of an aircraft to avoid or withstand a man-made hostile environment. Aircraft survivability, in general, has been defined as the ability of an aircraft to avoid and/or withstand hostile environments, including both man-made and natural.[16] Thus, combat survivability is

Table 1.5 Relationships between the disciplines

Environment	Discipline
Normal (internal failures, environmental factors, operator errors)	System safety
Hostile	
Natural (severe turbulence, lightning, midair collisions, crashes)	Survivability + system safety
Man-made (air defense, acts of terrorism)	Combat survivability

distinguished by the fact that only the man-made hostile environment is considered. Hostile environments that are not man-made, that is, the natural hostile environments, include severe turbulence, lightning strikes, midair collisions, and crashes. The threat posed by terrorist weapons, such as a bomb smuggled onboard in a piece of luggage or a MANPADS, is generally considered to be part of the survivability discipline, with a major participation by combat survivability personnel familiar with the effects of internal and external detonations of high explosive warheads.

The system safety discipline attempts to minimize those conditions known as hazards that can lead to a mishap resulting in material damage and personal death or injury in environments that are not made hostile by man. The hazards can be caused by internal system failures or features or to outside influences, such as environmental factors or operator errors. Thus, together, the system safety and survivability disciplines attempt to maintain safe operation and maximize survival of the aircraft in all environments in both peacetime and wartime.

Table 1.5 illustrates the relationships between the disciplines. Note that the division between system safety and survivability is not distinct; there are many safety issues that occur in the natural hostile environment, such as severe turbulence and lightning strikes. There are also issues associated with the natural hostile environment that are more survivability related, such as midair collisions and crash survivability. Of particular importance to both of these disciplines are those hazards and vulnerabilities associated with onboard fires and explosions.

1.1.15.1 System safety of military aircraft. The primary DoD document that governed system safety prior to 1994, when the DoD specifications and standards were cancelled by the Secretary of Defense (Note 37), was MIL-STD-882C, System Safety Program Requirements. The current version is MIL-STD-882D, Standard Practice for System Safety.[17] Safety is defined in MIL-STD-882D as "freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment." System safety is defined as "the application of engineering and management principles, criteria, and techniques to achieve acceptable mishap risk, within the constraints of operational effectiveness and suitability, time, and cost, throughout all phases of the system life cycle." System safety management consists of "all plans and actions taken to identify, assess, mitigate, and continuously track, control, and document environmental, safety, and health mishap risks encountered in the development, test, acquisition, use, and disposal of DoD weapon systems, subsystems, equipment, and facilities." The objective of system safety is to achieve acceptable mishap risk through a systematic approach of hazard analysis (identify the hazards and associated mishaps), risk assessment (evaluate the probability of occurrence and severity of each hazard/mishap), and risk management (eliminate the unacceptable hazards/mishaps).

Hazards and mishaps. The key to the system safety program is the identification and elimination of unacceptable hazards. A hazard is defined in MIL-STD-882D[17] as "any real or potential condition that can cause injury, illness, or death to personnel; damage to or loss of a system, equipment or property; or damage to the environment." A mishap is defined as "an unplanned event or series of events resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment." For example, the inability of a fuel control valve to provide fuel under pressure to the combustor of the single engine on an aircraft and the leakage of flammable hydraulic fluid from one of the two power cylinders of a dual, tandem hydraulic actuator are hazards. When the fuel control valve fails and there is no fuel provided to the combustor (a hazard), the engine will stop, and the aircraft will crash (a mishap). Any flammable hydraulic fluid that leaks from a cylinder (a hazard) may come in contact with a surface sufficiently hot to cause a hydraulic fluid fire. The fire may burn through the two bundled data buses carrying all of the flight control signals to the stabilator, causing the aircraft to fall out of control and crash (a mishap). Or the fire might only scorch a few nearby components (another mishap).

Associated with every mishap is the probability the mishap will occur and the severity of the mishap. According to MIL-STD-882D, the mishap probability is "the aggregate probability of occurrence of the individual events/hazards that might create a specific mishap." The severity of the mishap is "an assessment of the consequences of the most reasonable credible mishap that could be caused by a specific hazard."

There is a relationship between system safety, with its hazards and mishaps, and aircraft vulnerability, with its critical component kill modes and types of aircraft kill. In system safety, associated with a hazard is an estimated probability that it will result in a mishap with a particular severity. For example, there is a probability that the fuel control valve will fail, resulting in the loss of engine thrust and the loss of the aircraft; and there is a probability that flammable hydraulic fluid will leak from a particular hydraulic actuator as a result of normal operations and result in an onboard fire and eventual aircraft crash. Likewise, associated with a critical component is an estimated probability that a hit on that component will cause a kill of that component which results in a particular type of aircraft kill. Using the same two safety examples just given, there is a probability that a hit by a penetrator on the fuel control valve will result in the loss of fuel from the valve to the engine (the kill mode) and the subsequent loss of the aircraft (an attrition kill); and there is a probability that a hit on the hydraulic actuator will result in the leakage of flammable hydraulic fluid and subsequent fire (the kill mode), which causes the loss of the aircraft (an attrition kill). Thus, the environment, either normal or hostile, creates hazards or damage to the system that can lead to mishaps or aircraft kills.

Hazard analysis and the assessment of mishap risk. A major task in any system safety program is the hazard analysis. According to MIL-STD-882D,[17] "the hazard analysis is a detailed analysis of system hardware and software, the environment (in which the system will exist), and the intended usage or application." Historical hazard and mishap data, including lessons learned from other systems, are considered and used. In general, hazards can be identified using scientific and engineering analyses, such as the fault tree analysis and the failure mode and effects analysis (Note 38). The commonly used approaches for identifying hazards can be found in the *Defense Acquisition Deskbook* (described in Sec. 1.3.2); the *System Safety Society's System Safety Analysis Handbook*, available from the Society's web site at http://www.system-safety.org/MainHome.htm; the Society of Automotive Engineers (SAE) Aerospace Recommended Practice Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, SAE ARP4761; and the Federal Aviation Administration's Toolset entitled "System Safety Management Program" available online at http://fast.faa.gov/toolsets/safMgmt/ and "System Safety Handbook" available online at http://www.asy.faa.gov/risk/sshandbook/contents.htm.

In the assessment of mishap risk, the severity and the probability of occurrence of the mishap associated with each identified hazard are evaluated, classified, or categorized. According to MIL-STD-882D,[17] there are four suggested categories of mishap severity:

1) *Catastrophic (category I):* death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
2) *Critical (category II):* permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation.
3) *Marginal (category III):* injury or occupational illness resulting in one or more lost work days(s), loss exceeding $10K but less than $200K, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
4) *Negligible (category IV):* injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.

The severity of the mishap associated with the loss of the fuel control valve hazard just described is catastrophic because it results in the loss of the aircraft. The severity of the mishap associated with the leaking hydraulic fluid and subsequent fire hazard is catastrophic when it results in a loss of the aircraft. It is marginal if only a few components are scorched.

Mishap probability of occurrence can be expressed either qualitatively or quantitatively using probabilities. In MIL-STD-882D[17] the following five levels are suggested for the specific item, such as an aircraft:

1) *Frequent (level A):* likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.
2) *Probable (level B):* will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.
3) *Occasional (level C):* likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.
4) *Remote (level D):* unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.

Table 1.6 Example mishap risk assessment matrix with risk acceptance categories[a] and levels[17]

	Mishap severity			
Mishap probability	I, catastrophic	II, critical	III, marginal	IV, negligible
A, frequent	1	3	7	13
B, probable	2	5	9	16
C, occasional	4	6	11	18
D, remote	8	10	14	19
E, improbable	12	15	17	20

[a] Mishap risk categories: 1–5, high; 6–9, serious; 10–17, medium; 18–20, low.

5) *Improbable (level E):* so unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.

The probability of occurrence of the loss of the fuel control valve is estimated to be remote based upon previous experience with the valve, but the probability of a leak developing in the hydraulic cylinder is estimated to be occasional because of difficulties with sealing. If the hydraulic fluid is flammable and if there are sufficiently hot surfaces in the vicinity, the probability of occurrence of a fire resulting in the loss of the aircraft is estimated to be occasional. However, if there are no hot surfaces near the cylinder or if the hydraulic fluid is nonflammable, the probability of occurrence of the loss of the aircraft is estimated to be remote.

The degree or criticality of risk associated with any hazard is related to the particular combination of mishap severity and probability of occurrence. Obviously, those hazards that result in mishaps deemed catastrophic and estimated to occur frequently must be eliminated, whereas hazards that result in mishaps that are negligible and improbable can be ignored. Of concern are those combinations of severity and probability of occurrence that fall between these two extremes, such as a mishap that is critical and occasional. According to MIL-STD-882D,[17] prioritization of mishaps can be accomplished using the suggested mishap risk assessment matrix given in Table 1.6. The rows of the matrix are the five levels of mishap probability, and the columns are the four categories of mishap severity. Associated with each combination of probability and severity is a risk value. The four risk categories suggested in MIL-STD-882D of high, serious, medium, and low are given in Table 1.6.

The loss of fuel control valve hazard with the catastrophic mishap and remote probability is in the serious category, and the leaking hydraulic fluid hazard with the catastrophic mishap and the occasional probability is in the high category.

Risk management. The hazard/mishap combinations that pose an unacceptable risk are controlled or eliminated by employing one or more of the following four techniques: 1) eliminate the hazards through design selection, 2) incorporate safety devices, 3) provide warning devices, and 4) develop procedures and training.[17]

Example 1.11 describes a hazard analysis, risk assessment, and some of the safety features that could be used to control the hazard.

Example 1.11 Hazard Analysis, Risk Assessment, and Risk Management

Consider the hydraulic subsystem on an aircraft. An FMEA is conducted to identify hazards. A failure of a hydraulic seal is the assumed failure mode. The sequence of possible effects of this failure are 1) the flammable hydraulic fluid leaks from the failed seal on to a hot surface, 2) the fluid ignites, 3) the subsequent hydraulic fluid fire burns through the data bus carrying the bundled set of control signals to the stabilator, 4) the pilot loses control of the aircraft, and 5) the aircraft crashes. The mishap is classified as catastrophic and occasional with a risk value of 4, which puts it in the high risk category. The program manager decides that this hazard poses an unacceptable risk.

The hazard could be controlled at an acceptable cost by design (replacing the flammable fluid with nonflammable fluid and moving the control signal lines or adding a second, separated control path for redundancy), by a safety device (installing fire detection and extinguishing equipment in the vicinity of the actuator), by a warning device (a fire light in the cockpit will alert the pilot of the emergency condition), and by training (the pilot practices emergency fire procedures). The analysis for this hazard has been conducted in a timely fashion, and the hazard is controlled early in the design, thus minimizing the cost of eliminating the hazard. Note that all of the design features to eliminate the hazard also reduce the vulnerability of the aircraft.

Mishap rates and safe flying. There are several rate measures used to quantify the safety of flight operations. They include the number of mishaps per 100,000 flight hours, or per million aircraft miles flown, or per 100,000 departures. The independent variables in the first two rates, flight hours and miles flown, are considered to be continuous variables, whereas departures is a discrete variable analgous to the number of missions N in campaign survivability. Because of this difference, the equation used to compute the probability of safe flying over a given number of flight hours or miles flown, analogous to Eq. (1.8b) for campaign survivability, is the Poisson probability density function, which can be given in the form

$$P(\text{zero mishaps over the interval } t) = e^{-\lambda t} \tag{1.11}$$

where λ is the mishap rate (per 100,000 hours or per 1,000,000 miles flown) and t is either the independent variable time (in units of 100,000 flight hours) or miles flown (in units of 1,000,000 miles flown). When the numerical values of $N \cdot \mathrm{LR}$ and λt are equal and small compared to unity, the probabilities for campaign survival and safe flying are nearly equal.

Example 1.12 compares campaign survivability and safe flying probabilities using the loss rate for the 1991 Desert Storm campaign and the U. S. Air Force class A mishap rate of fighter/attack aircraft over the last 10 years for safe flying (Note 39).

Example 1.12 Surviving Combat Compared to Safe Flying

An interesting loss statistic is the probability that an aircraft would be killed in a military campaign relative to the probability that it will be involved in a peacetime class A mishap. A class A mishap is one with \$1M in damages, or a fatality, or a destroyed aircraft (a catastrophic or category I mishap).

The combat loss rate of U. S. tactical, fixed-wing aircraft in Desert Storm was approximately 0.4 aircraft killed per 1000 sorties. Thus, if an aircraft flies on 125 missions in a campaign with a loss rate of 0.04% per mission, the aircraft's probability of surviving the 125 missions is

$$P_S(125 \text{ combat missions}) = (1 - 0.0004)^{125} = 0.951$$

according to Eq. (1.8b).

The U. S. Air Force class A mishap rate of fighter/attack aircraft over the last 10 years is approximately 2.5 per 100,000 flight hours, and from 1984 to 1989 the average class A mishap rate of U. S. rotary-wing aircraft was also approximately 2.5.[18,19] Thus, the pilot who flies 2000 hours during a career with a constant mishap rate of 2.5 per 100,000 flight hours has a probability of not being involved in a class A mishap of

$$\text{Prob. (0 mishaps over 2000 flight hours)} = \exp(-2.5 \cdot 2000/100{,}000) = 0.951$$

according to Eq. (1.11).

Note that the probability of surviving 125 combat missions is essentially equal to the probability of flying 2000 hours without a class A mishap at the mishap and loss rates selected. ($0.0004 \cdot 125 = 2.5 \cdot 0.02 = 0.05$, which is small.)

1.1.15.2 Civilian aircraft survivability. Survivability has been of interest to military aircraft developers and users since the early years of the 20th century, when aircraft were first used in combat. On the other hand, because of the lack of a man-made hostile environment, the civilian aircraft community has been primarily concerned with system safety as described online at http://www.asy.faa.gov/Risk/. However, recent terrorist activities against civilian transport aircraft have created a serious man-made hostile environment, and the survivability of civilian aircraft to onboard bombs, as well as to readily available guns and missiles, has become important. The Federal Aviation Agency (FAA), in their Aircraft Hardening Program, has developed definitions and procedures for civilian aircraft survivability similar to the safety and combat survivability disciplines.

FAA safety certification of civilian transport aircraft requires that no Hazard Class I or Class II conditions for single system component failures are acceptable. The Class I (Catastrophic) Hazard Level consists of failure conditions that would prevent continued safe flight and landing. The Class II (Hazardous) Hazard Level consists of failure conditions that would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be a large reduction in safety margins or functional capabilities. The types of failures considered in the certification process are natural failures, that is, failures not caused by an intentional hostile act.

The survivability of a civilian aircraft to a man-made hostile threat is defined by the FAA Aircraft Hardening Program as the absence of a Class I Failure after an encounter with the threat. A civilian aircraft loss to a hostile threat (an aircraft kill) is defined as the inability of the aircraft to continue controlled flight or achieve a survivable landing. Three loss categories are associated with a Class I Failure: immediate loss, delayed loss (before landing), and landing loss (during landing) (Note 40).

The fundamentals of the aircraft combat survivability discipline apply, in general, to the survivability of civilian aircraft to terrorist threats. Civilian aircraft will survive if they avoid or withstand the man-made hostile environment. Civilian aircraft susceptibility can be reduced by taking measures to prevent terrorist bombs from being smuggled onboard, as well as using electronic attack equipment developed by the military to prevent hits by externally fired weapons. Vulnerability can be reduced by designing the aircraft to withstand the effects of any hit (or detonation), either external or internal. Of particular concern is the ability of the cargo area and luggage containers to withstand an internal detonation. Readers interested in civilian aircraft survivability are referred to the *Proceedings of the American Defense Preparedness Association's 1993 Transport Aircraft Survivability Symposium*[20] and to Ref. 21, which examines the man-portable SAM threat to civilian aircraft.

Go to Problems 1.1.83 to 1.1.87.

1.1.16 Battle Damage Repair

Learning Objective	**1.1.34**	**Describe the aircraft battle damage repair program and its contribution to aircraft availability.**

1.1.16.1 Effect of battle damage repair upon aircraft availability. The rapid repair of battle damage is a part of the ACS discipline, not because it increases the survivability of the individual aircraft, but because it enhances force reconstitution and consequently force survivability. Aircraft that are more survivable can return to base with damage more often because of their reduced vulnerability. If this damage cannot be rapidly repaired, the aircraft cannot be returned to action, and in essence it is a dead aircraft. Thus, in the mission effectiveness equation [Eq. (1.9b)], damaged aircraft that cannot be repaired in time to join the fight are removed from the available aircraft category, AA, and must be included with the killed aircraft in a new category of aircraft called not available aircraft, denoted by NOT AA. The probability an aircraft is in this category is P^c_{AA}. The probability that a hit aircraft will be damaged to the extent that it cannot be rapidly repaired is $P^c_{R|H}$. Thus,

$$P^c_{AA} = P_H(P_{K|H} + P^c_{R|H}) \qquad \text{where } P_{K|H} + P^c_{R|H} \leq 1 \tag{1.12}$$

1.1.16.2 Accomplishing rapid battle damage repair. In simple terms battle damage repair (BDR) is accomplished by first assessing the extent and nature of the damage and then making the appropriate repair. In general, the BDR discipline consists of a technology of materials, tools, and repair procedures that will quickly return battle-damaged aircraft to service and a methodology for performing design trade studies, system effectiveness analyses, and operational support requirements.[22] The BDR program considers many aspects of the repair problem. Included are manpower available; personnel skills; available training for damage assessors and repair technicians; the equipment, tools, and special BDR kits; materials and spares available; operating requirements of the damaged vehicle; the number of systems to be supported; the allowable BDR periods; and the wartime environment conditions, including working in an NBC-contaminated environment.

There are many design techniques available to improve the repairability of an aircraft. These include modular construction, interchangeable parts, proper location of components for ease of repair (while also considering the vulnerability of the aircraft), removable panels that allow the evaluation and repair of internal damage, replaceable substructures (particularly important with composites), and color coding of the electrical wiring. Electrical systems are particularly difficult to repair because of their complexity. There are miles of wires running throughout an aircraft. Repairing a particular wire bundle with perhaps 100 or more individual wires that have been cut can take many hours or even days if the repair technician cannot identify which wires go together. In some situations repair of the damage might be impossible. If rapid BDR has been designed into the aircraft, the time required to make the repairs can be significantly reduced. For example, computerized wiring maintenance aids have been shown to reduce the time required to repair damage to aircraft wiring from never or days to hours or minutes.

Guidelines for incorporating battle damage repair capability into the design of aircraft and other military vehicles are provided by Wallick and Kaplan,[23] and MIL-HDBK-2069 Aircraft Survivability, described in Sec. 1.3.4, contains the following guidance:

> An analysis should be performed to develop and evaluate concepts, criteria, procedures, and time estimates for rapid repair of nonlethal combat damage caused by nonnuclear and nuclear threats, including NBC contamination. The analytical emphasis will be on simple and rapid repair of system components under combat conditions, especially at forward operating locations. The analysis should determine 1) acceptable levels of degraded system and subsystem performance applicable to unrestricted, limited life, and one-time flight repairs; 2) ground rules for component repair (e.g., remove and replace, repair deferment, type of damage repairable at various maintenance levels, etc.); 3) if system redesign, or changes in personnel or support equipment, would allow field repairs of subsystems; 4) repair time estimates and procedures under all specified conditions (including NBC contamination) for inclusion in applicable maintenance and repair technical orders; 5) spares, long lead time items, and material storage requirements;

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6) support facility and equipment requirements, including special tools, clothing, and other resources for War Readiness Spares Kits; and 7) personnel and training requirements for combat damage repair operations.

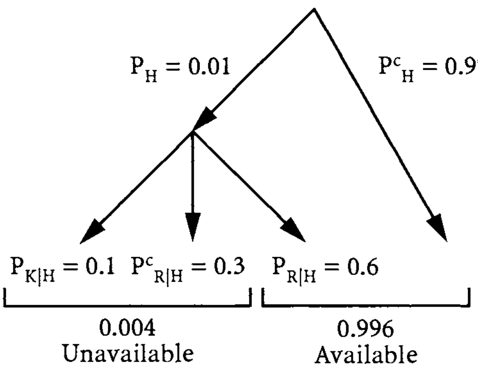
Example 1.13 is a demonstration of the importance of rapid battle damage repair to aircraft availability.

Example 1.13 Value of BDR

Consider the tree diagram shown next with the outcomes of aircraft hit and killed, aircraft hit but not killed and not repaired, aircraft hit but not killed and repaired, and aircraft not hit. If 1 out of every 100 aircraft on a mission are hit, $P_H = 0.01$, and if 1 out of every 10 aircraft hit are killed, $P_{K|H} = 0.1$. If 3 out of every 10 aircraft hit but not killed cannot be repaired in sufficient time to contribute to the campaign, $P^c_{R|H} = 0.3$. Thus,

$$P_K = 0.01 \cdot 0.1 = 0.001 \quad \text{and} \quad P^c_{AA} = 0.01 \cdot (0.1 + 0.3) = 0.004$$

according to Eqs. (1.2) and (1.12). The tree diagram for this example is shown here:



If 10,000 sorties are flown by 500 aircraft in a short-duration campaign,

$$0.001 \cdot 10000 = 10 \text{ aircraft are expected to be killed}$$

and

$$0.003 \cdot 10000 = 30 \text{ aircraft are expected to be awaiting repair}$$

for a total of 40 aircraft out of the original 500 unavailable to the force at the end of the campaign. If the 30 damaged aircraft could be rapidly repaired and returned to the fight, only the 10 aircraft killed would be unavailable at the end of the campaign.

Previous Page

Go to Problems 1.1.88 to 1.1.89.

1.2 Historical Perspective of Survivability

1.2.1 Historical Losses and Loss Rates

Learning Objective	**1.2.1**	**Describe some of the historical losses and loss rates and the trend of survivability.**

The first manned flight by a powered aircraft occurred in 1903 at Kitty Hawk, North Carolina. In 1907, the U. S. Army established the Aeronautical Section of the Signal Corp. A few years later, the Italians used aircraft for the first time to conduct aerial reconnaissance, artillery observation, and aerial bombing operations in Libya during the 1911–1912 Italo–Turkish war. A Russian named Sakoff, who was flying for the Italians, was the first pilot to return with rifle bullet holes in his aircraft, and another Russian named Kolchin was the first aviator to be killed in combat.[24] Since the beginning of air warfare in 1911, tens of thousands of U. S. aircraft have been downed or killed in combat in World War II, the Korean conflict, the Southeast Asia conflict, Operation Desert Storm, and several major raids (Note 41). Figure 1.16 presents the estimated combat losses and loss rates for some individual raids and some of the major conflicts beginning with WWII and continuing up to the present time. Note the downward trend in the loss rate for the major conflicts.

1.2.1.1 World War II attrition. As shown in Fig. 1.16, loss rates vary greatly, depending upon the conflict. In September of 1939, the single-engine Royal Air Force (RAF) Fairey Battle and twin-engine Bristol Blenheim bombers were sent to France to support the British Expeditionary Force. At the beginning of the German advance in early May 1940, "Thirty-two Battles took off to curb the German advance, but 13 of these were destroyed and 18 suffered severe damage. . . . On 12 May 1940 five Battles were dispatched to destroy the Bridges at Maastricht, but not one of them returned, all had been destroyed. The sad story continued on May 14 when 71 Battles took off, again on a routine bombing mission; only 31 returned, forty had been destroyed. The next day, May 15, Barratt [the RAF Air Officer Commanding (AOC) in France who had control of all aircraft] tallied up the amount of aircraft destroyed, an astounding 205 light bombers and fighter aircraft and not even a month had passed." (http://www.battleofbritain.net/section-2/appendix-10.html.)

In World War II the overall attrition suffered by the RAF Bomber Command on their nighttime bombing missions over Europe during 1942 and 1943 was nearly 4%, with some groups losing over 10% of the bombers. Heavily escorted daytime bombing attacks by the RAF during the latter half of 1942 suffered an overall loss rate of over 5%. This heavy loss rate on the escorted daylight raids caused the Bomber Command to conduct most of their subsequent operations at night.

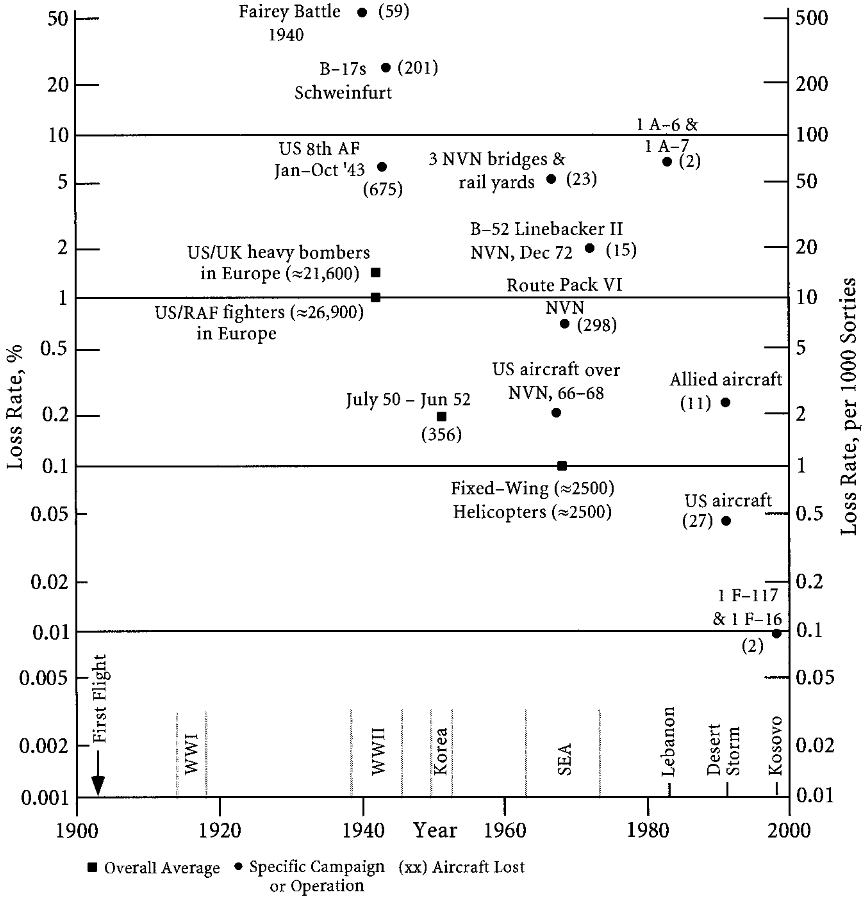
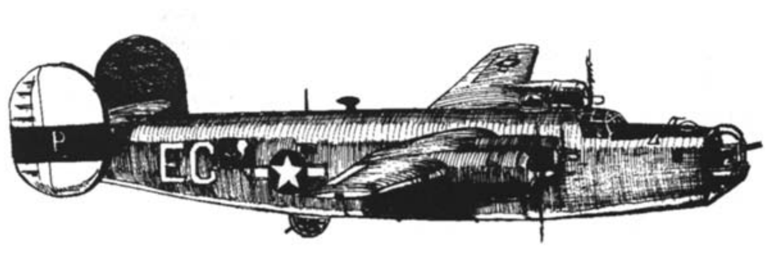
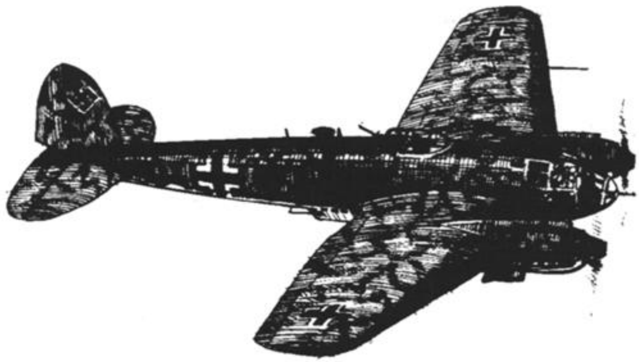


Fig. 1.16 Historical losses and loss rates (data prior to 1982 from Ref. 25).

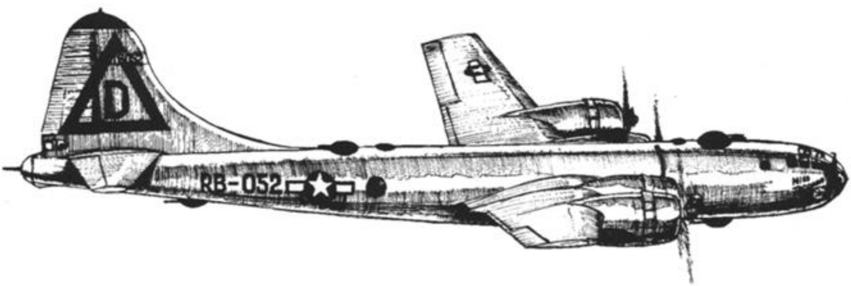


B–24



HE–111

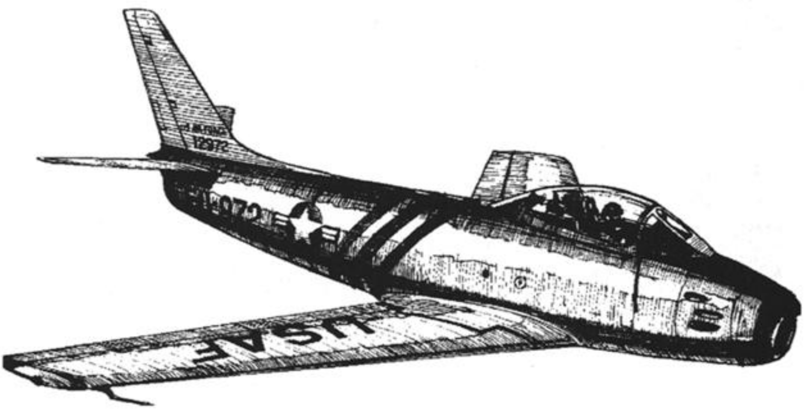
The U. S. 8th Air Force heavy bombers had a loss rate of over 6% on their daylight raids over Europe in 1943, and the losses over Schweinfurt in October were particularly heavy, when nearly 25% of the attacking force was lost. The German bombers suffered similar loss rates on their bombing missions against England, and U. S. B-29 operations against Japan in 1944 resulted in a loss rate of about 4%. The overall average loss rate for U. S. and U. K. heavy bombers in WWII was approximately 1.5%.



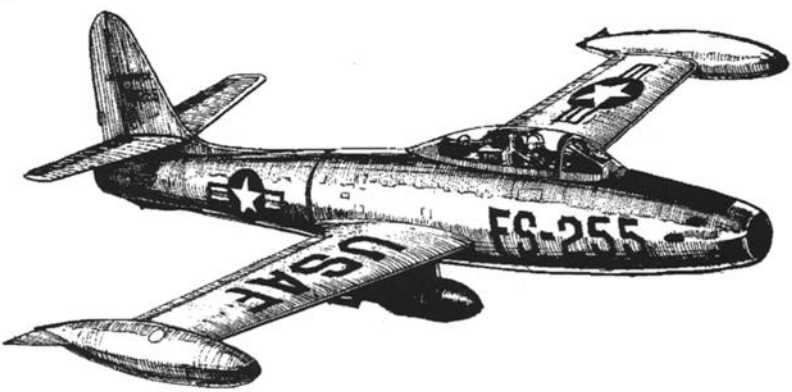
B–29

1.2.1.2 U. S. Air Force fighter attrition in the Korean conflict. In the Korean conflict the overall loss rate was approximately 2%. The loss rates (in ascending order) of the Air Force F-86 Sabre, F-80 Shooting Star, F-84 Thunderjet, and P/F-51 Mustang were between 1 and 3%, respectively. Nearly all of the F-80, F-84, and P/F-51 losses were to ground fire, whereas most of the F-86 losses were to enemy aircraft. When comparing the loss rates of these aircraft, the P/F-51 appears to be less survivable than the other aircraft. However, the missions of the aircraft and the intensity of the threat must be examined before that conclusion can be drawn. For example, the Mustang was heavily used in the dangerous low-level ground attack role because it was the only U. S. Air Force aircraft that had the necessary range, flying qualities, and endurance to carry sufficient ordnance to inflict damage. Care must be taken not to misinterpret combat data when comparing loss rates for aircraft with different missions.

F–80



F–86



F–84

Table 1.7 U. S. military aircraft losses in SEA[a]

Service	Fixed-wing	Rotary-wing	Total
U. S. Air Force	1679	58	1737
U. S. Navy	531	13	544
U. S. Marine Corps	194	270	464
U. S. Army	157	2246	2403
Total hostile action	**2561**	**2587**	**5148**
Operational mishaps	1159	2282	3441
Total	3720	4869	8589

[a] Data provided by Survivability/Vulnerability Information Analysis Center (SURVIAC) described in Sec. 1.3.4.

1.2.1.3 Combat losses and loss rates in the Southeast Asia Conflict. The United States was involved in a conflict with North Vietnam between 1962 and 1973. Over 5000 U. S. fixed- and rotary-wing aircraft were killed by the enemy in that conflict, and there were over 30,000 recorded incidents of combat damage. Table 1.7 lists the number of fixed- and rotary-wing aircraft killed by hostile action by service, and the number of aircraft lost in operational mishaps. The losses from several of the major campaigns in the conflict are indicated in Fig. 1.16. The 5000 aircraft lost in the SEA conflict is a relatively small number when compared to the nearly 50,000 U. S. and U. K. fighters and bombers lost in WWII. However, the losses in SEA are very large when compared with the number of new aircraft that have been purchased in the recent past and planned for in the near future.

1.2.1.4 Fixed-wing aircraft combat losses and loss rates in Operation Desert Storm. Operation Desert Storm consisted of five weeks of air operations by the Coalition aircraft (the U. S. and its allies) against Iraq in January and February 1991, followed by five days of combined air and ground operations. Nearly 65,000 combat sorties were flown by the Coalition's fixed-wing, combat aircraft. Two years after the operation ended, the *Gulf War Air Power Survey* was published. *Volume Five, A Statistical Compendium and Chronology*[26] contains the combat data for the Coalition fixed-wing aircraft that were damaged or lost during the operation. The official count of Coalition fixed-wing, combat aircraft damaged (hit and not killed) and killed (hit and killed) during this operation is given in Table 1.8a. According to the data given there, the sortie loss rate of the U. S. aircraft was approximately 0.4, a factor approximately 1/30 of the loss rate of the U. S. aircraft in WWII. The loss rate of the Allied aircraft was 2.3, and the loss rate for all of the Coalition aircraft was 0.6 (Note 42).

Note in Table 1.8a that the damage rate of the U. S. aircraft was 0.7 compared to the loss rate of 0.4, whereas the damage rate of the Allied aircraft was 1.0 compared to the loss rate of 2.3, a reversal of order. An estimate of the probability an aircraft was hit on a sortie in Desert Storm can be determined using the equation

$$P_H = \frac{\text{number of aircraft damaged} + \text{number of aircraft killed}}{\text{number of sorties flown}} \tag{1.13}$$

Table 1.8a Coalition aircraft combat losses in Desert Storm[26]

A/C[a]	Combat sorties	Damaged A/C	Damage rate	Lost A/C	Loss rate
		U. S. Air Force			
A-10	7,983	13	1.6	4	0.5
OA-10	657	1	1.5	2	3.0
AC-130	101	1	9.9	1	9.9
B-52G	1,741	5	2.9	0	0
EF-111	1,105	0	0	1	0.9
F-111F	2,420	3	1.2	0	0
F-15C	5,674	1	0.2	0	0
F-15E	2,142	0	0	2	0.9
F-16	13,066	4	0.3	3	0.2
F-4G	2,678	0	0	1	0.4
Total	**37,567**	**28**	**0.7**	**14**	**0.4**
		U. S. Navy			
A-6E	4,800	4	0.8	3	0.6
F-14	3,916	0	0	1	0.3
F/A-18	4,316	0	0	2	0.5
Total	**13,032**	**4**	**0.3**	**6**	**0.5**
		U. S. Marine Corps			
A-6E	793	1	1.3	0	0
AV-8B	3,349	2	0.6	5	1.5
F/A-18	4,934	8	1.6	0	0
OV-10	482	0	0	2	4.1
Total	**9,558**	**11**	**1.2**	**7**	**0.7**
U. S. Total	**60,157**	**43**	**0.7**	**27**	**0.4**
		Allies			
A-4	651	0	0	1	1.5
F-5	1,129	0	0	1	0.9
Jaguar	571	4	7.0	0	0
Tornado GR-1	2,482	1	0.4	9	3.6
Total	**4,833**	**5**	**1.0**	**11**	**2.3**
Grand total	**64,990**	**48**	**0.7**	**38**	**0.6**

[a] A/C = aircraft.

An estimate of the probability an aircraft was killed given a hit can be determined using the equation

$$P_{K|H} = \frac{\text{number of aircraft killed}}{\text{number of aircraft damaged} + \text{number of aircraft killed}} \tag{1.14}$$

The values for these two probabilities and P_K for a sortie are given in Table 1.8b using the data given in Table 1.8a for several aircraft to illustrate the computational procedure.

Table 1.8b Estimates of P_H, $P_{K|H}$, and P_K based upon the Desert Storm combat data given in Table 1.8a

Aircraft	P_H	$P_{K\|H}$	P_K
A-10	0.0021	0.24	0.0005
AC-130	0.0198	0.50	0.0099
F-16	0.0005	0.43	0.0002
A-6E (USN)	0.0015	0.43	0.0006
F/A–18 (USN)	0.0005	1.0	0.0005
F/A-18 (USMC)	0.0016	0.0	0.0
AV-8B	0.0021	0.71	0.0015
Jaguar	0.0070	0.0	0.0
Tornado GR-1	0.0040	0.90	0.0036

Having calculated these probabilities, the author would like to caution the reader when drawing any conclusions from them about the relative survivability of the aircraft. The missions the aircraft perform and the threats encountered on these missions can be significantly different, as noted in the presentation of the combat data for three fighters in the Korean conflict. Aircraft on a close air support (CAS) or air interdiction (AI) mission in Desert Storm were far more likely to encounter a vast array of air defense weapons than those aircraft flying air superiority missions. Thus, P_H could be expected to be higher for these aircraft. For example, 13% of the missions flown by the A-10 were CAS missions, whereas the F-16 flew CAS on 3% of its missions.[26] The P_H data given in Table 1.8b show that the A-10 was four times as likely to be hit as the F-16 while on a mission. The Navy Hornet flew only two CAS missions, whereas the Marine Hornet flew nearly 1800 CAS missions,[26] and the Marine Hornet was three times more likely to be hit than a Navy Hornet. The $P_{K|H}$ for a typical combat aircraft is highly dependent upon the size of the warhead on the weapon. A hit by a large SAM is more likely to cause a kill than a hit by a small SAM, such as a MANPAD. Thus, those aircraft that fly on missions where they encounter large SAMs are more likely going to have a higher $P_{K|H}$ than those aircraft that are hit by smaller weapons. Another factor to consider is that the amount of data is relatively small. The conclusions made from a small amount of data can be misleading.

Go to Problems 1.2.1 to 1.2.5.

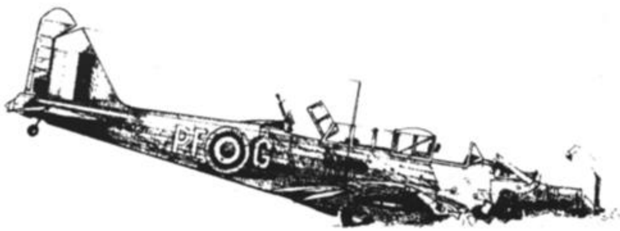
1.2.2 World Wars I and II

Learning Objective	**1.2.2**	**Describe some of the critical components and the survivability enhancement features used on the aircraft of WW I and II.**

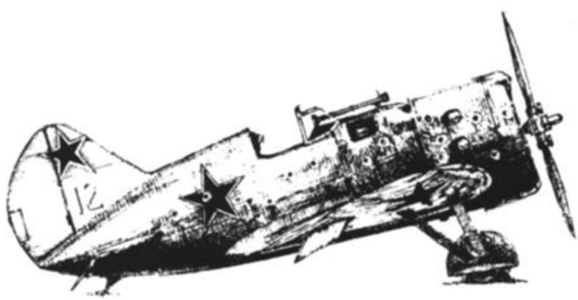
Survivability enhancement of military aircraft began in World War I with makeshift efforts by the pilots to provide themselves with some form of ballistic armor protection against surface and aircraft guns. This progressed from steel infantry helmets and stove lids nailed to the pilot seats to 0.8-in.-thick all-steel pilot seats. In 1917 Germany designed a twin-engine bomber with 880 lb of 0.20-in. steel-plate armor located in critical areas. The British also installed steel seats and 0.50–0.625-in.-thick nickel-chrome steel armor around radiators, fuel tanks, and the aircrew in some of their aircraft.

In the 1930s, although the United States began to install armor in some of their fighter aircraft, the main emphasis in aircraft design was on ruggedness and on the improvement of flight performance, such as maximum range and top speed. Then, on 10 May 1940 Germany invaded Holland, Belgium, and France. The British and French air units on the Continent conducted air strikes on the advancing German armor columns. Over 200 light bombers and fighters were lost in the first month of the invasion.

On 22 June 1941 Germany invaded Russia. The Russians met the German onslaught with I-16 and I-153 fighters. By noon on 22 June, 800 Russian aircraft had been destroyed, and by nightfall 1489 aircraft had been destroyed, most of them before they took off. The Germans lost 35 aircraft during that first day.

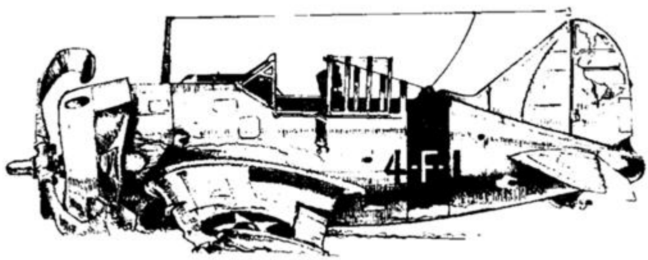


FAIREY BATTLE III



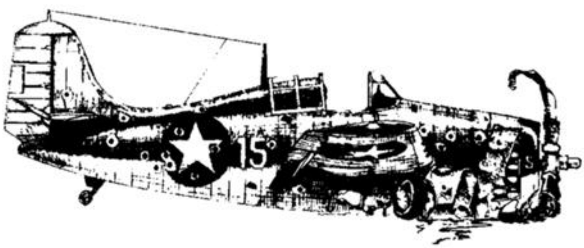
SOVIET 1–16

During the first months of the war in the Pacific, the Japanese Zero clearly showed its superiority over the Allied aircraft. In the battle for Java, which ended on 8 March 1942, over 550 Allied aircraft were destroyed, including large numbers of fighters such as the Brewster Buffalo, the Curtiss Hawk, the Curtiss P-40, and the Hawker Hurricane. The Brewster Buffalo was also used by the U. S. Marines in the defense of Midway in June 1942. In one raid 20 Buffalo fighters took off to intercept incoming Japanese aircraft. The Buffaloes were overwhelmed by the far superior Japanese Zero. Thirteen of the 20 Buffaloes were shot down, and the rest were badly damaged.



BREWSTER BUFFALO

The primary carrier-based fighter for the U. S. Navy during the early part of World War II was the Grumman Wildcat. It, too, was inferior to the Zero in almost all respects. The Wildcat was, however, capable of absorbing much battle damage. Nevertheless, only a very experienced pilot was capable of surviving a dogfight with the Japanese fighters.



WILDCAT

Clearly, the Fairey Battle, the Russian I-16, the Brewster Buffalo, and the Grumman Wildcat were no match for the fighters introduced by the Axis at the start of the war. New aircraft had to be produced and modifications made to existing aircraft if there were to be any hope of gaining control of the skies. The U. S. aircraft industry was able to meet this challenge, and a large number of excellent combat aircraft were eventually produced. The Army Air Corps developed the Lockheed P-38 Lightning, the Republic P-47 Thunderbolt, and the North American P-51 Mustang fighters. The main Air Corps bombers included the Boeing B-17 Flying Fortress, the Consolidated B-24 Liberator, the North American B-25 Mitchell, and the Douglas A-26 Invader. The Navy developed the Grumman F6F Hellcat and the Chance-Vought F4U Corsair fighters and the Grumman TBF/TBM Avenger torpedo bomber. A presentation of the specific survivability features of several of the most famous aircraft of World War II is given in Appendix A. Some of the susceptibility and vulnerability reduction features used in WW II are described next.

1.2.2.1 Susceptibility reduction in WWII. Susceptibility reduction has been a goal of the military tactician from the beginning. The tactics, weapons selection, mission planning systems, force packaging, and threat suppression used by the military manage attrition by balancing the requirement to accomplish the mission objectives with an acceptable number of aircraft losses. The susceptibility of World War II aircraft was reduced mainly by the introduction of more powerful engines, by the use of lethal self-defense armament, and by the tactics employed.

During the war, hundreds of B-17s flew across the English Channel at high altitude in box formations, escorted by P-47 and P-51 fighters looking for the enemy fighters. The massed bomber formations with their self-protection armament and fighter escorts provided a formidable shield against the enemy fighters. The bombers were located far enough apart so that an exploding shell from an antiaircraft artillery piece, known as flak, would not damage or kill more than one aircraft. But they were also close enough together so that the enemy fighters could not easily maneuver between them. They were loaded down with twin 50-cal machine guns mounted in electrically driven turrets, and eight of the ten crew members were firing guns at the enemy fighters. The weight of the self-defense guns and ammunition was approximately twice the weight of the bombs carried.[27]

The B-17s flew during the day, which made them more susceptible, because they used the Norden bombsight, which required the bombardier to see the target. The British flew their Lancaster and Halifax bombers at night because they had a better chance of avoiding the fighters and the flak. As a result, they were less susceptible and hence more survivable at night (an increase in the SR). However, it also was more difficult to destroy a particular factory or bridge when bombing at night (a decrease in the MAM).

Many bombers were lost, particularly on unescorted raids deep into Germany such as the Schweinfurt and Regensberg raids in 1943. The bomber flight paths were routed around the areas where the flak was the heaviest whenever possible, and decoy formations were often used to draw the enemy fighters away from the main force. Countermeasures, such as German-speaking radio operators on British aircraft, were used to confuse the enemy air defense personnel. Camouflage paint was used to hide aircraft on the ground, and contrails and engine exhaust flames were suppressed to make early detection in the air more difficult. A few aircraft had radar tail-warning devices to alert the pilot that an aircraft was approaching from behind. The development of electronic countermeasures to the early radar systems was a high priority item, and radar-reflecting chaff or 'window' was used extensively, after some early hesitation because of the fear the enemy would learn about its effectiveness and use it against the allied radars. References 28 and 29 present a detailed history of the use of electronic countermeasures in World War II.

Table 1.9a presents some of the SR features used in WWII, and each feature is related to one of the six susceptibility reduction concepts.

1.2.2.2 Vulnerability reduction in WWII. The VR features that were incorporated on the aircraft of World War II were, for the most part, added components necessitated by combat experiences. Most of the aircraft that were in use at the beginning of the war, such as the Fairey Battle, Brewster Buffalo, Grumman F4F Wildcat, and Boeing B-17, were either extensively modified during the war to make them more survivable or were used on missions with low threat levels. An excellent paper by F. Wertenson on the effects of enemy gunfire on the German Ju-88 notes that the cost of the Ju-88s lost in combat was the largest single expenditure

Table 1.9a Some susceptibility reduction features used in World War II

Reduction concept	Reduction feature
Threat warning	Tail-warning radar
Noise jamming and deceiving	Electronic noise jammers
Signature reduction	Camouflage paint, contrail and engine exhaust suppression
Expendables	Chaff/window
Threat suppression	Fighter escorts, massed formations of bombers with self-protection guns
Weapons and tactics, flight performance, and crew training and proficiency	More powerful engines, lethal armament, high-altitude flight, bomber formations, night operations, mission routes outside of the air defenses, decoy formations

of the entire program.[30] According to Wertenson, the operations of the Ju-88 were discontinued in 1944 because the opposition of the Allies standard pursuit aircraft had become so strong.

Studies indicate that the critical components leading to aircraft losses in World War II were, in order of magnitude, 1) engines, 2) lubrication systems, 3) fuel systems, and 4) flight controls.

Liquid-cooled engines were vulnerable mainly because of their exposed cooling systems. Modifications were made on numerous aircraft, such as routing the cooling lines away from the underside of the aircraft or relocating vulnerable cooling components. An emergency boost in engine power was provided by water injection systems. The power boost gave the pilot a chance to outrun chasing aircraft. Some of the multiengined bomber aircraft had a backup system for feathering the propellers on an engine that had to be shut down. If the propellers could not be feathered, the added drag on the aircraft could slow it down and cause it to drop out of formation, making it an easy target for the enemy fighters.

Fuel systems were self-sealing to a degree, except in most Japanese aircraft. Some attention was also directed to the suppression of fuel fires. A few aircraft had fuel-tank inerting systems, and some had a fuel-tank depressurization switch. Venting of fuel vapors from void areas was also done. Balsa wood was installed around some of the voids in wing fuel tanks to prevent fuel leakage and fires in those areas. Fire extinguishers were stowed in some crew compartments and in engine nacelles. The British experimented with fire-extinguishing systems in the fuel tank areas of some of their multiengined aircraft.

The use of armor plate was a common practice, except in the Japanese aircraft. Most aircraft had armor plate behind the pilot, and several had side and bottom cockpit armor as well. The available body armor in 1942 was awkward and heavy and thus was seldom used. The need for lightweight armor led to the development in 1943 of fiberglass bonded into a laminate and called Doron, after Col. G. F. Doriot. The introduction and use of flak suits significantly reduced casualties. None of the armor of this period was effective against armor-piercing incendiary (AP-I) bullets, however. Flat-plate laminated-armor glass was incorporated into the windshields of some combat aircraft as an added protection for the pilot, and some aircraft had armor shielding around such components as radiators and oil reservoirs.

One of the major contributors to the improvement in U. S. aircraft effectiveness was the development of more powerful engines. These engines allowed the weight of the aircraft to be increased, as well as providing a significant improvement in flight performance. The rugged construction of the successful aircraft of World War II was based more on the desire of the manufacturer to produce an aircraft capable of withstanding large aerodynamic forces than to produce an invulnerable aircraft. Fortunately, this construction also contributed greatly to the survivability of many aircraft. Rugged construction, by itself, was not enough to guarantee survival. The Buffalo and the Wildcat are prime examples of rugged, but killable, fighters.

References 27 and 31 present many of the vulnerability features used on several World War II aircraft. Some of these features are listed in Table 1.9b. Each feature was incorporated to prevent one or more of the system kill modes.

Table 1.9b Some vulnerability reduction features used in World War II

Reduction concept	Reduction feature
Component redundancy with separation	Fuel tank cross-over lines with shut-off valves-to prevent fuel supply depletion
	Back-up propeller feathering subsystem-to prevent loss of speed
Component location	Location of cooling & lubrication components-to reduce their likelihood of being hit
Passive damage suppression	Self-sealing fuel tanks-to prevent fuel leakage into dry bays
	Fuel venting and void space filling-to prevent fires/explosions in dry bags
	Fuel tank ullage inerting-to prevent ullage fires/explosions
	Rugged construction-to prevent the loss of structurul integrity
	Fuel tank depressurization-to mitigate fuel leakage from self-sealing tanks
	Firewalls-to delay the spread of a fire
Active damage suppression	Fire extinguishing (crew and engines)-to extinguish onboard fires
	Emergency extension of landing gear-to prevent damage during landing
Component shielding	Armor plating-to prevent damage to critical components
	Bullet-proof glass canopy-to shield the pilot
Component elimination	Air-cooled engines-to reduce the number of critical components

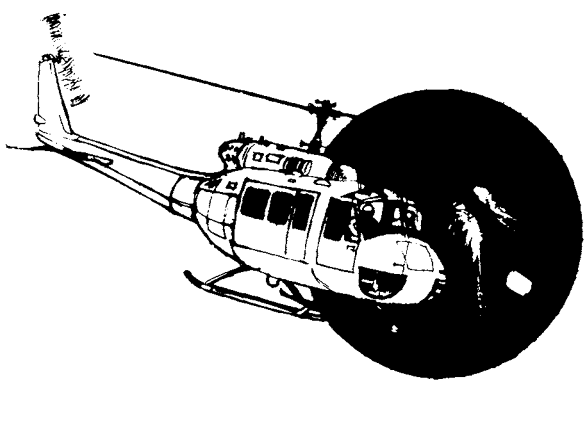
1.2.2.3 Summary. Looking back at all of the attempts during World War II to make aircraft more survivable, and hence more effective, we can see that all six concepts for reducing vulnerability and all six concepts for reducing susceptibility were used. In general, it took the combination of all of these concepts to make an effective weapon system.

Go to Problems 1.2.6 to 1.2.14.

1.2.3 Post-World War II and the Korean Conflict

In 1948 the First Working Conference on Aircraft Vulnerability was held at the U. S. Army Ballistic Research Laboratory at the Aberdeen Proving Ground, Maryland. The participants were from the Air Force Air Material Command, the Army Ballistic Research Laboratory, Johns Hopkins University Applied Physics Laboratory, University of Chicago Ordnance Research, General Electric Engine Company, New Mexico School of Mines, the Navy Ordnance Explosive Group, and the Rand Corporation. The purpose of this meeting was to define the problems of military aircraft vulnerability and to identify the technology required to develop design improvements. Unfortunately, the excellent beginning initiated by this group was curtailed by the emerging philosophy that all future wars would be fought with nuclear weapons.

During the Korean conflict, there was a limited revival of interest in nonnuclear survivability. The emphasis was primarily directed to fighter and attack aircraft. The major survivability enhancement techniques were mainly improvements in armor and self-sealing fuel tank designs. The use of coordinated tactics in air-to-air combat with fighter aircraft became an area of interest to the Air Force and the Navy and proved to be an important factor in the one-sided kill ratios enjoyed by the United States. After this conflict the emphasis of military aircraft design was again directed to general nuclear war considerations, and little attention was paid to the design for nonnuclear survivability during the 1950s and early 1960s. The conflict in Southeast Asia in the mid-1960s changed this attitude.



1.2.4 Southeast Asia Conflict, 1964–1973

Learning Objective 1.2.3 Describe some of the critical components and the survivability enhancement features used on the aircraft of the Southeast Asia conflict. In particular, describe the VR features retrofitted to the F-4 and F-105 and the support forces used in the 1972 Linebacker operations.

In the years from 1962 to 1973, the U. S. military services lost approximately 5000 aircraft to enemy fire in SEA. The losses were nearly equally divided between fixed-wing aircraft and helicopters. Many of the tactics used to avoid the hostile environment in SEA were essentially the same as those used in WWII, such as formations of bombers escorted by fighters. However, the formations were usually much smaller, and the bombers and attack aircraft, such as the B-52, F-105, F-4, A-4, A-6, and A-7, had little or no self-defense capability. They relied totally on the fighter escorts, such as the F-4 and F-8, to keep the enemy fighters away.

The surface-to-air guided missile emerged as a major threat to contend with, and onboard threat warning receivers and electronic jamming equipment, and the support jamming provided by aircraft such as the EA-6 and EB-66, became major contributors to survivability. Specially modified aircraft, such as the F-4 and F-105 Wild Weasel/Iron Hand, were used in the SEAD role to seek out and destroy the enemy AAA and SAM sites. Mission profiles were often used that kept the aircraft out of the high-altitude envelopes of the SAMs but put them within range of ground-based small arms and AAA fire. Reference 29 presents a brief history of the use of electronic warfare in the SEA conflict.

1.2.4.1 Helicopters. The employment of large numbers of U. S. helicopters in Southeast Asia in the mid-1960s resulted in a painful awareness of their susceptibility and vulnerability to hostile, nonnuclear weapon systems. This was the first time U. S. helicopters were used in large numbers in combat roles where exposure to enemy fire was commonplace. Introduced in limited numbers during World War II, the helicopter was employed in its first major combat-support roles during the Korean War, where it was used primarily for observation and as an air ambulance. The major problem facing the helicopter designers in the 1950s was not how to make the helicopter more survivable, but how to make it more practical in terms of lift capability and efficiency. Consequently, pilots sat on stove lids for vital protection, much the same as their ancestors did in World War I. The reciprocating engines were able to absorb a fair amount of small arms fire and continue to operate, and the transmissions on these early models, such as the H-21 and the H-34, could run for 30–60 min after complete loss of oil. The plywood and fabric rotor blades could also withstand hits by small arms fire as long as the blade spar was not damaged. The flight controls consisted of a simple cable and pulley system with no redundancy.

The first operational use of the helicopter for offensive combat was by the French in Algeria between 1956 and 1959. From their experiences the French concluded that suppressive fire delivered from the helicopter was a necessary requirement for reducing combat losses and that the helicopter had a relatively low vulnerability to 7.62-mm projectiles.

The U. S. Army recognized the threat of small arms and light antiaircraft weapons to aircraft operating in direct support of forward area units and, in the late 1950s, initiated action to develop protective measures for the aircrew and critical aircraft components against these threats. The Air Vehicle Environmental Research Team, consisting of technical representatives from the user and the appropriate technical service laboratories, was formed, and they developed the original concepts for ballistic protection systems that were later employed in all Army combat aircraft. These concepts were also used in varying degrees by the Air Force and Navy. These efforts led to the development of a new family of lightweight armor materials, damage-tolerant components, and major advances in fuel system protection.

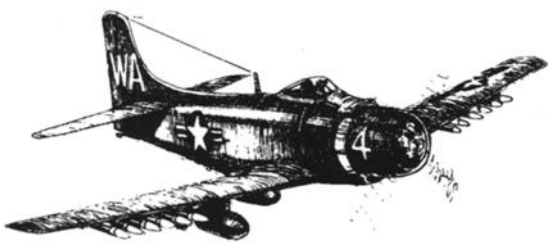
To increase the performance and efficiency of the helicopter, the heavy, rugged reciprocating engine was replaced with the lighter turboshaft engine. Introduction of the turboshaft engine, however, did not contribute to an increase in survivability. On the contrary, the turboshaft engine ran at high speeds and was constructed of lightweight materials, thus increasing its vulnerability to small arms fire. The high-speed transmissions associated with the turboshaft engines were also more vulnerable than the earlier ones, and loss of lubrication was almost always catastrophic.

Turboshaft helicopters were first used in combat in South Vietnam in 1962, with armed Bell UH-IA and UH-IB aircraft flying escort for H-21 troop-transport helicopters. The primary threats were 7.62- and 12.7-mm projectiles. The casualties in this period were relatively few, and, as expected, flight at the low altitudes and slow airspeeds used during troop insertions were the prime reasons for aircraft damage and loss.

The euphoria resulting from the low damage and loss rates associated with the early missions in South Vietnam was short-lived. After 1962 the level and caliber of weapons fire directed against helicopters significantly increased. By 1970 over 1500 U. S. helicopters had been lost, pilot survivability had become a severe problem, and steps were taken to improve survivability. Redundancy was achieved in the utility helicopters by using two pilots. If one pilot was incapacitated, the copilot could usually fly the helicopter, provided the injured/killed pilot did not bind the controls and the helicopter was not hovering at the time. In the single-piloted scout aircraft losses resulting from pilot incapacitation were significant. Lightweight composite armor was installed around the pilot's seat, but it only protected the torso. Many pilots placed personnel-type flak jackets in the cockpit for added protection.

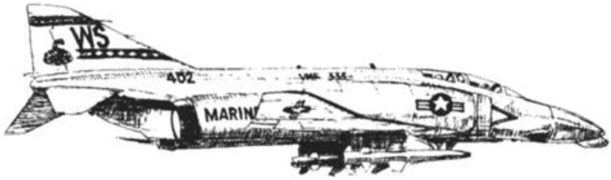
In the early 1970s a large number of helicopters were downed by 12.7- and 23-mm projectiles. The flight controls, rotor blades, fuel systems, engines, and transmissions were found to be highly vulnerable to the 23-mm antiaircraft fire. It was at about this time that the Soviet-built, man-portable SA-7 infrared seeking missile was introduced in Vietnam. A hit by an SA-7 missile, normally just behind the helicopter's engine exhaust, would completely sever the tail boom, causing an immediate crash. The heavy losses caused by the shift from a low-level threat environment to higher intensities indicated the need for more advances in survivability technology.

1.2.4.2 Fixed-wing aircraft. While the Army and Marines were losing helicopters, the Air Force, Navy, and Marines were experiencing significant fixed-wing aircraft losses. Many of the fixed-wing aircraft that fought in the Southeast Asia conflict were designed for high-altitude fighting with missiles and for nuclear war, and therefore they were ill suited for the type of combat experienced in SEA. For example, the two-seat McDonnell F-4 Phantom II was originally designed as a deck-launched interceptor for the U. S. Navy that would dash out to the enemy bombers approaching the carrier task force and kill them with radar-guided air-to-air missiles, and the single-seat Republic F-105 Thunderchief was designed to drop nuclear bombs from low altitude at high speed. In SEA both the F-4 and the F-105 were used as a fighter and a conventional bomber, and special versions were used in the threat suppression role. There was no (or very little) attention paid during the design of the F-4 and F-105 (or to the design of any other aircraft of that era) to the damage that enemy guns or guided missiles might do to the aircraft. As a result of this lack of attention to survivability during the requirements and design phases, the U. S. military began to lose a significant number of aircraft as the SEA conflict intensified.



A–1 SKYRAIDER

Because of these losses, the U. S. Air Force sent a fact-finding team into the area in 1966 to determine the loss cause(s). The team interviewed crew members who had been shot down and recovered and the wingmen of those not recovered. They also inspected and collected data on battle-damaged aircraft that had returned to base. The battle damage data were used to determine the location and types of damage that did not result in an aircraft loss. The original Air Force directive that identified the problem conjectured that the aircraft were falling out of the sky because of damage to the structure. However, the on-site team determined that the single most important cause of aircraft losses was actually fuel system fire or explosion. Another significant cause of aircraft losses was damage to the flight control system. Often, damage to the redundant (but adjacent) hydraulic components would result in hard-over control surface failures and an uncontrollable aircraft, forcing the pilot to eject—if he could. Many of the control failures were caused by a fuel or hydraulic fluid fire that destroyed the control components.



F-4 PHANTOM II

After the first U. S. Air Force team returned in 1966, they recommended a number of actions to reduce the future loss of aircraft. All were approved by U. S. Air Force Headquarters. One recommendation was to conduct vulnerability assessments on the tactical aircraft operating in North Vietnam (the F-4, RF-4, F-105, and RF-101) and to develop vulnerability reduction retrofit packages based upon the combat data collected and the vulnerability assessments. The primary emphasis was on the suppression of fuel system fire and explosion and the prevention of the loss of flight control. Self-sealing fuel tanks and lines and the placement of flexible, reticulated polyurethane orange foam into the fuel tanks were some of the VR features designed to prevent fuel-related fires and explosions. Several features designed to prevent the loss of control were added to both the F-105 and the F-4. These features are described next.[32]

Most of the combat aircraft that flew in the Vietnam conflict, like the F-105 and F-4, had two independent primary sources of hydraulic power that converged at the dual, tandem control surface actuators. A hit in the vicinity of any actuator powered by both primary sources could cause a total loss of hydraulic power at that actuator and possibly all actuators. When the power to move the control surface was lost, the surface would usually go hard-over, resulting in an uncontrollable aircraft. This type of vulnerability where a single hit at one location on the aircraft such as a hydraulic actuator can lead to an aircraft attrition kill is known as a single-point kill. Consequently, the area around the stabilator hydraulic actuator on most of the aircraft that flew in the SEA conflict proved to be a very vulnerable area (Note 25). To prevent this total loss of control power in the F-105, a one-way check valve was added to the stabilator hydraulic lines; if a line was damaged, the check valve prevented the fluid in the hydraulic cylinder from draining out and maintained some pressure. A warning light came on in the cockpit notifying the pilot that hydraulic power would soon be lost. The pilot quickly leveled the aircraft and threw a switch that activated a mechanical arm that locked the stabilator in place. The stabilator could not be moved to control pitch, but the pilot could continue to fly the aircraft until he entered into safe territory where he could eject with some assurance of being picked up by a search and rescue unit. This modified design is an example of the active damage suppression VR concept, that is, damage is sensed and some action is taken to constrain the damage or to reduce its effects.

On the F-4 an auxiliary power unit (APU) was added to the stabilator actuator to provide a third source of power, and armor was placed below the hydraulic components to shield them. Another change to the flight control system of the F-4 concerned the hydraulic power supplied to the aileron actuators, which were made of aluminum to save weight. The original hydraulic subsystem consisted of two primary flight control systems, PC1 and PC2, and the utility subsystem. The aircraft could be controlled provided either PC1 or PC2 was available at every actuator. Because both PC1 and PC2 supplied power to both aileron actuators, a hit on either of the aluminum aileron actuators (or a fatigue crack) could cause the loss of both PC1 and PC2 and the subsequent loss of control of the aircraft. In the more survivable redesign the aluminum actuators were replaced with steel actuators to prevent cracks from propagating from one hydraulic cylinder to the other cylinder in the actuator; and the hydraulic lines were rerouted, with utility replacing PC1 in one wing and PC2 in the other wing. With this less vulnerable design a hit on one aileron actuator could cause a loss of PC1 and utility, or PC2 and utility, but not both PC1 and PC2. Thus, the loss of hydraulic power in one wing did not result in the loss of control of the aircraft. This design modification to the hydraulic power at the aileron actuators changed the power from one of redundancy to redundancy with separation and thus eliminated two single-point kill locations on the aircraft.

This reduced vulnerability design of the aileron hydraulic subsystem was relatively easy to retrofit to aircraft in the theater, and it was part of the design on the F-4s built in the late 1960s. This feature alone saved the lives of at least 24 aircrews that were flying the modified F-4 when all hydraulic power was lost in one wing. Twelve of those aircraft were in a combat zone. The total savings caused by this particular feature was estimated to be \$51M (at \$2.5M per aircraft saved) plus the lives of the 24 aircrews. The cost of the modification was \$9M. However, if the original design had included the hydraulic redundancy with separation the cost would have been significantly less. The lessons to be learned from this example are that single-point kills must be eliminated early in the design of an aircraft and that this no-single-point-kill design requirement will reap benefits in both peace time and war time far exceeding any costs incurred.[32]

There are many other examples of aircraft modifications that were made to reduce vulnerabilities that were discovered in combat. A differential flap extension capability was added to the F-105 for a backup roll control mode, and bomb bay fire extinguishers, improved self-sealing fuel tanks, and redundant, self-sealing engine fuel feed systems were also installed on other aircraft. Armor was added around engines, hydraulic actuators, and flight control components on several aircraft. On another aircraft fuel vapors in voids were eliminated by the addition of a vent, and a fuel depressurization switch was added.

Some of the features incorporated on the aircraft that fought in SEA and the kill mode they were designed to prevent are listed in Table 1.9c. Most of these features were retrofitted to original designs that had not adequately considered vulnerability and most of them also contributed to aircraft safety.

Later in the conflict, when the numbers and sophistication of hostile weapon systems were raised to a level never before experienced by U. S. aircraft, many new and improved SR features were developed and employed. These included onboard radar homing and warning systems (RHAW gear) and electronic countermeasures equipment, IR suppression devices for aircraft engines, aural and visual signature reduction, evasive maneuvers against approaching SAMs, and special tactics. The survivability of these less susceptible aircraft was further enhanced by the accompanying fighters, standoff electronic countermeasures aircraft, and F-4 and F-105G Wild Weasel aircraft whose job was to suppress or destroy the enemy SAM and AAA systems with antiradiation missiles and bombs, known as Iron Hand support.

Table 1.9c Some vulnerability reduction features added to SEA aircraft

Reduction concept	Reduction feature
Component redundancy with separation	Rerouted hydraulics in wings-to prevent loss of control power
	Back-up flight controls and surfaces-to prevent loss of control
	Added APU-to prevent loss of control power
	Independent fuel feed tanks-to prevent fuel supply depletion
	Ram air emergency power package-to prevent loss of control power
Component location	
Passive damage suppression	Orange foam in fuel tanks-to prevent fires/explosions in ullages
	Improved self-sealing fuel tanks and lines-to prevent fuel supply depletion and fires
Active damage suppression	Stabilator lock-to prevent loss of control
Component shielding	Armor plating-to prevent damage to critical components
	Bullet-proof glass canopy-to shield the pilot
Component elimination	Air-cooled engines-to reduce the number of critical components

The 1972 Linebacker operations are briefly described next to illustrate the importance of susceptibility reduction in mission planning and force packaging.

1.2.4.3 1972 Linebacker Operations. The 1972 Linebacker bombing operations against North Vietnam in May and June (Linebacker I) and 18–24 and 26–29 December (Linebacker II) are examples of the maximum use of support assets to increase the survivability of the U. S. bombers by reducing their susceptibility. A book by Karl J. Eschmann[33] contains a detailed description of the tremendous efforts of the people involved in the operations to bring the SEA conflict to an end. A typical Linebacker I strike package consisted of 20–28 F-4s with laser-guided and conventional ordnance. The F-4s were supported by 65–79 aircraft, including four weather reconnaissance aircraft, three EB-66 standoff jammer aircraft, eight to twelve F-4 chaff bombers sowing chaff corridors five miles wide and 105 miles long, eight F-4s escorting the chaff bombers, 32 F-4s defending the strike and chaff forces by establishing a barrier between the enemy fighters and the strike and chaff forces (the MIGCAP mission), 16–20 F-4 strike escorts, 8–12 F-105G Wild Weasels flying Iron Hand (defense suppression) support, four F-4s providing support for the air-refueling tankers and search and rescue forces (the BARCAP/TANKER CAP mission), two photo-recon RF-4s, and two fighters escorting the photo-recon aircraft. Based upon these numbers, the smallest support force was about three times the size of the strike force, and during the strikes into Route Package VI (the geographical area containing Hanoi and Haiphong) the number of support force aircraft was about four times the number of strike aircraft.

Table 1.10 Combat data for Linebacker II, 18–29 December 1972 (Ref. 33)

Aircraft	Sorties	Lost	Loss rate (per 1000 sorties)
B-52	724	15 as a result of SAMs	20.7
Tacair	640	1 F-111 as a result of AAA	
Tacair support	2066	1 F-111 unknown	1.8
		2 F-4s as a result of Migs	
		1 HH-53 as a result of small arms (+1 A-7, O-2, and EB-66 because of mishaps)	
Navy/Marine Tacair	Unknown	2 A-6s and 1 F-4 because of AAA	Unknown
		1 RA-5 because of MIG	
		1 A-7 because of a SAM	
		1 A-7 and 1 A-6 unknown	

In the 11 days of Linebacker II operations, both day and night strikes were conducted. The daytime strike package consisted of F-4 and A-7 aircraft assigned to the bombing mission, with a supporting package similar to that of Linebacker I. At night the bombing was conducted by F-111 and B-52 bombers. On the first night of the operation, there were 129 B-52s in three waves, and each wave was supported by 39 tactical aircraft (Tacair) flying the same missions as the other support packages. The F-111 aircraft flew single-strike sorties against targets, such as air fields, SAM sites, and power plants. Naval Tacair strikes from the U. S. carriers were coordinated with the U. S. Air Force strikes. The aircraft lost during the operation are presented in Table 1.10.

The two Linebacker operations are another example of the important role survivability plays in combat. Compare the assignment of 75 support aircraft to protect 25 bombers to the lack of consideration given to survivability during the requirements and design phases of the aircraft that flew these missions. The appearance of new, more survivable aircraft after 1973 can be attributed to the hard lessons learned in this decade-long conflict.

Go to Problems 1.2.15 to 1.2.20.

A–4 SKYHAWK

RNAF HARRIER

1.2.5 Conflicts After 1972

Learning Objective	**1.2.4**	**Describe the impact of aircraft survivability on the outcomes of the conflicts since 1972.**

Many extended conflicts, relatively short military operations, and individual combat actions have taken place around the globe since 1972. These include the Yom Kippur War between Israel and Syria in 1973; the Iran–Iraq war beginning in 1980 and ending in 1988; Great Britain vs Argentina in the Falklands in the Spring of 1982; the Soviet Union occupation of Afghanistan from 1979 to1989; and the U. S. military intervention in Granada in October 1983; the air strike in Lebanon in December 1983; Operation El Dorado Canyon in Libya in March 1986; Operation Just Cause in Panama in December 1989; Operation Desert Storm in Iraq in January–February 1991; the mission in Somalia to round up top-level lieutenants loyal to the fugitive Somali militia leader in October 1993; the peace-keeping flights over Iraq and Bosnia throughout the 1990s, and Operation Allied Force in Kosovo in the Spring of 1999. Most of these have been either intense and short-lived or relatively quiet and long term. Each side has essentially fought with the supplies at hand, with little change in equipment. The survivability data and implications from five of these operations are presented next. Reference 34 contains a description and information on several of the conflicts that occurred between 1964 and 1983.

FRENCH-BUILT MIRAGE

1.2.5.1 1973 Yom Kippur War. Israel fought the Yom Kippur War in 1973 and has had a continuing, low-intensity battle with Syria for many years. On the first day of the 1973 Yom Kippur War, Israeli aircraft provided accurate ground support for Israeli tank units. These aircraft were equipped to jam the Syrian SA-2 SAM radars, but were completely susceptible to the semiactive homing SA-6. Consequently, losses on the first day were heavy. During the first afternoon, many aircraft were lost to either the SA-6 or to the radar-directed 23-mm cannon fire of the Soviet-built ZSU-23-4. The ZSU-23-4 was particularly deadly to aircraft flying at low altitudes in an attempt to avoid the SA-6 coverage. These early losses were so severe that subsequent air strikes were canceled over the Golan Heights. However, owing to the rapidly deteriorating ground situation, the strikes were eventually resumed, but the tactics were changed such that the aircraft operated on the perimeter of the battle zones, thus avoiding the concentration of the air defenses.

On the other hand, the Israeli aircraft losses suffered in their 1982 invasion into Lebanon were negligible compared to those in the 1973 war. The air defenses were directly attacked from the beginning with coordinated threat suppression tactics. Both the SA-6 and the mobile SA-8 were rendered ineffective. The combined use of electronic countermeasures, drones, antiradiation missiles, and ordnance were apparently too much for the defenses.

1.2.5.2 Falklands War in 1982. On 2 April 1982 Argentine forces invaded the Falkland Islands, and on the following day they invaded South Georgia. The official British position was that all of these islands were British sovereign territory.[35] The British responded to the invasion by sending a task force of over 100 ships to the area. On 25 April the task force repossessed South Georgia. On 1 May Port Stanley was bombed, and the first major landing on the Falklands Islands was made at San Carlos Water on the night of 20/21 May. Eventually, 10,000 British troops were put ashore. The Argentineans responded to the British actions by attacking the ships of the British task force, primarily with aircraft, and defending the islands against the invading British land and air forces. The conflict ended 14 June when Argentina surrendered.

The British tactical fixed-wing aircraft in the task force consisted of 28 naval Sea Harriers and 14 air force GR3 Harriers. The helicopters included Chinooks, Sea Kings, Wessex HAS.3s, and HU.5s, Lynxs, Scout AH.1s, and Gazelles. The Argentinean air order of battle included Douglas A-4B/C Skyhawks, French Mirage IIIEAs and Super Etendards, Israeli-built Daggers, British Canbaras MK 62s, and Argentinean Pucaras; and a number of helicopters.[36]

The primary land-based antiaircraft weapons used by the British included the optical version of the Rapier SAM and the Blowpipe and Stinger MANPAD SAMs. At sea the British defended their ships with the Sea Dart, Sea Cat, and Sea Wolf SAMs, and the Sea Harrier. The Harriers carried the AIM-9L Sidewinder and the 30-mm ADEN cannon. A variety of antiaircraft guns and small arms were also employed on land and at sea. The Argentinean air defense included two long-range, surveillance radars linked to the Skyguard and Super Fledermaus fire control systems that controlled twin 35-mm guns, a number of 20-mm cannons, the Tigercat and Roland SAM systems, the Blowpipe and SA-7 MANPADS (http://jmr.janes.com/samples/samples.html), and small arms.

The main air actions consisted of Argentinean air attacks against the British ships, British air-to-surface attacks in the close air support mission, and a variety of helicopter actions on both sides. The claimed aircraft kills and admitted aircraft losses by both sides are in dispute. The British admit to losing two Sea Harriers to small arms and one to a SAM, possibly the Roland, during 1100 combat air patrol and 90 offensive support sorties. Three GR3s were lost to ground fire on 125 attack and reconnaissance sorties. Three Gazelles, without offensive armament and in a country devoid of natural cover, were killed by ground fire, and one Scout was downed by a Pucara.[35] The Argentines claimed to have shot down four Harriers and severely damaged a fifth with the Roland SAM. Claims for 12 helicopter kills and nine probables were also made.

The British claimed 21 aircraft kills and three probables by Sea Harriers, 24 kills by land-based SAMs, with eight probables, 21 kills by sea-based SAMs, with two probables, and seven kills by guns, with one probable.[35] The Argentineans admit to losing 34 jet aircraft in 445 sorties and at least five Pucaras.[36]

Comparing the loss rates in the Falklands conflict with the historical U. S. loss rates given in Fig. 1.16 reveals that the aircraft employed in the Falklands were very killable. Nevertheless, one summary of the operations stated that "aircraft survivability against a defended target was rather high on both sides. For example, the relatively unsophisticated Harrier flew 150 sorties against Port Stanley with the loss of *only* three aircraft."

1.2.5.3 Operation Urgent Fury, Grenada 1983 (Ref. 37). From 25 October to 2 November 1983, the U. S. carried out Operation Urgent Fury in order to rescue and evacuate U. S. and other foreign nationals, neutralize opposing forces, and stabilize the internal situation in Grenada. The plan called for the capture of two airfields on Grenada to include the immediate neutralization of Cuban forces at Point Salines airfield as well as the near simultaneous seizure of several key targets and the rescue of U. S. citizens. (http:// 131.84.1.34/doctrine/jel/history/urgfury.pdf.)

The air operations involved 107 U. S. Army and U. S. Marine helicopters. Nine helicopters were hit by enemy fire, and four of them were killed; two AH-1T Sea Cobras during an attack mission, one CH-46E Sea Knight, and one UH-60 Black Hawk were also killed. According to the damage assessment, impacts indicated the threat was 7.62 mm in size, with possible 12.7 mm. Most of the hits were to the cockpit, cabin, aft fuselage, and tail boom. A few hits were noted on the main rotor head, none on the engine, although there were several on the inlet and exhaust shrouds, none on the main rotor controls about the cabin, and relatively few on main and tail rotor blades. In summary, with the exception of one fuel cell that did not self-seal, the damage to flight critical components was consistent with results of previous ballistic testing and vulnerability analyses of prototype hardware. The fuel leak can be attributable to imperfect sealing mechanics rather than an unexpected ability of the projectile to cause damage. According to the U. S. Army, the new helicopters were able to withstand antiaircraft fire and met or exceeded survivability and crashworthiness design specifications. Ten Black Hawks received combat damage with only one loss. One Black Hawk had 45 bullet holes, punctured fuel tanks, holes in the tail and main rotors, much of the control instrumentation destroyed, and five people, including the pilot, wounded. Yet the crew completed their missions. In fact, all combat damaged Black Hawks completed their missions.

1.2.5.4 Operation El Dorado Canyon, Libya 1986 (Ref. 38). On 15 and 16 April 1986 the U. S. launched simultaneous attacks against five targets in Libya. According to published reports, the purpose of the attacks was to avenge the bombing of a discotheque in West Berlin in early April, to thwart future terrorist operations, and to compel Col. Moammar Gadhafi to change his behavior regarding international terrorism. (http://www.fas.org/man/dod-101/ops/el_dorado_canyon.htm.) (Data for this section provided by SURVIAC.)

The primary strike aircraft included 18 FB-111F Aardvarks and 15 A-6E Intruders. An armada of aircraft provided support for the 33 bombers, including five EF-111 Ravens and several EA-6B Prowler ECM aircraft, 12 A-7E Corsairs and F/A-18 Hornets with Shrike and HARMs for air defense suppression, a number of F-14 Tomcats flying combat air patrol, and four E-2C Hawkeye aircraft proving long-range surveillance, strike coordination, and fighter control. Several helicopters were available if any search and rescue operations were required. One FB-111 did not return from the mission, and 13 FB-111s, 14 A-6Es, 6 F/A-18s, and 6 A-7Es were damaged during the operation for a total of 39 damaged aircraft out of the approximately 60 aircraft closely involved in the Operation.

1.2.5.5 Operation Just Cause, Panama 1989 (Refs. 39 and 40). On 20 December 1989 Operation Just Cause began with the objectives to protect U. S. lives and key sites and facilities, to capture and deliver Manuel Noriega, the head of state in Panama, to competent authority, to neutralize the Panamanian Defense Forces (PDF), to neutralize the PDF command and control, to support the establishment of a U. S.-recognized government in Panama, and to restructure the PDF. Eventually, the U. S. force included 170 Army helicopters and a number of Air Force C-130s, C-141s, and C-5s.

The Air Force transports flew approximately 400 sorties, and 14 of the aircraft were hit by ground fire, mostly in the form of small arms, for a P_H of 0.035. None of the hit aircraft were killed. Forty-five of the 170 Army helicopters were hit, mostly by small arms and mostly in the daytime. Four of the 45 hit helicopters were killed, for a $P_{K|H}$ of 0.089. The four downed helicopters included three AH-6 Little Birds and one OH-58 Kiowa. Twenty-five of the 41 damaged helicopters were UH-60 Black Hawks and three were AH-64 Apaches. Twenty-four of the 25 Black Hawks were returned to service within 24 hours or less. The one damaged Black Hawk that required more time to repair had sustained additional damage as a result of a hard landing.

1.2.5.6 First day in Operation Desert Storm 1991 (Ref. 41). On 2 August 1990 a large number of troops from Iraq began an invasion of Kuwait. From 7 August 1990 to 16 January 1991, the Coalition against Iraq (the U. S. and its allies) built up a very large ground, air, and naval force in and around the Arabian peninsula in Operation Desert Shield. Operation Desert Storm began early in the morning of 17 January 1991 when the Coalition's air forces conducted their first strike against Iraq. H-hour over the target was 0300, Baghdad time. One of the major objectives of the campaign was to gain and maintain air superiority quickly by destroying Iraq's ground-based medium- and high-altitude air defense forces and its fighter aircraft, both in the air and on the ground. To achieve this objective, U. S. Army Apaches were sent across the border before H-hour to destroy an early warning radar site in southern Iraq. Tomahawk land attack missiles (TLAMs) were launched from U. S. Navy ships in the Red Sea and Persian Gulf toward Baghdad and Basra, with a time on target between 0306 and 0311. B-52s from Louisiana were launched 12 hours before H-hour carrying conventionally armed cruise missiles aimed at critical Iraqi communications facilities and electrical power plants. F-117s were launched from deep in Saudi Arabia carrying 2000-lb laser-guided bombs to destroy critical targets in and around Baghdad.

United States F-111s and F-15Es were assigned targets throughout Iraq, while A-6 and F/A-18 aircraft struck targets in southern Iraq and Kuwait. Other Coalition aircraft, such as Saudi and British Tornados, French Jaguars, and Kuwaiti A-4 Skyhawks, flew strike missions. The RAF Tornados, with their JP 233 bomblet dispenser, were assigned the difficult mission of low-level strikes against Iraqi air base runways. E-3 AWACS and E-2 Hawkeyes provided airborne command posts and radar coverage for the Coalition aircraft. RC-135 Rivet Joint aircraft listened for transmitting Iraqi communications and radars, and EA-6 and EF-111 aircraft provided electronic jamming support. F-14 and F-15C fighters were assigned the air superiority mission. Decoys were launched to attract the attention of Iraqi radars, diverting them from the strike aircraft and setting them up for an attack by F-4Gs and other SEAD aircraft carrying HARMs.

Examining this first strike from a survivability point of view reveals that all six susceptibility reduction concepts listed in Table 1.3 were used. Threat warning was provided by the E-2, E-3, and RC-135 as well as equipment onboard the attacking aircraft. Electronic noise jamming and deceiving was used by the EA-6 and EF-111 aircraft as well as equipment onboard the attacking aircraft. Signature reduction was used by the F-117s, and the selection of a nighttime strike reduced the visual signatures of all of the aircraft. Expendables were used in the form of decoys, as well as chaff and flares, and threat suppression HARMs played a major role in destroying or intimidating the radars. The entire operation was planned using tactics that were designed to minimize aircraft losses while still accomplishing the desired objective of air superiority and the destruction of Iraq's ability to wage war.

The results were very impressive from both an offensive and a defensive point of view. By the end of the first day of the Operation, over 1000 sorties were flown into an air defense with an extensive network of radars and command centers, Iraqi Mirage F-1 and MiG-29 fighters, many medium- and high-altitude surface-to-air missile batteries, including the SA-2, -3, and -6 systems, low- to medium-altitude SA-8 and Roland mobile SAM systems, 7000 infrared SAMs, 1000 antiaircraft artillery sites, and 6000 mobile guns. By 0600 local time the first two waves of F-117s had dropped 33 bombs and hit their target 23 times. The Iraqi air defense no longer operated as an integrated system, many radars and SAM sites were destroyed, and much of Baghdad was without electricity. During that first day, only six Coalition aircraft were killed in combat. Prior estimates of aircraft losses ranged as high as 20–25. These results were beyond the expectations of most of those involved in the operation.

The combat data for all friendly Desert Storm fixed-wing aircraft that were damaged or lost during the Operation is contained in the *Gulf War Air Power*

Survey, Volume Five, A Statistical Compendium and Chronology.[26] These data, sorted by aircraft, are presented in Table 1.11 (Note 43).

1.2.5.7 Somalia in 1993. Somalia, a country located in eastern Africa on the Indian Ocean, was formed in 1960 by the union of British Somaliland and Italian Somaliland. Mogadishu, the capital of Somalia is located on the coastline. In the early 1990s, a civil war broke out between forces loyal to Ali Mahdi, who was supported by European nations and businesses, and those of Mohamed Farah Aidid, who favored the traditional tribal form of government known as kritarchy. The war resulted in severe famine throughout the land. In 1992 the United Nations (UN) established operations in Mogadishu for the purpose of humanitarian relief. In late 1992 and early 1993 the U. S. sent military forces to "save starving people and not to battle with Somalia's warlords."[42] However, conflict was inevitable. After a battle on 5 June 1993 between UN forces and those of Aidid, in which 24 Pakistani troops were killed, the UN called for his arrest.

Late in the afternoon of 3 October 1993, a U. S. air assault force departed the Mogadishu airport and proceeded toward a house in the heart of the capital city just three miles from the airport. The plan was to capture two of the leaders loyal to Aidid who were supposed to be in the house at the time. A multimedia web site account of this operation written by Mark Bowden of the Philadelphia Enquirer, with links to graphics, audio, and video, is located online at http://inquirer.philly.com/packages/somalia/sitemap.asp. A published account appeared in the *Atlantic Monthly* in 1999,[43] a book was published in 2000,[44] and a motion picture entitled *Black Hawk Down* was in distribution in 2002 (http://www.spe.sony.com/movies/blackhawkdown/.) The aircraft survivability aspects of the operation as originally described on the web site are summarized next.

The air assault force consisted of 17 helicopters carrying 75 U. S. Army Rangers and 40 Delta Force commandos. According to the operational plan, the helicopters would proceed from the airport to the city block containing the target house. Four UH-60 Black Hawk helicopters, each carrying a Chalk (the squad of Rangers assigned to each helicopter) and armed with miniguns, would position themselves above each corner of the block. The Rangers would rope down from the hovering aircraft and form a perimeter around the block. The Delta Force commandos would fly in to the target area aboard MH-6 Little Birds. The Little Birds would land in the alleys or on rooftops, and the commandos would quickly capture the leaders. Once they were captured, a convoy of 12 vehicles would arrive from the airport after a five-min drive and take the prisoners and the air assault team back to base. All of these actions would be observed from the air by OH-58 Kiowa helicopters and a U. S. Navy P-3 Orion. The operation was expected to last no more than an hour. The following is a brief description of what actually happened.

As the four Black Hawk helicopters approached the target block, they positioned themselves near the four corners of the block, and the troops roped down to the ground. The Rangers then formed a perimeter around the target block while the Delta Force commandos leaped from the Little Birds and stormed the house. However, not everything went according to the plan; the Somali resistance to the assault was much more intense than anticipated.

Two of the four Black Hawks that brought the Rangers in to the target block were hit and downed by rocket propelled grenades (RPGs) after the Rangers had

Table 1.11 Combat data from Desert Storm 1991 (Ref. 26)

No.	Date	Time	Aircraft	Country	Service	Unit	Mission	Loss/damage	Day/night	Combat	Position	Cause
79	2 Feb	0925 Z	A-10	US	USAF	23 TFW	BAI	Lost	Day	Yes	20 n.miles SW Kuwait City	IR SAM
117	15 Feb	1335 Z	A-10	US	USAF	354 TFW	BAI	Lost	Day	Yes	60 n.miles NE Kuwait City	IR SAM
119	15 Feb	1335 Z	A-10	US	USAF	354 TFW	BAI	Lost	Day	Yes	60 n.miles NW Kuwait City	IR SAM
134	22 Feb	1500 L	A-10	US	USAF	23 TFW	CAS	Lost	Day	Yes	——	IR SAM
11	17 Jan	0700 Z	A-10	US	USAF	10 TFW	CAS	Damage	Day	Yes	SE Iraq	AAA
15	17 Jan	1200 L	A-10	US	USAF	354 TFW	BAI	Damage	Day	Yes	——	AAA
48	23 Jan	1630 L	A-10	US	USAF	23 TFW	BAI	Damage	Day	Yes	——	AAA
61	29 Jan	0900 L	A-10	US	USAF	354 TFW	INT	Damage	Day	Yes	——	AAA
72	31 Jan	1600 L	A-10	US	USAF	354 TFW	INT	Damage	Day	Yes	——	AAA
75	31 Jan	1015 L	A-10	US	USAF	926 TFG	INT	Damage	Day	Yes	N3010 E04620	IR SAM
77	1 Feb	——	A-10	US	USAF	354 TFW	CAS	Damage	——	Yes	——	AAA
78	1 Feb	——	A-10	US	USAF	23 TFW	BAI	Damage	Day	Yes	——	AAA
84	2 Feb	——	A-10	US	USAF	354 TFW	INT	Damage	——	Yes	——	AAA
88	5 Feb	1500 L	A-10	US	USAF	354 TFW	INT	Damage	Day	Yes	——	AAA
90	6 Feb	1100 L	A-10	US	USAF	354 TFW	SEAD	Damage	Day	Yes	——	IR SAM
103	11 Feb	1130 L	A-10	US	USAF	23 TFW	BAI	Damage	Day	Yes	——	AAA
122	15 Feb	0830 L	A-10	US	USAF	23 TFW	BAI	Damage	Day	Yes	——	IR SAM
127	19 Feb	0622 Z	OA-10	US	USAF	23 TASS	FAC	Lost	Day	Yes	62 n.miles NW Kuwait City	IR SAM
147	27 Feb	0932 Z	OA-10	US	USAF	23 TASS	FAC	Lost	Day	Yes	KKMC	IR SAM
73	31 Jan	——	OA-10	US	USAF	23 TASS	FAC	Damage	Day	Yes	——	AAA
46	22 Jan	——	F-15C	US	USAF	1 TFW	DCA	Damage	——	Yes	Home Station	DEA Other
1	17 Jan	2012 Z	F-15E	US	USAF	4 TFW	INT	Lost	Night	Yes	16 n.miles SW Basra	AAA

(Continued)

Table 1.11 Combat data from Desert Storm 1991 (Ref. 26; Continued)

No.	Date	Time	Aircraft	Country	Service	Unit	Mission	Loss/damage	Day/night	Combat	Position	Cause
26	19 Jan	2219 Z	F-15E	US	USAF	4 TFW	INT	Lost	Night	Yes	Al Qiam	Radar SAM
28	19 Jan	1404 Z	F-16C	US	USAF	401 TFW	INT	Lost	Day	Yes	36 n.miles W Tallil	RF SAM
31	19 Jan	1557 Z	F-16C	US	USAF	401 TFW	INT	Lost	Day	Yes	Bagdad	RF SAM
150	27 Feb	1600 L	F-16C	US	USAF	50 TFW	BAI	Lost	Day	Yes	——	AAA
144	26 Feb	1230 Z	F-16A	US	USAF	174 TFW	CAS	Damage	Day	Yes	——	IR SAM
41	21 Jan	0900 Z	F-16C	US	USAF	388 TFW	INT	Damage	Day	Yes	Bagdad Nuclear Res Ctr	RF SAM
145	26 Feb	——	F-16C	US	USAF	388 TFW	INT	Damage	——	Yes	——	Unknown
151	27 Feb	1330 L	F-16C	US	USAF	388 TFW	INT	Damage	Day	Yes	——	IR SAM
30	19 Jan	0255 Z	F-4G	US	USAF	35 TFW	WW	Lost	Night	Yes	1 n.mile N KKMC	AAA
111	13 Feb	2239 Z	EF-111	US	USAF	20 TFW	EC	Lost	Night	Yes	30 n.miles NW Arar	DEA Other
12	17 Jan	0210 Z	F-111F	US	USAF	48 TFW	INT	Damage	Night	Yes	15 E Salmon Pac	AAA
17	17 Jan	0130 Z	F-111F	US	USAF	48 TFW	INT	Damage	——	Yes	1 n.mile S Balad Afld	AAA
18	17 Jan	0230 Z	F-111F	US	USAF	48 TFW	INT	Damage	Night	Yes	Unknown	AAA
16	17 Jan	——	B-52G	US	USAF	42 BW	INT	Damage	Night	Yes	——	IR SAM
54	26 Jan	0313 Z	B-52G	US	USAF	1708 PBW	INT	Damage	——	Yes	——	AAA
55	26 Jan	0313 Z	B-52G	US	USAF	1708 PBW	INT	Damage	——	Yes	——	AAA
143	26 Feb	1030 L	B-52G	US	USAF	379 BMW	INT	Damage	Day	Yes	——	ROR SAM
146	26 Feb	1029 L	B-52G	US	USAF	379 BMW	INT	Damage	Day	Yes	——	RF SAM
70	31 Jan	0325 Z	AC-130H	US	USAF	1 SOW	CAS	Lost	Day	Yes	12 n.miles N Ras Al Khafji	IR SAM
43	21 Jan	1900 Z	AC-130	US	USAF	1 SOW	INT	Damage	Night	Yes	——	IR SAM
22	18 Jan	0610 Z	OV-10	US	USMC	USMC	FAC	Lost	Day	Yes	14 n.miles NE Ras Al Mishab	IR SAM
141	25 Feb	0945 Z	OV-10	US	USMC	VMC 01	FAC	Lost	Day	Yes	S Kuwait	IR SAM
57	28 Jan	0707 Z	AV-8B	US	USMC	USMC	INT	Lost	Day	Yes	15 n.miles S Ahmadi	AAA
98	9 Feb	1304 Z	AV-8B	US	USMC	USMC	INT	Lost	Day	Yes	24 n.miles SW Kuwait City	IR SAM

(Continued)

Table 1.11 Combat data from Desert Storm 1991 (Ref. 26; Continued)

No.	Date	Time	Aircraft	Country	Service	Unit	Mission	Loss/damage	Day/night	Combat	Position	Cause
136	23 Feb	1930 Z	AV-8B	US	USMC	VMA 542	INT	Lost	Night	Yes	2 n.miles W Kuwait City	IR SAM
142	25 Feb	0700 Z	AV-8B	US	USMC	VMA 542	INT	Lost	Day	Yes	Ali Al Salem/Al Jaber Afld	IR SAM
148	27 Feb	0345 Z	AV-8B	US	USMC	VMA 331	INT	Lost	Day	Yes	30 n.miles NNE Kuwait City	AAA
106	12 Feb	——	AV-8B	US	USMC	VMA 542	——	Damage	——	Yes	——	AAA
138	23 Feb	——	AV-8B	US	USMC	VMA 311	——	Damage	——	Yes	——	AAA
6	17 Jan	2000 Z	A-6E	US	USN	USS Saratoga	INT	Lost	Night	Yes	10 n.miles SW H-3	RF SAM
20	18 Jan	1540 Z	A-6E	US	USN	USS Saratoga	INT	Lost	Day	Yes	Marsh-SW/Abadan-SE Basra	AAA
80	2 Feb	0840 Z	A-6E	US	USN	USS Roosvelt	INT	Lost	Day	Yes	20 n.miles E Kuwait City	AAA
132	21 Feb	——	A-6E	US	USMC	VMA 224	INT	Damage	——	Yes	——	AAA
9	17 Jan	——	A-6E	US	USN	USS Saratoga	INT	Damage	——	Yes	H3	AAA
40	21 Jan	——	A-6E	US	USN	——	——	Damage	——	Yes	——	——
104	11 Feb	——	A-6E	US	USN	USS Roosevelt	INT	Damage	Day	Yes	Faylaka Island	AAA
121	15 Feb	——	A-6E	US	USN	USN	——	Damage	——	Yes	——	Unknown
39	21 Jan	0354 Z	F-14	US	USN	USS Saratoga	OCA	Lost	Day	Yes	Al Asad (H2/H3)	RF SAM
4	17 Jan	0200 Z	F/A-18	US	USN	USS Saratoga	SEAD	Lost	Night	Yes	29 n.miles SE Bagdad	MIG 25
87	5 Feb	0610 Z	F/A-18	US	USN	USS Roosevelt	INT	Lost	Day	Yes	40 n.miles E Kuwait City	Unknown
100	9 Feb	——	F/A-18	US	USMC	——	INT	Damage	——	Yes	——	Poss IR SAM
129	21 Feb	——	F/A-18	US	USMC	VMFA 314	——	Damage	——	Yes	——	IR SAM
130	21 Feb	——	F/A-18	US	USMC	VMFA 121	——	Damage	——	Yes	——	IR SAM
133	21 Feb	——	F/A-18	US	USMC	VMFA 333	——	Damage	——	Yes	——	IR SAM
135	22 Feb	——	F/A-18	US	USMC	VMFA 451	——	Damage	——	Yes	——	IR SAM
139	24 Feb	——	F/A-18	US	USMC	VMFA 314	INT	Damage	——	Yes	——	IR SAM
140	24 Feb	——	F/A-18	US	USMC	VMFA 314	INT	Damage	——	Yes	——	IR SAM
152	27 Feb	——	F/A-18	US	USMC	——	FAC	Damage	——	Yes	——	Small Arms

(Continued)

Table 1.11 Combat data from Desert Storm 1991 (Ref. 26; Continued)

No.	Date	Time	Aircraft	Country	Service	Unit	Mission	Loss/damage	Day/night	Combat	Position	Cause
7	17 Jan	——	Jaguar	France	FAF	FAF	INT	Damage	——	Yes	——	AAA
8	17 Jan	——	Jaguar	France	FAF	FAF	INT	Damage	——	Yes	——	Unknown
10	17 Jan	——	Jaguar	France	FAF	FAF	INT	Damage	——	Yes	——	AAA
13	17 Jan	——	Jaguar	France	FAF	FAF	INT	Damage	——	Yes	——	IR SAM
3	17 Jan	1327 Z	A-4	KU	KAF	KAF	INT	Lost	Day	Yes	25 n.miles S Kuwait City	RF SAM
21	18 Jan	0001 Z	GR-1	Italy	IAF	IAF	INT	Lost	Night	Yes	20 n.miles NW Kuwait City	Unknown
2	17 Jan	1933 Z	GR-1	UK	RAF	No617SQDN	OCA	Lost	Night	Yes	8 n.miles NW Tallil	AAA
5	17 Jan	0632 Z	GR-1	UK	RAF	No15SQDN	OCA	Lost	Day	Yes	1 n.mile W Basra	RF SAM
24	19 Jan	0642 Z	GR-1	UK	RAF	No617SQDN	OCA	Lost	Day	Yes	51 n.miles SE Tallil	IR SAM
25	19 Jan	1700 Z	GR-1	UK	RAF	No15SQDN	OCA	Lost	Night	Yes	H-3	RF SAM
44	22 Jan	0200 Z	GR-1	UK	RAF	No16SQDN	INT	Lost	Night	Yes	N3306 E04002	Unknown
51	24 Jan	——	GR-1	UK	RAF	RAF	INT	Damage	——	Yes	——	RF SAM
94	7 Feb	——	GR-1	UK	RAF	No27SQDN	INT	Lost	——	Yes	——	RF SAM
114	14 Feb	0545 Z	GR-1	UK	RAF	No15SQDN	OCA	Lost	Day	Yes	40 n.miles NW Bagdad	RF SAM
27	19 Jan	——	GR-1	Saudi Arabia	RSAF	RSAF	INT	Lost	——	Yes	——	AAA
109	13 Feb	0630 Z	F-5	Saudi Arabia	RSAF	RSAF	INT	Lost	Day	Yes	50 n.miles W Wadi Al Khirk	Unknown

left the aircraft. The helicopter known as Super 61, on low orbit over the target area after delivering the troops, was hit in the tail boom by an RPG. The boom cracked, and the tail rotor stopped turning. This resulted in a loss of the sideways thrust that counters the torque caused by the main rotor. The helicopter began to spin and eventually crashed on its left side, with dark smoke in the cockpit but no flames or explosions. Both the pilot and copilot were killed by the crash. In the second loss incident Super 64, coming in to replace Super 61 in the orbit over the target area, took a hit by an RPG in the tail rotor gearbox. A chunk of the box flew off, and the lubrication fluid was lost. However, the Black Hawk tail rotor gearbox was designed to run dry for more than 30 min. Consequently, the helicopter continued to fly after the hit—for about a mile. Then the upper half of the vertical fin that supported the tail rotor broke off, and the helicopter nosed down and began to spin. Fighting gravity, the copilot was able to reach up and slow the spin rate by switching one engine to idle and the other to half power. As the helicopter approached the ground, it nosed up and crashed hard but flat into some flimsy tin huts. All four men onboard survived the crash. However, three were soon killed by the Somalis. Two Delta commandos who had come to their aid were also killed. The pilot was captured.

A Black Hawk carrying a search and rescue team to the aid of Super 61 was also hit by an RPG. However, this helicopter was not killed by the hit. The helicopter was hovering over the crash site, and two men were still on the ropes when the helicopter was struck on the left side of the fuselage behind the engines. The pilot managed to keep the helicopter in hover until the two men hit the ground. He then flew the three miles back to base, with holes in the main rotor blades and trailing a thin gray plume of smoke. They landed hard, but safely, and the crew walked away.

A second Black Hawk was also hit and damaged by an RPG.[45] The hit occurred on the right side of the helicopter directly behind the pilot's compartment. The airframe was severely cracked, the right landing gear strut collapsed, and three flight control rods were inoperative. However, the aircraft was able to return to the Mogadishu airport because of the redundancy and separation of the flight control rods. Both RPG-damaged helicopters were brought back to the U. S. for repairs. The search-and-rescue Black Hawk was repaired and returned to service. Larry Holcomb, deputy program executive officer for Army Aviation, "credits the aircraft's survivability to its extensive live-fire testing program over the last decade"[45] (Note 44).

When the fighting finally ended the following morning, 18 U. S. soldiers had been killed and 73 wounded by Somalis firing small arms and rocket-powered grenades. Two Black Hawk helicopters had been killed, and two more were severely damaged. Several other helicopters had received numerous small arms hits. The pilot of Super 64 was a prisoner. He was released 14 October 1993.

1.2.5.8 Operation Allied Force, Kosovo 1999. The Federal Republic of Yugoslavia (FRY) consists of the provinces of Serbia, Montenegro, and Kosovo. On 24 March 1999 NATO began a 78-day air campaign against the regime of Slobodan Milosevic, the President of the FRY, known as Operation Allied Force. The initial air strikes, phase I of the Operation, were conducted at night and above 15,000 ft against the FRY's integrated air defense systems in both Kosovo and Serbia. Phase II began on 27 March and extended the air attacks to the security and military infrastructure and the reinforcement forces. "During Allied Force, NATO aircraft flew approximately one-third the number of combat sorties (21,000) that were flown by coalition aircraft during Operation Desert Storm (69,000). However, the number of radar-guided surface-to-air missiles launched by the Serbs during Allied Force was almost the same as the number launched by the Iraqis during Desert Storm. As a consequence, the average aircrew participating in Operation Allied Force experienced a missile-launch rate three times that encountered by the average coalition aircrew during Desert Storm".[46]

Here is an excerpt from an interview with an F-16 pilot who flew in the operation:

> The Serbs launched over 500 radar-guided SAMs during the war. The threat was active and unpredictable. We could fly to one place one night and we would see a lot of SAMs and AAA. The next night, we might not see one shot in the same area. If they turned on a radar or fired a SAM, it moved immediately thereafter—whether it was an SA-3 or an SA-6. The AAA was all over the place. We never did figure out the Serbs SAM doctrine, or if they even followed a doctrine. Clear to the end of the war, they had enough radar-guided SAMs around to shoot at us in any part of the country.
>
> Getting shot at by SAMS—The best way I can describe the feeling of being shot at by a SAM is uncomfortable. No one got excited enough to scream on the radio or even talk real fast. We had to watch the airborne SAMs to make sure they were moving on the canopy, which meant they were not coming at us. By the time we figured out one was going away from us, the Serbs would often launch another one. These situations were made more difficult when more than one site was shooting SAMs. The SAMs fly for a good 30 or 40 s, which seems like forever. We never became complacent, but we gained experience.[47]

"Despite the larger number of radar-guided surface-to-air missiles fired at NATO aircraft flying over Serbia and Kosovo, the Yugoslavs achieved a much lower success rate than did the Iraqis."[46] Only two U. S. aircraft were killed by the Yugoslav air defense. On 27 March a U. S. F-117 stealth fighter was downed near Belgrade, and the pilot was rescued under very hazardous circumstances. (http://www.state.gov/www/regions/eur/kosovo_hp.html.) On 16 May a U. S. F-16 crashed inside the FRY as a result of engine damage caused by AAA fire, and the pilot was rescued. (http://www.fas.org/man/dod-101/ops/allied_force.htm, http://abcnews.go.com/onair/nightline/transcripts/n1000425_trans.html, and http://www.aircraft-survivability.com.) "Based on the ratio of combat losses to sorties, NATO aircrews participating in Operation Allied Force were six times less likely to be shot down than were coalition aircrews engaged in Operation Desert Storm. Overall, although Yugoslavia's integrated air defense system was very active against NATO aircraft during Operation Allied Force, NATO employment tactics rendered that system largely ineffective."[46]

A significant event of the operation, from a survivability perspective, was the decision by the Pentagon not to send the 24 AH-64 Apache helicopters in Albania into combat against the Serbian troops in Kosovo. Many published articles attributed this decision to the belief that the mission was too risky. Apparently, there was a strong desire not to lose any of the helicopters and flight personnel in combat or on noncombat missions, particularly after two Apaches crashed during separate training missions. Both the pilot and the copilot were killed in one of the mishaps (Note 45).

Go to Problems 1.2.21 to 1.2.25.

1.2.6 Lessons Learned

Learning Objective 1.2.5 Describe the lessons learned in combat regarding survivability.

History has shown that when a military aircraft has not been designed to survive in the environment it must operate in it will not be able to accomplish its mission with any regularity. The operational commanders will be forced to cancel raids, or to change tactics, or even to remove the aircraft from the area. Morale will become low, and the ability to conduct sustained air operations will be significantly reduced because of the lack of capable aircraft and crews. The reduction in the efficacy of air power because of the lack of aircraft survivability can have a disastrous effect on the campaign. The increasing intensity and sophistication of air defense systems will exacerbate this situation. Survivability cannot be ignored—its importance will not go away.

Go to Problem 1.2.26.

1.3 U. S. Military Survivability Policy, Instructions, Programs, and Organizations

The fundamental objective of the U. S. military survivability policy is to require that a thorough and systematic survivability program be conducted to ensure that effective survivability enhancement features are incorporated in current and future U. S. airborne weapon systems. This has been accomplished in different ways by each of the three departments within DoD. However, all departments base their programs on the DoD Directive 5000.1 and Regulation 5000.2-R. These 5000 Series documents and the individual service programs are very briefly described in the following subsections. These documents can be accessed using the *Defense Acquisition Deskbook* described in Sec. 1.3.2.

*1.3.1 DoD 5000 Series**

Learning Objective 1.3.1 Describe the DoD 5000 Series requirements for survivability.

The DoD 5000 Series consists of DoD Directive 5000.1, Defense Acquisition, and a number of Instructions and Regulations (Note 46).

*The DoD 5000 Series was cancelled in late 2002. Revised versions of DoD Directive 5000.1 and Instruction 5000.2 are expected in early 2003. DoD 5000.2-R has been redesignated as an Interim Guidebook.

1.3.1.1 DoD Directive 5000.1. DoD Directive 5000.1 provides the guiding principles for acquiring systems and material that satisfy the operational user's needs. According to the policy statement in the February 1991 version, "survivability is a critical system characteristic, that is, a characteristic of the system that has a critical role in the effectiveness of the system. Furthermore, the survivability of all systems that must perform critical functions in a man-made hostile environment shall be an essential consideration during the acquisition life cycle of all programs, including developmental and nondevelopmental programs. Survivability from all threats found in the various levels of conflict shall be considered. This includes conventional; electronic; initial nuclear weapon effects; nuclear, biological and chemical contamination; advanced threats, such as high-power microwave, kinetic energy weapons, and directed energy weapons; and terrorism or sabotage."

The 2001 version is considerably more general and does not make any specific statements regarding survivability. The directive does state that acquisition programs shall be managed to optimize total system performance and minimize the cost of ownership. The total system includes not just the prime mission equipment, but the people who operate and maintain the system; how the system operates in its intended operational environment; and how the system will be able to respond to any effects unique to that environment [such as NBC or information warfare (IW)]. Of interest to the survivability discipline is the operation of the system in a man-made hostile environment.

1.3.1.2 DoDI 5000.2 and DoDR 5000.2-R. DoD Instruction 5000.2, Operation of the Defense Acquisition System, "establishes a simplified and flexible management framework for translating mission needs and technological opportunities, based on validated mission needs and requirements, into stable, affordable, and well-managed acquisition programs that include weapon systems and automated information systems". It also "establishes a general approach for managing acquisition programs while acknowledging that every technology project and acquisition program is unique and that any particular project or program, particularly nonmajor programs, might not need to follow the entire process." The event-oriented acquisition process described in DoDI 5000.2 is based upon the milestone concept, wherein the process is structured in discrete phases separated by major decision points called milestones. The milestones and phases are shown in Fig. 1.17, which comes from DoDI 5000.2, Para. 4.7.1.10, Fig. F1. (http://web1.deskbook.osd.mil/5000model.asp.)

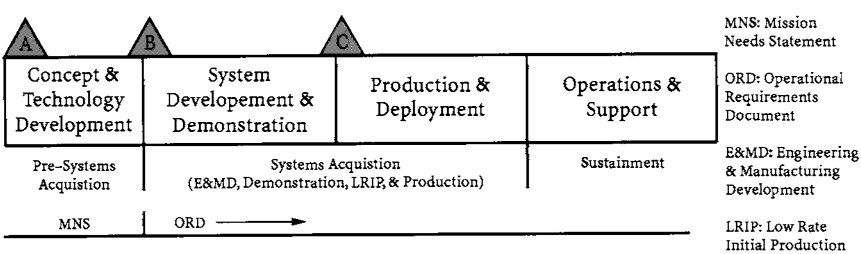


Fig. 1.17 Acquisition milestones and phases.

DoD Regulation 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs, specifies mandatory policies and procedures for MDAPS. According to Section C5.2.3.5.12 of DoD 5000.2-R (Program Design, Systems Engineering, Survivability),

> Unless waived by the MDA (Major Decision Authority), mission-critical systems, including crew, regardless of the ACAT (Acquisition Category), shall be survivable to the threat levels anticipated in their projected operating environment as portrayed in the System Threat Assessment Report. Design and testing shall ensure that the system and crew can withstand man-made hostile environments without the crew suffering acute chronic illness, disability, or death.

According to Section C5.2.3.5.12.1 "The Program Manager (PM) shall fully assess system and crew survivability against all anticipated threats at all levels of conflict, early in the program, but in no case later than entering system demonstration or equivalent. This assessment shall also consider fratricide and detection." According to Section C5.2.3.5.12.2,

> The PM shall establish and maintain a survivability program throughout the system life cycle to attain overall program objectives. The program shall stress early investment in survivability enhancement efforts that improve system operational readiness and mission effectiveness by:
>
> C5.2.3.5.12.2.1. Providing threat avoidance capabilities (low susceptibility);
>
> C5.2.3.5.12.2.2. Incorporating hardening and threat tolerance features in system design (low vulnerability);
>
> C5.2.3.5.12.2.3. Providing design features to reduce personnel casualties resulting from damage to or loss of the aircraft (casualty reduction);
>
> C5.2.3.5.12.2.4. Maximizing wartime availability and sortie rates via operationally compatible threat damage tolerance and rapid reconstitution (repairability) features;
>
> C5.2.3.5.12.2.5. Minimizing survivability program impact on overall program cost and schedule; and,
>
> C5.2.3.5.12.2.6. Ensuring protection countermeasures and systems security applications are defined for critical component's vulnerability to validated threats for systems survivability, including conventional or nuclear advanced technology weapons; nuclear, biological, or chemical contamination; and EW threats.

Appendix II, Operational Requirements Document (ORD) Mandatory Procedures and Format, provides some guidance for survivability requirements in the ORD. According to the document, "each concept proposed at Milestone A for continued evaluation in later phases shall be described in an initial ORD in terms that define the system capabilities needed to satisfy the mission need. The operational performance parameters in the initial ORD shall be tailored to the concept (e.g., satellite, aircraft, ship, missile, or weapon, etc.) and reflect system-level performance capabilities such as range, probability of kill, platform survivability, operational availability, etc. Objectives shall also be established for each parameter and shall represent a measurable, beneficial increment in operational capability or operations and support."

Another major aspect of survivability covered in DoDI 5000.2-R is the Live Fire Test and Evaluation (LFT&E) program. According to Sec. 3.8 (Test and Evaluation, Live Fire Test and Evaluation), LFT&E must be conducted on a covered system before it can proceed beyond low-rate initial production (LRIP). A covered system is the DoD term for any system that is required to undergo LFT&E. The term includes any vehicle, weapon platform, or conventional weapon system that includes features designed to provide some degree of protection to users in combat and that is an ACAT I or II program (Note 47). The LFT&E program is described in Section 6, Testing for Survivability, in this chapter.

The DoD 5000 Series and the acquisition process are contained in the Defense Acquisition Deskbook, which is described next.

Go to Problems 1.3.1 to 1.3.4.

*1.3.2 Defense Acquisition Deskbook**

Learning	**1.3.2**	**Describe the DoD Acquisition Deskbook.**
Objectives	**1.3.3**	**Describe the major survivability considerations at each acquisition milestone.**

The Defense Acquisition Deskbook (DAD) is an automated acquisition reference tool sponsored by the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics [OUSD(AT&L)], which provides DoD acquisition information for all services across all functional disciplines. The DAD concept provides the opportunity to support a basic change in the acquisition culture. By organizing the information in the Deskbook's Reference Information System into mandatory direction, discretionary practices, and advice categories, the DAD sends a clear message to the acquisition community that discretion and the use of judgment is a mainstream element of the DoD business process.

The DAD provides an easy-to-use, automated information retrieval system and real-time access to the most current acquisition information. The legacy DAD is available on a CD, or it can be accessed online at http://deskbook.dau.mil/legacydeskbook.asp.

It has become a primary acquisition reference tool for the entire DoD acquisition workforce, a means to integrate disciplines, and a vehicle to communicate acquisition reform. Initially, the system included DoD directives appropriate to the Air Force, Army, Navy, Marine Corps, Defense Logistics Agency (DLA), and

*The Defense Acquisition Deskbook was replaced in late 2002 by the Acquisition Knowledge Sharing System (AKSS), located online at http://deskbook.dau.mil/jsp/default.jsp. The deskbook is now referred to as the legacy Deskbook.

Special Operations Command (SOCOM). As the system evolves, more service and agency specific information is incorporated.

Of particular interest to the survivability community is Deskbook Topic 2.6.6, Survivability. (http://www.deskbook.osd.mil/irp/266.asp.) The guidelines are similar to the survivability program described in MIL-HDBK-2069, which is described in Sec. 1.3.4, and at one time the list of survivability considerations prior to each milestone listed in Table 1.12 were a part of the Deskbook.

Go to Problems 1.3.5 to 1.3.6.

1.3.3 U. S. Military Department Acquisition Programs

Learning Objective	**1.3.4**	**Describe the major policies, procedures, and organizations of the three U. S. military departments.**

1.3.3.1 Army. The Acquisition Streamlining initiative within the Department of Defense, beginning with the issuance of DoD Directive 5000.1, Defense Acquisition, and DoD Instruction 5000.2, Defense Acquisition Management Policies and Procedures, both dated 23 February 1991, has resulted in substantial changes in the guidance and substance of the management of acquisition programs. This, of course, includes the survivability discipline in the U. S. Army.

Policy guidance has been streamlined. To implement DoDI 5000.2, U. S. Army Materiel Command (AMC) Army Regulation (AR) 70-3, Survivability, was canceled in October 1993. In addition, Army Regulations AR 70-40, Nuclear Survivability of Army Materiel, 30 October 1984, and AR 70-71, Nuclear, Biological, and Chemical Contamination Survivability of Army Materiel, 1 April 1984, have been superseded by AR 70-75, Survivability of Army Personnel and Materiel, 10 January 1995. AR 70-75 specifically implements Part 6 F, Survivability of DoDI 5000.2 (1991). It prescribes survivability policies, responsibilities, and procedures for the sustainment of operational effectiveness and warfighting capability throughout the life cycle of systems, personnel, equipment, and support. Use of the term Survivability in AR 70-75 includes both soldiers and equipment.

In the Army the Combat Developer (CBTDEV) and Materiel Developer (MATDEV) share responsibility for the survivability of Army personnel and materiel. AR 70-75 and Department of the Army Pamphlet 70-3, Army Acquisition Procedures, 28 February 1995, outline procedures that enable CBTDEVs and MATDEVs to achieve their survivability goals. No fewer than 17 Army agencies are assigned responsibilities for survivability, reflecting a broad spectrum of functions from the program executive officers (PEOs) to the deputy chief of staff (Logistics) (DCSLOG) to the Army surgeon general.

In 1995 the Army began the consolidation of all test and evaluation (T&E) functions under one independent command, separate from the Army Materiel Command. The first step in 1996 was the forming of the Evaluation Analysis Center (EAC) at Aberdeen Proving Ground, Maryland. The independent evaluator mission and personnel were transferred to the EAC from the Army Material Systems

Table 1.12 Survivability considerations prior to each milestone

Milestone	Survivability considerations
Approval to conduct concept studies	The expected operational environment for each threat (i.e., conventional; electronic; initial nuclear weapons effects; advanced technology; nuclear, biological, and chemical contamination; and terrorism, or sabotage) should be highlighted and discussed in the mission need statement (MNS).
A: Approval to begin concept and technology development	The system threat assessment report (STAR) should specifically address the threat categories, making specific statements for or against their expected likelihood. Initial survivability objectives should have been defined and validation criteria established. The objectives should be identified in the operational requirements document (ORD). Key objectives should be included in the concept baseline. Critical survivability characteristics and issues that require test and evaluation should have been identified and included in the test and evaluation master plan (TEMP). Critical survivability technology shortfalls should be identified and research requirements established. Preliminary facilities characteristics required to support unique survivability characteristics should have been identified, to be tracked through the integrated logistics support plan (ILSP).
B: Approval to begin system development and demonstration	Critical survivability characteristics and issues that require test and evaluation should have been identified and included in the TEMP. Key survivability objectives are included in the development baseline. The system specification and integrated logistics support plan should incorporate the survivability objectives. If hardening is used as a method for achieving survivability, development of hardness assurance, maintenance, and surveillance programs should be included in the ILSP. The nuclear, biological, and chemical contamination assurance and maintenance plans should include information regarding decontaminability and compatibility. Survivability issues are addressed in the integrated program summary.
C: Approval to begin production and deployment	An assessment of how well the survivability objectives have been met has been completed, and the results are included in the beyond low-rate initial production report. All survivability issues have been resolved. Key survivability objectives are included in the production baseline. If hardening is used as a method of achieving survivability, the hardness assurance program should have been developed and made ready for implementation. For nuclear, biological, and chemical contamination (NBCC), the assurance program also included decontaminability and compatibility. Hardness maintenance and surveillance plans should have been completed with the exception of data from the hardness assurance program.

Analysis Agency (AMSAA), and additional evaluation related personnel were transferred from the Test and Evaluation Command (TECOM) and from the Army Research Lab/Survivability and Lethality Analysis Division (ARL/SLAD). As a result, all developmental evaluation functions, including live fire test and evaluation and survivability, were removed from the Army Materiel Command and transferred to the Operational Test and Evaluation Command [OPTEC already contained the operational testers (TEXCOM) and the operational evaluators (OEC)].

In 1999 additional consolidation occurred. TECOM was taken from AMC and was placed under OPTEC and was renamed the Developmental Test Command (DTC). This combined all operational and developmental testers and all operational and developmental evaluators in one command. OPTEC was then renamed the Army Test and Evaluation Command (ATEC), and the operational and developmental evaluators were combined and renamed the Army Evaluation Center (AEC). The current status is that all testing and all evaluation are now under ATEC. ATEC's mission is planning, conducting, and reporting developmental tests, independent operational tests, experiments, and integrated continuous evaluations of Army, joint, and multiservice systems and concepts in support of the combat, materiel, and training development processes. ATEC also designs and develops methodologies and test instrumentation; performs safety verifications; operates and modernizes assigned installations, ranges and test centers.

As the Army's independent evaluator, AEC provides integrated evaluations of the effectiveness, suitability, and survivability of Army, selected multiservice, and joint materiel type classification and materiel release decisions. AEC conducts the Army Continuous Evaluation Program and Live Fire Evaluation Program. AEC/ATEC has the responsibility of conducting all Army Live Fire T&E and survivability evaluations for all Army developmental equipment, including aviation programs. These evaluations are the responsibility of the Survivability Directorate of AEC, which is located at Aberdeen Proving Ground, Meryland. ARL/SLAD and others provide inputs to support these evaluations. The ATEC system evaluation reports (SERs) have a major impact on milestone decisions, including decisions affecting fielding. The live fire and survivability evaluations are contained within the SERs that are forwarded through the Department of the Army to OSD/DOT&E.

Currently, the principal agencies responsible for the Army aviation survivability discipline, from the MATDEV view, include the ARL/SLAD and the Joint Project Office (JPO) for Aircraft Survivability Equipment (ASE) and Advanced Threat Infrared Countermeasures (ATIRCM)/Common Missile Warning System (CMWS).

Army Pamphlet 70-3 states that SLAD is a primary focal point for technical survivability support. SLAD serves as the principal activity in the Army for determining the survivability/lethality and vulnerability (SLV) of Army systems to the full spectrum of battlefield threats. SLAD's function is to conduct necessary investigations, simulations, lab/field experiments, and analyses to quantify the SLV of Army and select foreign combat, combat support, and combat service support systems that can encounter electronic warfare, conventional ballistic, directed energy, and nuclear, biological, and chemical threats.

Under the SLAD concept of operations, SLV analyses are performed on specific Army systems using an integrated analysis team concept. For each system addressed, a team composed of technical experts from each SLAD division/technical area, as well as experts as appropriate from outside of SLAD, develop and execute detailed analysis plans in consonance with the principal member (PM)/Army community to determine the SLV of the system. Solutions are proposed if significant deficiencies are found.

In addition to supporting the development of Army systems, SLAD has major programs with the Army Battle Labs and Advanced Technology Demonstrations (ATDs). A significant aspect of SLAD's mission is the development of methodologies, tools, and techniques vital for maintaining and enhancing SLAD's SLV analysis capability. Based on AR 602-2, Manpower and Personnel Integration (MANPRINT) in the System Acquisition Process, 7 October 1994, SLAD is charged with preparing the Soldier Survivability Domain report for major systems' MANPRINT assessments.

SLAD also provides support to the PEOs and PMs by monitoring advanced technology programs that are being managed by the research, development, and engineering centers (RDECs) and the PEOs/PMs for potential SLV support. SLAD attends RDEC reviews and maintains an awareness of systems that are about to enter the acquisition cycle. It provides cost-shared SLV support based on a compromise between the needs of the PEOs/PMs, Department of the Army decision-maker priorities, and available resources. The web site address for the SLAD is http://www.arl.army.mil/slad/.

The PM-ASE/ATIRCM/CMWS is appointed by the PEO, aviation, to perform as the Army centralized manager for the assigned executive program element. The PM-ASE/ATIRCM/CMWS reports directly to the Army PEO and has the responsibility to provide direction and guidance for development, acquisition, testing, product improvement, fielding, and sustainment of Army aircraft survivability equipment systems. The mission of the JPO is to develop a family of systems designed to counter threats in the radio, infrared, and laser frequencies. The PM serves as the Army representative on the JTCG/AS Principal Member Steering Group (PMSG).[48]

1.3.3.2 Navy. In May 1974 the Chief of Naval Materiel (CNM) Adm. I. C. Kidd issued a policy statement that established CNM policy for survivability requirements in naval weapon systems. This policy memorandum stated the following:

> Survivability should be treated as follows during the Weapon System Acquisition process:
>
> 1) Threat analyses should be conducted and firm survivability objectives established during the conceptual phase of the acquisition process.
>
> 2) It is essential that both survivability requirements and measurement and validation criteria be specified upon entry into full-scale development; these requirements must be included in the contract.
>
> 3) The request for authorization to proceed into production must specify the survivability requirements to be imposed and the means for measuring their attainment.
>
> 4) Weapon systems should be tested against expected threat weapons whenever practicable.

> Operational weapon systems should be assessed regularly to ensure that changes to the threat environment are considered and advantage is taken of state-of-the-art advances in survivability enhancement.
> I expect each of you to ensure that survivability is fully considered in development proposals and that they are properly reflected in contracts.

NAVMAT Instruction 3900.16, Combat Survivability of Naval Weapon Systems, 27 November 1979, was the first policy statement within the U. S. Navy that established policies, procedures, and responsibilities within the Naval Materiel Command. The goal of this instruction was to improve achievement of combat survivability in naval weapons systems. It directed a vigorous program of research and development to develop concepts, procedures, materials, designs, and hardware and software for survivability enhancement of mission essential weapons systems (MEWS). It directed that survivability requirements be included during the earliest conceptual formulation of MEWS and become increasingly specific and comprehensive as the acquisition process progresses.

The current Naval Air Systems Command (NAVAIR) policy is provided in NAVAIR instruction 13040.1, Naval Air Survivability Program, 10 August 1989. The purpose of the instruction is to establish the policies, responsibilities, and organizational relationships for the Naval Air Combat Survivability Program (NACSP) and to implement specific requirements. The NACSP is comprised of the Weapon System Survivability Program to enhance the survivability of current and future NAVAIR weapon systems and the Survivability Research and Development (R&D) Program that develops hardware and methodology for use on NAVAIR weapon system survivability programs. NACSP management and coordination responsibilities reside with the NAVAIR Survivability Division (AIR-4.1.8).

The NAVAIR Survivability Division is a part of the Naval Aviation Systems Team (TEAM). The TEAM is comprised of six organizations working together as a team.[49] The Survivability Division personnel are physically located at, and organizationally attached to, two sites: the Naval Air Warfare Center—Aircraft Division, Patuxent River (NAWCADPAX) and the Naval Air Warfare Center—Weapons Division, China Lake (NAWCWDCL). Personnel located at the Naval Surface Warfare Center at Crane (NSWC—Crane) are also involved in aircraft survivability technology development. The NAWCWDCL's web site is http://www.nawcwpns.navy.mil/r1/Surviv.htm.

The specific areas of interest to the Division are weapon systems vulnerability reduction, weapon systems susceptibility reduction, personnel protection, countermeasures, CBR protection, and defense protection.

It is the policy of NAVAIR for all combat weapon systems that the following is true:

1) A survivability program will be established for each combat weapon system.

2) A mission-threat analysis will be conducted and survivability objectives established during the conceptual phase of the acquisition process in dialog with the Office of the Chief of Naval Operations (OPNAV) leading to the definition of the operational requirement (OR).

3) The mission-threat analysis will be revised as necessary to reflect significant changes in the threat, the weapon system, the weapon system employment

concept, or the operational requirement. The survivability objectives will be revised accordingly.

4) The OR and survivability objectives will be translated into survivability requirements for the Systems Development and Demonstration (SDD) program. The survivability requirements will be first tier specification requirements, included in appropriate development plans, the detailed weapon system specification, test and evaluation master plans (TEMPs) (Note 48), and other acquisition documents, and reflected in contracts.

5) The survivability assessment process will begin with the earliest OR and the earliest conceptual stages of development, concomitant with the establishment of the OR, and will be revised in depth and scope as appropriate through the engineering development stage of the combat weapon system. Requirements for a survivability test and evaluation will be included in the TEMP with necessary measurement and validation criteria, which includes the congressionally directed Live Fire Test Law.

6) The request for approval for full-rate or low-rate initial production must specify the survivability requirements that have been imposed and the means for ensuring that these requirements are met and maintained during production.

7) The weapon system and the survivability enhancement technology/hardware incorporated will be tested during development test and evaluation and operational test and evaluation against expected threat weapons and CBR stimulants in as realistic a scenario as practical. Ballistic tests and analyses representative of realistic combat operations which meet the intent of the LFT Law will be conducted to determine the weapon system's vulnerability.

8) Operational weapon systems should be assessed periodically to ensure that changes to the threat environment, the mission or design is considered, and advantage is taken of state-of-the-art advances in survivability enhancement technology.

In general, the survivability division responsibilities include the following: 1) providing quality life cycle survivability program management and engineering support for assigned customers; 2) ensuring that survivability is addressed to the level required for all air vehicle systems under cognizance of the Naval Aviation Systems Team (including Joint Programs); 3) translating mission need statements and operational requirement document survivability requirements/objectives (analyses, test, and design requirements) during all phases of the acquisition process; 4) developing program documentation (e.g., specifications, statement of work, test and evaluation master plan, contract data requirements list, and request for proposal requirements); 5) developing and implementing survivability engineering, analysis, modeling and simulation, databases, research and development, and testing processes for concept evaluation, specification definition, and design verification; 6) developing, verifying, and validating analytical and testing methods to support survivability assessments; 7) performing survivability (susceptibility and vulnerability) and related analyses of air vehicle systems in early conceptual stages and throughout the acquisition life cycle; 8) developing, operating, and maintaining competency facilities; 9) conducting RDT&E for survivability enhancement (i.e., vulnerability reduction and susceptibility reduction) technologies through the Naval Air Combat Survivability Program; 10) providing certification of survivability competency personnel; 11) participating in foreign military sales reviews; 12) participating in the review of DoD-sponsored industry internal research and development efforts; 13) providing joint service interface and conducting joint service survivability efforts through the JTCG/AS central office representative and various JTCG/AS subcommittees; and 14) supporting survivability education programs at the Naval Postgraduate School and within the Naval Aviation Systems Team.

1.3.3.3 Air Force. Air Force Policy Directive 62-2, System Survivability,[50] and Air Force Instruction 62-201, System Survivability,[51] are the current documents that prescribe the policy and procedures for the Air Force System Survivability Program. According to AFPD 62-2:

> 1) If the United States is to meet its national security objectives, the Air Force must be able to carry out its missions in manmade hostile environments. Systems that can survive and operate in such environments help deter and fight wars. Therefore, this directive establishes policies to ensure the Air Force makes survivability an essential consideration for all its systems.
>
> 2) The Air Force will establish survivability requirements and performance parameters for a system's entire life cycle, based initially on projected threats and how they constrain the system's operation. If survivability is necessary, it will be a critical system characteristic. The Air Force will not postpone system survivability during acquisition or design, nor defer it as a pre-planned product improvement.
>
> 3) If a system uses hardening to survive, the Air Force will have programs for hardness assurance, maintenance, and surveillance (HAMS).
>
> 4) Program management directives will specify actions to build in and maintain survivability throughout the life of a system. Although the Air Force may trade hardness for other system characteristics to improve a system's operation, changes will not degrade the system's overall survivability, unless requirements for survivability have already been lowered.
>
> 5) The Air Force will periodically assess system survivability through test and analysis to make sure the system can complete its specified mission.

According to AFI 62-201,[50] here are the expectations in the Office of the Secretary of the Air Force:

> 1) The Assistant Secretary of the Air Force for Acquisition (SAF/AQ) oversees system survivability for the Air Force, establishes survivability policy, and directs the research, development, and acquisition of survivable systems.
>
> 2) The Director of Long-Range Power Projection, Special Operations Forces, Airlift and Training Programs (SAF/AQQ) monitors the Air Force system survivability program and chairs the Survivability Review Group (SRG).
>
> 3) The Long-Range Power Projection Division (SAF/AQQS) oversees the Air Force system survivability program and serves as the office of primary responsibility (OPR) for AFPD 62-2 and this AFI.
>
> 4) The Survivability Review Group meets as necessary to review and resolve issues related to Air Force survivability policy; survivability requirements, parameters, or status of specific systems; and Air Force-wide status assessments of systems with survivability requirements. It forwards the Air Force-wide assessments to appropriate 2-letter organizations for review or necessary actions.

5) The SAF/AQ Mission Area Directors monitor the survivability status of their assigned systems, help users define reasonable survivability parameters for their systems and monitor all aspects of survivability throughout the system's life cycle, support the Air Force Systems Acquisition Review Council (AFSARC) or Defense Acquisition Board (DAB), and appoint a representative to the SRG. If required, the Directors oversee a specific survivability threat category, such as electronic warfare, nuclear effects, or nuclear, biological, and chemical (NBC) contamination.

6) The Headquarters (HQ) USAF Survivability OPRs act as HQ USAF points-of-contact for system survivability issues related to the threats for which they are responsible.

The following are the expectations according to AFI 62-201 on the Air staff:

1) The Deputy Chief of Staff for Plans and Operations (AF/XO) handles operational issues concerning survivability and ensures that the Air Force identifies and meets survivability requirements.

2) The Directorate for Operational Requirements (AF/XOR) reviews, evaluates, and manages system requirement documents; serves as the lead directorate for operational survivability; determines operational survivability requirements based on concepts of operation, test and evaluation, procedures for the employment of a system, and appraisals including strategies necessary to survive and perform in hostile environments.

3) The Deputy Chief of Staff for Logistics (AF/LG) oversees hardness assurance, maintenance, and surveillance (HAMS) programs; establishes policy, procedures, and programs to maintain the survivability and battle damage repairability of Air Force systems other than facilities and communications.

4) The Directorate of Test and Evaluation (AF/TE) develops survivability-related test and evaluation policy, programs, and resources; ensures that all requirements are testable; and ensures that responsible commands conduct required tests and evaluations of system survivability.

Go to Problem 1.3.7.

1.3.4 DoD MIL-HDBK-2069A

Learning Objective **1.3.5 Describe MIL-HDBK-2069A, including the survivability program, program tasks, and system survivability requirements.**

Acquisition programs for U. S. military aircraft prior to 1994 relied upon a large body of formal DoD specifications and standards that had evolved over many years to ensure an acceptable product.[52] Formal documentation of the requirements for a survivability program began in 1974, when the Navy issued Aeronautical Requirement AR-107, Navy Aircraft Survivability/Vulnerability (Nuclear and Non-nuclear). This document was superseded in 1977 by the USN MIL-STD-2072(AS), Military Standard: Survivability, Aircraft; Establishment and Conduct of Programs for. In 1981 the U. S. Department of Defense issued MIL-STD-2069, Requirements for Aircraft Nonnuclear Survivability Program, and the U. S. Air

Force followed in 1986 with MIL-STD-1799 (USAF), Survivability, Aeronautical Systems (for Combat Mission Effectiveness). These last two documents were prepared in recognition of the need for a standardized systems approach to improving the survivability of military aircraft. In 1994 the existing DoD specifications and standards were cancelled by the Secretary of Defense in an attempt to reduce the cost of procuring military aircraft (Note 37). As a result of this cancellation, the two military standards for survivability, MIL-STD-2069 and MIL-STD-1799, were combined into one DoD Handbook, MIL-HDBK-2069A, Aircraft Survivability.

DoD MIL-HDBK-2069A provides the guidance and criteria for establishing survivability requirements and conducting survivability plans and programs throughout the system life cycle for fixed- and variable-wing aircraft, helicopters, and remotely piloted vehicles. It applies to combat and combat support aircraft expected to be exposed to nonnuclear (i.e., conventional, chemical, biological, and directed energy) and nuclear threat environments. It is applicable to new and existing major and supporting nonmajor system acquisition programs, including relevant strategic and nonstrategic systems. This handbook also applies to aircraft systems designated as requiring nuclear survivability, nuclear survivability high-altitude electromagnetic pulse only, and nuclear, biological, and chemical contamination survivability in accordance with DoDD 4245.4, Acquisition of Nuclear Survivability Systems, 1987; DoDD 3150.3, Nuclear Force Security and Survivability, 1994 (http://www.dtic.mil/whs/directives/corres/html/31503.htm); and DoDI 4245.13 (cancelled), Design and Acquisition of Nuclear, Biological, and Chemical (NBC) Contamination-Survivable Systems, 1987.

The HDBK should be used as the basis for identifying the survivability program tasks and requirements to be included in statements of work, system and item specifications, and contract data requirements that form parts of system acquisition contracts or requests for proposal. The general guidance of MIL-HDBK-2069 is included in the following paragraphs because of its applicability to any survivability program.

1.3.4.1 Survivability program. An effective survivability program should be established and maintained throughout the system life cycle. The program should be structured to meet system effectiveness objectives identified in documents such as the mission need statement (Note 49), the test and evaluation master plan, the analysis of alternatives report (Note 50), and the program baseline (Note 51). The survivability program will be planned, integrated, and implemented in coordination with other system design, development, test, production, support, and operational aspects of the life cycle to minimize its impact on overall program cost and schedule and to accomplish specified survivability program tasks and requirements in a cost-effective and timely manner. Table 1.12 presents the major activities of a survivability program throughout the acquisition and operational phases.

Quantitative survivability requirements. Quantitative survivability requirements for the system, major subsystem, and applicable equipment should be included in the system and item specifications. System susceptibility and vulnerability requirements will be specified contractually and should be verifiable throughout the life cycle. Care must be taken to ensure that the survivability program optimizes overall system survivability, particularly when both nonnuclear and nuclear threats are considered.

Requirements verification. Specifications for susceptibility and vulnerability requirements should include the method used to verify that the requirements have been satisfied. An optimum mix of analyses, simulation, and testing will be a major issue in the planning and implementation of the survivability program. A clear audit trail of survivability design information and verification methods and results should be documented throughout the system life cycle to fulfill requirements for verification of survivability maintenance and surveillance capability.

1.3.4.2 Survivability program organization. The contracting activity will specify that contractor management, staffing, and organizational requirements necessary to implement and conduct the survivability program are clearly defined. The survivability organization should be integrated with all relevant design, support, production, and program management activities to ensure that system survivability requirements are effectively incorporated into the aircraft design.

1.3.4.3 Program reviews. Program reviews should be planned and scheduled as specified in contractual documents and the survivability program plan to permit the contractor, subcontractor(s), and government representatives to periodically examine the status of the survivability program.

1.3.4.4 Program tasks. The survivability program should include the 14 tasks listed here: 1) survivability program plan, which requires preparing and maintaining a plan that will permit an accomplishment of all program tasks and requirements for which the contractor is responsible; 2) survivability assurance program plan, which requires preparing and maintaining a survivability assurance plan to ensure that required survivability design characteristics are preserved throughout the development and production phases; 3) survivability maintenance/surveillance (M/S) plan, which requires developing and maintaining a plan to ensure that survivability design characteristics of a deployed system are maintained and preserved throughout its operational life; 4) mission-threat encounter analysis, which is described in Chapter 3; 5) flight and mission critical functions analysis, which is described in Chapter 5; 6) failure mode, effects, and criticality analysis, which is described in Chapter 5; 7) damage mode and effects analysis, which is described in Chapter 5; 8) computerized target description, which is described in Chapter 5; 9) Aircraft vulnerability analysis, which is described in Chapter 5; 10) susceptibility analysis, which is described in Chapter 4; 11) survivability analysis, which is described in Chapter 6; 12) survivability enhancement trade studies, which are described in Chapter 6; 13) combat damage repair analysis, which is described in Chapter 1; and 14) survivability design documentation, which requires documenting all survivability design features, including all associated analyses, trade studies, methodologies, test results and databases, starting with the development phase and updating as necessary, to provide a clear audit trail throughout the system's life cycle. These tasks are applicable to any phase of system acquisition where requirements for survivability are specified and should be tailored to the specific aircraft system and associated operational requirements. Most of these tasks are described in detail in the chapters indicated.

1.3.4.5 System survivability requirements. The basic survivability requirements given in MIL-HDBK-2069 are reprinted here:

> 1) *Susceptibility*—the contracting activity should establish design and configuration requirements which specify acceptable levels of the probabilities of aircraft detection, encounter, or damage by the specified threat systems. These requirements should be based on the results of the mission-threat analyses, survivability trade studies, and tests. Detection avoidance, in terms of aircraft signature levels, and threat avoidance and suppression should be quantified and be included in the contractual requirements. The threat avoidance and suppression requirements should include the identification of the specific equipment for 1) onboard threat warning; 2) detection of nuclear and laser radiation; 3) detection of chemical/biological contamination; 4) onboard ECM; 5) flares, chaff, and decoys; 6) lethal defense suppression capabilities; and 7) the appropriate tactics, maneuvers, and aircraft flight performance parameters.
>
> 2) *Vulnerability*—the contracting activity should establish design and configuration requirements which provide safe flight and recovery capability of the aircraft and which maximize the probability of mission completion, after exposure to the specified hostile environment. Secondary effects caused by the threat damage mechanisms (e.g., burning fuel, fire caused by engine damage, nuclear thermal radiation effects on crew members, etc.) should be prevented or contained in all critical subsystems where failure to do so would cause loss of the aircraft. The contracting activity should require 1) arrangement of the design configuration that results in the highest possible practical level of hardening protection with the least penalty (e.g., cost, weight, reduction in aircraft flight performance, etc.); 2) inclusion of detailed requirements for specified levels of vulnerability for each critical subsystem in the system and item specifications; and 3) specification of battle damage repairability requirements.
>
> 3) *Verification and demonstration*—a quality assurance (QA) requirement should be included in the system specification for each survivability-related requirement. The QA requirement establishes the methods and criteria by which required levels of susceptibility, vulnerability, and battle damage repairability can be verified or demonstrated. The contracting activity should specify the mix of analysis, test, and inspection that will be used by the contractor to satisfy verification or demonstration of compliance with the stated requirements. Systems threatened by conventional weapons must comply with the 1987 Live Fire Test Law. For systems with nuclear survivability requirements, satisfaction of the survivability criteria should be determined in preparation for Milestone C in accordance with DoDD 4245.4.

These requirements should be included in system and end item specifications, requests for proposal, statements of work, contract data requirements lists, and other contractual documents. The formulation of these requirements is dependent on the system program phase and on the availability of analytical results upon which to base the requirements. For the concept exploration and program definition phases quantitative susceptibility and vulnerability requirements for the system and its subsystems should be generated, using trade studies, for effective solutions to the system's survivability in a combat environment. For the full-scale development and later phases the survivability requirements should be in the form of signature levels, countermeasures capabilities, threat effects tolerance levels, and other criteria that are achievable, cost-effective, and measurable. It is essential that the survivability requirements be realistically formulated and stated in ways that make them meaningful to the designer, permit freedom of design choices, and allow them to be contractually met and verified.

Go to Problems 1.3.8 to 1.3.13.

*1.3.5 Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS)**

Learning Objective	**1.3.6**	**Describe the purpose and the mission of the JTCG/AS.**

As a consequence of the high loss rates of U. S. aircraft during the Southeast Asia conflict and the common survivability problems among the services, the Joint Logistics Commanders (JLC) in 1971 chartered the triservice organization known as the Joint Technical Coordinating Group on Aircraft Survivability. The JTCG/AS was organized to bring together the best expertise in each of the services to plan and execute a program to reduce the vulnerability of current fleet aircraft and to develop design criteria and improved technology to increase the survivability of future aircraft. The charter was revised and renewed by the JLC on 22 June 1977. In 1985 the JLC established the Joint Aeronautical Commanders Group (JACG) and assigned line oversight responsibility of the JTCG/AS to the JACG. The latest charter by the JACG occurred on 22 August 1991.

1.3.5.1 Purpose. The purpose of the JTCG/AS is to provide a mechanism to do the following:

1) Coordinate the interservice exchange of information on individual service aircraft survivability programs to increase the survivability of all aeronautical systems in a nonnuclear threat environment.

2) Implement efforts to complement service aircraft survivability programs.

3) Maintain close liaison with service staffs to ensure that aircraft survivability research and development data, analytical methodologies and systems criteria are made available to the developers of new aircraft and supporters of aircraft systems.

*In January 2003, the Joint Technical Coordinating Group on Aircraft Survivability was changed to the Joint Aircraft Survivability Program (JASP).

1.3.5.2 Mission. The mission of the JTCG/AS is to achieve increased economy, readiness, and effectiveness through the use of joint development and coordination of survivability (susceptibility and vulnerability reduction) technologies and survivability assessment methodologies. The following tasks are dedicated to this mission:

1) Provide technical data and inputs for survivability improvements to cognizant managers of service aircraft programs and systems.
2) Establish and maintain survivability as a design discipline.
3) Interface with Joint Directors of Laboratories (JDL) on research and development efforts contributing to the reduction of vulnerability and/or susceptibility for aeronautical systems in a threat environment.
4) Plan and propose joint critical technology development and methodology programs that capitalize on common requirements and potential solutions.
5) Interface with the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) (Note 52).
6) Collect, review, and analyze data on combat damage of aeronautical systems.
7) Serve as the JACG focal point for aircraft survivability matters.
8) Conduct studies to assess enhanced survivability design features in a combat environment.
9) Plan, coordinate, and conduct joint service tests.
10) Serve with the JTCG/ME as executive agent for the DoD Survivability/Vulnerability Information Analysis Center (SURVIAC), described in the next section.
11) Determine and implement methods of instruction to the user commands to provide quantified survivability direction in required operational capabilities (ROCs), statements of need (SON), and operational requirements (OR).
12) Survey customers to determine research and development requirements and provide appropriate feedback.

A full-time staff is assigned for duty in the JTCG/AS Central Office to manage and coordinate joint aircraft survivability research and development efforts. Projects of the JTCG/AS are performed by individuals from service laboratories and other appropriate organizations who are specialists in specific technologies relevant to aircraft survivability. To function in all areas of survivability, the JTCG/AS is organized into three subgroups: 1) survivability assessment (susceptibility, vulnerability, advanced threats, SAM threats, gun threats, air-to-air threats, and methodology integration); 2) susceptibility reduction [EO/IR, radio frequency, low observables (LO), and flares]; and 3) vulnerability reduction (flight systems, fuel systems, propulsion, structures and materials, and armor and crew); and two special committees: Aircraft Battle Damage Repair and Survivability Design Standardization.*

Go to Problems 1.3.14 to 1.3.16.

*The current location of the JTCG/AS Central Office(now the JASP office, or JASPO) is JTCG/AS Central Office, 1213 Jefferson Davis Highway, Suite 1103,Arlington, VA 22202. The telephone number is (703)607-3509 or DSN221-3509, and the fax number is (703)604-1033. The e-mail address is weinbergp@navair.navy.mil.The JTCG/AS is online at http://jas.jcs.mil. The key personnel, links, calendar of events, publications, and newsletters can be obtained from this website.

1.3.6 Survivability/Vulnerability Information Analysis Center (SURVIAC)

Learning Objective **1.3.7 Describe the SURVIAC and the services and products it provides.**

The Survivability/Vulnerability Information Analysis Center is the DoD center of technical and analytic excellence for nonnuclear survivability and vulnerability data, information, methodologies, models, and analyses relating to U. S. and foreign aeronautical and surface systems. SURVIAC's scope covers the survivability of U. S., allied, and other nonadversary systems to threat weapons, as well as the effectiveness of U. S., weapons against foreign systems. SURVIAC's thrust is to support and influence development of more survivable systems by providing information resources and analytic services that are effective and responsive to the needs of the defense community.

SURVIAC is a center of excellence, providing a centralized information and analytical resource for all aspects of nonnuclear survivability, lethality, and munitions effectiveness. The Center's technical span encompasses such threats as the conventional guns and guided missiles, the directed energy weapons, and the chemical/biological weapons. The targets consist of a broad range of U. S. and foreign aeronautical and surface systems, including ships. SURVIAC maintains libraries, computer models, methodologies, and databases; and disseminates information and the models to the user community, such as government and industry personnel involved in weapon system research, development, procurement, concept analysis, mission planning, and combat operations.

1.3.6.1 Technical area tasks. Technical area tasks originate from user requests for specialized expertise or quick reaction analyses beyond the scope of normal inquiry response. These tasks are important because they are sources of new information and methodologies for the Department of Defense and the survivability and lethality communities. The general criteria for acceptance of technical area tasks ensure that they are within the center's primary technical interests, scope, and objectives; enhance its technical capabilities; and acknowledge SURVIAC sponsorship and control over project quality and products. The technical areas relevant to SURVIAC's mission include 1) survivable conventional force requirements, 2) survivability technologies, 3) optimizing survivability and lethality, 4) live-fire testing, 5) methodology advancement, and 6) support of combat operations.

1.3.6.2 SURVIAC databases and major holdings. The SURVIAC Information Resource consists of technical libraries, computer programs, numerical databases, and major data collections. Databases maintained by SURVIAC include 1) Desert Storm Combat Data Base, 2) Joint Live Fire/Live Fire Test Information System, 3) JUST CAUSE—Panama Data Base, 4) ACFTDAB—Southeast Asia Fixed-Wing Aircraft Data Base, 5) HELODAB—Southeast Asia Rotary-Wing Aircraft Data Base, 6) GNDVEHSEADB—Southeast Asia Ground Vehicle Data Base, 7) YOM KIPPUR—1973 Arab–Israeli Ground Vehicle Data Base, 8) Laser

Reference Library, 9) General Survivability/Vulnerability Reference Library, and 10) Vehicle Signatures Reference Library.

1.3.6.3 SURVIAC computer models. SURVIAC serves the analysis needs of the survivability and lethality communities by maintaining selected survivability and lethality computer models. The objective of SURVIAC's modeling resource is to provide a single focal point for the distribution and expert advice on these models. SURVIAC maintains and disseminates the computer codes and documentation, provides technical advice regarding their use, conducts workshops on their applications and operations, and is the clearinghouse for changes and updates for these models. The models in the current inventory are briefly described in Sec. 1.5 of this chapter. A SURVIAC Model Guide that describes each of these models in greater detail is available from the SURVIAC Central Office. In addition, SURVIAC is familiar with, and provides advice and recommendations on, many other computer models that might be appropriate for solving specific problems.

1.3.6.4 Product and service information. SURVIAC provides information resources and analytical services to support the development and fielding of more survivable and effective combat systems. The *SURVIAC Bulletin*, a current awareness publication, is produced bimonthly and is free.

The computer models and their documentation, selected SURVIAC products, as well as nominal requests for information are provided free of charge to government requesters. Fees are required from nongovernment persons or organizations involved in weapon systems research, development, acquisition, and support for computer models, products, etc. Both government and industry can take advantage of a SURVIAC subscription plan. The subscription plan, tailored to special needs, provides extra value to repeat users. Product guides, model guides, brochures, and descriptions of products and services are provided free of charge to all Defense Technical Information Center registered users.*

Go to Problems 1.3.17 to 1.3.20.

1.4 Designing for Survivability (Note 53)

1.4.1 Survivability Requirements for U. S. Military Aircraft

Learning Objective	**1.4.1**	**Describe the evolution of the survivability requirements for U. S. military aircraft.**

Combat survivability as a formal design discipline for aircraft is a relatively new concept. During WWII, when many thousands of U. S. military aircraft were shot down, the usual approach before the war was to design the aircraft with little

*The current address of SURVIAC is 46 OG/OGM/OL-AC, 2700 D Street, Building 1661, Wright-Patterson Air Force Base, OH 45433-7605. The telephone number is (937)255-4840 or DSN 785-4840, and fax number is (937)255-9673. The e-mail address is crosthwaite_kevin@bah.com. Further information on SURVIAC and its products and services can be obtained by contacting the center at any of the preceding numbers or by accessing it online at http://iac.dtic.mil/surviac/.

consideration given to survivability, other than flying high and fast. Later in the war, the hard lessons learned in combat were used to design more survivable aircraft. (Appendix A contains specific details on the survivability design and operations of several aircraft.) For example, guns were added for self-defense, fuel systems were protected from fires and explosions, better tactics were developed, electronic countermeasures were developed, more realistic training was provided, structures were made more resistant to damage by enemy fire, and camouflage paint schemes were applied. However, all of this was done within the context of the individual aircraft design disciplines. No attempt was made to justify the inclusion of any of these survivability enhancement features in the design other than to note that aircraft that had them lived longer in combat and were "better" or more effective than the aircraft that did not have them.

There were at least two reasons for the lack of a formal survivability discipline during WWII and the following 25 years. First, the systems approach to aircraft design had not been fully developed. Second, there were no specific design requirements imposed by the military services on the various measures of survivability, such as the maximum allowable vulnerable area or radar cross section, because survivability was not considered to be a formal attribute of military aircraft. Completing the circle, because there were no requirements for survivability, there was no apparent need for a formal survivability discipline.

The importance of survivability increased dramatically in the middle 1960s when many aircraft, not specifically designed to be survivable against guns and missiles, were shot down in Southeast Asia. As a result of the approximately 5000 aircraft lost in the 1962–1973 SEA conflict, a major revolution in the design priorities of military aircraft began: first in the late 1960s when serious consideration was given to the design for reduced vulnerability, and then in the middle 1970s when the first stealth aircraft programs were started in an attempt to reduce aircraft susceptibility without the use of large numbers of supporting aircraft. Perhaps the first publication to bring attention to the technology that could make aircraft more survivable was the paper "Design of Fighter Aircraft for Combat Survivability," published in 1969 (Ref. 53). Today, survivability requirements for both susceptibility and vulnerability are routinely specified for U. S. military aircraft. Figure 1.18 shows the history of the general survivability considerations for U. S. aircraft developed since 1950.

Go to Problems 1.4.1 to 1.4.6.

1.4.2 Designing for Low Susceptibility

Learning Objective 1.4.2 Describe some of the effects that designing for low susceptibility has upon aircraft design.

Designing for low susceptibility means designing the aircraft to avoid the man-made hostile environment. Low susceptibility is acheived using the six concepts of susceptibility reduction listed in Table 1.3 and shown in Fig. 1.19 with some typical techniques (Note 54).

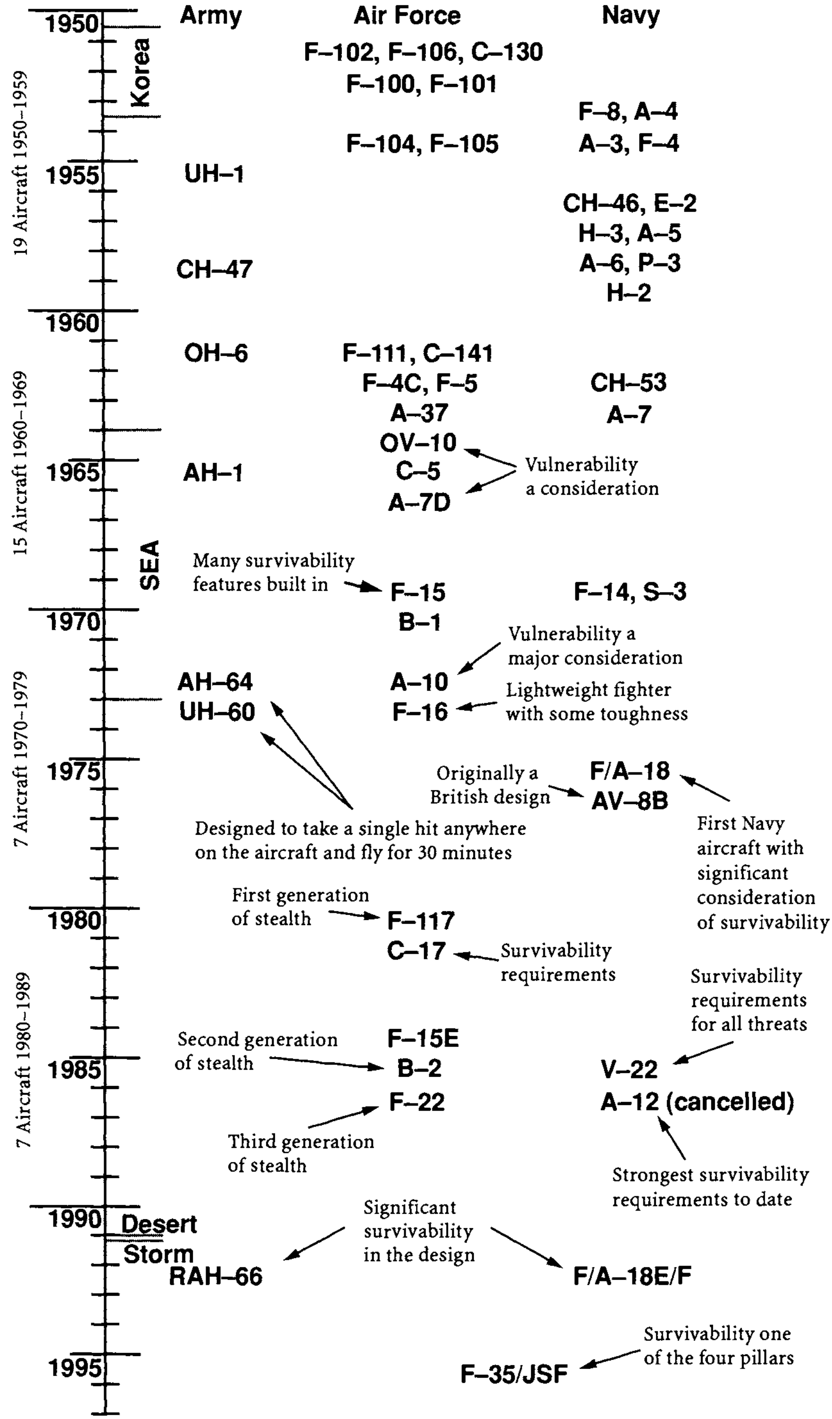


Fig. 1.18 General survivability considerations for U. S. military aircraft (adapted from Ref. 54).

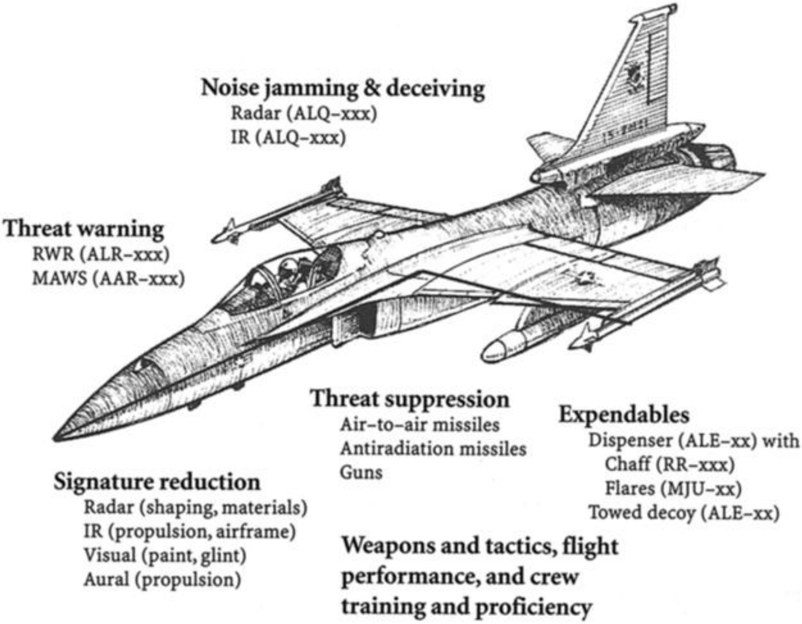


Fig. 1.19 The six susceptibility reduction concepts with some typical techniques.

Of the six susceptibility reduction concepts shown in Fig. 1.19, the one with the most obvious impact on the design of an aircraft is signature reduction. The stealthy aircraft, such as the F-117, A-12, F/A-22, RAH-66, and the B-2, look different. Their engine inlets and exhausts are modified, their wing sweep angles are high, some of them lack the traditional vertical tail, and they do not have the many bumps, bulges, and holes that nonstealthy aircraft have. Even the relatively small stealth aircraft carry their ordnance inside. All of these features contribute to a reduction in one or more of the aircraft's signatures, such as the radar signature or the IR signature.

There are many other changes associated with signature reduction that are not so obvious. Because of the stealthy design, the flight control system might have to contend with a statically unstable aircraft. Manufacturing procedures must contend with different materials, higher tolerances, and complex shaping requirements, and the sensors on the aircraft must be properly located to minimize their contribution to the aircraft's signatures while maintaining their ability to sense. Nevertheless, the experience that has been gained designing, producing, and operating stealth aircraft the past 20 years has been used to reduce the performance and cost burdens of the latest combat aircraft, such as the F-35 Joint Strike Fighter (JSF) (Note 55).

Some other not-so-obvious design impacts because of SR are related to the requirements associated with the electronic warfare equipment carried by the aircraft. This equipment provides the concepts of threat warning, noise jamming and deceiving, and expendables. Adequate space, cooling, and electrical power for the processors, sensors, and data buses put additional requirements on the design.

Some major design questions to be answered are as follows: should the countermeasures equipment be carried externally in a pod or internally, where should the antennas and the chaff and flare dispensers be located, and what effect will this equipment have upon the radar signature?

Another not-so-obvious impact of susceptibility reduction, but one that can be a major contributor to aircraft weight, is the mission flight profile. Aircraft are designed to fly a particular flight profile, such as high-low-high. With this profile the aircraft takes off, climbs to high altitude, and efficiently cruises toward the target. When it approaches a defended area, it descends to a low altitude to avoid detection by the enemy's air defense sensors and high-altitude SAMs and might jink to avoid being hit by enemy gunfire. The target is attacked at low altitude, and a pop-up maneuver might be required to locate the target. After attacking the target, the aircraft turns around and heads for home, first at a low altitude until out of the enemy's weapon envelopes, and then at a high altitude for optimum cruise efficiency.

The descent to low altitude, which is solely for enhanced survivability against medium- and high-altitude SAMs and to delay detection, puts the aircraft in a much more severe flight environment. Drag increases significantly, fuel is burned at a much higher rate to maintain the fast speed required to survive the transit through the enemy territory, and the air loads on the aircraft are much higher than those at high altitude with no maneuvering. Consequently, one of the most attractive features of a stealth aircraft with precision-guided weapons is the use of a high-medium-high flight profile; it keeps the aircraft out of the range of the ground-based guns, a long-time, lethal foe of aircraft. Today, many operational commanders will not allow the use of low-altitude tactics; the aircraft is simply too susceptible at low altitude.

In addition to the altitudes flown, the directional path of the aircraft as it flies the mission can have a major impact on the design. As the aircraft passes through the defended area, the location of the threat weapons around the aircraft will vary. Designing the aircraft with a relatively low, uniform signature from all aspects (known as a fuzz ball) is usually not feasible. Reducing the signature from the frontal aspect only (known as a pacman) can result in large signatures presented to weapons located at the side and behind the aircraft. A third option is to shape the aircraft such that the signatures are relatively large in only a few narrow directions (resembling a spider).

Go to Problem 1.4.7.

1.4.3 Designing for Low Vulnerability

Learning Objectives	**1.4.3**	**Describe how to reduce the vulnerability of an aircraft.**
	1.4.4	**Describe some of the vulnerability features used on the A-10A, the F/A-18A, and the UH-60A.**

Designing for low vulnerability means designing the aircraft to withstand any hits by the damage-causing mechanisms created by the enemy warheads, such as metallic penetrators and fragments, incendiary particles, and blast. This is accomplished by using the six concepts for reducing vulnerability to prevent the loss of one or more essential functions caused by the component and system kill modes listed in Table 1.4 and to ensure that the critical components on the aircraft continue to function after the aircraft is hit.

Many of the aircraft flying today were designed during and after the SEA conflict. The lessons learned in combat in that conflict have strongly influenced the vulnerability design of these aircraft. Three of these aircraft, the Air Force's A-10A Thunderbolt II (affectionately known as the Warthog), the Navy's F/A-18A Hornet, and the Army's UH-60A Black Hawk, have been selected as examples to illustrate the technology for reducing vulnerability that evolved from the late 1960s through the middle 1980s. For more information on the VR features of these three aircraft see Tables 5.12–5.13. These three aircraft, as well as the F-117 and many other aircraft involved in the operation, proved to be survivable aircraft in Desert Storm. They took some hits, but suffered very few losses. This combat experience validated the approach to survivability design that was taken during the 1970s and 1980s.

1.4.3.1 A-10A. The A-10's primary mission was to kill tanks with a 30-mm gun and air-to-surface missiles. In this role it would face a variety of guns and missiles, and its vulnerability would be tested in combat. Consequently, the aircraft was the first modern fixed-wing aircraft to be designed, from its inception, to a complete set of survivability requirements. It incorporates over 100 VR features, many of which were verified by ballistic testing. Figure 1.20a illustrates some of the VR features on the A-10 (Ref. 55). Each feature noted in Fig. 1.20a prevents the occurrence of a particular kill mode. For example, the two independent, separated jam-free flight control systems prevent the loss of control caused by the disruption of the control signal path kill mode, and the fuel transfer lines inside the fuel tanks prevent the fuel supply depletion kill mode.

The survivability and battle damage repair features that were designed into the A-10 paid off in Desert Storm when the aircraft had an opportunity to show what it could do. According to an article in *Aviation Week and Space Technology,*[56] "Survivability features designed into the Fairchild A-10 proved their worth during its first exposure to combat in Operation Desert Storm, when many Thunderbolts flew home despite extensive battle damage sustained in successful low-level attacks on enemy tanks and artillery. . . . Most of the damaged aircraft were returned quickly to service by U. S. Air Force aircraft battle damage repair (ABDR) crews. . . . Of 20 aircraft that were at least 'significantly' damaged, only one could not be returned to service by ABDR crews." According to Capt. Paul Johnson, who flew home from a mission over Kuwait with a gaping hole in his A-10's right wing, "We always expected the A-10 to be a tough customer, but it hadn't been proven," and "the guys developed a great affection for the airplane and a very healthy respect for what it could absorb."[57]

1.4.3.2 F/A-18A. The F/A-18A. Hornet was the Navy's first aircraft in which survivability considerations played a major role in the design. Trade studies were performed to determine the payoffs and costs associated with each

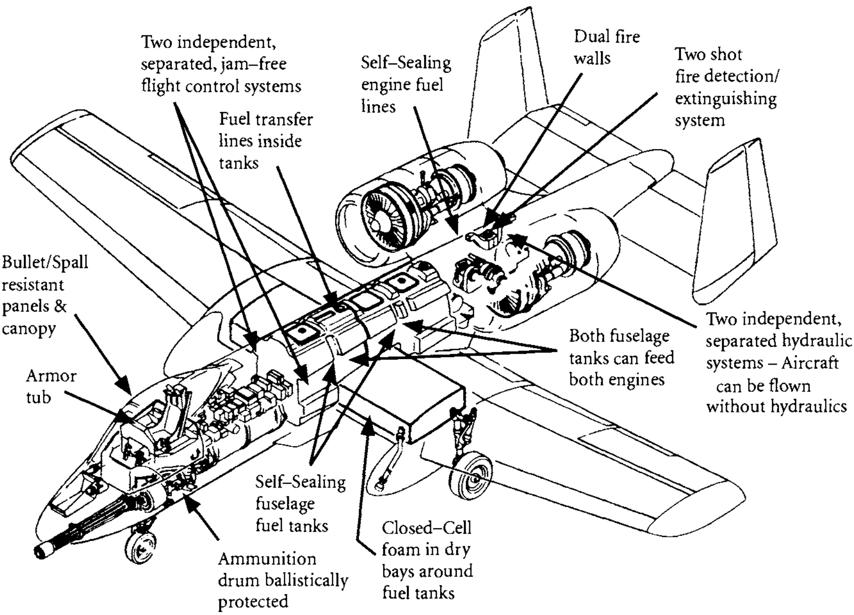


Fig. 1.20a Some vulnerability reduction features on the A-10A (Reproduced with permission of Fairchild Republic Aircraft Co. Farmingdale, NY).

enhancement feature considered. Those features that had high benefits with relatively low costs were incorporated because the Hornet is both a fighter and an attack aircraft and had to perform well in both roles. It, too, proved itself to be a survivable aircraft in Desert Storm. Figure 1.20b illustrates some of the VR features on the F/A-18A (Ref. 58). Again, each feature is designed to prevent a kill mode from occurring. The latest version of the Hornet, the F/A-18E, is both less vulnerable and less susceptible than the A model, even though it is larger (Note 56).

1.4.3.3 UH-60A. Because of the large number of Army helicopters lost to small arms fire in SEA, the UH-60A, which was the winning design for the Utility Tactical Transport Aircraft System (UTTAS) competition, had a firm design requirement on vulnerability. The helicopter in forward flight was to be capable of safe flight for at least 30 min after a single hit by a 7.62-mm AP-I projectile.[59] In the vernacular of the vulnerability engineer, the helicopter must have zero vulnerable area for a B-level attrition kill. A minimum vulnerable area to the 23-mm HE-I was a design goal (Note 57). The reduced vulnerability paid off in Grenada. "The BLACKHAWK played a key role in combat during the 1983 Grenada invasion. . . . It sustained and survived small arms and 23-mm antiaircraft fire while carrying out its mission of transporting and supporting Army Rangers. Of the 32 BLACKHAWKS used in Grenada, 10 were damaged in combat. One helicopter had 45 bullet holes that damaged the rotor blades, fuel tanks, and control

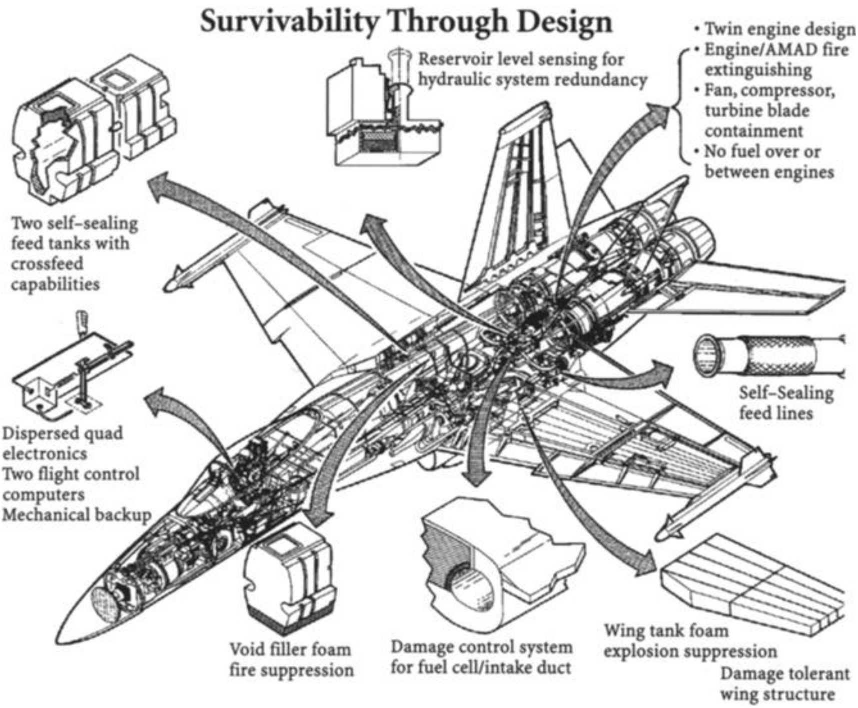


Fig. 1.20b Some vulnerability reduction features on the F/A-18A (Reproduced with permission of The Boeing Company, St. Louis, MO).

systems, yet it still managed to complete its mission."[60] Figure 1.20c illustrates some of the VR features on the UH-60A (Ref. 61).

Go to Problems 1.4.8 to 1.4.11.

1.4.3.4 Other aircraft. Some of the vulnerability reduction features on the F/A-18C/D Hornet, the F/A-18E/F Super Hornet, the V-22A Osprey, and the AH-1 Cobra are listed online at http://www.nawcwpns.navy.mil/~survive/ under the "accomplishments" link.

1.4.4 Designing for User Survivability

Learning Objectives	**1.4.5**	**Describe how the people onboard an aircraft can be killed or injured when an aircraft is hit.**
	1.4.6	**Give some examples of design features that can reduce the number of casualties on a hit aircraft.**

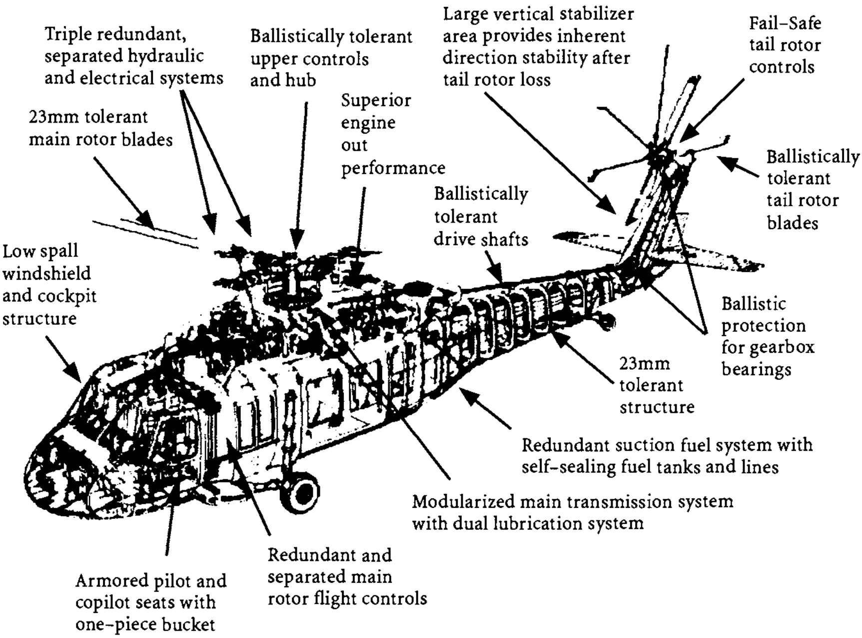


Fig. 1.20c Some vulnerability reduction features on the UH-60A (Reproduced with permission of Sikorsky Aircraft, Stratford, CT).

Designing an aircraft to maximize the likelihood that the aircrew and any passengers onboard the aircraft will survive a mission into hostile territory is of paramount importance to the survivability discipline. Enhancing the survivability of the people onboard is achieved primarily by designing the aircraft to avoid being hit and to withstand any hits that do occur. Aircraft that are designed to take one or more hits and keep flying will return to base. But that is not enough. Special attention must be given to the design of the aircraft to ensure that the people onboard are neither injured nor killed when the aircraft is hit.

There are several situations to consider when designing the aircraft to reduce the likelihood the people onboard the aircraft are killed or injured when an aircraft is hit. Crew and passenger casualties can occur when 1) the aircraft is hit and not killed, but there are casualties as a result of the hit, or when 2) the aircraft is hit and killed, and the crew and passengers are killed or injured either while attempting to eject from the aircraft or when the aircraft crashes on land or water with the crew and passengers onboard.

Consider the first situation where the aircraft is not killed by the hit but there are casualties as a result of the hit. The causes of user casualties include penetrator or fragment penetration, blast, burns, toxic fume inhalation, and blunt trauma. Examples of design features that can reduce casualties are the use of spall-resistant materials and spall shields around the crew and passengers; bullet-resistant transparencies, the use of nontoxic or noncombustible materials in and around crew and passenger compartments; the use of fire walls to prevent the spread of a fire into occupied compartments and the ventilation of these compartments to prevent smoke inhalation; the location of components that can violently react when hit or when subjected to a fire, such as a liquid-oxygen bottle, munitions, or fuel tanks, away from the crew and passengers; and the use of armored seats and side panels to shield the people onboard.

Next, consider the second situation where the people onboard an out-of-control aircraft are unable to depart the aircraft safely. Recall that the second goal of the survivability discipline is to design the aircraft to allow a graceful degradation of the system capabilities when loss is inevitable, giving the crew a chance to depart the aircraft over friendly territory. The tail booms and rotor blades on helicopters that can survive a hit by a 23-mm HE warhead and aircraft fuel tanks that don't explode when hit are examples of VR features that save the lives of the crew because the aircraft does not immediately fall out of control when hit. Had these critical components suffered catastrophic damage when hit, the aircraft most likely would have tumbled out of the sky, and the crew and any passengers would have perished in the ensuing crash. The graceful degradation of system capabilities on fixed-wing aircraft should provide enough time for the crew and passengers to use ejection seats and parachutes to safely depart the aircraft. Graceful degradation on rotary-wing aircraft should allow the use of auto-rotation of the rotor blades to slow the descent.

For those situations where the people onboard are unable to escape a killed aircraft, the aircraft should be designed to maximize the likelihood the crew and passengers survive the crash. Crash survivability is achieved by designing the aircraft structure to absorb energy while maintaining the integrity of the crew and passenger compartments, by using crew and passenger crash-absorbing seats that reduce the *g* loads on the human body and air bags that prevent the onboard personnel from striking any nearby hard surfaces, and by designing a crash-resistant fuel system with fuel line shut-off valves and tear-resistant fuel bladders that prevent the leakage of fuel and a subsequent fire. For those crashes that occur at sea, flotation bags that prevent the aircraft from immediately sinking are essential.

Go to Problems 1.4.12 to 1.4.13.

1.5 Survivability Modeling and Simulation

1.5.1 Models and Simulations

Learning Objectives	**1.5.1**	**Define a model and a simulation.**
	1.5.2	**Describe the difference between deterministic models and random or stochastic models.**
	1.5.3	**List some of the ways modeling and simulation is used in survivability studies.**
	1.5.4	**Describe the Defence Modeling and Simulation Office, Joint Modeling and Simulation System, and verification, validation, and accreditation.**

1.5.1.1 What is a model and what is a simulation? According to the Department of Defense Modeling and Simulation (M&S) Glossary (https://www.dmso.mil/public/resources/glossary/), a model is a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process, and a simulation is a method for implementing a model over time. There are three general categories of simulations (https://www.dmso.mil/public/):

> 1) live simulations, where real people operate real systems; 2) virtual simulations, where real people operate simulated systems; and 3) constructive simulations, where simulated people operate simulated systems.

In general, M&S for survivability either is digital M&S that is based upon a set of mathematical equations that describe the appropriate phenomena and processes or is a combination of digital M&S, hardware-in-the-loop (HITL or HWIL), and people-in-the-loop capabilities. One example of a model is the set of mathematical equations that predict the maximum range a radar can detect an aircraft. Another example of a model is the set equations that describe the trajectory or flight path of a guided missile as it intercepts an airborne target. When these equations are incorporated into a digital computer program that can be used to compute the numerical values for the radar detection range or the missile trajectory for a given scenario, the computer program is referred to as a digital simulation and the model is deterministic. However, if the actual target tracking radar is used to track the aircraft, and if the tracking signal is sent to a digital computer program that describes the flyout of the guided missile toward the aircraft, the simulation is referred to as an HITL simulation. Modeling and simulation facilities that allow real people to operate equipment that is a model of the real equipment are sometimes referred to as manned simulators, for example, a flight simulator.

1.5.1.2 Deterministic vs random models and simulations. Models and simulations predict outcomes, such as the radar detection envelope or the trajectory of a missile. Models and simulations can be based upon deterministic processes or random processes. The outcome of any deterministic process can be predicted with certainty, whereas the outcome of any random or stochastic process cannot be predicted with certainty. Consider a simulation whose outcome is the trajectory of SAM as it intercepts an airborne target. If all of the equations in the model use parameters and variables that have the identical numerical value for each execution or trial of the simulation, then the trajectories of the final missile miss distance will be identical for each simulation and the model is deterministic. However, if the parameters and variables are assumed to be random and have slightly different values for each simulation then the trajectories from each simulation will be different and the model is random. For example, if the duration of the missile motor burn is assumed to be a random parameter with a distribution instead of a fixed value for every simulation then the burn time will be different for each simulation, and consequently the resulting trajectories will be different for each simulation.

One approach to solving problems involving random processes is the Monte Carlo method. In this method a random draw is made for each of the random parameters, such as the motor burn time, each time the simulation is run. A very large number of simulations are executed, resulting in distributions of variable outcomes. These distributions can be used to determine the expected values and

Table 1.13 Some applications of models and simulations

Education and training	R&D	T&E	Military studies
Command and unit training	Requirements development	System performance assessment	Mission analyses
Doctrine and tactics development	Engineering design support	Test design	Campaign analyses
Operational planning and rehearsal	System configuration determination	Excursion and sensitivity analyses	Force structure assessment

standard deviations of the important variables, such as the missile miss distance and aircraft P_K. The reader interested in more detail on deterministic and random processes is referred to Appendix B.

1.5.1.3 How are models and simulations used in survivability? Models and simulations have many military applications. Some of these applications are listed in Table 1.13.

Of interest here are those models in the four categories that involve survivability. For example, in the education and training, R&D, and military studies categories, mission and campaign models can be used in an attempt to develop tactics and the system configuration requirements for those attributes of an aircraft that affect susceptibility, such as the RCS, and vulnerability, such as the vulnerable area. M&S can be used in engineering and design support studies to develop the shape of the aircraft to achieve the required RCS, and it can be used in system performance studies to determine if the fuel tank structure can withstand the forces of hydrodynamic ram. Of particular interest here are those models and simulations that can be used to predict the survivability of an aircraft against guns and missiles. M&S can play a role in many aspects of T&E, provided it is used in support of empirical tests and not in place of such tests. The simulation, test, and evaluation process (STEP) for integrating M&S with T&E in a model-test-model paradigm is described online at http://www.acq.osd.mil/te/programs/tfr/step.htm.

1.5.1.4 Defense Modeling and Simulation Office and Defense Modeling and Simulation Information Analysis Center. The Defense Modeling and Simulation Office (DMSO) is the lead for modeling and simulation activities within the U. S. Department of Defense. It is a technology transition and support organization charged with maximizing the efficiency and effectiveness of M&S efforts across the department and fostering interoperability and reuse among the DoD's models and simulations. It approaches those tasks through the promotion of cooperation among the DoD components and the broader domains of interest, such as training, analysis, and acquisition. The web site of the DMSO is https://www.dmso.mil/public/. The DMSO and the M&S developer and user communities are supported by the Defense Modeling and Simulation Information Analysis Center (MSIAC). The web site of the MSIAC is http://www.msiac.dmso.mil/.

1.5.1.5 Joint Modeling and Simulation System. The Joint Modeling and Simulation System (JMASS) is a simulation support environment that is being developed to provide users with a common simulation environment for building, storing, and executing models and simulations. It consists of a collection of well-defined, well-documented interface standards to which a model should be built and includes a tool kit that allows modelers to build representations of real-world systems, configure those models, assemble them into simulations, execute those simulations, and process the results. The completed model or simulation can be stored in a local model library, and ultimately JMASS will have a link to the DMSO model and simulation resource repository. Full customer support is available for the current release of JMASS. The Program Office also provides model integration support. All members of the DoD or academia are eligible to register for free access to the JMASS software. More details can be found at the JMASS web site (http://www.redstone.army.mil/amrdec/jmass/).

1.5.1.6 DoD Catalog of Wargaming and Simulation Models. Many of the models used in military studies are described in the DoD Catalog of Wargaming and Simulation Models. The catalog contains descriptions of the simulations and models in general use throughout the Department of Defense. The individual models are listed alphabetically. Each catalog entry includes model type, the date of implementation, the proponent, point of contact, purpose, description, construction, limitations, input, output, hardware and software, users, and the security classification of the model. The most recent version of the catalog can be obtained from the web site of the National Technical Information Service (NTIS) at http://www.ntis.gov/search/product.asp?ABBR=ADA246431&starDB=GRAHIST.

1.5.1.7 Verification, validation, and accreditation. For a model or simulation to be useful, its predicted results and outcomes must be credible. A verification, validation, and accreditation (VV&A) process for establishing the credibility of a model or simulation has been developed by the Department of Defense. This process is described in DoDI 5000.61, DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation, which can be obtained online from the Project Areas of the DMSO Document Library (https://www.dmso.mil/public/resources/documents?tree-e=eJyLVneEAncPC1t1HQU4PzIvFIXvUZlvqx4LAB-lDB0).

According to the definition given in the DMSO Glossary (https://www.dmso.mil/public/resources/glossary/), verification is the process of determining that a model or simulation implementation accurately represents the developer's conceptual description and specification. Verification also evaluates the extent to which the model or simulation has been developed using sound and established software engineering techniques. In other words, has the computer model been properly coded? Are there any computer bugs in the model? Are all of the equations correct? Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Consider the model of the target tracking radar in a SAM system. Do the results of the model, such as the range at which the target is first detected and the location of the aircraft vs time, agree with the results from empirical tests of the actual radar? Accreditation is the official certification that a model, simulation, or federation of models and simulations is acceptable for use for a specific purpose, for example, the target-tracking radar model has been accredited for use in tracking aircraft with conventional RCS levels, but it is not accredited for use against stealthy aircraft.

The VV&A organization originated by the JTCG/AS is the Joint Accreditation Support Activity (JASA). JASA's mission is to provide the DoD M&S community with a cost-effective means of defining and meeting M&S credibility requirements. The JASA web site is http://www.nawcwpns.navy.mil/~jasa/.

Go to Problems 1.5.1 to 1.5.4.

1.5.2 SURVIAC Digital Models and Simulations

Learning Objective **1.5.5 Describe each of the SURVIAC digital models and simulations.**

Over the past three decades, many computer programs were developed to assess aircraft survivability. Some of these programs were widely used, whereas others were used only by the developing organization. In developing the models and gathering the data, each organization used its own criteria as to how to model or simulate a particular scenario element or event and what data were needed for a study. Thus, study results from different organizations were not directly comparable even though they were studying the same problem, and there were no accepted standards. As a consequence, the JTCG/AS has adopted a set of controlled standard models (and data) for use throughout the DoD survivability assessment community. These models are maintained and disseminated by SURVIAC. (http://www.bahdayton.com/surviac/model%20list.htm.) The controlled models do not represent the only models of their type, but rather, they represent a standard against which an analyst can compare his or her own model. There are 16 digital computer models in the SURVIAC model repository as of February 2003. Eleven of the models have been arranged for clarity of presentation into the eight categories listed in Table 1.14 and are described next. The description provided for each model is based upon the description provided in the 1995 SURVIAC Model Guide available online at http://www.bahdayton.com/surviac/introduction.htm. For information on how to contact SURVIAC for more detail on the models, refer to Sec. 1.3.6 of this chapter. Several other models used in survivability studies are also listed in Table 1.14 and described in the following section.

1.5.2.1 Radar detection envelopes—AIRADE and ALARM.

AIRADE. The Airborne Radar Detection (AIRADE) model is an interactive computer program for evaluating radar performance of airborne radars. It is used as a tool for design, analysis, and mission planning for airborne radar surveillance and fire control systems. AIRADE has been under development since 1981

Table 1.14 Models used in survivability

Category	Description
	SURVIAC models
Radar detection envelopes	AIRADE and ALARM
Vulnerability assessment	BRL-CAD, FASTGEN, and COVART
Aircraft flight-path generation	BLUEMAX
Engagement: surface-to-air missiles	ESAMS
Engagement: air-to-air missiles	TRAP
Engagement: antiaircraft artillery	RADGUNS
Mission/air combat	MIL-AASPEM and BRAWLER
	Other models
Endgame	AJEM
Mission/combat	SUPPRESSOR, SWEG, JIMM, and EADSIM
Campaign	THUNDER

by the National Air Intelligence Center (NAIC) at Wright-Patterson Air Force Base, Ohio. The original application of AIRADE was the performance analysis of foreign airborne radars and the development continues to emphasize airborne surveillance and track performance for pulse-Doppler radars. AIRADE has been validated extensively by independent agencies during its course of development by analysis and by comparison with other radar simulations. As a result, AIRADE is an accepted standard for airborne radar performance evaluation.

Input: The inputs include the radar parameters, aircraft flight path, clutter and multipath, target RCS and flight path, and any onboard ECM techniques.

Output: The outputs include the radar and target-centered azimuth and elevation plane detection envelopes and track mode probability of detection.

Limitations: The limitations are one-on-one, no maneuvering, and no standoff ECM.

ALARM. The Advanced Low Altitude Radar Model (ALARM; http://www.bahdayton.com/surviac/alarm.htm) determines the detection performance of ground-based radar systems against aircraft targets. ALARM is a generic radar simulation model capable of representing radars operating in either a search mode or track mode. The types of radars that can be simulated are pulsed, pulsed with moving target indication (MTI), pulse-Doppler, and continuous wave (CW). ALARM uses detailed forms of the radar range equation to determine the ability of the system to detect the target in the presence of terrain, clutter, and multipath. Terrain is modeled using digitized terrain data or as a round, smooth earth. Lincoln Lab's Spherical Earth/Knife Edge (SEKE) diffraction models are used for low-altitude targets. The model also permits the representation of either a standoff jammer or an onboard jammer.

Input: Inputs include detailed characteristics of the radar system, jammers, target RCS, digitized terrain data, and target flight path (or azimuth and elevation angles of interest).

Output: Outputs include signal levels returned from any jammers, the target, clutter, and multipath. Detection contours are output in a format acceptable by standard plotting packages.

Limitations: ALARM is not a waveform level model.

The basic radar detection theory used in AIRADE and ALARM is presented in Chapter 4, Sec. 4.3.3.

1.5.2.2 Vulnerability assessment—BRL-CAD, FASTGEN, and COVART. The procedure for the vulnerability assessment of an aircraft to a warhead depends upon whether the warhead is a contact warhead or a proximity warhead. For the contact warhead two SURVIAC computer programs are required to compute the $P_{K|H}$ or single-hit vulnerable area of the aircraft. They are either BRL-CAD or FASTGEN, in conjunction with COVART. The BRL-CAD and FASTGEN programs are preprocessing programs that are used to develop the shotline or line-of-sight (LOS) descriptions of aircraft targets for use as input data to COVART, which computes $P_{K|H}$ and A_V. A planar grid is first superimposed over the target model normal to the attack direction of interest, and a shotline or ray in that direction is then randomly located within each of the grid cells. Either BRL-CAD or FASTGEN can be used to determine the list of components and fluid and air spaces that are intersected by each of the shotlines.

BRL-CAD. The U. S. Army's Ballistic Research Laboratory's Computer Aided Design (BRL-CAD) program is a solid modeling system designed to interactively create and analyze three-dimensional geometric target descriptions. BRL-CAD includes an interactive geometry editor, a ray tracing library, and a large collection of related tools and utilities. BRL-CAD supports a large variety of geometric representations, including an extensive set of traditional combinatorial solid geometry primitive solids such as blocks, cones, and torii; solids made from closed collections of uniform B-spline surfaces, as well as nonuniform rational B-spline surfaces; purely faceted geometry; and n-manifold geometry. Geometric objects can be combined using boolean set-theory operations such as union, intersection, and subtraction.

Input: The input includes coordinate and vector description data for all components included in the three-dimensional geometric target description. Additional inputs include material properties and other attribute properties such as reflectivity, transparency, and color.

Output: The primary output is a three-dimensional geometric target file. Additional output includes wire frame plots, rendered images, LOS data files, and text summary files. Additional tools are also available for managing and enhancing image files, generating animation, and converting to/from BRL-CAD format.

Limitations: BRL-CAD requires medium-level experience to generate a geometric target description.

FASTGEN 4. The Fast Generation (FASTGEN) program (http://www.bahdayton.com/surviac/fastgen.htm) automates the manual techniques of generating shotline data required for vulnerability analyses. The shotline method involves projecting a number of parallel rays through a target from a specific direction. This method assumes that the penetrators have been fired at a sufficient distance from the target that their trajectories can be represented by a set of parallel rays. As these rays pass through the target, the intersections with the internal and external components are recorded. Components encountered along each shotline are referred to as LOS file.

A required input to FASTGEN is a file consisting of a geometric description of all significant target components. The geometric model is constructed based on the assumption that all surfaces can be described by a series of adjacent triangles, cones, cylinders, spheres and rods. The preparation of the geometric model requires an extensive design effort depending on the detail required. Care should be taken in construction of the model to ensure compliance with the requirements and limitations of FASTGEN.

Input: The input includes a binary or ASCII target description and azimuth and elevation data.

Output: The program produces a LOS data file and target summary file. Target summary file records possible component interferences and errors encountered in processing geometric target descriptions.

Limitations: FASTGEN requires a high level of experience to generate a geometric target representation. Body shapes are approximated using triangles, cones, cylinders, spheres, or rods.

COVART 4. The Computation of Vulnerable Area and Repair Time (COVART; http://www.bahdayton.com/surviac/covart.htm) program is used to assess the vulnerability of aerial targets, both fixed-wing and rotary-wing, and ground targets. The vulnerable areas are calculated for a single hit by a penetrator or fragment (COVART 3) and by a contact-fuzed HE warhead (COVART 4). The program determines the individual component vulnerable areas and corresponding aircraft vulnerable area in each grid cell because of a hit along the randomly located shotline in that cell. The weight and speed reduction for the penetrator or fragment is computed for each encounter with the surface of a target component along the shotline. Whenever a critical component is intersected by a shotline, the probability that component is killed by the hit is computed using input $P_{k|h}$ functions that are based upon the weight of the damage mechanism and its impact velocity on the component.

Input: The input includes the LOS files from BRL-CAD, FASTGEN, or another shotline generator program; the critical components, both nonredundant and redundant, and their $P_{k|h}$ functions; the material type and thickness for all components; the attack directions of interest; and the specific impacting threat and impact velocity.

Output: COVART provides component and aircraft vulnerable areas and presented areas for the selected attack directions.

Limitations: The penetrator or fragment is assumed to travel along the shotline, ricochet and spall are not modeled, and blast effects are not considered.

1.5.2.3 Aircraft flight-path generation—BLUEMAX. The BLUEMAX computer program generates the data that describe the aircraft status at short intervals as it executes commanded maneuvers. (http://www.bahdayton.

com/surviac/bluemax.htm.) The model, which can be run in an interactive or automatic mode, produces three-dimensional aircraft flight-path data suitable for inputs to models such as RADGUNS and ESAMS. The modeled flight path is comprised of a sequence of flight segments. During each segment, a set of command variables is used to control the flight—heading, altitude, speed, and time for the segment. The maximum allowed g-factor, g-factor rate, and maximum roll rate specify the maneuver limits. Terrain-following and terrain-avoidance capabilities are also modeled. Aircraft status is defined by the following set of primary variables: time, position, velocity, roll angle, g-factor, throttle setting, fuel remaining, speed-brake setting, and the number of external stores.

Input: The input includes aircraft performance characteristics such as lift tables, drag tables, and thrust tables, for the specific aircraft being simulated; terrain data; and flight-path commands. The required performance data for several aircraft are included in the program.

Output: The output includes aircraft status at a user-specified interval. A variety of output formats are available, including RADGUNS and ESAMS compatible formats, Excel format, and IVIEW format. (IVIEW is a graphical program available from SURVIAC that provides three-dimensional interactive views of a scenario over time, such as the intercept of an aircraft by a missile.)

Limitations: The aircraft maneuvers are generated by changing its roll angle, g-factor, throttle setting, and speed-brake setting; sideslip maneuver (a nonzero yaw angle) cannot be simulated. The pilot is assumed to have direct control over time derivatives of roll rate, g-factor rate, throttle setting, and speed-brake setting.

1.5.2.4 Engagement model: Surface-to-air missile simulation—ESAMS.

ESAMS 3. The Enhanced Surface-to-Air Missile Simulation (ESAMS; http://www.bahdayton.com/surviac/esams.htm) is an enhanced version of the Surface-to-Air Missile Simulation (SAMS), which grew from the family of computer missile simulations called TAC ZINGER. It is a digital computer program that models the interaction between a single airborne target and a SAM air defense system. ESAMS provides a one-on-one framework for evaluating air vehicle survivability and missile evasive maneuver optimization. The target is defined by its flight path, its signature, and its vulnerability. The SAMs are modeled using detailed data from the latest intelligence information on the Russian Federation land-based SAMs SA-2 through SA-15 and the naval SAMs SA-N-1, SA-N-3, SA-N-4, SA-N-6, SA-N-7, and SA-N-9 guided missile systems.

The primary elements and events of a SAM engagement simulated in ESAMS include sensor lock-on and tracking, missile flight dynamics, missile guidance and control, electronic countermeasures, and the endgame between the proximity-fuzed HE warhead and the target aircraft. The target kill probability is based upon the warhead fragment characteristics, including fragment size and velocity, the aircraft's vulnerability to the fragments, and the aircraft's vulnerability to the warhead blast. Based upon these calculations, the model then computes the total P_K of the target by the missile. An engagement ends when a successful intercept occurs or the missile flies past the target, or impacts the ground, or self-destructs. Although the primary model result is the probability of target kill, the ESAMS user can examine the details of other aspects of the engagement, such as the missile flight path, guidance characteristics, and the effects of ECM and terrain. The ESAMS model also includes the Generic Radar and Clutter Estimator (GRACE) model, which provides a standardized basis for making clutter calculations, and the Defense Mapping Agency's (DMA) Digital Terrain Evaluation Data, which are used to generate terrain masking data.

Input: The inputs include missile and radar type, target signature, target vulnerability, target flight path, multipath/clutter data, and terrain.

Output: The output consists of missile launch conditions, missile flight data, and endgame data, including P_K and the missile miss distance.

Limitations: ESAMS is a one-on-one simulation. Multiple launches from a single site or launches from different site locations are modeled as independent events.

The operations and capabilities of the radar and infrared detection and tracking systems modeled in ESAMS are described in Chapters 3 and 4. The theory used to develop the target vulnerability model is described in Chapter 5, and the general theory used to determine the P_K is presented in Chapter 6.

1.5.2.5 Engagement model: Air-to-air missile simulation—TRAP. The Trajectory Analysis Program (TRAP) is a general purpose digital simulation designed specifically for modeling the performance of aerodynamic weapons, including air-to-air missiles, air-to-surface missiles, and unmanned aerial vehicles. TRAP can simulate up to three vehicles: a launch aircraft, the missile, and a target. The missile can be simulated as a modified point mass system with three, five, or six degrees of freedom, depending on the missile information available. The launch and target aircraft are modeled at a more simplified level and can be simulated either as point sources flying "canned" maneuvers, or, if the aircraft data are available, as point mass models. TRAP can be used to simulate single-shot launch scenarios, multiple stacked shots, or in an iterative mode to generate the maximum and minimum launch acceptable region boundaries in both the horizontal and vertical planes. The TRAP model can also be used to estimate unknown missile attributes given a set of known data and observations as constraints, and the results for the LARs can be used as inputs for air combat simulations such as MIL-AASPEM and BRAWLER.

Input: The inputs include missile aerodynamics, mass properties, propulsion, autopilot, guidance, and seeker characteristics, as well as a scenario control file and any files associated with a nongeneric launch or target aircraft.

Output: TRAP produces a time history of any variable within the simulation as specified by the user to aid in analyzing the performance of the missile during a flight.

Limitation: TRAP does not model the endgame.

1.5.2.6 Engagement model: Antiaircraft artillery simulation—RADGUNS. The Radar Directed Gun Simulation (RADGUNS) includes a set of programs that simulate target detection, tracking, and shooting performances of several antiaircraft artillery weapon systems against a passive aerial target. Each program is a complete one-on-one simulation and includes the parameters of a specific gun system and its operators, the target model with radar cross sections and vulnerable areas, the aircraft flight path, and the environment with clutter and multipath effects. Components of the weapon system are modeled at either the subsystem or circuit level, including the radar search and track systems, the characteristics of the antiaircraft gun(s) and projectiles, the fire control computer servosystem used to aim the gun(s), and the crew to operate the system. The models can be run using a Monte Carlo simulation option with randomized clutter, multipath, and target glint. Probabilities of hit and probabilities of kill are calculated using distribution theory. RADGUNS can assess many aspects of a weapon system's performance, including target detection, tracking performance (e.g., range-at-first-track, tracking errors, and break locks), probability of hit, probability of kill for each round fired and for the entire engagement, the expected number of hits, and detailed studies of system performance under different situations, such as jamming.

Input: Inputs include the weapon system configuration, clutter, and multipath parameters, the target flight path, the radar search mode, and any ECM information.

Output: The model produces tabular, graphics, and data files for plotting the results of the simulation runs.

Limitations: RADGUNS models one-on-one engagements only, there is no target reactive maneuvering capability, and only aircraft with all nonredundant critical components are analyzed correctly.

The operations and capabilities of the radar detection and tracking systems modeled in RADGUNS are described in Chapters 3 and 4. The theory used to develop the target vulnerability model is described in Chapter 5, and the theory used to determine the P_K is presented in Chapter 6.

1.5.2.7 Mission/air combat models—MIL-AASPEM and BRAWLER.

MIL-AASPEM. The purpose of the Man-in-the-Loop Air-to-Air System Performance Evaluation Model (MIL-AASPEM; http://www.bahdayton.com/surviac/milaaspem.htm) is to provide a comprehensive tool to perform air combat analysis in a realistic few-on-few combat environment. MIL-AASPEM consists of a family of four models; the Advanced Missile Flyout Model; the Aircraft, Missile, and Avionics Performance Simulation; the Interactive Tactical Air Combat Simulation; and the Automatic Decision Logic Tactical Air Combat Simulation. Aircraft and missiles are explicitly flown incorporating Air Force specified missile guidance laws and missile propulsion characteristics. MIL-AASPEM flies its vehicles using a pseudo five -degree-of-freedom mathematical model and can control mixed environments of aircraft and missile types with different load-outs of missiles on the aircraft. Unlike its predecessor, the Piloted Air Combat Analysis Model (PACAM), which was a close-in combat analysis tool, MIL-AASPEM has both within visual range and beyond visual range air engagement capabilities. MIL-AASPEM has been used extensively for studies of the effectiveness of new aircraft, missiles, countermeasure system designs, and concept development.

MIL-AASPEM is also used to explore tactics, maneuver vs detection, launch ranges, flight testing, and mission planning considerations.

Input: MIL-AASPEM can accept up to 24 aircraft and have up to 75 aircraft and missiles in flight concurrently. It also accepts six aircraft types and six missile types. Aircraft and weapons description files define the basic aerodynamics, propulsion, sensors, signatures, and type of guidance.

Output: Reports include a basic time history data printout; an event summary that tracks events; aircraft survivability and missile probability of kill; and effectiveness of countermeasures used. MIL-AASPEM generates vehicle trajectory data for display that can be used to determine if the tactics make sense for the particular weapon systems.

Limitations: The amount of interaction between input areas is a function of the option selected. Insufficient program checks do not ensure that this interdependency has been accounted for, therefore, caution must be exercised when generating inputs. Considerable time is required to create scenarios and ensure realistic combat engagement. Maneuvers selected depend on geometry between aircraft, sensor capability, and priority assigned for offensive or defensive postures.

BRAWLER. BRAWLER (http://www.bahdayton.com/surviac/brawler.htm) is designed to simulate air-to-air combat between multiple flights of aircraft in both visual and beyond visual range arenas. Special emphasis has been placed on simulating cooperative tactics and on capturing the importance of situation awareness in this environment. The user selects options for the mission and tactical doctrines, the pilot's aggressiveness, the pilot's perception of the enemy and reaction time, and the quality of the decisions made. BRAWLER models the aircraft and missile aerodynamics, the radars and communications, and other capabilities, such as infrared search and track (IRST), identification of friend or foe (IFF), noncooperative target identification (NCID), radar warning, and missile launch warning. BRAWLER is structured as an event-store simulation with most real-world stochastic features operating on Monte Carlo principles.

Input: BRAWLER requires the scenario information, the number of aircraft, ground control information, any SAMs and standoff jammers, the initial aircraft formations and headings, and the set of rules that the pilots will use to make their flight decisions. BRAWLER can simulate up to 20 total aircraft, up to 10 independent flights of aircraft, and a maximum of eight aircraft in any one flight.

Output: The BRAWLER output consists of five files. One file contains the log of the scenario that includes detection, weapons firing, and kills. The second file contains the input data read in and provides more detailed information about the activities that took place. The third file provides event summaries and graphical outputs. The fourth file enables the user to restart a run from a previous time during a run, allowing the user to fine tune a flight, and the fifth file is used for statistical calculations in the analysis of multiple runs.

Limitations: The creation of the input file takes a considerable amount of time for realistic combat to be simulated, and BRAWLER does not model terrain effects.

Go to Problems 1.5.5 to 1.5.9.

1.5.3 Other Digital Models and Simulations

Learning Objective	**1.5.6**	**Describe the Advanced Joint Effectiveness Model (AJEM), SUPPRESSOR, Simulated Warfare Environment Generator (SWEG), Extended Air Defense Simulation (EADSIM), and THUNDER.**

1.5.3.1 Endgame program—AJEM. The Advanced Joint Effectiveness Model (AJEM) is a computer simulation of the terminal conditions that result when a weapon engages an air target. The types of weapons considered are AP and AP-I ballistic projectiles, HE and HE-I projectiles with contact fuzes, HE warheads with proximity fuzes, and external blast. The endgame involves elements of projectile trajectories, missile flyout and guidance, fuzing, and warhead interactions with targets. AJEM allows the user to combine the elements of target modeling, encounter geometries and kinematics, generation of weapon burst positions from proximity or contact fuzing, propagation of the damage mechanisms to the target, damage mechanism/target interaction (penetration, fire, blast, etc.), target systems relationships (functionality, redundancies, etc.), and target remaining capability or loss of function definitions to perform endgame analyses. Output metrics include damage states/vectors, target presented area, target vulnerable area, and target probability of kill. AJEM is structured to contain several options for handling level of complexity vs speed of computation and level of detail known about the target and the threat. The address of the AJEM web site is http://www.ajem.com (Refs. 62 and 63).

1.5.3.2 Mission/combat models—SUPPRESSOR, SWEG, JIMM, and EADSIM

SUPPRESSOR. SUPPRESSOR is a player-oriented, event-stepped combat simulation system for modeling multiple sided, many-on-many conflicts involving air, ground, naval, and/or space-based forces. SUPPRESSOR simulates players interacting with other players. The scenario region can be as large as theater level, and the time frame can range from hours to weeks. The weapon systems include surface-to-air missile systems; antiaircraft artillery; fighter and bomber aircraft; antiradiation missiles; electronic combat (EC) systems, including sensors, communications, and ECM; and naval vessels. Terrain might be included in the simulation. The level of detail for the systems to be modeled is specified by the user. Some of the results from SUPPRESSOR are the number of aircraft killed, the number of shots at aircraft, the number of detections, the threat emitters killed, and the quantity of ordnance on target.

SWEG. The Simulated Warfare Environment Generator (SWEG) is a distributed interactive system (DIS) capable, event-stepped, object-oriented, general purpose conflict simulation developed by the Navy at the Air Combat Environment Test and Evaluation Facility (ACETEF), Naval Air Warfare Center—Aircraft Division. SWEG can participate in a network with other simulations, simulators, hardware, and operator-in-the-loop systems, or run in a stand-alone constructive manner. Multiple-sided conflicts involving air, ground, naval, and space forces can be simulated. SWEG represents the mental aspects of organizational structures, responsibilities, tactics, contingency plans, attitudes, perceptions, memory, and motivations. It also represents the physical aspects of the environment, communications, information gathering and exchanging, physical influence, disruption, and movement. Players consist of platforms, elements, systems, and expendables and can perform move, shoot, talk, sense, disrupt, and think functions. The Navy web site for ACETEF is http://arf.navair.navy.mil/acetef.cfm.

JIMM.[64] The Joint Interim Mission Model (JIMM), which began in March 1998, is a mission-level model (MLM). A MLM is capable of evaluating the effectiveness and survivability of a composite force of air and space systems executing operational objectives in a specific scenario against an integrated air and space defense system. JIMM is a merger of the capabilities of SUPPRESSOR into SWEG. The result is a single model capable of constructive, virtual, federated, distributed, hardware-in-the-loop/software-in-the-loop and warfighter-in-the-loop simulations. This allows a user to conduct constructive runs for analysis and easily integrate other models or a system under test to improve fidelity when necessary. JIMM will progress from a very effective low-fidelity constructive and virtual model to a far more robust, physics-based engineering support environment of medium to high fidelity (often through federation or interfaces with higher-fidelity models). It focuses on the Precision Strike or Strike Warfare Domain of the Joint Synthetic Battlespace, but can interface with other domains such as Full-Dimensional Protection (Joint Vision 2010's concept for full protection of U. S. forces and facilities) through High-Level Architecture (HLA) Federations or Distributed Interactive Simulation interfaces.

JIMM is a data-driven, event-stepped, general purpose, conflict simulation system. An event-driven model is one in which the interactions within a given scenario are updated when a new interaction occurs rather than at a specific increment of time. This methodology allows for very efficient and fast execution of the model because only those interactions that have changed are being processed.

As with SWEG and SUPPRESSOR, JIMM can simulate many different systems and war-gaming effects at various levels of fidelity. These include sensors (such as radio frequency, infrared, electro-optical, radar warning, sonar, and acoustic), communication systems, jammers, weapons, movers (such as tanks, planes, missiles, and trucks), signatures (infrared, radio frequency, and acoustic), and tactics. JIMM and SUPPRESSOR use a flat-Earth model, but users have built around this for space objects. For the model to implement these systems and effects in a realistic fashion within a scenario, eight generic functions were implemented within JIMM: 1) move, which is the process by which an object changes position and orientation within a scenario; 2) shoot, which is the transmission of matter or energy within a scenario with the intent of damaging or destroying a target; 3) talk, which is the cooperative exchange of information between entities or objects; 4) sense, which is the noncooperative gathering of information about other entities or objects; 5) disrupt, which is the ability to interfere with the sending or communicating functions of an object; and 6) think (notice, digest, react), which provides the capability to realistically model human behavior.*

EADSIM. The Extended Air Defense Simulation (EADSIM) is a work station-hosted, system-level simulation that is used by combat developers, materiel

*The web site for JIMM is http://www.hanscom.af.mil/esc-cx/JIMM.

developers, and operational commanders to assess the effectiveness of theater missile defense and air defense systems against the full spectrum of extended air defense threats. The EADSIM sponsor is the U. S. Army Space and Missile Defense Command. EADSIM provides a many-on-many theater-level simulation of air and missile warfare, an integrated analysis tool to support joint and combined force operations, and a tool to augment maneuver force exercises at all echelons with realistic air defense training. EADSIM models fixed-and rotary-wing aircraft, tactical ballistic missiles (TBMs), cruise missiles, infrared and radar sensors, satellites, command and control structures, sensor and communications jammers, communications networks and devices, and fire support in a dynamic environment, which includes the effects of terrain and attrition on the outcome of the battle. EADSIM supports the four pillars of theater missile defense in a full tactical context by modeling active defense (surface-to-air engagements, air-to-air engagements, multitier engagements, and TBM engagements), passive defense (radar and infrared signatures), attack operations (air-to-surface attacks, surface-to-surface attacks, surveillance, and intelligence collection), and battle management/C^3I (engagement logic, command and control structure, communications networks, and protocols.)

EADSIM can easily be confederated with high-fidelity models, such as BRAWLER. EADSIM is being used by all four U. S. military services, individually and jointly, at over 300 subscriber sites around the world. It is also being used by the United Kingdom, Israel, Australia, and the SHAPE Technical Center under Memoranda of Agreement with the U. S. Army. Of particular note, EADSIM was used successfully by the U. S. Air Force Studies and Analyses Agency to analyze attrition, suppression of enemy air defense missions, and refueling operations during Desert Shield and Desert Storm. The web site for EADSIM is http://www.eadsim.com/.

1.5.3.3 Campaign model—THUNDER. THUNDER is a force-on-force level campaign model that determines the effects of changes in force effectiveness, force structure, and force deployment on a military campaign. THUNDER is a two-sided, theater-level simulation with a comprehensive blue/red air, land, and naval system representation and joint interaction of those systems with one another and their environment. It provides insight into the full range of potential outcomes of a military campaign. THUNDER's ground war combat results were derived from deterministic play of U. S. Army Concepts and Analysis Agency. THUNDER is a data-driven model. Scenarios, force structure, terrain, and weapon systems are described in input data. Emphasis is placed on traceability of data back to intelligence/service documents or lower-level model outcomes. THUNDER is a stochastic model that supports Monte Carlo simulation and statistical inference. A web site for THUNDER is http://www.s3i.com/Default.htm.

Go to Problems 1.5.10 to 1.5.13.

1.6 Testing for Survivability

Because of the many random outcomes in a one-on-one encounter between an aircraft and a threat weapon, survivability is measured by the probability P_S. Thus, testing for survivability ultimately means determining the value of P_S in each of the one-on-one scenarios identified in the mission-threat analysis. To determine the aircraft's P_S for each threat weapon in the scenarios, the test program should include the use of the actual aircraft, configured for combat, flying the assumed flight path over the appropriate topography and encountering the actual threat weapon in a realistic manner. If supporting forces are part of the survivability package for the aircraft, these forces, as well as those of the enemy's air defense, should be included in the test plan.

Many test flights would be required to develop a sufficient database that could be used to determine P_S. This database would consist of the major outcomes of the individual phases of the one-on-one scenario shown in Fig. 1.3 and all of the important variables associated with each phase, such as the range at which the aircraft was first detected, the separation distance between a launched missile and the aircraft as a function of time, and the effect an onboard countermeasure device has upon that distance. Simply put, testing for survivability should include real weapons that are fired at real aircraft in realistic scenarios.

The general test program just described is both impractical and unreasonably expensive for many obvious reasons. Consequently, most of the testing for survivability has been divided into the two categories of susceptibility testing and vulnerability testing. Furthermore, the testing in each category is typically divided into developmental testing, which is conducted relatively early in the life cycle, and operational testing, which is generally conducted on the finished aircraft, or portions of the aircraft. Developmental testing for susceptibility might consist of the examination of the radar signature of subscale models of the aircraft and the testing for the IR signature of candidate designs for the engine exhaust duct. Operational testing for susceptibility might consist of testing to determine the effectiveness of those design features and equipment that reduce susceptibility, such as the level of the actual aircraft's signatures and the effectiveness of any onboard ECM and expendables in increasing the separation distance between a launched missile and the aircraft. Vulnerability testing ranges from the developmental static tests of small components to the realistic system level, full-up tests on the actual aircraft using live ammunition.

The U. S. Department of Defense owns and operates a large number of test laboratories. The DoD major Range and Test facility Bases (MRTFB) is a set of 21 test installations, facilities, and ranges which are regarded as national assets. The members of the MRTFB and their web sites are listed here:

1) Kwajalein Missile Range, Kwajalein Atoll (http://www.smdc.army.mil/FactSheets/RTS.html);
2) 30th Space Wing, Vandenberg AFB, California (http://www.vandenberg.af.mil/30sw/);
3) Naval Air Warfare Center, Weapons Division, Point Mugu, California (http://www.nawcwpns.navy.mil/);
4) Naval Air Warfare Center, Weapons Division, China Lake, California (http://www.nawcwpns.navy.mil/);
5) AF Flight Test Center, Edwards AFB, California (http://www.edwards.af.mil);

6) Air Warfare Center, Nellis AFB, Nevada (http://www.nellis.af.mil);
7) Yuma Proving Ground, Yuma, Arizona (http://www.yuma.army.mil);
8) Dugway Proving Ground, Dugway, Utah (http://www.dugway.army.mil/default.htm);
9) Utah Test and Training Range, Hill AFB, Utah (http://www.hill.af.mil/);
10) USA Electronic Proving Ground, Fort Huachucha, Arizona;
11) Joint Interoperability Test Command, Fort Huachucha, Arizona (http://jitc.fhu.disa.mil/);
12) White Sands Missile Range, White Sands, New Mexico (http://www.wsmr.army.mil/);
13) 46th Test Group, Holloman AFB, New Mexico (http://www.46tg.af.mil/);
14) Arnold Engineering Development Center, Tullahoma, Tennessee (http://www.arnold.af.mil/);
15) AF Development Test Center, Eglin AFB, Florida (http://www.acq.osd.mil/te/mrtfb/commercial/afdtc);
16) Aberdeen Test Center, Aberdeen, Maryland (http://www.atc.army.mil);
17) Naval Air Warfare Center, Aircraft Division, Patuxent River, Maryland (http://www.nawcad.navy.mil/);
18) 45th Space Wing Patrick AFB, Florida (http://www.patrick.af.mil/455W/pa/public.htm);
19) Naval Air Warfare Center, Aircraft Division, Trenton, New Jersey (closed);
20) Atlantic Undersea Test and Evaluation Center, Andros Island, Bahamas (http://www.npt.nuwc.navy.mil/autec);
21) Atlantic Fleet Weapons Training Facility, Roosevelt Roads, Puerto Rico (http://www.globalsecurity.org/military/facility/afwtf.htm).

Figure 1.21 shows the member locations by number. These assets are sized, operated, and maintained primarily for DoD test and evaluation missions. However, the MRTFB facilities and ranges are also available to commercial and other users on a reimbursable basis.

The U. S. DoD facilities and programs for testing susceptibility and vulnerability are briefly described in the next section.

1.6.1 Susceptibility Testing

Learning Objective	**1.6.1**	**Describe the types of susceptibility tests and the DoD susceptibility test facilities.**

Of interest here are those organizations that can conduct susceptibility testing. Susceptibility testing can be divided into the five broad categories listed in the left-hand column of Table 1.15. The types of test facilities that can conduct these types of tests are listed in the right-hand column of Table 1.15 with examples given for a radar-guided missile weapon system. Each of these facilities is briefly described next. Most of the descriptions are taken from the referenced web sites.

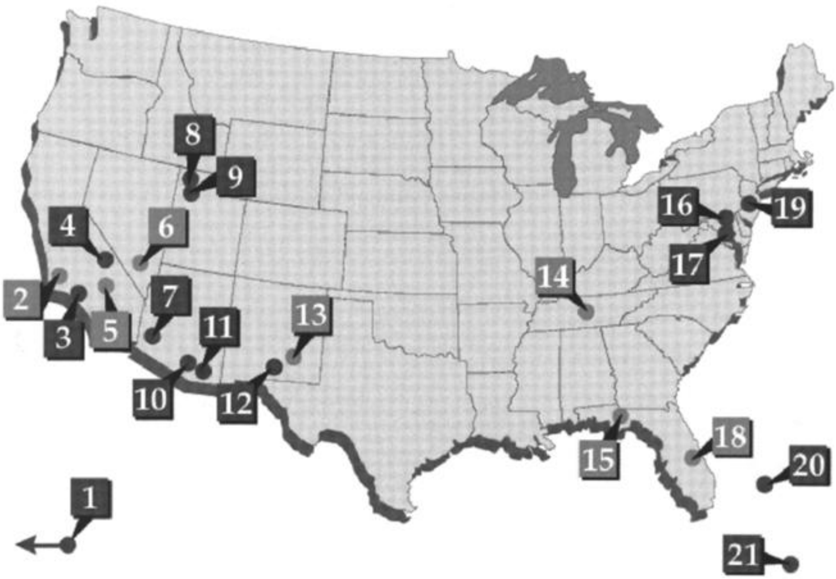


Fig. 1.21 Locations of the members of the MRTFB.

1.6.1.1 Aircraft signature test facilities.

Air Force's NRTF (RATSCAT). The National Radar Test Facility (NRTF), formerly known as the Radar Target Scatter Division (RATSCAT), is a primary DoD facility for outdoor static radar cross section measurements. NRTF is located on the White Sands Missile Range, Holloman AFB, New Mexico, and is comprised of two physically separate sites, the Mainsite and the RATSCAT Advanced Measurement System (RAMS) site. At NRTF full-scale, flyable aircraft and missiles, operational vehicles, aerospace models, and miscellaneous targets can be measured accurately for both monostatic (radar transmitter and receiver colocated) and bistatic (radar transmitter and receiver widely separated) radar target signatures. These measurements support low-observable (stealth) weapon systems development, technology assessments, product improvements and tactical planning for the Department of Defense and U. S. Government-sponsored efforts. The web site for NRTF is http://www.acq.osd.mil/te/pubfac/holloman.html#Radar Target Scatter (RATSCAT).

Navy's Junction Ranch. Signature testing can also be conducted at the Naval Air Warfare Center's Etcheron Junction Ranch Range in California. The range provides the instrumentation suite, test coordination, targets, and support functions for a wide range of tests. The 65-square-mile facility offers excellent air and ground security because of its isolated location, rugged terrain, restricted airspace, and controlled borders and ground space. Remoteness offers a quiet environment free from EMI. The web site for Junction Ranch is http://www.nawcwpns.navy.mil/~pacrange/r1/Etcheron.htm.

Table 1.15 Types of susceptibility tests and facilities

Types of susceptibility tests	Types of test facilities with examples for an RF missile
Aircraft signature testing	*Aircraft signature test facilities* NRTF (RATSCAT) Junction Ranch Radar Reflectivity Laboratory
Aircraft detection testing	*Open-air ranges* Several ranges are used for detection testing.
Missile/projectile trajectory and miss distance testing	*Open-air ranges* White Sands Missile Range NAWC Land Ranges *Ground-mounted seeker test facility* NAWC Electronic Combat Range *Hardware-in-the-loop test facility* Army Missile Command RFSS
Fuze testing to determine fuzing points	*Fuze test facility* MESA
Testing for the effects of countermeasures on the effectiveness of the weapon	*Electronic combat ranges and test facilities* NAWC Electric Combat Range AF Electromagnetic Test Environment AF Electronic Combat Range and Nellis Range Complex *Hardware-in-the-loop test facilities* AFEWES TEMS

Navy's Radar Reflectivity Laboratory. The Radar Reflectivity Laboratory (RRL), located at the Naval Air Warfare Center—Weapons Division, Pt. Mugu, California, is the Navy's premier indoor radar signature test facility. Its purpose is to measure, analyze, and synthesize monostatic and bistatic radar signature data from a wide spectrum of targets, including reentry vehicles, air-to-air missiles, drone targets, aircraft and ship models, low RCS vehicles, components, and others. The RRL operates three indoor anechoic chambers, two of which implement compact range collimating reflectors to produce indoor far-field results. The Bistatic Anechoic Chamber is shown in Fig. 1.22. The radar signature characteristics are determined for a wide range of targets, and detailed signal analysis is performed with in-house developed software and display tools. The RRL supports a broad customer base, including Navy, Army, Air Force, other DoD users, the aerospace industry, and foreign countries. The web site for the RRL is http://www.nawcwpns.navy.mil/~rrl.

1.6.1.2 Aircraft detection test facilities. Several open-air ranges are used to test the detectability of aircraft.

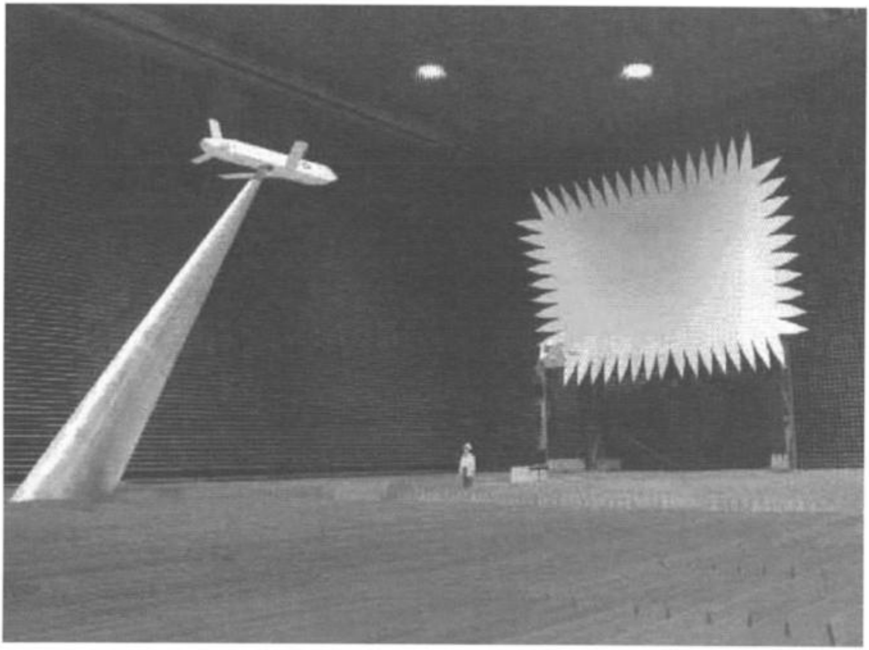


Fig. 1.22 RRL Bistatic Anechoic Chamber. (http://www.nawcwpns.navy.mil/~rrl.)

1.6.1.3 Missile and gun projectile trajectory and miss distance test facilities.

Open-air ranges. 1) The Army's White Sands Missile Range (WSMR) is a multiservice test range whose main function is the support of missile development and test programs for the Army, Navy, Air Force, NASA, other government agencies, and private industry. The White Sands range is under operational control of the U. S. Army Test and Evaluation Command, Aberdeen Proving Ground, Maryland. The missile range is in the Tularosa Basin of south-central New Mexico. At almost 3200 square miles the range is the largest military installation in the country and could easily encompass the states of Delaware and Rhode Island. White Sands Missile Range has more than 1500 precisely surveyed instrumentation sites and some 1000 of the newest and most modern types of optical and electronics instrument systems. These include long-range cameras, tracking telescopes, interferometer systems, radars, and telemetry. Other range services include calibration, communication, meteorological, photographic, television, and aerial target support. The headquarters area is 20 miles east of Las Cruces, New Mexico, and 45 miles north of El Paso, Texas. The WSMR web site is http://www.wsmr.army.mil/.

2) The Navy's Land Ranges are part of the Naval Air Warfare Center Pacific Ranges and Facilities. With over 1.1 million acres the ranges provide a large, secure, highly instrumented air range and ground range complex for testing live

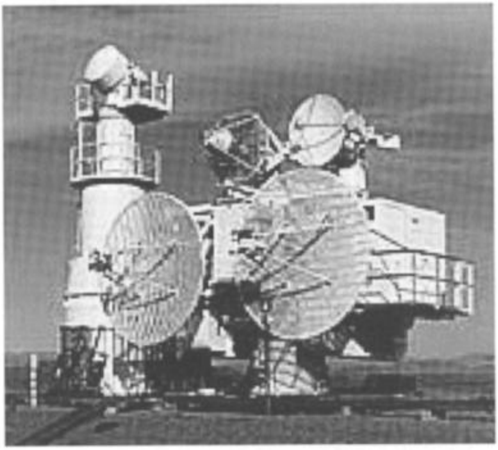


Fig. 1.23a Some radars at the ECR. (http://www.nawcwpns.navy.mil/~ pacrange/r1/Ecr.htm.)

and inert missiles, rockets, guns, lasers, and aircraft systems. A broad selection of targets is available. Capable of day and night operations, the Land Ranges provide an ideal environment for testing conventional weapons and aircraft systems. They provide the general management, administration, scheduling, and support required to conduct surface-to-air missile tests, as well as a many other types of tests. Instrumentation includes radars, the GPS, lidar (light/laser radar), video tracking systems, telemetry receiving, meteorological data gathering systems, fixed and tracking optical cameras, real-time data processing, and displays. The Land Ranges web site is http://www.nawcwpns.navy.mil/~pacrange/r1/Land1.htm.

Ground-mounted seeker test facility—the NAWC Electronic Combat Range. The Naval Air Warfare Center (NAWC) Electronic Combat Range (ECR) is another part of the NAWC Pacific Ranges and Facilities. It is a secure, open-air laboratory that provides engineering support, developmental and operational test and evaluation, analyses, and training resources for users of systems that counter or penetrate air defenses. It is the Navy's principle open-air range (OAR) for the T&E of airborne EC systems. The range supports all types of electronic countermeasure testing for multiple threat systems—either actual, surrogate, or simulated—using a broad range of radar technologies, including pulse, continuous wave, Doppler, and multispectral systems. Other test emitter spectrums are infrared, electro-optic, and laser. The types of testing include electronic attack effectiveness testing, radar warning receiver testing, antiradiation missile flight testing to evaluate seekers and avionics, and tactics development against surface-to-air threats. Figures 1.23a and 1.23b show some of the radars and other equipment at the ECR. The web site of the ECR is http://www.nawcwpns.navy.mil/~pacrange/r1/Ecr.htm.

1.6.1.4 Fuze test facility—Missile Engagement Simulation Arena. The Missile Engagement Simulation Arena (MESA) is located at the NAWC, Weapons Division, China Lake, California. It is a state-of-the-art laboratory that combines

Fig. 1.23b F-18 over the sea site at the ECR. (http://www.edwards.af.mil/capabilities/docs_html/flighttest.html.)

innovative simulation technology and facility design to provide an effective way to evaluate the interactions between a missile fuze sensor and its target. MESA was designed from the ground up to be a unique laboratory. It consists of a test range and secure spaces. MESA's range is a high-bay simulation arena that is 150 ft wide, 405 ft long, and 90 ft high. Interior surfaces are designed to minimize and control background clutter to aid in accommodating a variety of sensor systems. The interior layout of MESA is shown in Fig. 1.24a, and the arena, a full-scale target, and a fuze are shown in Fig. 1.24b.

MESA's advanced engagement simulation hardware includes 1) an instrumentation radar, 2) a three-axis sensor positioner, 3) a sensor transporter, 4) a midrange target support, 5) a downrange target support, and 6) two controllers that can position calibration spheres in two dimensions. The MESA simulation software consists of the Engagement Generation Software, Control Software, Data Acquisition Software, Quality Assurance Software, and Fault Diagnostics Software. The Engagement Generation Software translates the desired end-game geometry into MESA range coordinates. The output is used by the MESA Control Software to set up the missile target engagement for data acquisiton. The Control Software moves and positions the simulation hardware, provides the operator interface to control the progress of the simulation, and logs operations for future reference.

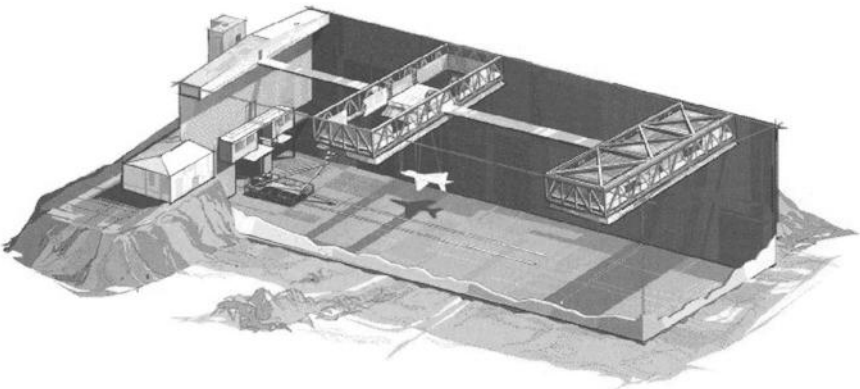


Fig. 1.24a Interior layout of the MESA range. (http://www.nawcwpns.navy.mil/~fuzing/.)

Fig. 1.24b Target and a fuze in the MESA range. (http://www.nawcwpns.navy.mil/~fuzing/.)

The Data Acquisiton Software collects, processes, and stores the signals from the sensor on each data collection run. A number of full-scale and subscale missile, jet aircraft, and helicopter targets are available. The web site. for MESA is http://www.nawcwpns.navy.mil/~fuzing/.

1.6.1.5 Facilities for testing the effects of countermeasures on weapon effectiveness.

Electronic combat ranges and test facilities. 1) For information regarding the NAWC Electronic Combat Range, refer to the preceding description.

2) The Air Force's Electromagnetic Test Environment (EMTE) is an extensive open-air test range providing over-land and over-water weapon effectiveness testing for munitions and electronic combat systems. It is part of the Air Armament Center (AAC), formerly the Air Force Development Test Center (AFDTC), and is located at Eglin Air Force Base (AFB), 7 miles northeast of Fort Walton Beach, Florida. AAC is the parent organization to the 46th Test Wing, which conducts the developmental test and evaluation (DT&E) and operational test and evaluation (OT&E) mission at Eglin AFB. Specialized testing at the EMTE includes characterization and effectiveness testing, foreign material exploitation, signature measurement, and air-to-air and air-to-ground munitions in an EC environment. The web site for the EMTE is http://www.acq.osd.mil/te/pubfac/eglin.html#Capabilities.

3) The Air Force's Flight Test and Open-Air Ranges are used to evaluate electronic warfare (EW) systems. Typically these resources are divided into subcategories of test ranges and airborne testbeds and includes ground test, test track, and flight test in the evaluation of airborne electronic warfare devices and systems. In evaluating systems under real-world representative environment and operating conditions, open air range testing is used to validate system operational performance and effectiveness at a high level of confidence. The electronic warfare flight-test ranges—the Electronic Combat Range and the Nellis Range Complex—are instrumented and populated with high-fidelity, manned or unmanned threat simulators. Additional emitter-only threat simulators are used to provide high signal density, typical of operational electronic warfare environments. The Air Force Flight Test Center's airborne testbeds range from small aircraft with pod-mounted components or systems to large aircraft designed for spread-bench installation and testing of electronic warfare components, subsystems, systems, or functions of avionic suites in early development and modification—often before the availability of prototype or production hardware. Information on the Complex is available on the Web at http://www.edwards.af.mil/products_svc/index.html.

Hardware-in-the-loop test facilities. 1) The Air Force Electronic Warfare Evaluation Simulator (AFEWES), is a secure, government-owned, HITL test laboratory, located at Air Force Plant 4 in Fort Worth, Texas. Managed by the Air Force Flight Test Center's (AFFTC) 412th Test Wing at Edwards AFB, California, AFEWES develops and operates high-fidelity radio frequency and infrared threat simulators that evaluate the effectiveness of DoD and Allied EC systems in a controlled, ground-based laboratory environment. Figure 1.25 illustrates the various electronic aspects of an encounter between an aircraft and a ground-based

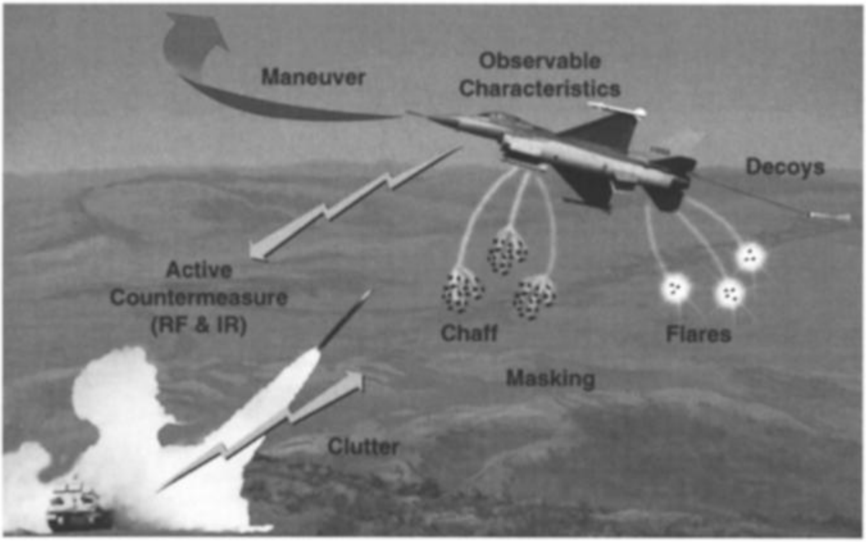


Fig. 1.25 AFEWES mission overview. (http://edwards.af.mil/capabilities/docs_html/afewes.html.) Courtesy of 412 Test Wing, Electronic Warfare Directorate, Edwards AFB, CA.

threat that can be simulated in the AFEWES. Simulated engagements are conducted at actual frequencies, in real time, incorporate hostile operator-in-the-loop effects, and produce vector miss distance and other endgame data products. Defensive EC systems and tactics, from advanced concepts through actual fielded hardware, can be evaluated in AFEWES against surface-to-air missiles, antiaircraft artillery, airborne interceptors, and air-to-air missiles in an instrumented laboratory environment. Over its 40-year history, AFEWES has successfully evaluated many different types of defensive avionics systems and tactics to enhance warfighter survivability. The web site for AFEWES is http://afewes.edwards.af.mil/

2) The Test and Evaluation Modeling and Simulation (TEMS) facility at Edwards AFB provides DT&E and OT&E flight-test programs with virtual real-time simulations (real people operating simulated systems) and constructive non-real-time simulations (simulated people operating simulated systems). The TEMS can model a multiday, theater-level campaign, simulating a force-on-force, air-land battle. Where mission-level metrics are required, TEMS has the ability to model air superiority and survivability to simulate a many-on-many, air-land battle using SUPPRESSOR and the Digital Air Defense Systems (DIADS). The DIADS at TEMS will provide a hardware-in-the-loop capability for evaluating operational effectiveness of electronic combat components in a real-time simulated enemy integrated air defense systems environment. DIADS is the follow-on core simulation system of the Real-Time Electromagnetic Digitally Controlled Analyzer Processor (REDCAP) facility, which was previously located in Buffalo, New York. The new

DIADS facility at Edwards will incorporate the hardware-in-the-loop subsystems previously located at REDCAP. The HITL subsystems allow operator-in-the-loop operations within the IADS command and control structure. The TEMS web site is http://afftc.edwards.af.mil:80/capabilities/docs_html/tems.html.

Go to Problems 1.6.1 to 1.6.2.

1.6.2 Vulnerability Testing

Learning Objectives	**1.6.2**	**Describe the three major service vulnerability test facilities.**
	1.6.3	**Describe the Joint Live Fire test program and the Live Fire Test law.**

Testing for vulnerability began shortly after WWII, when surplus U. S. Air Force bombers were shot at with live ammunition to determine the ability of the bombers to withstand the hit. Since then, developmental testing for vulnerability has been an integral part of military aircraft acquisition programs. The major DoD vulnerability test facilities are the Army Research Laboratory SLAD Airbase Range Facility, the Air Force Aircraft Survivability Research Facility, and the Navy Weapons Survivability Laboratory. Reference 65 contains descriptions of the three test facilities.

1.6.2.1 Army Research Laboratory SLAD Airbase Range Facility. The U. S. Army Research Laboratory SLAD Airbase Range Facility is located at Aberdeen Proving Ground, Maryland, and can be used to conduct component through system-level experiments on fixed-wing aircraft and helicopters to generate data for vulnerability/lethality (V/L) analyses, model and simulation support, vulnerability reduction, and Army aircraft Live Fire Testing and Joint Live Fire programs. Specialized features at the facility include an outdoor environmental blast pad area for large HE warhead firings, a covered, full-scale dynamic turbine engine and helicopter drive train test pad, indoor and outdoor ballistic ranges for component and system-level experiments, an Environmental Protection Agency (EPA) approved spill containment and fluid separator system, a mobile airflow generator capable of producing winds as great as 500 kn, and a centralized instrumentation and control building. Figure 1.26a shows the Range Facility.

The environmental blast pad area is a concrete pad 6-ft thick with a 100 by 100-ft primary pad and a 50 by 50-ft secondary pad. A full-scale aircraft, with airflow, can be operated on this pad. High explosive charges as large as 100 lb can be detonated to determine the vulnerability of full-up aircraft, subsystems, and components. The Structural Research Building is an 85 $\times$ 50-ft bunkered building with a structural floor attachment system, overhead crane, and two 60-ft roll-open doors in the front and rear walls, providing an enclosed structure for the testing of whole aircraft or aircraft sections against projectiles and high explosives. This building is capable of withstanding blast from detonations as large as 25 lb of high

Fig. 1.26a SLAD Airbase Range Facility (courtesy of the U. S. Army).

explosive with the doors open and 5 lb with the doors closed. Figure 1.26b is a photo of the Structural Research Building.

1.6.2.2 Air Force Aerospace Vehicle Survivability Facility. The Air Force Aerospace Vehicle Survivability Facility (AVSF) is operated and maintained by Aerospace Survivability and Safety Flight, Munitions Test Division, 46th Operating Group, 46th Test Wing at Eglin AFB, FL (46 OG/OGM/OL-AC). The AVSF is located at Wright-Patterson AFB, Dayton, Ohio, The AVSF is used to conduct research, development, test and evaluation of combat survivable aerospace vehicles by testing the system performance of today's and tomorrow's weapon systems and system components under realistic threat conditions. It is the Air Force's Center of Expertise for Live Fire Test and Evaluation. Primary capabilities consist of Ranges 1-3, Range A, and the Aircraft Engine Nacelle Fire Test Simulator (AENFTS). Ranges 1 and A are used for basic research and development, for developing threat simulations and test range instrumentation, and for evaluating material and component ballistic tolerance. Range 2 is used for research and testing involving fueled and non-fueled vulnerability test programs. Range 3, shown in Figs. 1.27a and 1.27b, is used to conduct ballistic vulnerability test and evaluation on full-scale (fighter-size) aerospace vehicles and test articles and for large-scale technology research and development programs. The AENFTS is used to conduct research and development in aerospace vehicle engine nacelle fire initiation and sustainment. It is a DoD Center of Expertise for aerospace vehicle fire extinguishing (agents, detection, and extinguishing systems)

Fig. 1.26b Structural research building (courtesy of the U. S. Army).

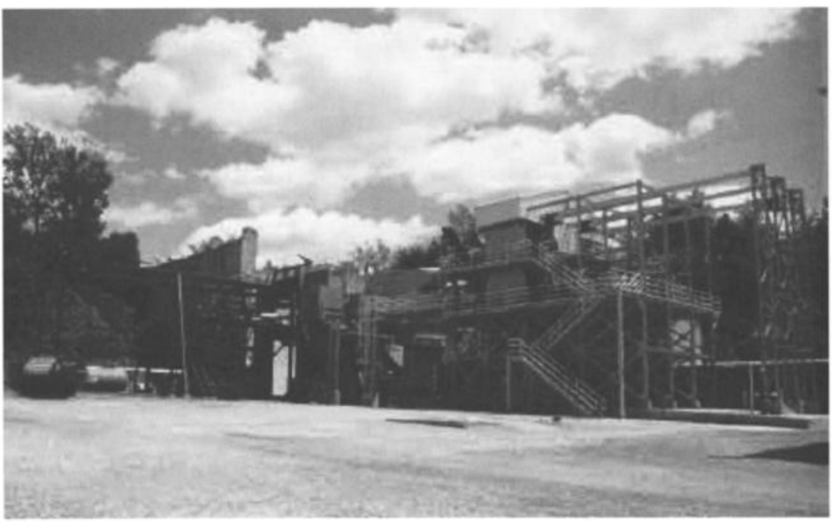


Fig. 1.27a AVSF Range 3 (courtesy of the U. S. Air Force).

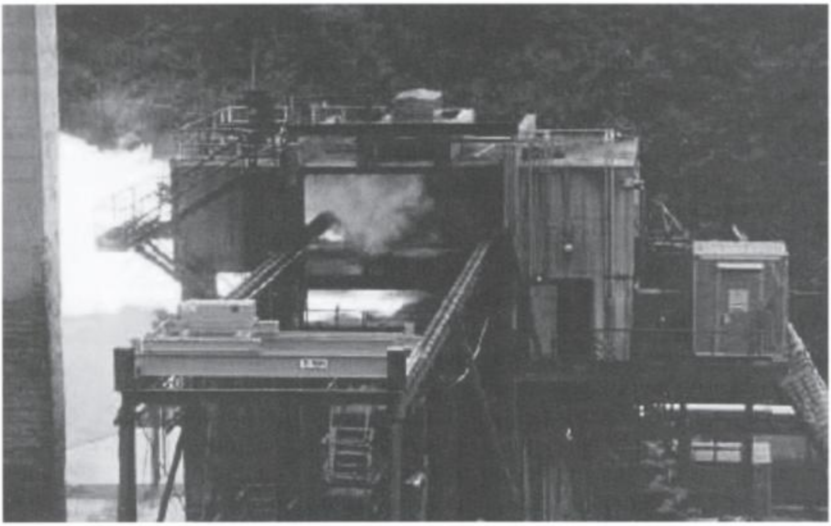


Fig. 1.27b AVSF Range 3 (courtesy of the U. S. Air Force).

Each facility has a stand-alone data acquisition system designed to record data at up to 10 million samples per second on multiple channels. Airflow over the test article is provided by five TF-33 jet engines at Range 3. These engines provide a 25-ft^2 airflow area at up to 500 kn. Other flight simulation equipment at the facility provides airframe/structure loading, fuel conditioning, aircraft system operation, and other aspects of flight conditions. The AENFTS is a unique facility in the DoD that provides realistic operating conditions in engine nacelles and the dry bays surrounding the nacelle, including temperature, internal airflow exchange rate, and aircraft systems operations. Tests in the AENFTS are repeatable, allowing statistical analyses of fire conditions and fire extinguishing systems.*

1.6.2.3 Navy Weapons Survivability Laboratory. The Navy Weapons Survivability Laboratory (WSL) is an 8-square-mile facility located in a remote, secure area at the NAWC, Weapons Division, China Lake, Clifornia. It is capable of conducting survivability and lethality tests on U. S. and foreign hardware ranging from full-scale aircraft and subsystems to smaller-scale developmental hardware, simulators, replicas, components, and materials. The test weapons include small arms and AAA gun projectiles up to 40-mm, actual missile HE warheads up to 200-lb net explosive weight, and single fragments up to 7200 fps. There are six test pads, ranging from a 170 by 105-ft heat-resistant concrete pad, shown in Fig. 1.28a, to a 75 by 235-ft dirt pad. The test stands include jet engine stands capable

*The point of contact for the AVSF is John Murphy (alt. Thomas Holthaus) 46 OG/OGM/OL-AC, Bldg. 1661, 2700 D Street, Wright-Patterson AFB, OH 45433-7605; telephone: (937)255-6302×204, or DSN 785-6823/6302×204; Fax:(937)255-2237; e-mail:john.murphy@wpafb.af.mil.

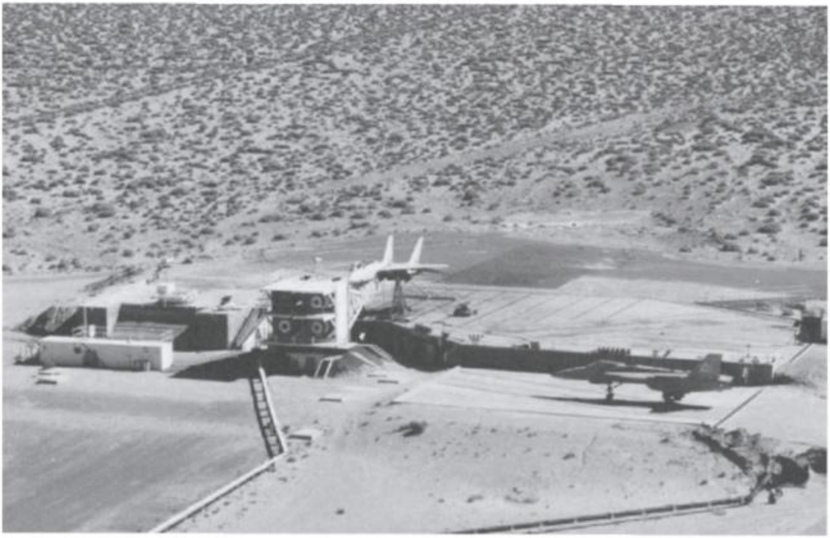


Fig. 1.28a Main test pad at the WSL (courtesy of the U. S. Navy).

of mounting most turbojet or turbofan engines, full-scale aircraft stands capable of mounting full-scale aircraft up to transport size, and a rolling crane capable of carrying 60,000 lb. Airflow conditions are simulated using the High Velocity Airflow System (HIVAS), shown in Fig. 1.28a. Airflow velocity can range from 40 kn over 110 ft^2 to 550 kn over 18 ft^2. Considerable data acquisition and display equipment are available, including up to 200 recordable data channels, 120 instrumentation amplifiers for signal conditioning, two 14-track wide-band instrumentation recorders, and a real-time control room data display system with high-speed documentary motion picture cameras and seven color video systems.

Since its establishment in 1970, the WSL has hosted a wide spectrum of customers including the Office of the Secretary of Defense, NAVAIR, Naval Sea Systems Command, the Air Force and Army, France, Israel, and most of the U. S. aircraft manufacturing companies. Examples of tests that have been conducted are 1) tests on full-scale aircraft, as shown in Fig. 1.28b; 2) propulsion systems tests on both missiles and aircraft; 3) hydrodynamic (hydraulic) ram tests on fuel systems; 4) tests of fire-detection and fire-extinguishing systems; 5) fuel-ingestion tests on engines under full-up and simulated full-up operating conditions; and 6) warhead detonations against running engines or airframes with or without airflow, as shown in Fig. 1.28c. The WSL web site is http://www.nawcwpns.navy.mil/~survive/wsl2.htm.

Go to Problems 1.6.3 to 1.6.4.

1.6.2.4 Live fire testing of aircraft. In the middle 1980s, as a consequence of the increasing concern about the vulnerability of current and future U. S. aircraft,

Fig. 1.28b IR live-fire missile test (courtesy of the U. S. Navy).

two major test programs were established in which live ammunition is fired at actual aircraft or at their major components. These two programs are the Joint Live Fire (JLF) Test Program and the Live Fire Test Law and Program.

Joint Live Fire Program. In March of 1984, the Deputy Under Secretary of Defense for Research (T&E) established the charter of the Joint Live Fire Test Program. The objectives of the JLF program are as follows:

1) Gather empirical data on the vulnerability of U. S. systems to foreign weapons and the lethality of U. S. weapons against foreign targets.
2) Provide insight into design changes necessary to reduce vulnerabilities and improve lethalities of U. S. weapons systems.
3) Enhance the database available for battle damage assessment and repair.
4) Validate current vulnerability and lethality methodologies.

There are two major programs associated with JLF: the antiarmor program and the aircraft program. In the antiarmor program threat weapons are used against U. S. ground systems, and U. S. weapons are fired at threat-representative armor. In the aircraft program front-line U. S. aircraft are subjected to hits by live threat-representative rounds, and threat-representative aircraft are tested against live U. S. warheads and rounds. The testing for the vulnerability of the U. S. aircraft was assigned to the JTCG/AS. The particular aircraft selected for testing were the

Fig. 1.28c Joint live-fire fuel ingestion test on the F/A-18 (courtesy of the USN).

F-15, F-16, F/A-18, A-6E/F, AV-8B, UH-60, and AH-64. The fuel, propulsion, flight control, and structural systems have received the primary emphasis in JLF. Over 60 JLF tests have been conducted since 1984. For further information on the JLF program, contact the JTCG/AS central office described in Sec. 1.3.5.

Live Fire Test Law and Program. In Fiscal Year 1987, because of the perceived inadequacy of the current platform vulnerability and weapon lethality testing of new weapons systems within the DoD, the U. S. Congress amended Title 10, U. S. Code, by adding Section 2366, "*Major Systems and Munitions Programs: Survivability and Lethality Testing; Operational Testing*." This law is known as the Live Fire Test Law. The LFT law requires that the Secretary of Defense conduct realistic survivability, lethality, and initial operational testing and evaluation on covered weapons systems before they proceed beyond low-rate initial production. Covered systems include new, major acquisitions or any product improvement that significantly affects vulnerability or lethality. According to the law, realistic survivability testing means testing for the vulnerability of the system in combat (full-scale) by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the operational requirements and combat performance of the system. Configured for combat (full-up) means loading or equipping the system with all dangerous materials (including all flammables and explosives) that would normally be onboard. Such full-up, system-level testing shall be conducted sufficiently early in the development phase of the system to allow any design deficiency demonstrated by the testing to be corrected in the design of the system, before proceeding beyond low-rate initial production (Note 58).

The Secretary of Defense may waive the requirement for realistic tests, that is, the full-up, system-level tests, if the Secretary certifies to Congress, before the system enters engineering and manufacturing development, that live fire testing would be unreasonably expensive and impractical. Any such certification must include an alternative strategy approved by the director, operational test and evaluation (DOT&E), describing the plans to evaluate the survivability or lethality of the system. Waiver of the requirement for realistic survivability testing does not remove the requirement for survivability testing of components, subsystems, and subassemblies. For example, an alternative plan can include testing of a system by firing munitions likely to be encountered in combat at components, subsystems, and subassemblies, together with performing design analyses, modeling and simulation, and analysis of combat data in lieu of testing the complete system configured for combat.

According to the Live Fire Test and Evaluation (LFT&E) Guidelines from the Test and Evaluation Committee, Office of the Secretary of Defense, the objective of the LFT&E program is to provide a timely and thorough assessment of the vulnerability/lethality of a system as it progresses through its development and subsequent production phases. That assessment should include live fire testing complemented by modeling/simulation efforts in the evaluation process. LFT&E should demonstrate the ability of the weapon system to provide battle resilient survivability or lethality and provide insights into the principal damage processes occurring as a result of the munition/target interaction and into techniques for reducing personnel casualties or enhancing system survivability/lethality.

According to the LFT&E Guidelines there are nine steps to be accomplished by the military services in the LFT&E process of a particular weapon system. The first step is a study of the vulnerability requirements of the system, the relationship of the system to the operational setting, and the current and future threat projections. The second step consists of a vulnerability assessment of the system. Step number three is the identification of the goals of the test program. The measures of evaluation are identified in step four, and the test objectives are defined in step five. Derivation of the data requirements is accomplished in step six. In step seven the evaluation procedures are identified. The resources required for the test and the evaluation are determined in step eight. The final step consists of developing the strategy for including the LFT program in the TEMP and obtaining approval of the plan by the LFT office.

The LFT program is currently headed by the Deputy Director, Operational Test and Evaluation/Live Fire Test and Evaluation. This office observes, oversees, and formally reviews the LFT&E strategies and prepares all reports required in the LFT&E program. These reports include the Annual Report to Congress, as well as the independent Office of the Secretary of Defense LFT&E Report, which also is submitted to the committees of Congress prior to any full-rate production decision. The current location, phone numbers, and e-mail address of the Director, LFT&E are as follows: DOT&E/LFT&E, Pentagon Room 1C730, Office of the Secretary of Defense, Washington, DC 20301; telephone: (703)614-3991, Fax: (703)614-3992; and e-mail: Larry.Miller@osd.mil. The LFT&E program has a web site at http://www.dote.osd.mil/lfte/INDEX.HTML.

Go to Problems 1.6.5 to 1.6.9.

1.7 Conclusions and Points to Remember

1.7.1 Where We Are Today

Because of the U. S. military's experience over the past five decades with aircraft that were not specifically designed to survive in combat, survivability is now a critical system characteristic that has evolved into a distinct and important design discipline. A viable, cost-effective technology exists for reducing susceptibility and vulnerability, a methodology exists for assessing survivability, education in survivability is available, testing for survivability is mandated, top-level survivability design guidance is prescribed, and quantified requirements on the susceptibility and vulnerability of aircraft are now routinely specified. Much of the credit for the increased emphasis on the combat survivability of aircraft goes to the JTCG/AS, which was established in 1971 with a goal to develop survivability as a design discipline. Credit also goes to the DoD survivability organizations and dedicated personnel, the survivability engineers in the aircraft industry, and those military program managers who wanted their aircraft to be survivable.

One of the most obvious, and difficult, aspects of the ACS discipline is the breadth of the engineering disciplines and operational organizations and personnel that can influence an aircraft's survivability. Here is a summary of the major contributors to (or detractors from) survivability: susceptibility, which encompasses threat warning equipment, ECM equipment, expendables, aircraft signature specialists, threat suppression weapons, tactics organizations, flight performance, payload and weapons carried, escorts and supporting aircraft, cockpit design, mission planning systems, navigation equipment, target acquisition equipment, weapons delivery equipment, and the crew; and vulnerability, which encompasses fuel system design, propulsion system design, flight control system design, structural system design, electrical system design, avionics system design, ECS system design, power train /blade design, and the crew.

Go to Problems 1.7.1.

1.7.2 Remember These Points

In closing this overview of the fundamentals of ACS, several very important points should be emphasized.

First, although survivability is but one of many attributes that contribute to an effective military aircraft it might be the most important. Who wants to fly into combat in a killable aircraft?

Second, survivability is obtained using many different enhancement features, and the design should be properly (not necessarily evenly) balanced between susceptibility reduction and vulnerability reduction. The optimistic assumption that the aircraft will never get hit might not be valid over the lifetime of the aircraft. In addition, the pessimistic assumption that a hit aircraft is a dead aircraft and nothing can (or should) be done about it is also wrong. In the best scenario the survivable aircraft will seldom get hit, but when it does get hit it will either get back home, or the crew will eject over friendly territory. And it is affordable if done early and correctly.

Third, survivability must be seriously considered by everyone during the early design phases of the aircraft. It is at this stage that survivability enhancement features can best be incorporated. Retrofitting survivability features into existing aircraft, or adding them in the full-scale development phase, usually creates weight, cost, and other performance penalties that could have been avoided if the features had been included in the early design. This is particularly true for signature reduction and vulnerability reduction.

Fourth, the people who are responsible for the survivability analysis and design of an aircraft weapon system must not work in a vacuum or be ignored. They must have contact with the aircraft designers, the program manager, and the operators on a continuing basis, pointing out the importance of those features of the aircraft design and utilization that contribute to the reduction of the susceptibility and the vulnerability of the aircraft. Remember, the goals of survivability are to increase the cost effectiveness of the aircraft as a weapon system and to increase the likelihood the crew of an aircraft that is terminally damaged will be recovered—not to design the most survivable aircraft possible.

Finally, history has shown time and time again that designing survivability into military aircraft pays off: fewer wars are fought, more missions are accomplished, more battles are won, and more lives are saved when aircraft are designed to be survivable.

Go to Problem 1.7.2.

Endnotes

1. The specific use of the term *susceptibility* to refer to the occurrence of an undesirable event (the inability of an aircraft to avoid being hit by the air defense) and *vulnerability* to refer to the undesirable consequence of that event (the inability of the aircraft to withstand the hit) is not widely known outside of the aircraft combat survivability discipline. The term *vulnerable* is generally used by those unfamiliar with the discipline to describe something that can be killed or injured in a particular situation.

   For example, in an Associated Press article in the *San Francisco Chronicle*, 17 July 1998, p. A17, that described the results of a new study of earthquakes in the Los Angeles area, the reporter wrote: "Geologists have dug up evidence that at least two earthquakes of magnitude 7.2 to 7.6 struck downtown Los Angeles within the last 15,000 years, suggesting the region is vulnerable to more powerful quakes than previously known." In the survivability discipline this would have been written as "..., suggesting the region is *susceptible* to more powerful quakes than previously known." That is, more powerful earthquakes are more likely to occur than previously thought. In the vernacular of the ACS discipline, the vulnerability of the area to a more powerful earthquake depends upon the inability of the buildings, bridges, and roads to withstand the more powerful earthquake.

   In the military world if an Air Force General asks "What is the vulnerability of the B-2 bomber?," he or she may want to know "What is the killability of the B-2 bomber on a particular mission?" or "What is the likelihood the B-2 bomber is killed given that it is hit by a particular weapon?" Both definitions are possible and acceptable using the general definition of vulnerability just given. In the first interpretation the particular situation is the mission, whereas in the second interpretation the particular situation is the aircraft is hit. The latter interpretation, where the aircraft is hit, is the only one used by the "guns and missiles" survivability community for vulnerability; the term *killability* is used for the term *vulnerability* in all other situations.

To complicate matters further, other survivability communities, such as chemical/biological survivability and electronic warfare, have different definitions for the terms susceptibility and vulnerability. This ambiguity in terminology must be kept in mind by the members of the guns and missiles survivability community when communicating with those unfamiliar with the combat survivability discipline. Dividing the event of an aircraft kill by the air defense into two sequential parts—the inability of the aircraft to avoid the hostile environment or susceptibility and the inability of the aircraft to withstand the environment or vulnerability—is very useful to the survivability community, but this distinction in meanings might not be familiar to everyone else.

For example, the medical community, when writing about the Acquired Immuno Deficiency Syndrome (AIDS), which is the late stage of infection caused by the Human ImmunoDeficiency Virus (HIV), also uses the words susceptibility and vulnerability. My search of the Internet in 2002 using the Google search engine found 56,400 sites that contained the words AIDS and susceptibility; 86,300 sites that contained the words AIDS and vulnerability; and 4740 sites that contained AIDS and both susceptibility and vulnerability. These numbers seem to indicate that, in general, people use either susceptibility (40%) or vulnerability (60%) to refer to both contact with, or infection by, the HIV and the inability of the human body to withstand the virus. No distinction is made between contact with the HIV and the reaction to the HIV. Perhaps susceptibility could be used to indicate the likelihood a person comes in contact with the HIV and vulnerability could be used to refer to the likelihood that a person infected with HIV is unable to withstand the infection caused by the virus?

2. The reader unfamiliar with the concept of probability and elementary probability theory should read Appendix B: Probability Theory and Its Application to Survivability Assessment.
3. Definitions of many of the kill categories and levels used in survivability are given in Chapter 5, Sec. 5.2.2.
4. The term *killability* is not to be confused with the term *lethality*, which is the ability to kill. Killability has the same relative meaning as the term *maintainability*. Maintainability refers to the ease with which the aircraft is maintained; killability refers to the ease with which the aircraft is killed.
5. The P_K given by Eq. (1.2) is the joint probability of aircraft hit and kill given hit and should be denoted as $P_{(H\ AND\ K)}$, the probability the aircraft is hit and killed. However, the requirement that the aircraft must be hit to be killed is an obvious one, and consequently the event of hit and kill is shortened to just kill; the hit is implied. Similar omissions are made in sequential conditional probabilities throughout the textbook when the omitted prior conditions are obvious. However, the reader is reminded to keep the omitted prior conditions in mind.
6. In general, the threats to aircraft are weapons. A weapon is an object used in fighting to cause bodily injury or physical damage, and a weapon system consists of the weapon and the components required for its operation. For example, guns and guided missiles are weapons. A loaded gun mounted on a wheeled vehicle with target acquisition

and fire control equipment is a weapon system. For simplicity, the word *weapon* will be used hereafter to denote either a weapon or a weapon system when the distinction is unimportant. The ability of a weapon, or weapon system to kill its target is often referred to as either the effectiveness or the lethality of the weapon or weapon system. The term *warhead lethality* is used to denote the ability of the warhead on the weapon to kill the target given a direct hit or a proximity burst.

7. A number of sites on the Worldwide Web dedicated to air defense weapons are listed in Chapter 3.
8. "Studies say the military misled the United States during the 1980s. Pentagon overstated the Soviet threat, the ability of (new U. S.) weapons, and understated costs," according to a three-year study by the General Accounting Office (GAO). "Present and former defense officials have vigorously denied any misrepresentation."[66]
9. References 67 and 68 and the Website http://www.fas.org/spp/aircraft/part03.htm contain an examination of the historical effectiveness of air defense.
10. The tree diagram is described in detail in Appendix B, Sec. B.5.
11. The concept of an active threat in the survivability discipline is very similar to the concept of an available weapon in the reliability discipline. The subtle difference is that a weapon that is available to the enemy, that is, it is reliable, might not be used for several reasons, such as the inability of the weapon's daytime detection and track sensors to function at night.
12. This is the situation when the U. S. F-117 aircraft flew over Baghdad on the first night of Operation Desert Storm in January 1991. They were exposed to the enemy's air defense weapons, but they were not detected. However, although not detected, the F-117s could have been killed by unaimed or barrage fire from guns or by unguided SAMs. In this situation the requirements for detection and engagement given detection are bypassed. The sequence of probabilities becomes P_A and $P_{I|A}$, the probability of a successful intercept by an unaimed projectile or unguided missile fired by an active weapon.
13. The conditional probability $P_{E|A}$ is stated as the probability the aircraft is engaged given an active threat. One is tempted to say of course the threat must be active to engage the aircraft; inactive threats do not engage aircraft. But that is the wrong interpretation. The correct interpretation is $P_{E|A}$ is the probability the aircraft would be engaged if the threat had the opportunity to engage it. Perhaps the threat is active, perhaps it is not; but if it is active, then the aircraft's probability of being engaged by the active threat is $P_{E|A}$.
14. The phrase independent shots implies independent shot outcomes, that is, independent shots have independent outcomes, and dependent shots have dependent outcomes.
15. A more detailed description of the many missions of military aircraft is given in Chapter 3, Sec. 3.1.
16. Lt. Goodman took the author's Aircraft Combat Survivability course while attending the Naval Postgraduate School soon after his experience in Lebanon. He said he never saw the missile that hit his aircraft.
17. The concept of the expected number of aircraft that would be killed while flying on a mission can be difficult to understand. To illustrate this concept using a simple example, consider the toss of a fair coin. Each toss of the coin is analogous to one aircraft flying the mission. There are two possible outcomes of each toss: a head or

a tail. Assume that the outcome of a head is analogous to the aircraft surviving the mission and a tail is analogous to the aircraft being killed while on the mission. If you toss a fair coin once, the probability you will get a tail is 0.5 (analogous to P_K). If you toss the coin A times (analogous to A aircraft flying the mission), the expected number of tails is 0.5A. In the actual event of A tosses, the number of tails can vary from zero to A, and the expected number is 0.5A. Refer to Appendix B, Secs. B.5 and B.6 for more details.

18. From *A Wing and a Prayer*, by Harry H. Crosby, who flew 37 missions in B-17s with the 8th Air Force, "by the end of the war the 100th had lost 200 planes and 86% of its original crews."[69]
19. Other definitions of sortie generation rate are the number of sorties flown divided by the total inventory and the number of sorties flown divided by the number of available aircraft divided by the number of days of operations. Using the latter definition, if 100 aircraft fly 600 sorties in 3 days, the SGR is 2 sorties (per aircraft) per day.
20. From an interview with Capt. Ray Alcorn, the Commander, Naval Air Station, Fallon, Nevada, in the *San Francisco Chronicle*, 9 July 1989:

    > The pilot has to navigate to a target that may be three miles or 400 miles away. He's probably going to be at low altitude, high speed, just in order to survive. He may be in an area where there are not even any charts to help him, and there may be a thousand switches to operate. Maybe there are 20, 30 planes with him, and they all must be in the right place. Basically, somebody is trying to kill him in the process of his doing his job.

21. The assumption is made in Fig. 1.9 that the aircraft must also survive the return to home base for the mission to be considered a success. If this assumption is not valid, which was the situation for the Japanese Kamikaze aircraft, the aircraft must at least survive long enough to accomplish the mission objectives, and the tree diagram would stop at that node.
22. Each F-105 bomber typically carried 6000 lb of bombs on a mission to North Vietnam, which was about the same bomb load as that normally carried by a B-17 late in World War II.
23. The many missions of military aircraft are described in Chapter 3, Sec. 3.1.
24. Checkmate was a wargaming group operated by the Air Force Studies and Analysis and located in the Pentagon. The group developed the early plans for the strategic air campaign known as Instant Thunder. Black Hole was the unofficial name given to the strategic planning cell in Saudi Arabia where the target list, Master Air Attack Plan (MAAP), and the daily Air Tasking Order (ATO) were developed. The official name of this cell was the Special Planning Group.
25. Lieutenant Randall 'Duke' Cunningham, the U. S. Navy's only ace in Vietnam, was nearly killed on 10 May, 1972, by a proximity detonation of the HE warhead on an SA-2 missile because of this particular vulnerability on his F-4 Phantom II. According to Cunningham, "When an F-4 loses hydraulics, the stabilizer locks, forcing the aircraft's nose to pitch straight up. The stick has no effect on the controls, and only the rudder and power are available to maneuver the aircraft. Sure enough, when PC-2 went to zero, the nose went straight up."[70] Cunningham was able to get feet wet (over the water) by a series of climbing and diving half-rolls using alternate full rudder throws, extension and retraction of the speed brakes, and engine idle and full afterburner commands. An onboard explosion during the 20-mile roller coaster ride to the beach added to the challenge. Just as the aircraft crossed over the beach,

a second explosion took out the utility hydraulic system that had been powering the rudder. According to Cunningham,

> With the hydraulics gone and the rudder useless, I was unable to force the nose back down on the upswing. The F-4 stalled and went into a spin. On each revolution I could see land, then ocean, then land again. Fear kept me in the aircraft. We were close to the beach, and the winds normally blew landward. I told Irish (L.j.g. Bill Driscoll, his RIO or backseater) to stay with me for two more turns as I attempted to break the spin and get more water behind us. I deployed the drag chute with no effect.[70]

The two ejected as the aircraft continued to spin and were picked up in the water 15 min later. Earlier in this mission, before the SAM incident, Cunningham had downed three MiGs, a record for the Vietnam conflict. This particular vulnerability, the redundant hydraulic power sources merging at each actuator, was not unique on the F-4. The same design was used on many other aircraft, such as the F-8, F-105, and A-7.

26. Note that lower-case subscripts refer to components and upper-case subscripts refer to the total aircraft. For example, the presented area of a component is denoted by A_P, and the presented area of the aircraft is denoted by A_P. The distinction is important; it eliminates the ambiguity between a reference to the aircraft's components and the aircraft itself.
27. The concept of vulnerable area is analogous to the bull's eye in a dart board. If your opponent throws a dart and hits the bull's eye, you lose. Similarly if the ballistic projectile or fragment hits the vulnerable area of any of the nonredundant critical components, the aircraft is killed. The larger the bull's eye, the more likely you will lose; the larger the aircraft's vulnerable area, the more likely it will be killed given a hit.
28. The ullage of a fuel tank is the internal volume of the tank above the surface of the fuel where air and fuel vapor can form a combustible mixture.
29. The reader interested in learning more about the survivability of space systems is referred to Refs. 71 and 72.
30. Both component location and component proliferation can also reduce susceptibility. Component location is a form of threat avoidance when the critical components of a system are located outside the reach of the enemy's weapons, and component proliferation can reduce the susceptibility of the individual components because it increases the number of targets with which the enemy air defense must contend.
31. This aspect of force survivability, that is, the replacement of lost units, plays a large role in force survivability and can mean the difference between winning a battle or losing it.
32. References 73 and 74 contain the first efforts to formulate the DE survivability discipline in the terms of the ACS fundamentals presented here.
33. The terms *soft kill* and *hard kill* have different meanings to different people. In general, they may refer to the damage mechanism that causes the kill; radiation causes a soft kill whereas fragments cause a hard kill. Or they may refer to the length of time the affected system or component is out of action; soft kill denotes a temporary effect that may or may not require repair, whereas hard kill denotes permanent physical damage to the system or component rendering it inoperative.
34. Reference 75 is a presentation of the NBC contamination survivability discipline and its relationship to the conventional ACS discipline. Much of this section is taken from that reference.

35. This instruction was canceled when DoD Directive 5000.1 was updated on 23 February 1991.
36. This was indeed the situation when the Iraqis launched their SCUD missiles toward Israel and Saudi Arabia in 1991.
37. In 1994 the DoD specifications and standards were cancelled by the Secretary of Defense in an attempt to reduce the cost of procuring military aircraft. The new way of doing business was to use performance specifications when purchasing new systems or making modifications to current systems. If it was not practical to use a performance specification, a nongovernment standard was to be used. Because there will be cases when military specifications are needed to define an exact design solution because there is no acceptable nongovenrment standard or because the use of a performance specification or nongovernment standard is not cost effective, the use of military specifications and standards was authorized as a last resort, with an appropriate waiver.[76] As a result of the uniqueness of MIL-STD-882, it was designated a Standard Practice in 2000 and does not require a waiver.
38. The FTA and FMEA are also used in vulnerability assessments to identify the critical components.
39. The U. S. General Accounting Office published a report in 1998 entitled Military Aircraft Safety, Serious Accidents Remain at Historically Low Levels.[77] The reader who is interested in learning more about U. S. military aircraft mishap statistics should visit the following web sites: http://safety.kirtland.af.mil/AFSC/RDBMS/Flight/stats/statspage.html for the flight safety data for U. S. Air Force aircraft, http://safety.army.mil/stats/index.html for U. S. Army aircraft mishap statistics, and http://www.safetycenter.navy.mil/ and http://www.hqmc.usmc.mil/safety.nsf, for the U. S. Navy and Marine Corps Internet sites for safety, respectively.
40. The phrase *aircraft kill* used for military aircraft is replaced by *aircraft loss* by the civilian aircraft community.
41. Apparently no U. S.-built aircraft fought in World War I; the American Expeditionary Force flew French-built aircraft;[78] and Route Pack VI in Fig. 1.16 was the geographical area around Hanoi and Haiphong.
42. Another official count of Coalition aircraft sorties and losses appears in the 1991 Defense Almanac (http://www.defenselink.mil/news/Aug2000/n08082000_20008088.html). According to the Almanac, the U. S. lost 40 fixed-wing aircraft (28 combat and 12 noncombat) and 23 helicopters (5 combat and 18 noncombat), and the Allies lost 12 fixed-wing aircraft (9 combat and 3 noncombat).
43. The missions listed in Table 1.11 are described in Chapter 3, Sec. 3.1.
44. The vulnerability design requirements and reduction features for the UH-60 Black Hawk are described in Sec. 1.4, and the Live Fire Test Program is described in Sec. 1.6. The author would like to add that credit for the survivability of the UH-60 also goes to those who set the stringent requirements for a low vulnerability (LV) design. An LV design starts with the design requirements.
45. Other reasons offered for the refusal to use the Apaches were that the helicopters would have trouble coping with the region's high mountains, weapons would have to be sacrificed for the external fuel pods required to fly over the high-altitude terrain, "the capability to detect and track ground targets in Kosovo was constrained both by the enemy's employment of defensive tactics (Serbian ground forces were widely dispersed, well camouflaged, and employed decoys) and by the lack of friendly ground forces in Kosovo, . . . Coordinating rotary-wing aircraft operations into the Air Tasking Order proved problematic because this is not a traditional mission defined in Army

doctrine nor is it exercised on a regular basis in joint training,"[45] and innocent civilians in Kosovo could be killed during Apache attacks against the entrenched Serbs.

46. The definitions of the DoD Directive, Memorandum, and Instruction are as follows (http://www.dtic.mil/whs/directives/general.html): A DoD Directive "is a broad policy document containing what is required by legislation, the President, or the Secretary of Defense to intiate, govern, or regulate actions or conduct by the DoD Components within their specific areas of responsibilities. DoD Directives establish or describe policy, programs, and organizations; define missions; provide authority; and assign responsibilities. One-time tasking and assignments are not appropriate in DoD Directives." A DoD Directive-Type Memorandum "is a memorandum issued by the Secretary of Defense, Deputy Secretary of Defense, or Office of the Secretary of Defense (OSD) Principal Staff Assistants (PSAs) that, because of time constraints, cannot be published in the DoD Directives System. Directive-type memoranda signed by PSAs are procedural in nature. They implement policy documents, such as DoD Directives, Federal laws, and Executive orders. Directive-type memoranda signed by the Secretary or Deputy Secretary of Defense are policy-making documents. A directive-type memorandum shall be converted into a DoD Directive or DoD Instruction within 90 days, unless the subject is classified with limited distribution or is material of limited or temporary relevance." A DoD Instruction "is a DoD issuance that implements the policy, or prescribes the manner or a specific plan or action for carrying out the policy, operating a program or activity, and assigning responsibilities."
47. The definitions of Acquisition Category I and II are as follows: "ACAT I programs are Major Defense Acquisition Programs (MDAPs). An MDAP is defined as a program estimated by the Under Secretary of Defense (Acquisition, Technology and Logistics) (USD(AT&L)) to require eventual expenditure for research, development, test, and evaluation of more than $365 million (fiscal year (FY) 2000 constant dollars) or procurement of more than $2.19 billion (FY 2000 constant dollars), or those designated by the USD(AT&L) to be ACAT I, ACAT II programs are defined as those acquisition programs that do not meet the criteria for an ACAT I program, but do meet the criteria for a major system. A major system is defined as a program estimated by the DoD Component Head to require eventual expenditure for research, development, test, and evaluation of more than $140M in FY2000 constant dollars, or for procurement of more than $660M in FY2000 constant dollars or those designated by the DoD Component Head to be ACAT II.[79]
48. The description of the Test and Evaluation Master Plan is as follows: The TEMP "documents the overall structure and objectives of the test and evaluation (T&E) program. It provides a framework within which to generate detailed T&E plans and it documents schedule and resource implications associated with the T&E program. The TEMP identifies the necessary developmental test and evaluation (DT&E), operational test and evaluation (OT&E) and live fire test and evaluation (LFT&E) activities. It relates program schedule, test management strategy and structure, and required resources to: critical operational issues (COIs), critical technical parameters, objectives and thresholds documented in the Operational Requirements Document (ORD), evaluation criteria, and milestone decision points."[79]
49. According to http://web1.deskbook.osd.mil/irp/1122.asp, "All acquisition programs are based on identified, documented, and validated mission needs. Mission needs result from ongoing assessments of current and projected capabilities. Mission needs may seek to establish a new operational capability, improve an existing capability, or exploit an opportunity to reduce costs or enhance performance. The Mission Need

Statement (MNS) shall identify and describe the mission deficiency; discuss the results of mission area analysis; describe why non-material changes (i.e., doctrine or tactics) are not adequate to correct the deficiency; identify potential material alternatives; and describe any key conditions and operational environments that may impact satisfying the need."

50. The analysis of alternatives (AoA), previously known as the cost and operational effectiveness analysis (COEA), is "an analysis intended to aid decisionmaking by illuminating the risk, uncertainty, and the relative advantages and disadvantages of alternatives being considered to satisfy a mission need. The AoA shows the sensitivity of each alternative to possible changes in key assumptions (e.g., threat) or variables (e.g., performance capabilities)."[79]
51. The acquisition program baseline (APB) is "a document that contains the most important cost, schedule, and performance parameters (both objectives and thresholds) for the program. It is approved by the Milestone Decision Authority and signed by the program manager and his/her direct chain of supervision."[79]
52. The JTCG/ME was established in 1964 to ensure standardization of weapons effectiveness data among the services. The mission of the JTCG/ME is to develop and publish operational effectiveness estimates for all U. S. nonnuclear weapons. This is accomplished by preparing, updating, and publishing Joint Munitions Effectiveness Manuals (JMEMs) for air-to-surface, surface-to-surface, antiair, and other nonnuclear weapon systems as directed; promoting the establishment of standardized procedures for evaluating effectiveness parameters associated with munitions effectiveness; managing joint service efforts to improve the database in weapons characteristics, delivery accuracy, and target vulnerability and the analytical methodology used in the determination of nonnuclear effects; conducting special studies to determine the effectiveness of existing and improved nonnuclear munitions and munitions/weapons systems; maintaining continuous liaison with other JTCGs in order to avoid duplication of areas of consideration; and managing efforts to determine the degrading effects of various terrain environments on nonnuclear munitions effectiveness and ensure that such information is included in the various effectiveness manuals or special publications. Information on how to obtain JMEMs and JTCG/ME special reports can be obtained from the JTCG/ME Publications Management Office (OC-ALC/TILUB), Tinker AFB, OK 73145-9160. For further information on the JTCG/ME, contact the U. S. Army Materiel Systems Analysis Activity, AMXSY-J, 392 Hopkins Road, Aberdeen Proving Ground, MD 21005-5071; telephone: (410)278-6580 or DSN 298-6580; Fax: (410)278-2788 or DSN 298-2788; and e-mail: erwin@amsaa.army.mil. The JTCG/ME's web site is http://www.amsaa.army.mil/jtcg/jtcg.htm.
53. Much of the material in this section first appeared in Ref. 54.
54. The designations AAR, ALE, ALQ, and ALR apply to specific types of electronic equipment and are part of the Joint Electronics Type Designation System presented in Table 4.31.
55. Reference 80 contains information on the payoffs and the penalties associated with designing for low RCS.
56. The E model has the VR features of the A model shown in Fig. 1.20b plus a stabilator fault management system (the mechanical backup was removed) and an active dry bay fire suppression system.
57. The vulnerability requirements for the U. S. Army's Advanced Attack Helicopter (AAH), the YAH-63A and YAH-64A, were similar to those for the UTTAS for

the conditions of both forward flight and hover and applied to the 12.7-mm AP-I.

58. In the 2002 version of DoD 5000.2-R, the term full-scale is replaced by system-level. According to that document, a covered system and a full-up, system-level (realistic survivability) test are defined as follows (http://web1.deskbook.osd.mil/htmlfiles/rlframe/REFLIB_Frame.asp?TOC=/htmlfiles/TOC/031drtoc.asp?sNode=L2-1&Exp=N&Doc=reflib/mdod/031dr/012/031dr012doc.htm&BMK=C1021.):

> AP3.2.1. Covered system. A system that the DOT&E, acting for the Secretary of Defense, has determined to be:
> (A) a major system within the meaning of that term in 10 USC 2302(5) that is ——
> (i) user-occupied and designed to provide some degree of protection to its occupants in combat; or
> (ii) a conventional munitions program or missile program; or
> (B) a conventional munitions program for which more than 1,000,000 rounds are planned to be acquired; or
> (C) a modification to a covered system that is likely to affect significantly the survivability or lethality of such a system.
> *Note:* The term *covered system* as just defined is the DoD term that is intended to include all categories of systems or programs identified in 10 USC 2366 as requiring live fire test and evaluation. In addition, non-traditional systems or programs that do not have acquisition points referenced in 10 USC 2366, but otherwise meet the statutory criteria, are considered covered systems for the purpose of this regulation.
> AP3.2.3. Full-up, system-level test.
> (A) vulnerability testing conducted, using munitions likely to be encountered in combat, on a complete system loaded or equipped with all of the dangerous materials that normally would be onboard in combat (including flammables and explosives), and with all critical subsystems operating that could make a difference in determining the test outcome; or
> (B) lethality testing of a production-representative munition or missile, for which the target is representative of the class of systems that includes the threat, and the target and test conditions are sufficiently realistic to demonstrate the lethal effects the weapon is designed to produce.
> *Note:* The term *full-up, system-level testing* is that testing that fully satisfies the statutory requirement for realistic survivability testing or realistic lethality testing as defined in 10 USC 2366.

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Problems

1.1.1 What is the definition of aircraft combat survivability (ACS)?

1.1.2 What is another term for the man-made hostile environment?

1.1.3 Describe the aircraft attribute susceptibility.

1.1.4 List four major factors that influence aircraft susceptibility.

1.1.5 A very susceptible aircraft is easily killed by the air defense: True or False.

1.1.6 Describe the aircraft attribute vulnerability.

1.1.7 List three major factors that influence aircraft vulnerability.

1.1.8 The level of vulnerability of a P-3 Orion to a 7.62-mm ballistic projectile while flying over Maine is the same as it is while flying over Iraq: True or False.

1.1.9 An aircraft with a very low level of susceptibility must also be very vulnerable: True or False.

1.1.10 A very vulnerable aircraft has a high probability of being hit by enemy fire: True or False.

1.1.11 Describe the aircraft attribute killability.

1.1.12 Assume you are the commanding officer of an F/A-18 squadron. Your squadron is scheduled to conduct a strike mission within the next 48 h. You have complete control over all aspects of the mission planning and execution. What are some of the actions you might take regarding mission preparation and tactics to reduce the susceptibility of your squadron's aircraft.

1.1.13 The following changes have been made to either your aircraft, your tactics, or the threat. Will the particular change result in a net increase in susceptibility (I), a net decrease in susceptibility (D), a possible net increase or decrease in susceptibility (ID), or have little or no effect on your aircraft's susceptibility (NA)? Explain your answer.

(a) Two joint standoff weapons (JSOWs) are mounted internally in the bomb bay of your aircraft rather than externally on a wing pylon.

(b) In Desert Rain the payload of your attack aircraft is changed from 5 Maverick missiles to 10 Mk 82 bombs.

(c) Your aircraft is retrofitted with canards to increase its high angle-of-attack performance for air combat maneuvering (ACM).

(d) You are about to depart on a day air-to-surface mission. The plane captain paints your curved canopy with a material that reflects sunlight in order to reduce the sunlight glare inside the cockpit.

(e) You are on a surveillance mission. Your fighter escort is called away to support another mission.

(f) Enemy troop movements force an immediate ground attack by your squadron. You must now launch an attack at 1300 local time vs 2300.

(g) To increase the use of engine afterburning, the radar-intercept officer (RIO) in the back seat of your aircraft is removed and replaced with an additional fuel tank.

(h) An onboard inert gas generating system (OBIGGS) is installed in your aircraft's fuel tanks to prevent in-tank explosions.

(i) It's night. You are ingressing toward the target area. You see gunfire on the ground, and it's apparently aimed at your aircraft. You deploy chaff and flares.

(j) You have just completed your bombing run. During your egress from the target area, you switch the engine into afterburner.

(k) The enemy replaces a relatively inaccurate, large-caliber, slow-firing gun with a relative accurate, small-caliber, rapid firing gun.

1.1.14 The following changes have been made to either your aircraft, your tactics, or the threat. Will the particular change result in a net increase in vulnerability (I), a net decrease in vulnerability (D), a possible net increase or decrease in vulnerability (ID), or have little or no effect on your aircraft's vulnerability (NA)? Explain your answer.

(a) Two JSOWs are mounted in the bomb bay of your aircraft rather than externally.

(b) A backup set of flight control signal lines from the pilot to the surface actuators is added to your aircraft. Furthermore, the backup lines are physically separated from the primary control signal lines so that a single hit cannot kill both sets of lines.

(c) A second handle is added to the pilot's ejection seat.

(d) You, the designer, remove the externally mounted engines from the wings and relocate them close together within the narrow fuselage.

(e) Your aircraft is coated with a paint that absorbs incident sunlight.

(f) To achieve more range, you remove the RIO in the back seat of your aircraft and replace him/her with an additional fuel tank.

(g) You install reticulated foam inside the fuel tank you just added to your aircraft to prevent an in-tank explosion.

(h) You remove the automatic fire extinguishing system installed in the engine bay in your single engine aircraft, leaving only the fire warning system, to reduce costs.

(i) The enemy fires a high-explosive round at your aircraft instead of an armor-piercing round.

(j) The enemy replaces a relatively inaccurate, large-caliber, slow-firing gun with a relative accurate, small-caliber, rapid firing gun.

1.1.15 Why are the aircraft attributes survivability, killability, susceptibility, and vulnerability measured by probabilities?

1.1.16 Match the following aircraft survivability attributes with their probability measure(s):

___Aircraft survivability	1. P_K
___Aircraft killability	2. $P_{K\|H}$
___Aircraft susceptibility	3. $P_{K\|F}$
___Aircraft vulnerability	4. $1 - P_H P_{K\|H}$
	5. $P_H P_{K\|H}$
	6. $1 - P_K$
	7. P_H
	8. P_S
	9. $1 - P_S$

1.1.17 Match the following terms and probabilities:

___Most survivable aircraft	1. $P_S = 0.4$
___Not possible	2. $P_S = 1.2$
___Most killable aircraft	3. $P_S = 0.75$
	4. $P_K = 0.1$

1.1.18 Killability is a measure of how easily the aircraft is killed when hit: True or False.

1.1.19 Why do we need to design our aircraft to survive in combat?

1.1.20 A laser is a unconventional threat to aircraft: True or False.

1.1.21 What is one distinction between conventional weapons and unconventional weapons?

1.1.22 This textbook considers which threats?

1.1.23 Describe the term weapon envelope.

1.1.24 What is the purpose of the STAR?

1.1.25 Describe engagement-level survivability assessment.

1.1.26 Sketch the tree diagram for a one-on-one scenario between a helicopter and an infrared SAM with an HE warhead and proximity fuze. Indicate when the exposure, encounter, engagement, and endgame begin, and indicate the regions of susceptibility and vulnerability on the diagram.

1.1.27 A B-52 crew is given a threat briefing for tomorrow's interdiction mission. The crew is told the target is protected by an SA-2 SAM. However, the SA-2's radar was rendered inoperable by a strike on the previous day and is expected to be down for this mission. What is the P_A of the SA-2 threat weapon system for this scenario?

1.1.28 If $P_A > 0$, an aircraft located within an area defended by a threat is exposed to that threat: True or False.

1.1.29 The encounter begins.
(a) when the propagator intercepts the aircraft.
(b) when the aircraft is detected.
(c) when the aircraft enters airspace defended by an active threat.
(d) when the aircraft is hit by blast and fragments from warhead detonation.
(e) none of the above.

1.1.30 The engagement begins.
(a) when the aircraft enters the hostile airspace.
(b) when the aircraft is detected.
(c) when the aircraft enters the airspace defended by an active threat.
(d) when the aircraft is hit by the blast and fragments from a warhead detonation.
(e) none of the above.

1.1.31 Consider a one-on-one scenario between a helicopter and a single-barrel 57-mm gun with a proximity-fuzed HE projectile. The gun fires one round at the aircraft. Calculate the probability the helicopter will be engaged, the probability the helicopter will be hit, and the helicopter's survivability given the following probability estimates for the single-shot scenario: $P_A = 0.96$, $P_{I|L} = 0.80$, $P_{L|D} = 0.92$, $P_{K|F} = 0.71$, $P_{F|I} = 0.95$, and $P_{D|A} = 0.85$.

1.1.32 In a one-on-one scenario the probability an antiaircraft gun misses its target with a single contact-fuzed HE round is 0.849. From the following probability data determine the probability of intercept given a launch: $P_A = 0.80$, $P_{L|D} = 0.60$, $P_{K|H} = 0.80$, $P_{H|I} = 0.90$, and $P_{D|A} = 0.70$.

1.1.33 An attack aircraft launches at dawn on a close-air-support (CAS) mission along the forward line of own troops (FLOT). While on patrol, the aircraft is called upon to assist friendly troops pinned down by enemy fire. As the aircraft approaches the enemy troops, an enemy rifleman fires a burst of 20 rounds at the aircraft with his 7.62-mm automatic rifle. Each shot has a $P_{K|SS} = 0.001$. What is the probability the aircraft survives the 20-shot engagement?

1.1.34 Suppose another gunner fired a burst of two rounds of 14.5-mm projectiles at the aircraft. Although the aircraft survived the first hit, the left engine was killed. Would you expect both P_H and $P_{K|H}$ to change for the second shot in this scenario? Explain your answer.

1.1.35 In another aircraft vs gunner scenario, the gunner fires four rounds of 23-mm HE rounds at the aircraft as it departs the area. Assume that each shot outcome is unaffected by the previous shots, that is, the shot outcomes are independent. Each shot has the following probabilities: $P_K^{(1)} = 0.12$, $P_K^{(2)} = 0.10$, $P_K^{(3)} = 0.08$, and $P_K^{(4)} = 0.06$. What is the probability the aircraft is killed by the third shot given it survived the first two shots? What is the probability the aircraft survives the four-shot gun engagement?

1.1.36 Describe mission-level survivability assessment.

1.1.37 On a recent mission during Operation Desert Rain, two air-refueling tankers, eight fighter escorts, one standoff electronic jamming aircraft, and 32 attack aircraft took off during the early morning hours to conduct a strike against a well-defended communications center. Two shooter aircraft were killed by the air defense. What was the combat loss rate of the shooter aircraft?

1.1.38 A flight of four attack helicopters enters a heavily defended area while escorting eight troop transport helicopters. The area is defended by antiaircraft guns, SAMs, and interceptor aircraft. Assume each attack helicopter encounters one gun, one SAM, and one interceptor. The attack helicopter's one-on-one survivability against each of the weapons is given by the following independent probabilities: P_S (gun) $= 0.98$, P_S (SAM) $= 0.90$, and P_S (interceptor) $= 0.95$.

(a) What is the predicted mission survivability of each attack helicopter?
(b) How many attack helicopters are expected to be killed on this mission?
(c) What is the probability that none of the four attack helicopters on the mission is killed?
(d) The mission is over. The attack helicopters were able to suppress the enemy air defense, and all of the transport helicopters successfully delivered their troops with no opposition from the air defense. However, one of the attack helicopters was killed by a gun. What is the combat loss rate for this mission, and is this rate an acceptable value for future missions? Why?

1.1.39 A large naval air strike is to take place against an enemy surface action group. Fifteen attack aircraft will make a simultaneous, moderately low-altitude daylight assault on the enemy flag ship. The flag ship has five radar-directed 76-mm antiaircraft guns aboard. The guns fire a proximity-fuzed HE shell. Because all of the aircraft are attacking simultaneously, the five guns will only be able to engage one aircraft each, and the fire control doctrine is that no aircraft is engaged by more than one gun. Each gun has a 25-shot magazine and will not have time to reload during the attack. The enemy air defense radar is up and ready for the attack ($P_A = 1$), and the gunners are cleared to fire ($P_{\mathrm{L|D}} = 1$). Friendly intelligence reports that in a recent training exercise against drones conducting a similar low-altitude daylight attack the well-trained operators of the 76-mm guns detected the drones ($P_{\mathrm{D|A}} = 1$), and each gun fired all 25 rounds at its designated drone ($n = 25$). An average of four of the 25 rounds successfully intercepted the drone. Of the rounds that intercepted the drone, an average of 0.7 of those rounds fuzed. A vulnerability assessment of the aircraft to the proximity-fuzed 76-mm HE shell determines that $P_{K|F} = 0.20$. Determine the following:

(a) What is the probability that any one particular aircraft will be assigned to a gun?
(b) What is the probability each assigned aircraft will be killed by the gun?
(c) What is the expected number of aircraft killed in the attack?
(d) What is the expected loss rate for this scenario?

1.1.40 What is the difference between campaign survivability and mission survivability?

1.1.41 You are in charge of the 2000 aircraft that will fight in the upcoming campaign Sly Fox. You estimate that the campaign will last for 20 missions. Your aides inform you that you can expect a loss rate that is 75% of that suffered by U. S. fixed-wing aircraft in the 1962–1973 Southeast Asia conflict.

(a) What is the predicted campaign survivability of your aircraft?
(b) How many aircraft do you expect to lose during the campaign? Assume there are no replacement aircraft available. How many aircraft would you expect to lose if every downed aircraft was immediately replaced in the 2000-aircraft, 20-mission campaign?
(c) Suppose you were able to degrade the effectiveness of the air defense using threat suppression such that the loss rate for the first 10 missions was 0.06% and was 0.03% for the second 10 missions. How many aircraft would you lose during the campaign?
(d) Suppose the enemy air defense during this campaign was heavy and lethal, and consequently the campaign loss rate was estimated to be the same as the loss rate for bombers during all of WWII. How many aircraft would you expect to lose during the campaign with and without replacement?

1.1.42 Assume the office in charge of selecting the acceptable survival probability for a tour of duty in Operation Long Time selects 0.95. She predicts that the enemy air defense will be intense and estimates the loss rate at five. What is the corresponding tour of duty?

1.1.43 Describe the three general ways to enhance survivability.

1.1.44 What is the objective of a survivability enhancement feature?

1.1.45 Flying your helicopter in hostile country at night rather than during the day is a survivability enhancement feature: True or False.

1.1.46 Employing long-range, precision-guided munitions rather than dumb bombs against a heavily defended surface target is a survivability enhancement feature: True or False.

1.1.47 The use of flammable hydraulic fluid on an aircraft is a survivability enhancement feature: True or False.

1.1.48 Match the survivability enhancement feature given here with one or more probabilities it can affect:

___Threat warning	1. P_A
___Chaff	2. $P_{D\|A}$
___Fighter escort	3. $P_{L\|D}$
___Redundant and separated hydraulics	4. $P_{I\|L}$
___Low signatures	5. $P_{H\|I}$
___Afterburning engines	6. $P_{K\|H}$
___Mission planning	
___Fire/explosion suppression	
___Crew training and proficiency	
___Armor	

1.1.49 List the essential functions for flight.

1.1.50 An aircraft's vulnerability is caused by the vulnerability of its components: True or False.

1.1.51 Describe a critical component.

1.1.52 Give an example of a nonredundant critical component.

1.1.53 Give an example of a redundant critical component.

1.1.54 Give an example of each of the 12 survivability enhancement concepts.

1.1.55 Describe the two goals of the aircraft survivability discipline.

1.1.56 Why is it desirable to incorporate survivability features into the design as early as possible?

1.1.57 You are developing a new military transport aircraft that will deliver troops and supplies to landing zones close to the battle front. You must develop an affordable and effective aircraft. What are the three top-level attributes of your aircraft that influence its effectiveness, and how can they be measured? Give an example of each these attributes for your transport aircraft.

1.1.58 How can the three top-level attributes described in Section 1.1.10 be combined into one simple measure of operational effectiveness?

1.1.59 Do these three attributes influence each other? If so, give an example of the dependence of one attribute upon another attribute for your transport aircraft.

1.1.60 A military aircraft must be survivable to be effective: True or False.

1.1.61 A survivable military aircraft is always an effective military aircraft: True or False.

1.1.62 You are a flight leader sitting in the ready room at Friendly Field. You have been assigned the mission to destroy four ballistic missile launchers located 500 miles away. The launch unit is defended by RF SAMs. You have five aircraft under your control. One of your aircraft is not available for the mission as a result of a lack of spare parts. You assign the remaining four aircraft to the mission. Each aircraft is assigned one launcher to destroy using Mk 82 500-lb bombs. As a result of the strike by your four aircraft, three of the launchers are destroyed. However, one of your aircraft is killed. How successful was the aircraft used on this mission from the standpoint of operational effectiveness? Quantify your answer using the MOME and the three attribute measures, AA, MAM, and SR. Suggest some changes to this scenario that could increase the effectiveness of aircraft on this mission.

1.1.63 Describe the difference between managed attrition and virtual attrition. Give an example of each concept.

1.1.64 List four reasons for assessing survivability.

1.1.65 What is the first task in a survivability assessment, and why is this task first?

1.1.66 What are the units of an aircraft's radar and infrared signatures?

1.1.67 Describe a hit plot, and explain what information can be gained from the analysis of locations where no hits are recorded.

1.1.68 What is a component's single-hit vulnerable area? What is an aircraft's single-hit vulnerable area?

1.1.69 An aircraft is randomly hit by a 12.7-mm armor-piercing ballistic projectile. One of the critical components in the aircraft has a presented area of 4 ft^2 and is masked by two noncritical components. The impact velocity of the projectile on the aircraft is 1800 fps. After penetration through the two masking noncritical components, the projectile impacts the critical component at 1450 fps. The component's $P_{k|h}$ for this damage mechanism at this velocity is 0.3. What is the component's vulnerable area for these conditions?

1.1.70 The vulnerable area of the four nonredundant, nonoverlapping critical components on an aircraft for a 23-mm AP-I threat from a particular attack direction are 0.37, 1.56, 2.11, and 0.44 ft^2. What is the aircraft's vulnerable area A_V? If the aircraft's presented area in the attack direction is 400 ft^2, what is the $P_{K|H}$?

1.1.71 Why are trade studies conducted?

1.1.72 What is the difference between system survivability and aircraft survivability?

1.1.73 Match the survivability enhancement feature given here with appropriate system survivability strategy:

___Threat warning	1. Threat avoidance
___Chaff	2. Deception
___Fighter escort	3. Active defense
___Redundant and separated hydraulics	4. Hardness
___Low signatures	5. Redundancy
___Afterburning engines	6. Threat-effect tolerance
___Mission planning	7. Proliferation
___Fire/explosion suppression	8. Reconstitution
___Crew training and proficiency	
___Armor	

1.1.74 Consider the survivability of a space system consisting of 16 satellites, eight ground-based transmitters/receivers, and two command and control (CC) centers with communication links between each of the elements. Relate the following system survivability enhancement features to the eight survivability strategies:

___Very high-altitude satellites	1. Threat avoidance
___Only 12 out of 16 orbiting satellites required	2. Deception
___Barbed-wire fence around each building with an armed guard the entrance	3. Active defense
___Coatings for sensitive sensors that deflect electromagnetic radiation from antisatellite lasers	4. Hardness
___Low satellite signatures	5. Redundancy

___CC centers below ground	6. Threat-effect tolerance
___Maneuvering satellites	7. Proliferation
___Onboard sensors and equipment that can detect and compensate for component damage	8. Reconstitution

1.1.75 List the three primary directed-energy weapons.

1.1.76 List the important parameters of the beam from a directed-energy weapon.

1.1.77 What are the aircraft components that are most vulnerable to the low-power directed-energy weapons?

1.1.78 The vulnerability of sensors to EM radiation damage can be reduced by

________________.

1.1.79 The N in NBC contamination survivability stands for the prompt radiation from a nuclear burst: True or False.

1.1.80 Sketch the three-ring vulnerability diagram for NBC contamination survivability.

1.1.81 Relate the following NBC contamination survivability terms to the ACS terms:

___Hazard	1. Vulnerability
___Accessibility	2. Killability
___Susceptibility	3. Susceptibility
___Vulnerability	4. Damage mechanism

1.1.82 In nuclear survivability the primary damage mechanisms from a nuclear burst (the products) depend upon what factors?

1.1.83 What is the distinction between system safety, aircraft survivability, and aircraft combat survivability?

1.1.84 Give an example of a hazard on an aircraft.

1.1.85 How are mishaps classified?

1.1.86 Relate the system safety terms hazard and mishap to the analogous ACS terms.

1.1.87 A new aircraft is undergoing operational testing and evaluation. You are the test pilot. The system safety and reliability people tell you that the rate of class A mishaps early in the test program is estimated to be 10 per 100,000 flight hours.

You are scheduled to fly this aircraft 200 hs. What is the probability you will suffer one or more class A mishaps?

1.1.88 You are in charge of the battle damage repair program on a new attack helicopter. The helicopter structure is to be composed of a few, very large parts made from advance composite materials. What are some of your main concerns?

1.1.89 Suppose the large-scale composite construction changes the $P^c_{R|H}$ from 0.1 to 0.5. What is the impact of this change upon the number of aircraft available after a campaign of 100,000 sorties? Assume $P_H = 0.005$ and $P_{K|H} = 0.1$.

1.2.1 What were the loss rates for U. S./RAF fighters and bombers in Europe in WWII?

1.2.2 How many U. S. fixed-wing aircraft were killed in combat in the SEA conflict, and what was the approximate loss rate for the entire conflict?

1.2.3 How many U. S. helicopters were killed in combat in the SEA conflict?

1.2.4 How many U. S. fixed-wing aircraft were killed in combat in Desert Storm, and what was the loss rate?

1.2.5 What was the probability an allied aircraft would be hit while on a mission in Desert Storm?

1.2.6 Name four aircraft at the beginning of WWII that were shown to be very killable.

1.2.7 Describe the bomber tactics that were used in WWII to reduce susceptibility.

1.2.8 Give an example of how threat suppression was used to reduce susceptibility during WWII.

1.2.9 Give an example of how signature reduction was used to reduce aircraft susceptibility during WWII.

1.2.10 Give an example of how expendables were used to reduce aircraft susceptibility during WWII.

1.2.11 List, in order, the four critical components that resulted in aircraft losses in WWII.

1.2.12 List five vulnerability reduction features used during WWII and relate each one to one of the vulnerability reduction concepts.

1.2.13 Give an example of how vulnerability was reduced by relocating a component on an aircraft during WWII.

1.2.14 Most WWII Japanese aircraft carried self-sealing fuel tanks: True or False.

1.2.15 What was thought to be the primary threat to fixed-wing aircraft during the SEA conflict, and what measures were taken to increase survivability?

1.2.16 List some of the critical components on U. S. helicopters used in the SEA conflict that were found to be highly vulnerable to 23-mm antiaircraft fire.

1.2.17 Describe the redesign of the hydraulic power supply to the aileron actuators on the F-4.

1.2.18 How many F-4 aircrews were saved by the modification made to aileron actuators and their hydraulic power supply?

1.2.19 List five vulnerability reduction features used during the SEA conflict, and relate each one to one of the vulnerability reduction concepts.

1.2.20 List the types of aircraft used to support the bombers in the 1972 Linebacker operations.

1.2.21 Give an example of managed attrition and virtual attrition in the Yom Kippur war.

1.2.22 The loss rates of the British and Argentinean aircraft in the Falklands conflict were approximately the same as those the U. S. suffered in SEA: True or False.

1.2.23 Describe how each susceptibility reduction concept was used on the first day of Operation Desert Storm.

1.2.24 What is the $P_{K|H}$ of the Black Hawk when hit by a rocket-powered grenade? Use the combat data from the 1993 air assault in Mogadishu.

1.2.25 What two U. S. aircraft were downed by the FRY air defense in Operation Allied Force?

1.2.26 Describe the major lesson that has been learned in combat.

1.3.1 The DoD Directive 5000.1 provides the detailed requirements for acquiring systems and material that satisfy the operational user's needs: True or False.

1.3.2 Detailed requirements for survivability are specified in the 1998 version of DoD 5000.1: True or False.

1.3.3 DoD Instruction 5000.2-R specifies mandatory policies and procedures for major defense acquisition programs: True or False.

1.3.4 Briefly describe the requirements for survivability stated in DoD 5000.2-R.

1.3.5 The Defense Acquisition Deskbook (DAD) is an automated acquisition reference tool that provides DoD acquisition information for all services across all functional disciplines: True or False.

1.3.6 Briefly describe some of the survivability considerations at each milestone.

1.3.7 List the primary survivability organizations in each of the three U. S. military departments.

1.3.8 What is the purpose of MIL-HDBK-2069A?

1.3.9 MIL-HDBK-2069A applies only to nonnuclear threat environments: True or False.

1.3.10 MIL-HDBK-2069A applies only to new systems in development: True or False.

1.3.11 According to MIL-HDBK-2069A, quantitative survivability requirements for the system, major subsystems, and applicable equipment should be included in the system and item specifications: True or False.

1.3.12 According to MIL-HDBK-2069A, only testing should used verify that the requirements have been satisfied: True or False.

1.3.13 According to MIL-HDBK-2069A, the contracting activity should establish susceptibility design and configuration requirements that specify acceptable levels of the probabilities of aircraft detection, encounter, or damage by the specified threat systems and vulnerability design and configuration requirements that provide safe flight and recovery capability of the aircraft and that maximize the probability of mission completion: True or False.

1.3.14 Why was the JTCG/AS (now JASP) established?

1.3.15 One of the mission tasks of the JTCG/AS is to establish and maintain survivability as a design discipline: True or False.

1.3.16 What are the three subgroups within the JTCG/AS?

1.3.17 Briefly describe SURVIAC.

1.3.18 List the three types of antiaircraft threats covered by SURVIAC.

1.3.19 SURVIAC does not have a library of vehicle signatures: True or False.

1.3.20 SURVIAC products and services are available only to U. S. government agencies: True or False.

1.4.1 Survivability has been a major design consideration beginning in WWI and continuing to the present time: True or False.

1.4.2 The importance of combat survivability became very apparent during the SEA conflict: True or False.

1.4.3 What was the first U. S. Navy aircraft with a significant consideration of survivability?

1.4.4 What was the first U. S. Air Force aircraft in which vulnerability was a major consideration?

1.4.5 What U. S. Air Force aircraft was the first generation of stealth?

1.4.6 Which two U. S. Army helicopters were designed to take a single hit anywhere on the helicopter and continue to fly for 30 min?

1.4.7 List one design impact for each of the concepts for reducing susceptibility.

1.4.8 Describe the general procedure for designing for low vulnerability.

1.4.9 List two vulnerability reduction features found on the A-10A flight control system and the kill mode each feature prevents.

1.4.10 List two vulnerability reduction features found on the F/A-18A fuel system and the kill mode each feature prevents.

1.4.11 List two vulnerability reduction features found on the main rotor system of the UH-60A aircraft and the kill mode each feature prevents.

1.4.12 Describe how the people onboard an aircraft can be killed or injured when an aircraft is hit.

1.4.13 List three examples of design features that can reduce the number of casualties on a hit aircraft.

1.5.1 Based upon the definitions given, a simulation is another word for a model: True or False.

1.5.2 When is a model deterministic?

1.5.3 What models are of particular interest here?

1.5.4 Describe the terms verification, validation, and accreditation.

1.5.5 If you want to determine the range at which a ground-based radar system can detect an aircraft target, which SURVIAC program would you use?

1.5.6 If you want to determine the vulnerable area of an aircraft to a contact weapon, which SURVIAC programs would you use?

1.5.7 What SURVIAC program(s) would you use to determine the performance of an SA-6 missile system against an aircraft?

1.5.8 TRAP is used to determine the performance of air-to-air missiles: True or False.

1.5.9 BRAWLER is used to simulate air-to-air combat between multiple flights of aircraft: True or False.

1.5.10 What non-SURVIAC program would you use to determine the vulnerability of aircraft to both contact and proximity warheads?

1.5.11 EADSIM is the acronym for what program?

1.5.12 SWEG is an Air Force program for simulating many-on-many conflicts involving air, ground, naval and/or space-based forces: True or False.

1.5.13 What non-SURVIAC program would you use to determine the outcomes of a campaign involving air, land, and sea forces?

1.6.1 List the five types of susceptibility tests and give an example of each type.

1.6.2 List some of the parameters that would be measured in each of the five types of susceptibility tests.

1.6.3 List the primary vulnerability test facility of each of the three departments.

1.6.4 You want to conduct a live fire test on a full-scale aircraft with airflow. Which vulnerability test facilities can be used to conduct the tests?

1.6.5 What is the difference between the JLF test program and the LFT program in terms of the aircraft to be tested?

1.6.6 What does the LFT law require for U. S. DoD aircraft?

1.6.7 What is realistic survivability testing?

1.6.8 Under what conditions can the Secretary of Defense waive the requirement for the full-up, system-level tests?

1.6.9 What is the objective of the LFT&E program?

1.7.1 List some of the major "players" in ACS.

1.7.2 What are the five points to remember about ACS?

Chapter 2
Aircraft Anatomy

2.1 General Features and Flight Essential Functions

Learning Objectives	**2.1.1**	**Describe the general features of all aircraft.**
	2.1.2	**Describe the essential functions for continued safe flight.**

Aircraft come in many different shapes, sizes, and configurations that are determined by the intended role or roles of the aircraft. They are classified as fixed-wing aircraft when the primary lift surfaces, for example, wings, are fixed during takeoff and flight and as rotary-wing aircraft when the primary lift surfaces, for example, rotor blades, rotate during takeoff and possibly flight. In the fixed-wing world there are the sleek, high-speed, interceptors with their thin, delta-shaped wings and huge, thirsty engines; and then there are the slower, stubby attack aircraft that must carry prodigious warloads over long ranges or loiter for long periods of time near the battle zone. The newest members of the fixed-wing world are those aircraft that can take off either vertically or in a short distance and land vertically, known as vertical/short take off and landing (V/STOL) aircraft. V/STOL aircraft have some means for obtaining lift when taking off or landing vertically, such as a large fan mounted horizontally in the fuselage or pivoting air ducts that can point downward. In the rotary-wing world the helicopter, valued for its vertical takeoff and landing capability, can be large and bulky in order to carry large amounts of cargo or thin and angular for agility and speed in the attack role. The newest rotary-wing aircraft is the tilt-rotor aircraft. This aircraft has engines mounted on wings. The engines drive large propellors or rotors that rotate in the horizontal plane when the aircraft is taking off or landing and that tilt to rotate in the vertical plane when the aircraft is flying. The wings on the tilt-rotor aircraft provide the primary lift force during flight. Another distinction between aircraft is whether or not there are people onboard as the aircraft performs its missions. Aircraft that do not have people onboard are referred to as unmanned (or uninhabited) aerial (or air) vehicles (UAVs) or as unmanned combat air vehicles (UCAVs) when they are used in a combat role.

Regardless of the roles or missions for which the aircraft was designed, the final product will have surfaces, fixed or rotating, that provide a lift force on the aircraft and possibly a thrust force in the direction of flight; a powerplant that provides a thrust force and possibly a lift force; and a means for controlling the direction of flight by providing relatively small forces at several locations around the aircraft. If any of these forces (lift, thrust, and control) are lost, the aircraft will eventually crash. Consequently, they are referred to as essential functions for flight. A fourth essential function is structural integrity; the aircraft structure must remain sufficiently intact to allow the development of the lift, thrust, and control forces.

The four essential functions of structural integrity, lift, thrust, and control are usually provided by the following major aircraft systems: structural, propulsion, flight control, fuel, avionics, electrical, environmental control, and crew. In addition, a launch and recovery system is required for safe takeoff and landing, and the armament system is a major part of a combat aircraft. The relative importance of each of the systems just listed to the survivability of the aircraft depends upon the particular aircraft design. To give the reader an understanding of the part each system plays in the survivability of aircraft, a brief description of each system is given for both fixed- and rotary-wing aircraft. In the presentation that follows, a system is made up of a group of subsystems. Subsystems are composed of assemblies, and subassemblies are composed of parts. The generic term 'component' will be used throughout this textbook for any one of these terms. For example, a fuel tank, which is an assembly of parts in the fuel storage subsystem of the fuel system, and an engine, which is an assembly of parts in the engine subsystem of the propulsion system, will be referred to as components. The reader should be aware that the particular system/subsystem categorization used here is not universal. Some of the subsystems listed next are referred to as systems elsewhere.

2.2 Fixed-Wing Aircraft

Learning Objective	**2.2.1**	**Describe the general arrangement and the major systems of a fixed-wing aircraft.**

2.2.1 General Arrangement

An illustration of the general arrangement of the components on the F-15A is shown in Fig. 2.1. Note the location of the various components. The forward part of the aircraft typically contains the crew and many of the avionics components. The center portion of the aircraft, including the wings, usually contains the fuel tanks and the armament. The fuel and armament are located here, close to the center of mass of the aircraft, because they will change drastically in weight as the mission progresses. The fuel will be consumed, and the armament will be expended. Locating these items close to the center of mass will cause the center to remain essentially in the same location during the entire mission. Thus, the flying qualities will not change significantly during the mission. The engines and part of the flight control system often make up the aft portion of the aircraft, although the engines are sometimes supported by the wings.

2.2.2 Structural System

Illustrations of the major structural assemblies and the structural arrangement of the F-15A are given in Figs. 2.2a and 2.2b, and the substructure material distribution on the F/A-18E is shown in Fig. 2.2c. The major functions of the structural system are to provide structural integrity, rapid access to all internal compartments, and

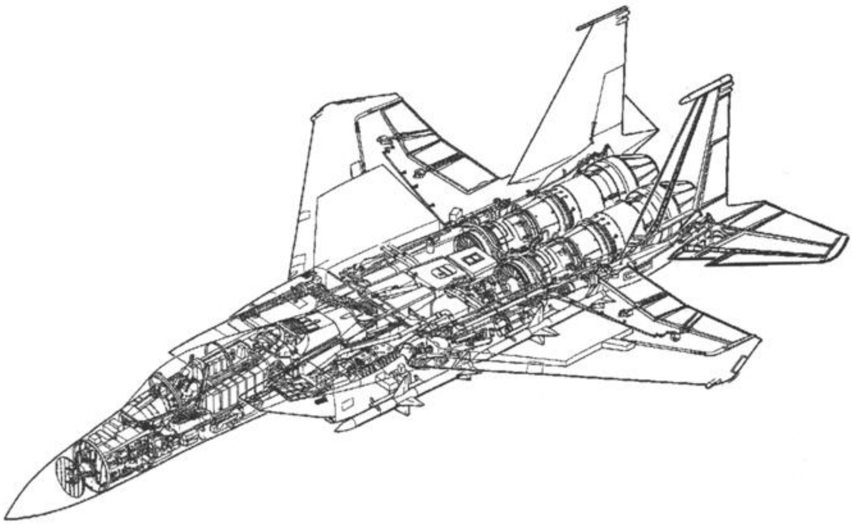

Fig. 2.1 General arrangement of the F-15A (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

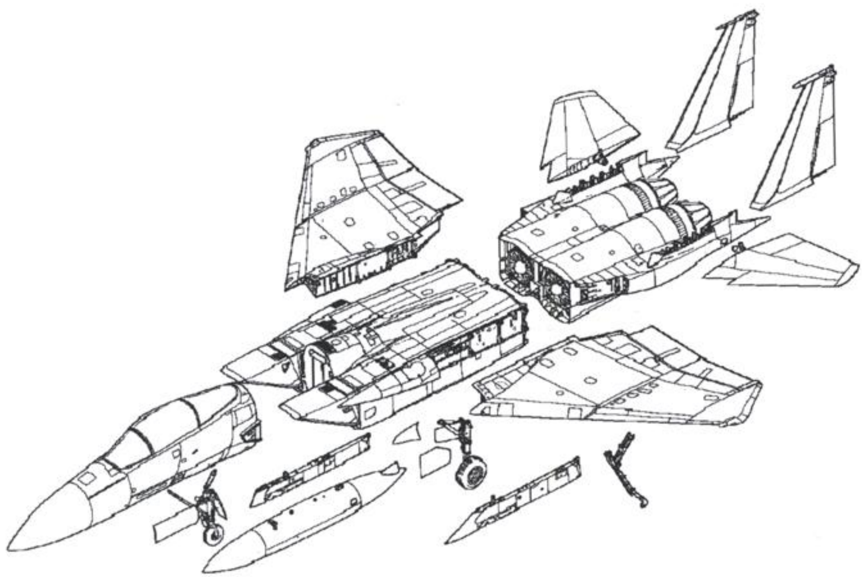

Fig. 2.2a F-15A major structural assemblies (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

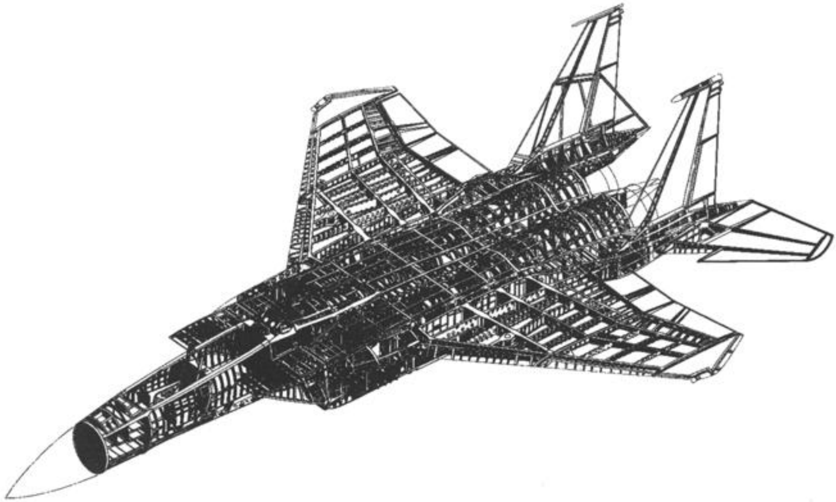

Fig. 2.2b F-15A structural assemblies (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

pressurized compartments. The major structural subsystems or groups are the wings, the fuselage, and the tail or empennage.

Materials used in the structure typically include aluminum, steel, and titanium alloys, alclad sheets, sandwich construction, and graphite- or carbon-epoxy and boron-epoxy advanced composites.

2.2.2.1 Wing structure. The wing consists of one or more major beams called spars that run spanwise (root to tip) along the wing and several formers or

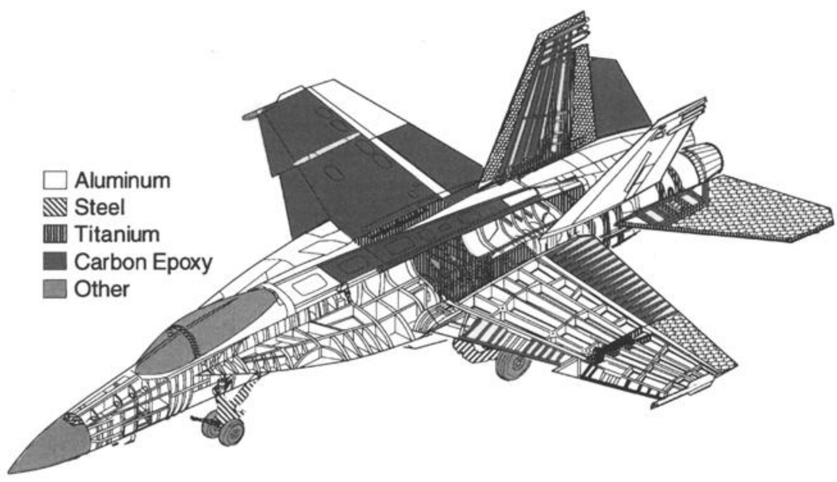

Fig. 2.2c F/A-18E substructure material (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

ribs that run chordwise (leading edge to trailing edge). A spar has upper and lower flanges connected by a solid web or struts. The ribs form the aerodynamic shape or airfoil of the wing and can be built up as a rigid frame or truss or can be made solid, like a bulkhead. The wing skin over the spars and ribs provides the major lifting surface of the aircraft. The skin, when thin, can be stiffened by lightweight, spanwise members called stringers. The combination of spars, ribs, and stiffened skin form a box beam, torque box, or wing box. The box beam on each side of the aircraft can be cantilevered from the fuselage, or the beam can be continuous from wing tip to wing tip. Naval aircraft carried on ships usually require a folding wing. The skin over the leading and trailing edges of the wing is usually nonstructural and serves to direct the flow of air over the wing.

2.2.2.2 Fuselage structure. The fuselage structure is typically of semimonocoque construction and is usually divided into three sections: forward, center, and aft. In semimonocoque construction, sometimes referred to as stressed skin, the fuselage skin is stiffened by several members running lengthwise called stringers, if they are light, or longerons, if they are heavy. The skin shape is maintained by several lateral frames or bulkheads. A major fuselage beam running lengthwise is referred to as a keel.

2.2.2.3 Tail structure. The tail group is attached to the aft fuselage and usually consists of one or more fins or vertical stabilizers and a horizontal stabilizer or tail plane. When the trailing edge of the wings extends back to the aft end of the fuselage, the horizontal stabilizer is either removed entirely or replaced by small stabilizers on each side of the forward fuselage known as canards. The construction of the vertical and horizontal stabilizers is similar to that of the wings. The stabilizers can be rigidly attached to the fuselage, or they can be attached by means of a torque tube and bearing arrangement that allows the entire stabilizer to rotate. The purpose of the stabilizers is to provide lifting surfaces that can develop the necessary aerodynamic forces to control the flight of the aircraft.

2.2.3 Propulsion System

The major functions of the propulsion system are to provide controlled thrust and possibly lift, air to and from the engine, and power for the accessory equipment. The main subsystems of the propulsion system are the engine, any propellers, the engine air inlets and exhausts, the lubrication subsystem, the engine controls, and secondary power. If the aircraft has propellers, the transmission or reduction gears and shafting between the high revolutions per minute (rpm) engine shaft and the lower rpm propellers are referred to as the power train. Figures 2.3a and 2.3b illustrate the location of the air inlets, the engines, and the exhausts on the F-15A and F/A-18E, respectively.

2.2.3.1 Engines. The engines in fixed-wing aircraft are either buried within the airframe or podded. The forward thrust necessary for flight can be provided by engine-driven propellers or internal fans, or by the jet exhaust from one or more engines, or by a combination of these two methods. Engine types are the piston, the ramjet, and the gas turbine.

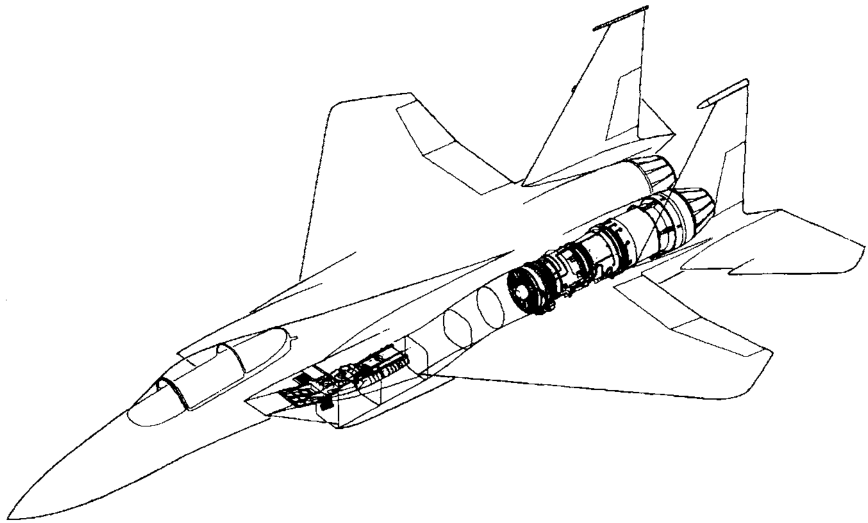

Fig. 2.3a F-15A propulsion system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

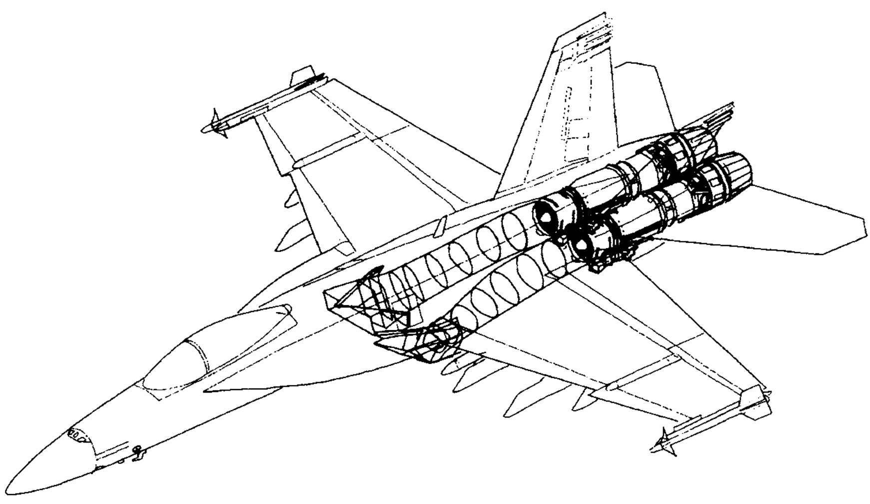

Fig. 2.3b F/A-18E propulsion system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

Piston engines. Piston engines, also known as reciprocating, internal combustion engines, drive a propeller or airscrew to produce a thrust. These engines are cooled either with air or with a liquid. The air-cooled engines have the cylinders arranged either in a radial fashion around the axis of the engine or in one or more rows along the axis of the engine. The liquid-cooled engines nearly always have one or more rows of cylinders along the axis of the engine. The liquid-cooled engines require a radiator or heat exchanger to dissipate the heat of the coolant. When operating at high altitude, piston engines usually require a supercharger to increase the amount of air entering the engine and thus obtain an adequate amount of power.

Ramjets and gas turbines. The airbreathing ramjet engine takes in, slows down, and compresses atmospheric air through an inlet duct, heats the air in a combustion chamber or combustor by burning fuel, and directs it out an exhaust duct or nozzle. The hot, accelerated exhaust gas provides the thrust. If the inlet air is compressed with the aid of a high-pressure compressor that is driven by a turbine that is turned by the exhaust gas, the engine is a type of gas turbine called a turbojet. If the power developed by the turbine also turns a propeller, the engine is called a turboprop. If a low-pressure compressor, called a ducted fan, is added and if some of the inlet air is bypassed around the high-pressure compressor, the engine is called a bypass turbojet or turbofan. The fan can compress all of the air entering the engine or only the bypass air. The total thrust from the turbofan engine is made up of the thrust from the hot exhaust gas that passes through the primary duct consisting of the high-pressure compressor, the combustor, the turbine, and the exhaust nozzle, and the thrust on the fan caused by the acceleration of the inlet air. (In the turbofan engine the fan acts like an internal propeller.) The hot exhaust gas and the bypass air can be mixed and flow out of one exhaust nozzle, or they can exit through separate ducts, with the cooler bypass air usually surrounding the hot exhaust gas. Additional thrust in gas turbines can be obtained by burning fuel in the exhaust duct or augmentor. This is referred to as afterburning or reheat.

Gas turbines are typically built with several spools, each spool containing a portion of the total turbine and fan wheels. For example, in a two-spool engine the high-pressure turbine (the first turbine after the combustor) can drive the high-pressure compressor on one spool, and the following low-pressure turbine can drive the inlet fan on the other spool. Turbofan engines usually are most efficient at low and medium subsonic flight speeds. However, the addition of afterburning extends the utility of turbofans to the supersonic region. The turbojet is usually most efficient at transonic and supersonic speeds, and the ramjet operates at relatively high supersonic speeds.

2.2.3.2 Engine air. Piston engines are used only on subsonic aircraft, and the air required for their operation is taken in through small scoops on the cowling around the engine.

The inlets to gas turbines, on the other hand, must capture air from the freestream and possibly decelerate it to provide uniform, subsonic airflow to the engine face throughout the aircraft flight envelope at various attitude conditions. The inlet opening might be located and shaped to take in air over a wide range of angles of attack and is often positioned away from the surface of the aircraft so that it is out of the surface boundary layer. The inlet opening might be of a fixed size, or it might have a variable opening geometry provided by one or more hinged ramps or movable bodies that adjust and contour the amount of air entering the engine when the aircraft is traveling at high subsonic speeds and above. Bypass doors in the inlet duct that open to allow excess, high-velocity inlet air to escape are sometimes used, and sometimes inlet doors that take air in at low velocity are employed.

The exhaust duct provides the path for the engine exhaust gas. The duct must be shaped to minimize losses. The nozzles on supersonic aircraft are usually built with a variable area throat and exit opening for improved performance at all flight speeds and altitudes, and some aircraft have exhaust nozzles that can pivot and change the direction of thrust. The nozzle is usually circular or axisymmetric; however, the use of rectangular or two-dimensional nozzles is sometimes used to reduce the infrared signature.

2.2.3.3 Engine lubrication, cooling, control, and secondary power. The lubrication subsystem is usually a self-contained, pressurized oil subsystem that provides pressure lubrication to the engine bearings and accessory drives. It has a storage tank, pressure and temperature indicators, pumps, lines, and coolers. The coolers typically use air or fuel for the heat dissipation.

The engine cooling subsystem can consist of a closed, pressurized liquid subsystem with pumps, lines, and a radiator, or it can use the freestream air for cooling. The requirement for the cooling of turbofan engines is minimized by the availability of the bypass air for cooling. Typically, air scoops or inlet duct slots gather and direct boundary layer or inlet air through the length of the engine compartment, thus cooling the engine as well as venting the compartment of any fuel vapors. The cooling air is usually expelled near the tail of the aircraft so as to minimize drag.

The major engine control consists of a power setting or throttle lever and linkage to the fuel control on the engine for regulating thrust. Detents usually exist at the off, idle, military, and maximum positions. The engine indicators for a gas turbine typically consist of engine rpm, turbine inlet temperature, engine fuel flow, and the exhaust nozzle setting for aircraft with variable exhaust nozzles.

The accessory drives of the secondary power subsystem, shown in Figs. 2.3c and 2.3d for the F-15A and F/A-18E, respectively, provide power to such things as fuel pumps and controls, an overspeed governor, a tachometer, one or more electrical generators, a lubrication pump, one or more hydraulic pumps, and perhaps a variable exhaust area power unit. The accessory drives are either airframe-mounted (AMAD) or engine-mounted (EMAD).

2.2.4 Flight Control System

The control of the flight path of an aircraft is accomplished using devices called controls that position movable surfaces on the aircraft called control surfaces. The force required to position a control surface is usually provided by a hydraulic power unit called a servoactuator, although electrical or electrical-hydraulic servoactuators might be used on future aircraft. Consequently, the flight controls, control surfaces, and hydraulic subsystems make up the flight control system. Figure 2.4a shows the location of the controls, surfaces, and actuators on the F-15A. The

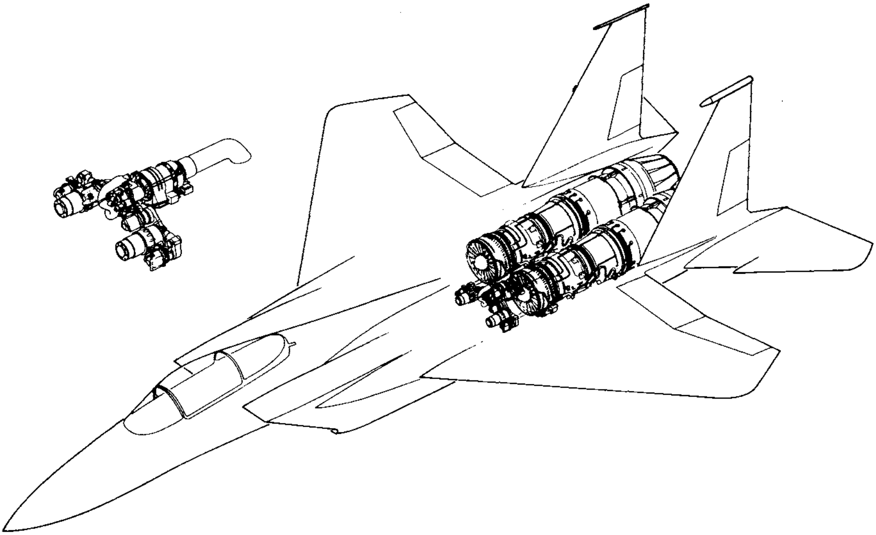

Fig. 2.3c F-15A accessory drive for secondary power (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

major function of this system is to provide control about the three axes of motion, as commanded by the pilot, throughout the flight envelope.

The three axes of an aircraft about which motion can take place are 1) the longitudinal or rolling axis that runs from the tail to the nose, 2) the lateral or pitching axis that runs from the left wing tip to the right wing tip, and 3) the vertical or yawing axis that is normal to the plane containing the other two axes. The motion of the aircraft about these three axes is dependent upon the flight characteristics of the aircraft and the ability of the pilot to control the motion.

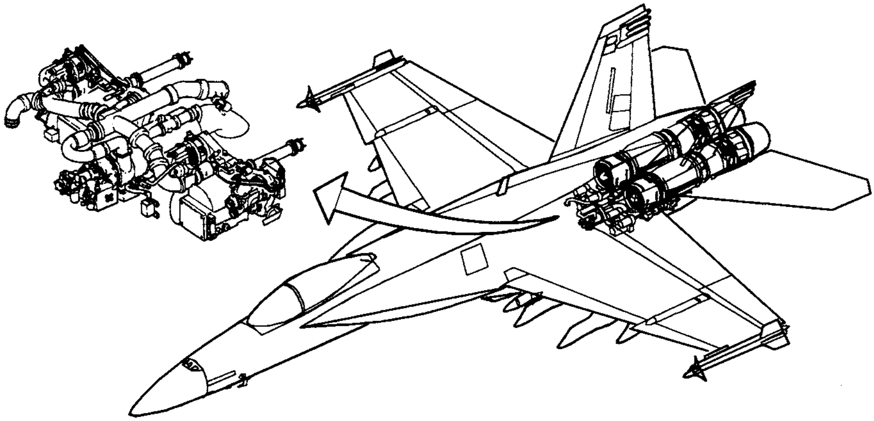

Fig. 2.3d F/A-18E accessory drive for secondary power (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

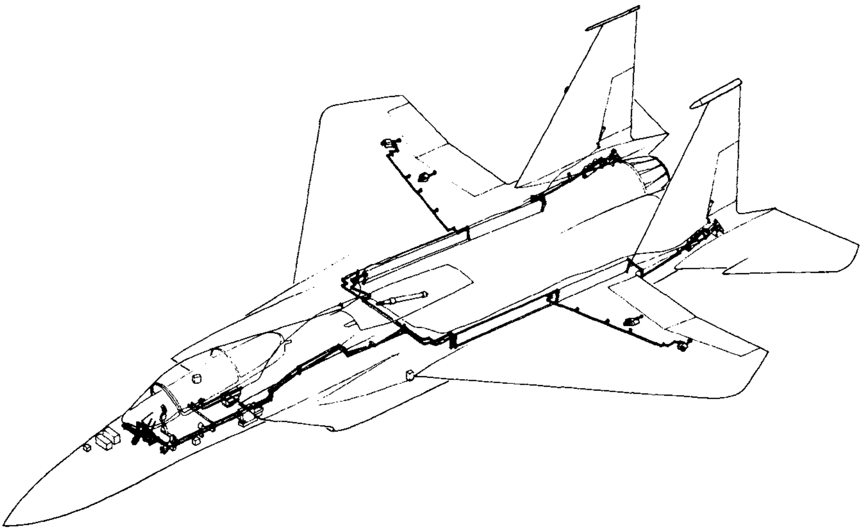

Fig. 2.4a F-15A flight controls, control surfaces, and surface actuators (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

2.2.4.1 Aircraft stability. Aircraft can be statically and dynamically stable, or neutral, or unstable. A statically stable aircraft will develop aerodynamic forces and moments that tend to return the aircraft to its original position after its equilibrium has been slightly disturbed by a gust of wind or a change in load. If the aircraft is also dynamically stable, the return path will be either in the form of damped oscillations about the original position or a nonoscillatory or deadbeat return, depending upon the damping characteristics of the aircraft. When the aircraft oscillations following a disturbance are divergent, the statically stable aircraft is said to be dynamically unstable. When the oscillations neither decay nor diverge, the aircraft has neutral dynamic stability.

A statically unstable aircraft will develop aerodynamic forces and moments that increase the initial disturbance. For example, if a gust causes a change in the angle of attack, the ensuing motion of the aircraft will be such as to increase the change. Neutral static stability exists when the aircraft neither returns to the original position nor departs in the direction of the disturbance.

The longitudinal stability of an aircraft about the pitch axis is provided mainly by the horizontal stabilizer. Directional stability about the yaw axis is provided by the vertical stabilizers and any ventral fins, and lateral stability about the roll axis is provided by a combination of wing slope (upward is dihedral and downward is anhedral), wing location, and wing sweep.

The more stable an aircraft is, the more difficulty the pilot has when attempting to change its direction. Very stable aircraft are sluggish and hard to maneuver. On the other hand, as the aircraft becomes less stable, the pilot's ability to maneuver the aircraft increases, but precise control of the aircraft flight path decreases. Controllability continues to decrease as the aircraft approaches neutral stability, and the aircraft eventually becomes uncontrollable when a certain level of static instability

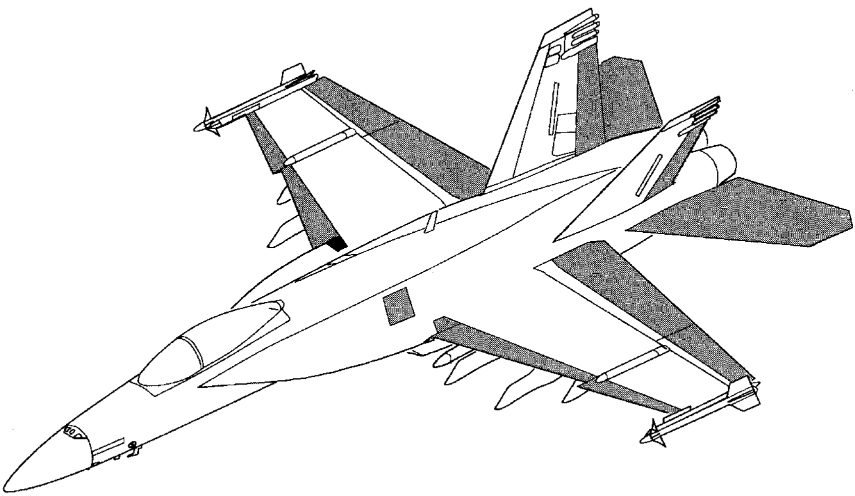

Fig. 2.4b F/A-18E control surfaces (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

or negative static stability is reached. Consequently, most aircraft have been designed to be slightly stable, with the degree of stability depending upon the stability axis and the role of the aircraft. However, the advent of computer-controlled flight has allowed new aircraft to be designed with relaxed static stability. The computer can continuously provide all of the fine adjustments of the various control surface positions that are required to maintain the flight path selected by the pilot. Without the computer the pilot may or may not be able to control the aircraft, depending upon the particular design.

2.2.4.2 Control surfaces. Conventional control surfaces are basically panels that are hinged to portions of the wings, the fuselage, and the vertical and horizontal stabilizers. The control surfaces on the F/A-18E are shown in Fig. 2.4b. Movement of a panel changes the airflow over the supporting member and hence changes the aerodynamic force on the local structure. If the control surface reaction is felt by the pilot as a feedback through the control system, the system is called reversible. If the forces required to position the surfaces are too large for the pilot, servoactuators are used, and an artificial-feel subsystem is added to provide the pilot with a responsive feel when flying the aircraft. This type of system is called irreversible.

The conventional control surfaces or panels are the ailerons, the elevators, and the rudder. In general, the ailerons and rudder are used together to roll and turn the aircraft, and the elevators are used to change the climb angle or angle of attack. One aileron is usually located along an outer portion of the trailing edge of each wing. They can be counterrotated either up or down. When the left aileron pivots upward, the right aileron pivots downward. The lift force on the left wing will decrease, and that on the right wing will increase, causing the aircraft to roll counterclockwise about the roll axis. (The aircraft will also tend to yaw during a roll as a result of unbalanced forces.) Directional motion about the yaw axis is controlled by the rudder, a panel that is hinged to the trailing edge of the vertical stabilizer and that can rotate in both directions. The elevators are panels hinged to the trailing edge of the horizontal stabilizer. They affect the pitching motion of the aircraft. For example, rotating the elevators upward causes the nose of the aircraft to pitch upward because of the reduction in the aerodynamic lift force on the horizontal tail.

There are many deviations from these three basic surfaces, particularly with respect to the elevators. For example, allowing the horizontal stabilizer to rotate as a unit slab called a stabilator can eliminate the need for the elevators. Breaking the unit horizontal stabilzer into two stabilizers and allowing each stabilizer to pivot independently provides both pitch and roll control and can eliminate the need for the ailerons. This type of control, referred to as differential stabilizers or tailplane, is sometimes used on aircraft with variable geometry wings because the ailerons can become ineffective when the wings are fully swept back. A mixer assembly is required to convert the pilot's control inputs into the proper surface movement. On tailless aircraft there might be no elevators, stabilators, or differential stabilizers. Their functions might be provided by the ailerons, which are called elevons in this application.

Two other hinged surfaces that can be used for control are spoilers and speed brakes. Spoilers, sometimes called flaperons, are usually panels hinged to the upper surface of the wings. They only rotate in one direction and serve to reduce the lift on the wings. They can assist in the roll control of aircraft with and without ailerons. Speed brakes are panels hinged to the fuselage or wings that are extended into the airflow to slow the aircraft down. They can also be used to control the motion of the aircraft in an emergency. Split ailerons can also be used as a speed brake by rotating the upper half upward and the lower half downward.

Other movable surfaces that are primarily intended to provide extra lift, such as wing leading and trailing-edge flaps and leading-edge slats can also be used as supplementing or backup control surfaces.

A small tab is often located at the trailing edge of a control surface. This tab is called a trim tab and is used to finely balance or trim the aircraft. A deviation of the trim tab position will cause an opposing deviation in the position of the control surface. The trim tab reduces the magnitude of the hinge moment required to position the control surface and, hence, reduces the required control forces.

2.2.4.3 Flight controls. The aircraft flight controls that transmit the control signal to move the control surfaces include the control column (a stick or wheel) for moving the elevator and ailerons and the control pedals for moving the rudder. The column and pedals can be mechanically linked to the surfaces or to the controlling servoactuators by cables, push-pull rods, torque tubes, bell cranks, and quadrants, or electrically linked by wires from the column and pedals through a computer and on to the servoactuators. The use of electrical wiring to carry the control signals is referred to as fly-by-wire. Artificial-feel devices or packages are inserted in the linkage or control path to provide force cues and feedback to the pilot.

2.2.4.4 Automatic flight control system. The pilot may be assisted in the flying of the aircraft by an automatic flight control system (AFCS). The AFCS normally provides two functions: 1) it augments the aircraft's natural damping characteristics, and 2) it provides automatic commands to the controls for holding the attitude, altitude, and heading selected by the pilot. The first function, the modification of the aircraft damping characteristics, decreases the tendency of the aircraft to oscillate and is carried out by the stability augmentation subsystem (SAS) or the control augmentation subsystem (CAS). A computer is used to process inputs from the pilot's controls and from aircraft motion sensors. It then generates the necessary control surface commands for roll, pitch, and yaw to reduce oscillations and maintain stability. Aircraft that are designed with relaxed static stability might not be controllable without the SAS. The second function of the AFCS is provided by the autopilot. The autopilot relieves the pilot of much of the workload required to fly the aircraft by maintaining a hold on the selected attitude, altitude, and heading.

2.2.4.5 Hydraulics. On small aircraft that fly at slow speeds, the control surfaces can be moved physically by the pilot directly through the mechanical linkage from the cockpit controls to the control surfaces. However, the forces required to position the control surfaces on high speed or large aircraft can be excessive. Consequently, either a power-boosted or a power-operated control system is used. A power-boosted system employs a servoactuator in parallel with a mechanical linkage to assist the pilot in positioning the surface. A power-operated system uses the servoactuator to supply all of the force required to position the surface.

Most powered systems use servoactuators that are powered by a hydraulic fluid under very high pressure, typically 3000 psi on older aircraft; newer military aircraft use 4000 or 5000 psi. The hydraulic fluid is pressurized by an electrical pump in the secondary power subsystem, and the pressurized fluid is supplied to the servoactuators and other hydraulically operated components, such as the flaps, bomb bay doors, and landing gear, by pressure and return tubes or lines linking the pump, accumulator, and reservoir configuration. The servoactuator contains a control or servovalve that receives the input control signal and accordingly meters the hydraulic fluid to one or more power cylinders that make up the actuator. The servoactuator is usually located close to the surface to be moved. Figures 2.4c and 2.4d show the location of many hydraulic subsystem components on the F-15A and F/A-18E, respectively.

The hydraulic fluid used in military aircraft until the end of the conflict in SEA was MIL-H-5606, a common mineral fluid used in many civil and military aircraft. Because this fluid is very flammable and a large number of aircraft losses were attributed to this flammability, many military aircraft now use the fire-resistant synthetic hydrocarbon MIL-H-83282 to reduce aircraft vulnerability. A hydraulic fluid that is nonflammable is MIL-H-53119, known as CTFE.

Electrically powered actuators replace the older hydraulic-powered actuators in modern, more-electric or all-electric aircraft. Self-contained electrically powered actuators can consist of two dc electric motors with a gear train transmission and ram, known as an electromechanical actuator (EMA), or an electric motor that drives a small hydraulic pump and ram, known as a electrohydraulic or electrohydrostatic actuator (EHA). This type of power supply is referred to as power-by-wire (PBW). (See news release online at http://www.dfrc.nasa.gov/Newsroom/PressReleases/1998/98-84.html.)

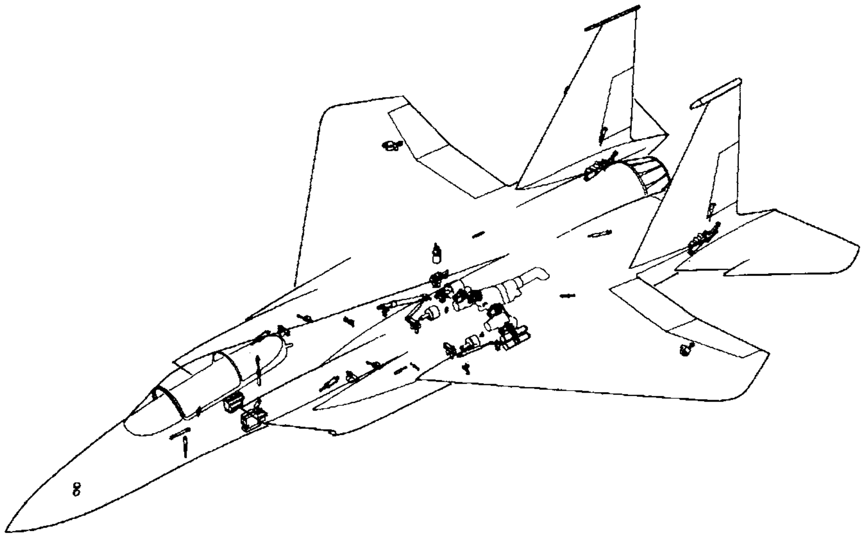

Fig. 2.4c F-15A hydraulic subsystem (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

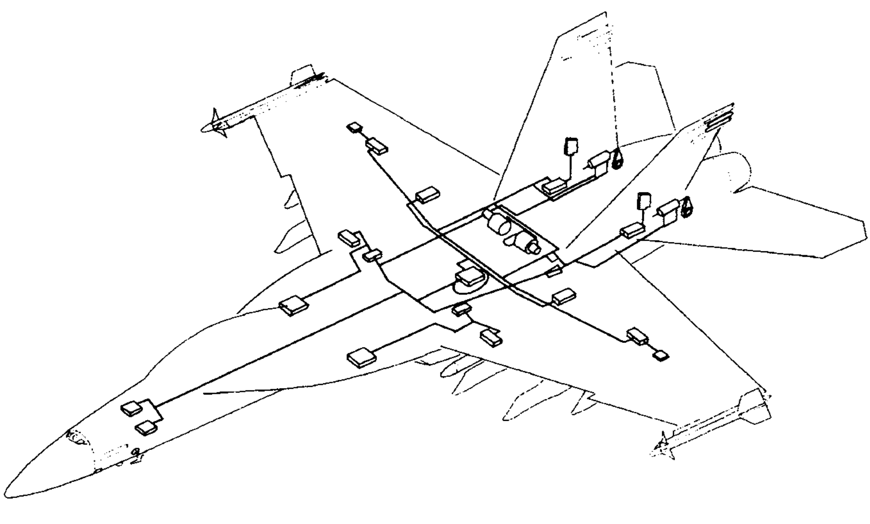

Fig. 2.4d F/A-18E hydraulic subsystem (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

Aircraft that rely totally on hydraulic power for the control forces can become uncontrollable when a hydraulic failure occurs. Consequently, most military aircraft employ more than one source of hydraulic power for safety of flight, and each source is independent from the other sources. The hydraulic subsystems that provide power to the flight control actuators are usually referred to as the power control (PC) subsystems, and the subsystem that provides power to the nonflight essential actuators is known as the utility subsystem. Each PC subsystem can have more than one circuit. For example, the hydraulic subsystem on the F/A-18E shown in Fig. 2.4d has two independent power control subsystems: HYD 1 and HYD 2. One engine drives the HYD 1 hydraulic pump and the other engine drives the HYD 2 pump through the secondary power accessory drives. Both HYD 1 and HYD 2 are divided into two independent circuits: A and B. All of the flight control actuators are pressurized by two or more subsystems. For example, a particular actuator can be powered by HYD 1A and HYD 2B. A backup hydraulic power source, such as a ram air turbine (RAT) or hand pump, can be provided for emergency operation of selected components.

2.2.5 Fuel System

The major function of the fuel system is to provide the fuel for combustion in the powerplant. The fuel can also be used for cooling and hydraulic power. The system consists of the internal and external storage tanks, the distribution subsystem, the refueling/dumping subsystem, and the indicating subsystem. The internal storage and distribution subsystems on the F-15A and F/A-18E are shown in Figs. 2.5a and 2.5b, respectively.

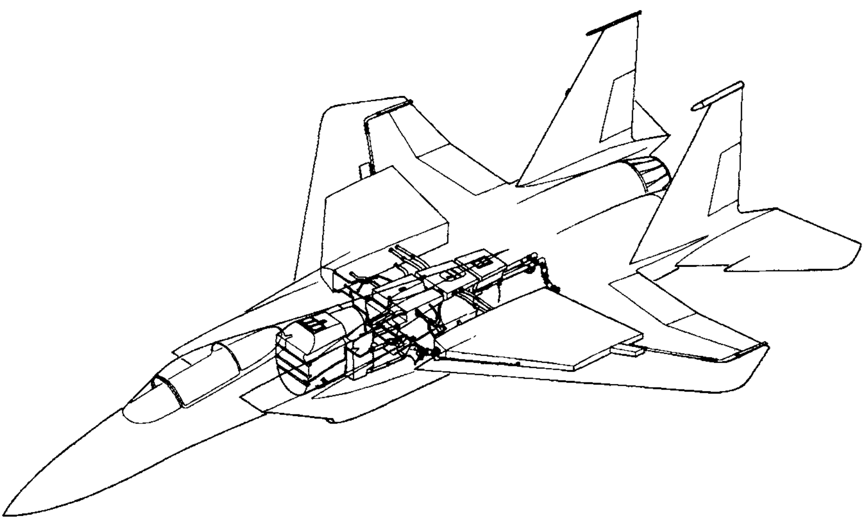

Fig. 2.5a F-15A fuel system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

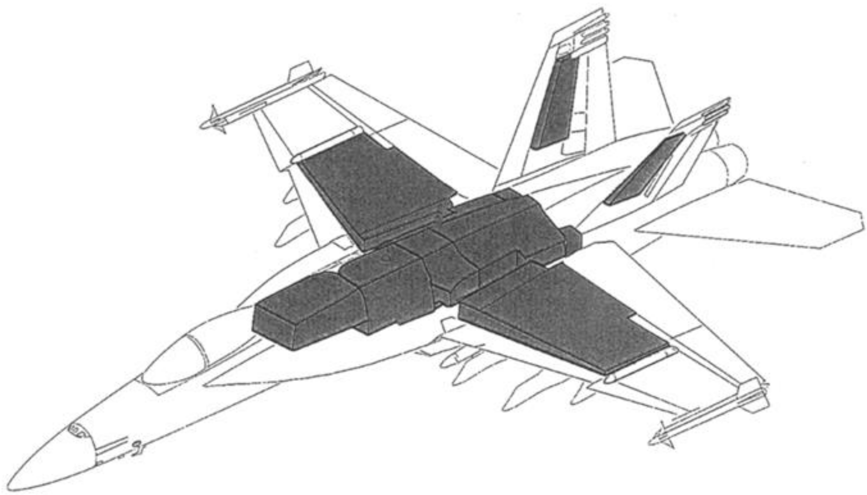

Fig. 2.5b F/A-18E fuel system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

2.2.5.1 Storage. Most of the fuel carried by an aircraft is usually stored internally in the fuselage and/or wings in one or more closed tanks or cells located near the center of mass of the aircraft. The tanks might be "leak-proof" metal boxes or metal cavities formed by the structural elements of the aircraft, such as the skin, spars, ribs, and bulkheads. The latter are known as integral or wet tanks. The fuel might also be stored in semiflexible bags or bladders that fit inside the tank. The bladders, typically made of rubber and nylon fabric, might require a special supporting structure or backing board that separates the bladder from the external skin or other structural elements of the aircraft. Wet tanks are seldom used in the fuselage as a result of leakage problems, but most wing tanks are wet.

The external storage consists of expendable metallic or nonmetallic tanks carried under the fuselage and/or under the wings on pylons. These tanks are referred to as drop tanks although they are usually jettisoned only in an emergency.

2.2.5.2 Distribution. Typically, several internal and external tanks are used, and the fuel is continuously transferred between the tanks to maintain an even balance of the fuel load. Any external fuel is usually transferred to the wing tanks as the wing tanks transfer their fuel to the fuselage tanks. When the external fuel is totally transferred, the wing tanks begin to empty. If the fuel is used to absorb the heat from engine accessory drives, lubrication oil, or hydraulic fluid, the hot fuel can be recirculated back to the wing tanks for cooling. Thus, the wing tanks might always contain a certain amount of fuel.

The fuel can be transferred between tanks by several methods. It can be moved from one tank to another by one or more electric boost pumps, by motive flow, or by gravity flow. (Motive flow works on the Venturi principle.) A net positive pressure in the tank ullage (the internal space above the fuel surface) is usually provided by a combination of air vents and a pressure air supply (usually bleed air from the engine) to assist in the fuel transfer and to prevent the fuel from boiling when the aircraft is at high altitudes. The ullage pressure is regulated to prevent both a relatively large net internal pressure buildup during aircraft ascent and a net external pressure buildup during descent.

The tank that supplies the fuel to the engine is called the feed or sump tank. It is usually the lowest fuselage tank. The fuel is pumped or flows from the feed tank through the feed line to the engine. If the fuel is not pressurized in the feed line, vaporization or vapor lock can occur causing engine flameout. A compartment or baffles in the feed tank can provide a limited fuel supply during negative g or inverted flight. The pump that supplies high-pressure fuel to the engine combustor is the main fuel pump and is typically located with the engine accessories.

In addition to supplying the engine and cooling the accessories, the fuel is sometimes used as a hydraulic fluid to operate components such as a variable area engine exhaust nozzle.

2.2.5.3 Other subsystems. The refueling/dumping subsystem consists of the piping and valves required to fill the storage tanks with fuel and to dump excess fuel from the tanks. An in-flight refueling probe is installed on some aircraft, and nearly all aircraft have the capability to dump fuel overboard from the tanks. The indicating subsystem consists mainly of the fuel quantity in the various tanks.

2.2.5.4 Fuel. Aviation fuel is currently obtained from petroleum.[1] (http://www.afcee.brooks.af.mil/pro-act/fact/feb99a.asp and http://members.aol.com/afp1fire/fuels.htm.) There are several grades of fuel available. Because the fuel used by piston engines is pressurized in a hot cylinder prior to ignition, a relatively light fuel, known as gasoline or AVGAS, is used that contains additives to prevent premature detonation or knocking. In a gas turbine, on the other hand, the combustion process is continuous at a constant pressure, and the antiknock requirement does not exist. Consequently, the choice of fuel for gas turbines is based upon efficiency, safety, operation at low temperatures, cost, and availability. Kerosene, a heavy fuel called JP-1, would be a good fuel, except for its poor performance at low temperatures. Consequently, a lighter fuel must be used for cold weather or very high-altitude operations. The Air Force used the highly volatile JP-4 (Avtag, NATO F-40) until 1996, when it completed the conversion to JP-8 (NATO F-34), a less volatile fuel. The Navy uses the low volatility JP-5 (Avcat, NATO F-44) to minimize the likelihood of a fire onboard the aircraft carrier. These are mixtures of various grades of fuel extractable during the refining process. JP-4 is a blend of gasoline and kerosene, and JP-5 is a less volatile, heavier kerosene-based fuel. Other fuels sometimes used are the commercial aviation fuels Jet A and Jet A-1, which are essentially equivalent to JP-8, and Jet B, which is equivalent to JP-4.

2.2.6 Other Systems

The other systems include a crew, avionics, armament, environmental control, electrical, and launch and recovery. The location of some of the components of these systems is shown in Figs. 2.6a–2.6d for our two example aircraft.

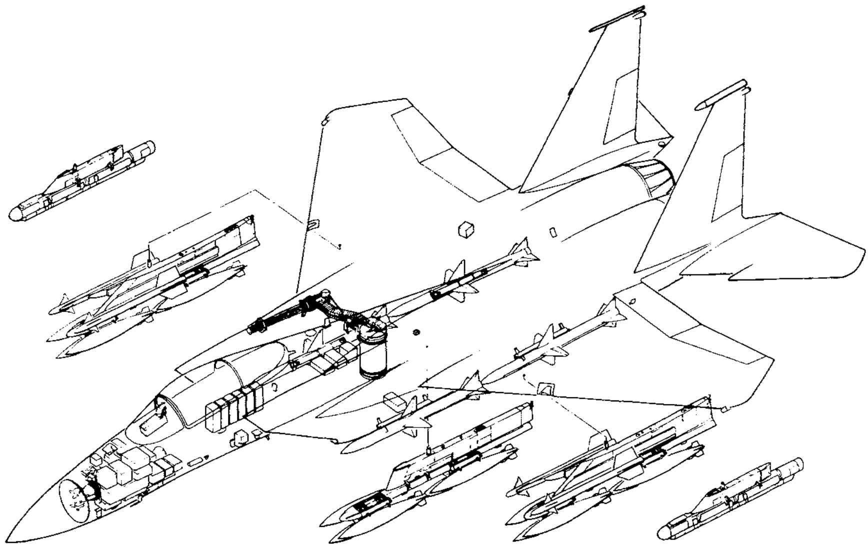

Fig. 2.6a F-15A avionics and armament systems (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

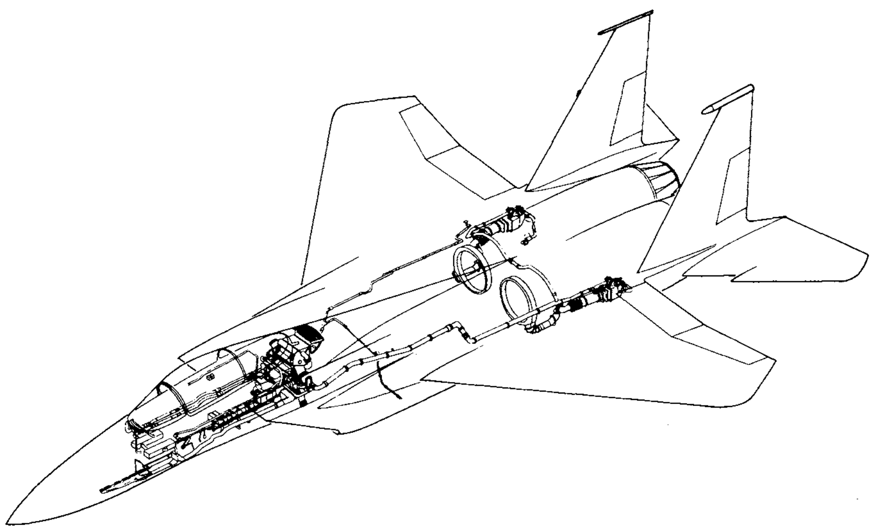

Fig. 2.6b F-15A environmental control system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

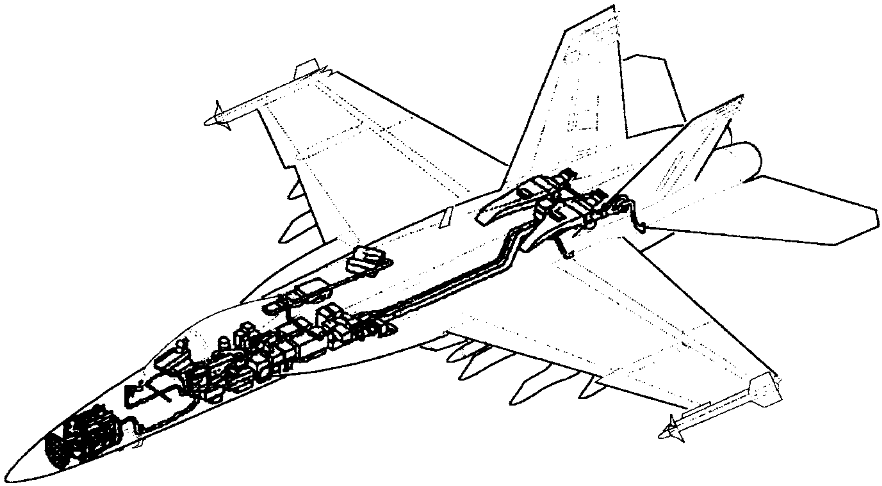

Fig. 2.6c F/A-18E environmental control system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

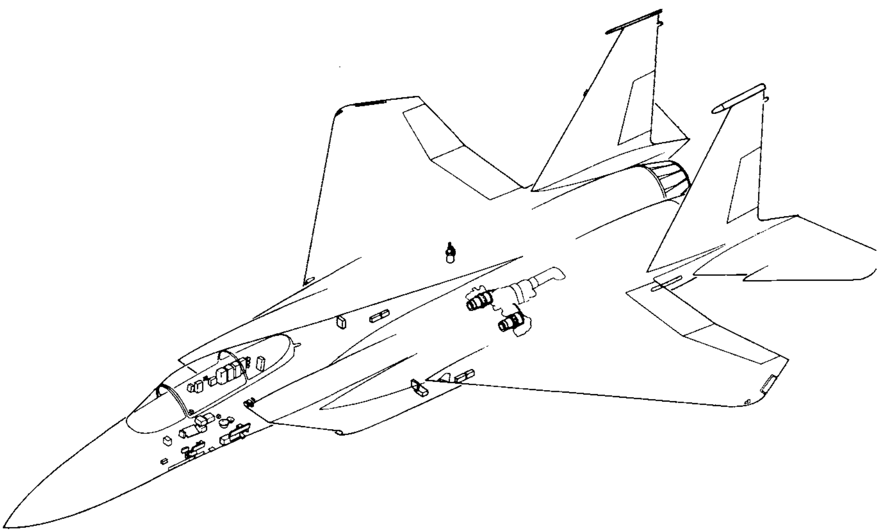

Fig. 2.6d F-15A electrical system (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

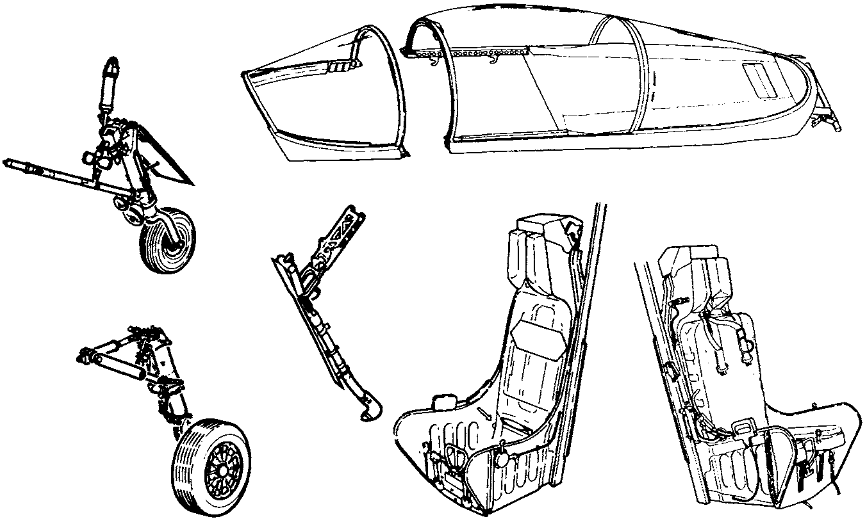

Fig. 2.6e F-15A landing gear and escape subsystems (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

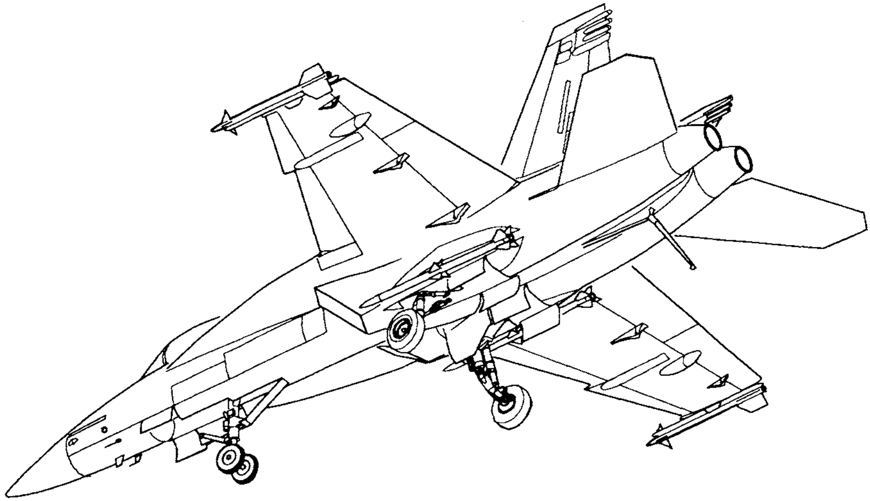

Fig. 2.6f F/A-18E modified landing gear (Reproduced with permission of The Boeing Company, St. Louis, Missouri).

The crew obviously operates the aircraft and can range in number from one to many members.

The avionics system can include the automatic flight control system discussed earlier and the stores management, fire control, navigation, motion sensors, and internal and external communications subsystems.

The armament system consists of the bombs, guns and ammunition drums, rockets, missiles, mines, and torpedoes carried by the aircraft for offensive and defensive purposes.

The environmental control system (ECS) includes the air-conditioning, oxygen, and air-pressurization subsystems. The air-conditioning subsystem provides ventilation, heating, cooling, moisture control, and pressurization for the crew stations and equipment bays. The oxygen subsystem typically consists of a liquid-oxygen (LOX) storage container or an onboard oxygen-generating system (OBOGS) and the associated controls, valves, and piping to the crew stations. The air-pressurization subsystem typically uses a mixture of hot bleed air from the gas turbine high-pressure compressor section and freestream ram air. This high-pressure air is supplied to the air-conditioning subsystem, the gun bay for purging the gun gas, the rain repellent subsystem for cleaning the windscreen, the deicing subsystem, and the fuel tanks for internal pressurization.

The electrical system consists of ac and dc subsystems that include generators, batteries, controls, and distribution components. This system provides the electrical power throughout the aircraft. The electrical system is becoming the primary power supply system in new aircraft as electrical power is replacing hydraulic and pneumatic power on the more-electric aircraft, and eventually it might replace all other power systems on the all-electric aircraft.[2]

The onboard takeoff/launch and recovery system includes the landing gear and sometimes a drag chute or arresting hook for quicker stops.

2.3 Rotary-Wing Aircraft

Learning Objective	**2.3.1**	**Describe the general arrangement and the major systems of a rotary-wing aircraft.**

Rotary-wing aircraft require lift, thrust, and control to fly, just like fixed-wing aircraft. They have the same five major systems that provide these functions as fixed-wing aircraft, except the power train and rotating blades are usually identified as a separate system. The major lifting surfaces are the main rotor blades. However, some rotary-wing aircraft have wings that provide some lift during forward flight, thus reducing the load on the rotor. The thrust is also provided by the main rotor(s), and the aerodynamic forces required to control the direction of flight are provided by a combination of rotors.

2.3.1 General Arrangement

The general arrangement of the UH-60A Black Hawk is illustrated in Figs. 2.7a and 2.7b, and the helicopter dimensions and general arrangement of the RAH-66A Comanche are illustrated in Figs. 2.7c and 2.7d. The forward portion of the aircraft

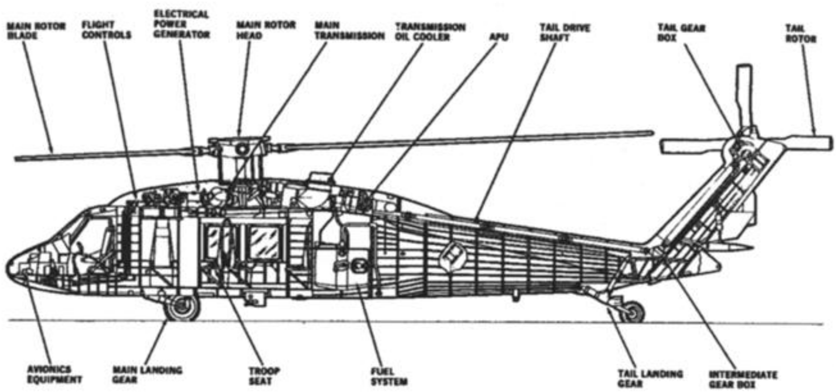

Fig. 2.7a UH-60A general arrangement, elevation view (Reproduced with permission of the U. S. Army).

usually contains some of the crew and avionics components. The center portion of the aircraft contains the main rotor, the engines, usually on top, the fuel tanks, usually on the bottom, any wings, and the payload. The aft portion contains the tail rotor and any vertical and horizontal tail planes. Other rotor arrangements are two coaxial main rotors that rotate in the opposite direction, two main rotors in tandem, and two main rotors side by side.

2.3.2 Structural System

Helicopters typically use the same kind of construction as fixed-wing aircraft. The fuselage is semimonocoque, possibly with one or more keels, and any wings and vertical and horizontal stabilizers are single- or multiple-spar box beams. The tubular semimonocoque or trussed portion of the fuselage that runs from the center bay back to the tail rotor is called the tail cone or boom.

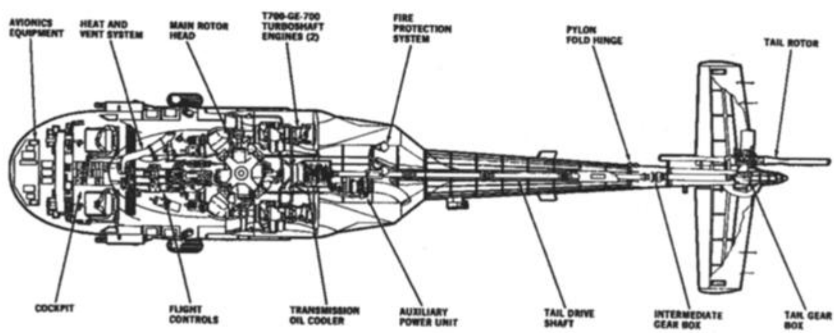

Fig. 2.7b UH-60A general arrangement, plan view (Reproduced with permission of the U. S. Army).

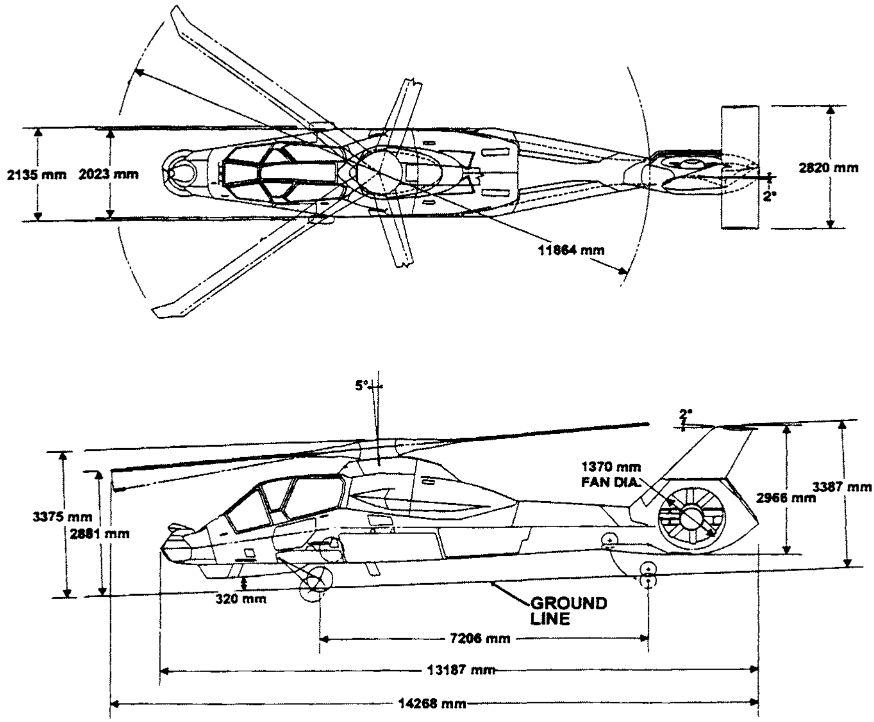

Fig. 2.7c RAH-66A dimensions (Reproduced with permission of the U. S. Army).

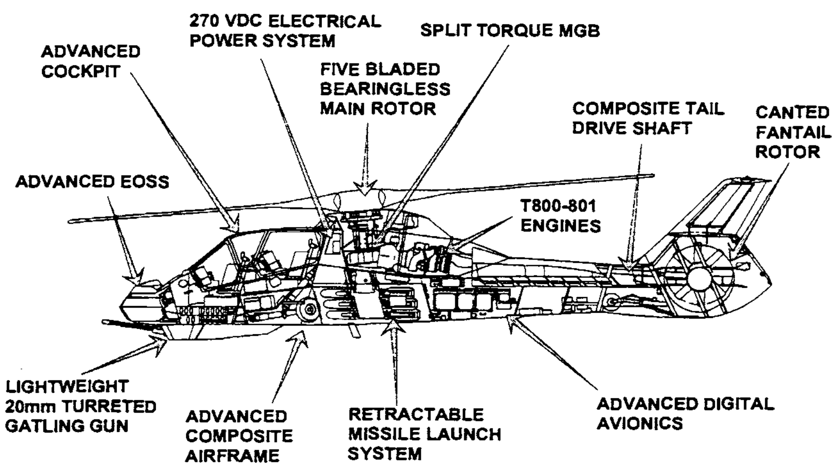

Fig. 2.7d RAH-66A general arrangement, elevation view (Reproduced with permission of the U. S. Army).

Much of the helicopter structure is designed to be crash resistant for reasons of safety. In particular, the fuel tanks should be designed to retain their integrity during a crash.

Aluminum has been the most common material used in helicopters, but advanced, lightweight composites can be used in the most recent designs, such as the Comanche.

2.3.3 Propulsion System

Helicopter powerplants usually consist of air-cooled gas turbines that turn shafts in the power train system that eventually turn the rotor blades. These engines are called turboshaft engines. The main objective of the turboshaft engine is to convert as much of the output power into the shaft power as possible. The engines are either buried within the fuselage or are carried externally in pods or nacelles. Air for the engine operation enters through the inlet in the cowling. This inlet air can also be used for cooling purposes, and a scheme for preventing foreign object damage (FOD) to the engine is usually included in the inlet duct or engine inlet. The engine installation for the UH-60A and the RAH-66A is shown in Figs. 2.8a and 2.8b, respectively.

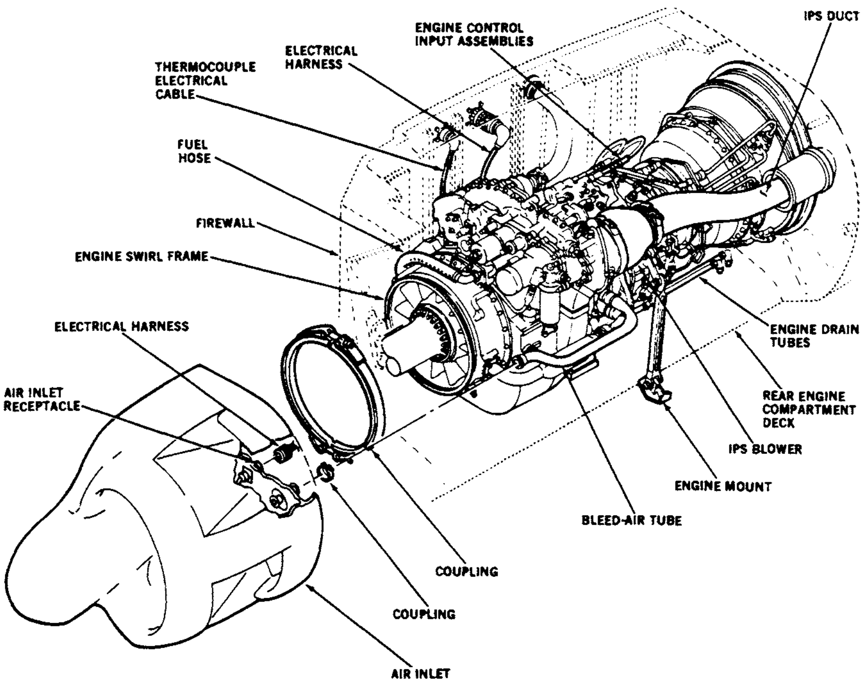

Fig. 2.8a Engine installation on the UH-60A (Reproduced with permission of the U. S. Army).

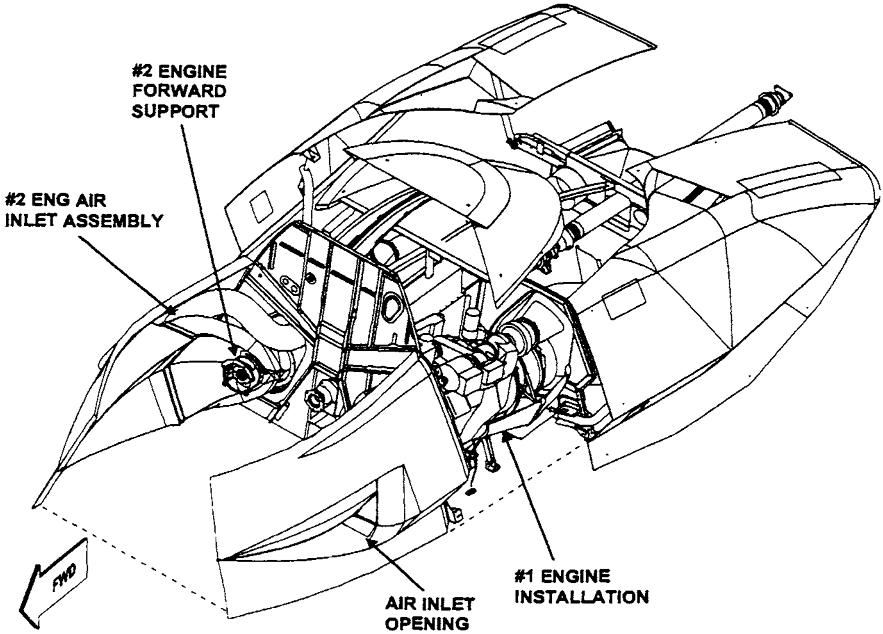

Fig. 2.8b Engine installation on the RAH-66A (Reproduced with permission of the U. S. Army).

2.3.4 Power Train and Rotor Blade System

2.3.4.1 Power train. The power or drive train of the UH-60A is illustrated in Figs. 2.9a and 2.9b, and in Figs. 2.9c and 2.9d for the RAH-66A. The power train typically consists of a main transmission or gearbox, smaller gearboxes that connect the engine drive shaft(s) with the engine-to-transmission or input drive shaft(s), a main rotor drive shaft, and either tail rotor and pylon drive shafts with intermediate and tail rotor reduction gearboxes, as used in the UH-60A, or a fantail drive shaft, quill shaft, and fantail gearbox, as used on the RAH-66A. The main transmission converts the high speed of the input shaft to the much lower speed of the main and tail rotor/fantail drive shafts. The gearboxes also allow a change in direction and speed between the input and output rotating shafts. In some designs the rotor drive comes directly from an engine output gear box. Some form of lubrication and cooling of the transmission and gearboxes is usually required.

The main rotor drive shaft is supported by a rotor support structure. The tail rotor/fantail drive shaft is composed of individual assemblies that are connected by a flexible coupling and supported by hanger bearings, dampers, and antiflail sleeves. The rotor hub is at the top or end of the rotor drive shaft and connects the rotor blades to the shaft. Figure 2.9b shows the main rotor shaft, the rotor hub, and the connections to the main transmission for the UH-60A, and Fig. 2.9d shows the main dynamics module for the RAH-66A.

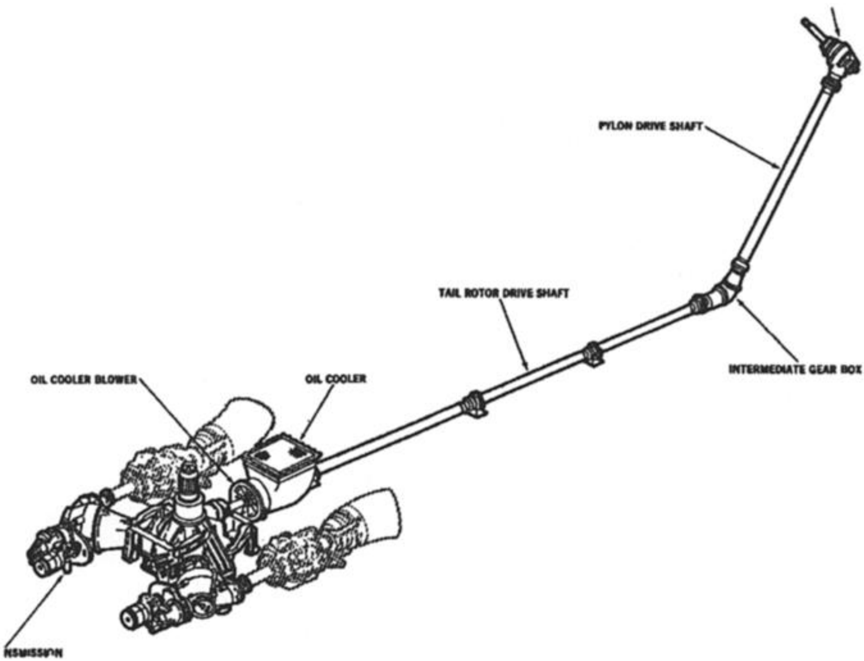

Fig. 2.9a UH-60A power train (Reproduced with permission of the U. S. Army).

2.3.4.2 Rotor blades and fantail. The main, tail, and fantail rotor blades are beam-like structures that are built in the shape of an airfoil. They can be attached to the hub in a variety of ways. The pitch of the blades, which governs the amount of lift, is usually set by pitch links (shown in Figs. 2.9b and 2.9d) that are attached to a swashplate (also shown in Figs. 2.9b and 2.9d) that rotates with the rotor. The rotating swashplate turns on or within a stationary swashplate whose position is governed by the flight control system. Displacement of the stationary swashplate changes the pitch of the blades.

2.3.5 Flight Control System

The major control surfaces of a helicopter are the rotor blades. The lateral, longitudinal, and directional control of the helicopter is provided by a collective stick, a cyclic stick, and two foot pedals. The collective mostly affects the total main rotor lift. The cyclic mostly affects the direction of the main rotor lift vector by varying the pitch of each blade as it rotates and, hence, provides the lateral and longitudinal control. The pedals, sometimes referred to as rudder pedals, provide directional control by positioning the pitch of the tail/fantail rotor blades, which affects the lateral force on the tail of the helicopter. This lateral force is required at all times on single rotor aircraft under powered flight to counteract the torque caused by the main rotor-powered rotation. A cambered vertical tail plane or stabilizer is sometimes used to provide this counteracting force during forward flight, and a horizontal stabilator can be used to assist in the longitudinal control.

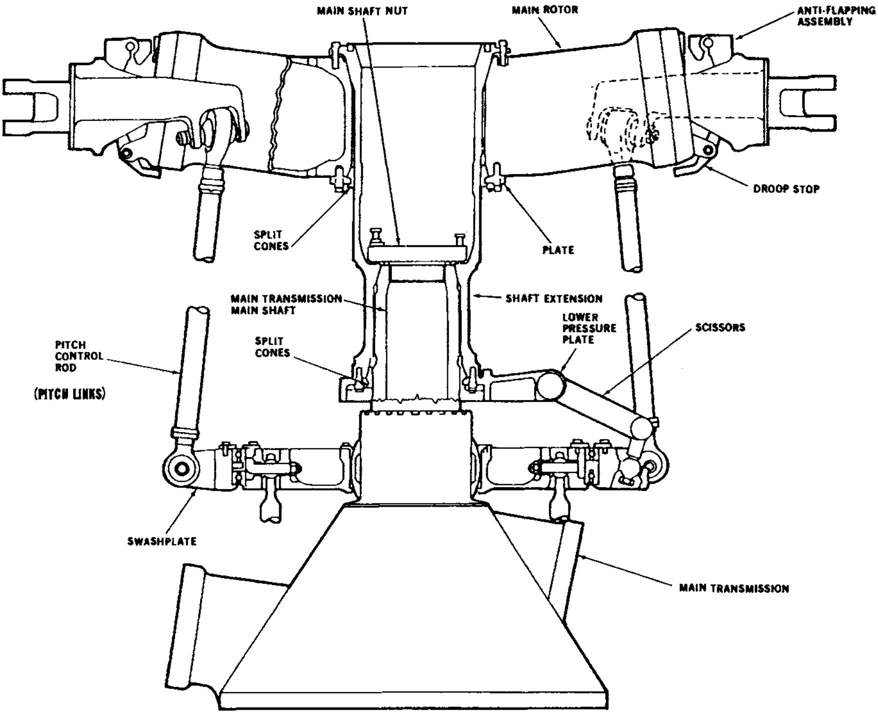

Fig. 2.9b UH-60A transmission and main rotor head (Reproduced with permission of the U. S. Army).

The sticks and pedals are connected to servoactuators that position the pitch links. The connection can be mechanical, through push-pull rods, cables, bell cranks, and quadrants, or electrical through wires. A mechanical mixer assembly provides interconnections between the controls and the rotor blades to account for such things as the required increase in tail rotor pitch caused by an increased collective command.

An automatic flight control subsystem can assist the pilot in flying the aircraft. The AFCS can have both stability augmentation and autopilot capabilities.

The hydraulic subsystem typically consists of one or more pumping and distribution subsystems that provide hydraulic power to operate the flight controls, an APU start motor, the rotor brake, and weapons.

2.3.6 Fuel System

The fuel system on rotary-wing aircraft usually includes the same subsystems used on fixed-wing aircraft. However, in most helicopters the fuel is usually stored in tanks located below the engines, as illustrated in Fig. 2.10 for the RAH-66A, often outside the fuselage in sponsons, and gravity flow cannot be used. Consequently, the fuel must be transferred either by positive boost pressure or by suction up to the engines. If suction transfer is used, a scheme for priming the fuel lines

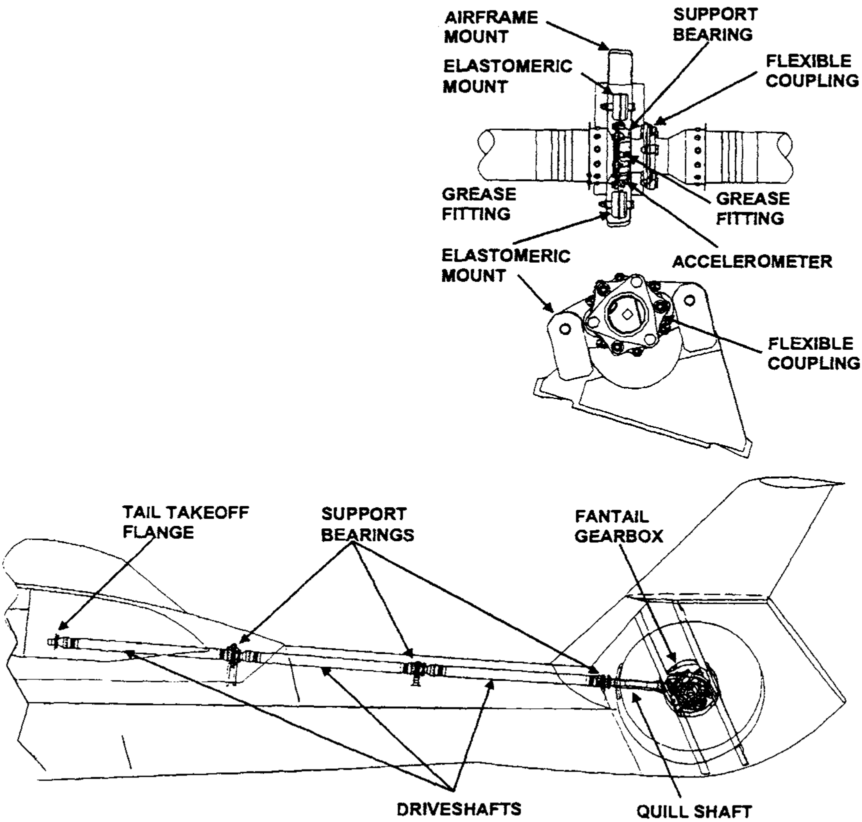

Fig. 2.9c RAH-66A fantail drive system (Reproduced with permission of the U. S. Army).

must be provided. The fuel used by rotary-wing aircraft is typically JP-4, JP-5, or JP-8.

2.3.7 Other Systems

Rotary-wing aircraft require crew, avionics, armament, ECS, electrical, and launch and recovery systems, just like fixed-wing aircraft, and they operate in much the same way as those on the fixed-wing aircraft. Perhaps the major difference between the two lies in the launch and recovery system. This system supports special takeoff and landing procedures that differ considerably from those of fixed-wing aircraft. The normal takeoff and landing procedure is vertical. However, environmental and load conditions can require a horizontal run to build up sufficient lift for vertical flight. A unique feature of the helicopter is its ability to land relatively slowly with no engine power, using the autorotational feature where the rotor blades are turned by the upward motion of the air passing through the rotor (thus generating lift) as the helicopter descends.

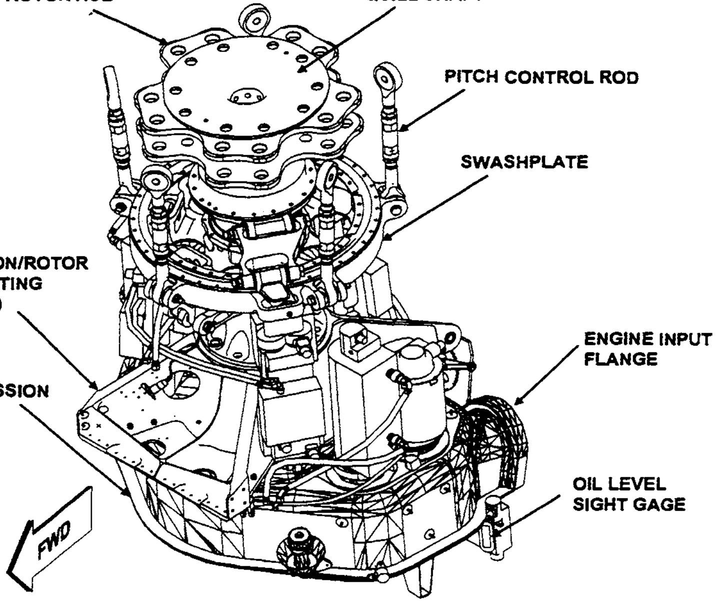

Fig. 2.9d RAH-66A main dynamics module (Reproduced with permission of the U. S. Army).

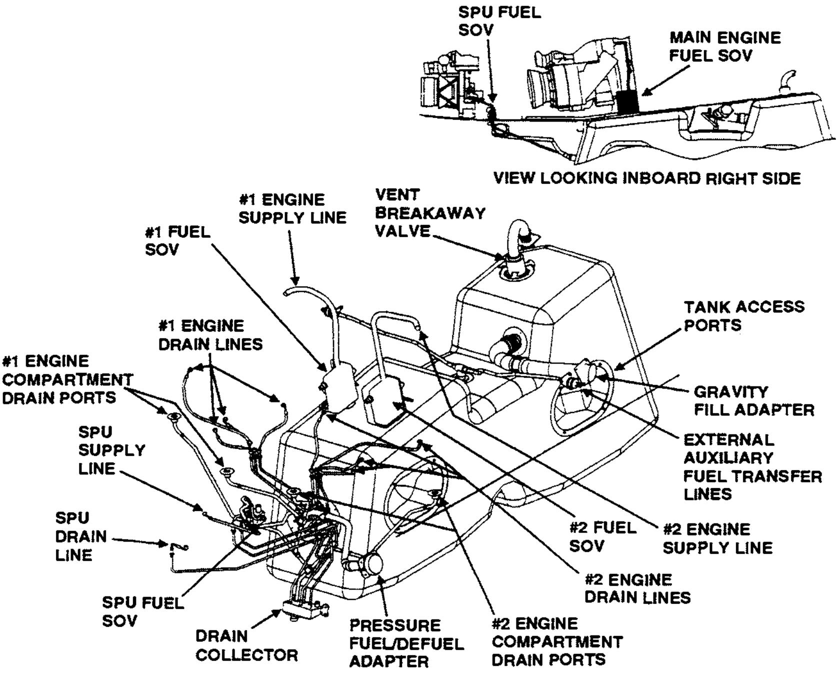

Fig. 2.10 RAH-66A fuel system (Reproduced with permission of the U. S. Army).

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Chapter 3
Missions, Threats, and Threat Effects

3.1 Military Aircraft Roles and Missions

Learning Objective 3.1.1 Describe the roles and missions of military aircraft.

Military aircraft are designed to execute one or more roles, such as fighting other aircraft, bombing enemy targets on the ground, or transporting cargo to a theater (Note 1). U. S. military aircraft are usually designated as fighters (F) when they battle other aircraft. Bombers (B) and attack aircraft (A) conduct strike operations against enemy targets on the surface. Antisubmarine aircraft (S) search for, prosecute, and kill submarines. Transport aircraft (C) carry personnel and cargoes; and patrol aircraft (P), observation aircraft (O), and special electronic aircraft (E) are used in a variety of roles. Fixed-wing aircraft with a vertical or short takeoff and vertical landing capability (VTOL/STOVL) have a V designation. Helicopters use similar designators with the suffix H. Some typical helicopter roles are utility (UH), antisubmarine (SH), cargo (CH), search and rescue (HH), attack (AH), observation (OH), reconnaissance (RH), and multimission (MH). Unmanned aerial vehicles are known as UAVs in general and as unmanned combat aerial vehicles or UCAVs when they carry weapons in a combat role. When an aircraft is designed for more than one role, the designators might be combined, such as F/A for an aircraft that can perform in both the fighter and attack roles and RAH for the reconnaissance and attack helicopter. On the other hand, some combat aircraft are designed to fight other aircraft and attack targets on the surface, and only the F designator is used. These F-designated aircraft can be referred to as multirole fighters or fighter-bombers, and the B designator is reserved for the heavy bombers.[1]

Military aircraft fly missions. A mission is "the dispatching of one or more aircraft to accomplish one particular task."[2] Missions can be divided into combat (tactical and strategic) and combat support. Tactical combat missions or air operations are used to "1) gain and maintain air superiority; 2) prevent the movement of enemy forces into and within the objective area, and to seek out and destroy those forces and their supporting installations; and 3) join with friendly ground or naval forces in operations within the objective area in order to attain an immediate objective."[2] The tactical combat missions typically involve air operations against other aircraft (air-to-air) or enemy forces on the Earth's surface (air-to-surface) to achieve the immediate objectives. The strategic missions or operations are "directed against one or more of a selected series of enemy targets with the purpose of progressive destruction and disintegration of the enemy's warmaking capacity and will to make war. . . . Strategic missions are designed to have a long-range rather than immediate effect on the enemy and its military forces"[2] (Note 2). Combat missions are also referred to as shooter missions. The combat support, or non-shooter, missions include a variety of tasks that assist, protect, or supply the friendly forces, such as reconnaissance, surveillance, scouting and observation, electronic warfare, search and rescue, and the transport or airlift of personnel, supplies, and equipment.

The survival of an aircraft on a mission is affected by the type of mission, by the amount of support from friendly forces, and by the intensity and effectiveness of any hostile air defense environment encountered during the execution of the mission. Almost all air combat missions involving fighters and bombers, such as fighter escort and close air support, will involve encounters with one or more air defense elements. Combat support aircraft that conduct missions near the forward line of own troops (FLOT) or forward edge of the battle area (FEBA), or in the vicinity of battle zones, and transport aircraft in transit to or from or within a theater of combat operations, particularly when landing, could very likely encounter a threat to their survival (Note 3).

One of the primary goals of any military operation is to gain and maintain air superiority. Air superiority is "that degree of dominance in the air battle of one force over another that permits the conduct of operations by the former and its related land, sea, and air forces at a given time and place without prohibitive interference by the opposing force."[2] Having air superiority means friendly aircraft can operate effectively without the threat of an active, effective air defense. Thus, air superiority is a major contributor to aircraft survivability.

Table 3.1 lists many of the combat and combat support missions in use today. The remainder of this section presents a brief, and very unofficial, description of these missions and a list of the aircraft that normally fly them (Note 4). The specific encounter conditions between an aircraft and the threats to that aircraft for a particular mission are determined using the mission-threat analysis, which is described in Sec. 3.8 of this chapter.

3.1.1 Tactical Combat Missions

The tactical combat missions typically involve operations against enemy aircraft and missiles, known as air-to-air operations, or operations against enemy surface forces, known as air-to-surface operations, or both (Note 5).

3.1.1.1 Air-to-air. The three primary air-to-air missions include interception, offensive counterair (which can also include air-to-surface operations), and defensive counterair. The weapons carried by the aircraft flying these missions include air-to-air guided missiles, such as the Sidewinder Air Intercept Missile (AIM-9) and the Advanced Medium Range Air-to-Air Missile (AMRAAM) (AIM-120), and guns, such as the M61A1 six-barrel Vulcan 20-mm Gatling gun. (Data for these weapons are available online at http://www.chinfo.navy/mil/navpalib/factfile/missiles/wep-side.html, http://www.chinfo.navy.mil/navpalib/factfile/missiles/wep-amr.html, and http://www.wpafb.af.mil/museum/arm/arm8.htm.) If the offensive counterair mission includes the possibility of air-to-surface operations, bombs, missiles and rockets might also be carried.

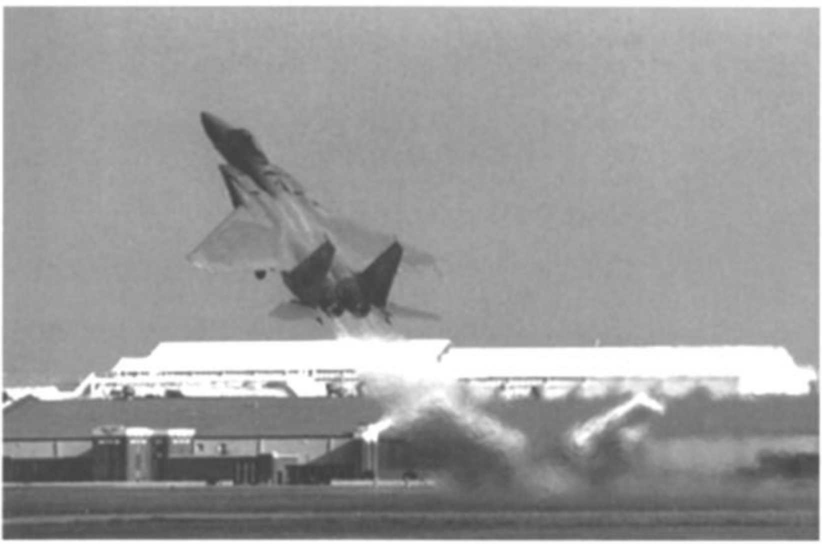
Table 3.1 Military missions

Combat	Combat support
Tactical	General
Air-to-Air	Early warning, communications, and strike and traffic control
Interception	
Offensive counterair (OCA)	Electronic support and countermeasures
Air superiority	Forward air control (FAC)
Fighter escort (FE)	Reconnaissance/observation/scouting and surveillance
Fighter sweep	Long-range targeting
TARCAP	Photoreconnaissance
Defensive counterair (DCA)	Tactical photoreconnaissance
Combat Air patrol (CAP)	Combat search and rescue (CSAR)
BARCAP	Airborne mine countermeasures
MIGCAP	Transport of supplies, equipment, and personnel
Air-to-Surface	Special operations
Close air support (CAS)	Air-to-air refueling
Antiarmor	Army aviation[a]
Air interdiction (AI)	Command, control, and communications
Air defense suppression/SEAD	Air movement
Antiship	Electronic warfare
Submarine detection and prosecution/ASW	Combat search and rescue
Army aviation[a]	Air traffic services
Reconnaissance	Aerial mine warfare
Security	
Attack	
Air assault	
Theater missile defense	
Special operations	
Support by fire	
Strategic/strategic attack	

[a] See Ref. 3.

Interception. The interception mission consists of the identification and destruction of incoming enemy bombers, cruise missile carriers, and other airborne objects typically from long range and in any weather, day or night. The interceptor aircraft is quickly 'scrambled' when early warning of an incoming attack is received. A quick takeoff and rapid climb followed by a high-speed dash, usually supersonically, are used to enable the interceptor to meet the approaching bombers as far from the defended territory as possible. Long-range, radar-guided missiles are the typical weapons of choice, but short-range missiles and guns are also carried. Aircraft that can be used on the interception mission are the F-14 Tomcat with the long-range, multiple-target Phoenix missile system, the Tornado F.3 (ADV version), and the MIG-31. (Data for the Tomcat and Phoenix are available online at http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-f14.html and http://www.chinfo.navy.mil/navpalib/factfile/missiles/wep-phoe.html.) These aircraft are sometimes referred to as air interceptors (AI), and the naval version is known as a deck-launched interceptor used for fleet air defense. The general threat to aircraft on an interception mission consists of the self-defense weapons carried by the incoming bombers and any fighters that are accompanying the bombers.

Offensive counterair. The offensive counterair (OCA) mission is to achieve a desired degree of air superiority by the destruction, disruption, or neutralization of the enemy aircraft, missiles, launch platforms, and their supporting structures and systems both before and after launch, but as close to their source as possible.[2] Thus, the OCA mission can involve both air-to-air and air-to-surface operations. Offensive counterair operations range throughout enemy territory and are generally conducted at the initiative of the friendly forces. These operations include air-to-air fighter escort, fighter sweep, target area combat air patrol (TARCAP), and surface-to-air attack and suppression of enemy air defenses. Some of the aircraft that can perform OCA mission are the F-14 Tomcat, the F-15 Eagle, the F-16 Fighting Falcon, the F/A-18 Hornet, the F/A-22 Raptor, the MIG-29, Mirage 2000, and the JA37 Viggen. (Data for the Eagle, Falcon, Hornet, and Raptor are available online at http://www.af.mil/news/factsheets/F_15_Eagle.html, http://www.af.mil/news/factsheets/F_16_Fighting_Falcon.html, http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-fa18.html, http://www.nadepni.navy.mil/FA-18_str/FA18info.htm, and http://www2.acc.af.mil/library/factsheets/fa-22.html.) The general threat to aircraft on an OCA mission consists of the surface-based air defense supporting the enemy surface forces and the enemy fighters.



F-15 Eagle

The air superiority mission is dedicated to the destruction of airborne enemy aircraft, both bombers and fighters, so that friendly forces can conduct operations without prohibitive interference from the enemy's air forces. Because the air superiority fighter must combat enemy fighters, very agile flight performance and the quick release of medium- and short-range weapons is desirable.

The fighter escort (FE) mission is the dedication of fighter aircraft to protect or defend other aircraft, such as a strike package ingressing and egressing a target area. The fighter sweep is an offensive mission by fighter aircraft to seek out and destroy enemy aircraft or targets of opportunity in an allotted area of operation. One version of the fighter sweep mission is a preemptive sweep or purge of enemy fighters along the route and over the target of ingressing friendly aircraft on an interdiction mission. Enemy aircraft on the ground are also targets for aircraft on the fighter sweep mission. The TARCAP mission is a patrol over an enemy target area to destroy enemy aircraft and to cover friendly shipping in the vicinity of the target area in amphibious operations.

F-18 Hornet

Defensive counterair. Defensive counterair (DCA) missions are designed "to detect, identify, intercept, and destroy or negate enemy forces attempting to attack or penetrate the friendly air environment."[2] DCA missions include several versions of the combat air patrol (CAP) mission. Aircraft that can perform DCA mission are typically the same fighters that can perform the OCA mission. The threat to aircraft on a DCA mission consists of the attacking enemy aircraft.

F-22 Raptor

The CAP mission consists of an aircraft patrol that is conducted over a specific area for the purpose of intercepting and destroying hostile aircraft or missiles before they reach their target. The ability to loiter for long periods of time over the area patrolled, using air-to-air refueling, is very important; otherwise, several aircraft must be cycled out to the station and back to the home base in specific time-sequenced patterns that maintain a constant surveillance of the area and allow the on-station aircraft to return for fuel and rest. Specialized versions of CAP are barrier CAP (BARCAP), the establishment of a barrier by the patrol between the probable direction of attack by hostile aircraft and the friendly force assets to be protected, and MIGCAP, a defensive patrol barrier between a known concentration of hostile aircraft and a group of friendly aircraft on a strike mission.

3.1.1.2 Air-to-surface. Tactical air-to-surface operations consist of actions taken by friendly aircraft against enemy surface forces, particularly those engaged in combat. Air-to-surface missions are sometimes referred to as strikes or raids

(Note 6). The weapons carried include conventional free-fall bombs [e.g., 500-lb (Mark 82) Snakeye (high-drag) iron bombs); (http://www.fas.org/man/dod-101/sys/dumb/mk82.htm)]; aerial rockets; cluster bomb units (CBU) composed of a dispenser and submunitions (http://www.fas.org/man/dod-101/sys/dumb/cluster.htm); guided iron bombs [e.g., the laser-guided Paveway II Guided Bomb Unit (GBU-12) (http://www.raytheon.com/products/paveway/); the GPS/inertially guided bomb known as the Joint Direct Attack Munition (JDAM) or GBU-32 (http://www.af.mil/news/factsheets/JDAM.html); guided missiles using lasers, electro-optic equipment, terrain-following equipment, or inertial with GPS [e.g., the laser- or IR-guided Maverick Air-to-Ground Missile (AGM-65) (http://www.af.mil/news/factsheets/AGM_65_Maverick.html)]; and guns, such as the internal 30-mm Avenger on the A-10 (http://www.au.af.mil/au/database/projects/ay1996/acsc/96-004/hardware/docs/gau8.htm). Aircraft on an air-to-surface mission can also carry air-to-air missiles for self-defense.

There are four primary missions usually associated with tactical air-to-surface operations over land: close air support, antiarmor, interdiction, and air defense suppression. A major air-to-surface mission at sea is the antiship mission. The general threat to aircraft on an air-to-surface mission consists of the surface-based air defense supporting the enemy surface forces and any enemy aircraft on CAP or launched as air interceptors.

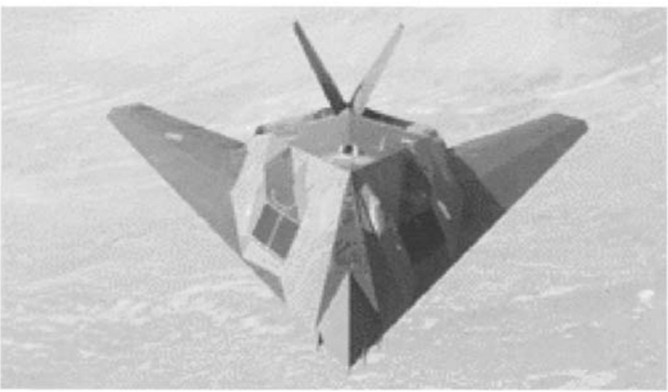
Close air support. The close air support (CAS) mission involves air action against hostile targets "that are in close proximity to friendly forces and that require detailed integration of each air mission with the fire and movement of those forces."[2] The CAS mission can be performed day or night and in bad weather. The mission can be preplanned or immediate, where the attack plan is formulated as the pilot flies toward the target. The important attributes of CAS aircraft are the ability to carry large payloads, loiter for long periods over the battlefield while waiting for an assignment, quickly locate the correct target, and survive intense ground fire from guns and missiles as weapons are delivered. Some of the fixed-wing aircraft that might conduct this mission are the AV-8B Harrier, the F-16, the F/A-18, the A-10 Thunderbolt II, the AC-130H/U Gunship, and the Su-25 Frogfoot. (Data for the Thunderbolt and Gunship are available online at http://www.af.mil/news/factsheets/A_10_OA_10_Thunderbolt_II.html and http://www.af.mil/news/factsheets/AC_130H_U_Gunship.html.) The AV-8B, A-10, and Su-25 were designed specifically for this mission (as well as the antiarmor mission). The mission is referred to as close-in fire support (CIFS) by the U. S. Marines when helicopters, such as the AH-1 Cobra and the AH-64 Apache, are used to support the ground troops. (Data for the Cobra and Apache are available online at http://www.redstone.army.mil/pub_affairs/amcom_fact/aFACTCO~1.html and http://www.redstone.army.mil/pub_affairs/amcom_fact/aFACTAP~1.html.)

Antiarmor. The antiarmor or antitank mission is flown by aircraft carrying ordnance specifically designed to destroy heavily armored vehicles, such as tanks. The ability to approach the target undetected, fire lethal weapons, and quickly remask is important. Fixed-wing aircraft designed for the close air support

mission, such as the AV-8B and A-10, are often used on the antiarmor mission. The AH-64 Apache, the AH-64D Apache Longbow (http://www.redstone.army.mil/pub_affairs/amcom_fact/aFACT64D.html), and the Mangusta A-129 helicopters were specifically designed for this mission. Lighter helicopters, such as the Lynx and Bo-105, also have the capability to fly this mission. The ordnance carried can include a large caliber, rapid-firing gun, such as the GAU-8 30-mm Gatling gun carried by the A-10, and air-to-surface guided missiles, such as the Hellfire and TOW (tube-launched, optically tracked, and wire-guided) missiles.

AH-64D Apache Longbow

Air interdiction. Air interdiction (AI), or simply interdiction, missions are "conducted to destroy, neutralize, divert, or delay the enemy's surface military potential before it can be used effectively against friendly forces at such distance from friendly forces that detailed integration with the fire and movement of the friendly forces is not required."[2] Typical targets include petroleum, oil, and lubrication storage centers (POL), lines of communication (LOC), and lines of supply (LOSP). Air strikes against targets deep within the enemy territory are sometimes referred to as strategic interdiction. Air interdiction missions conducted relatively close to the FLOT are referred to as battlefield air interdiction (BAI). The important attributes of aircraft used for this mission are the ability to carry large payloads, fly relatively long distances, at low and high altitudes, and accurately deliver their ordnance, such as dumb and laser-guided bombs (LGBs) and missiles, in any weather, day or night. Accuracy of weapon delivery at night is achieved using special equipment such as the Low-Altitude Navigation and Targeting Infrared for Night (LANTIRN; http://www.lockheedmartin.com/factsheets/product/95.html). Aircraft that can conduct the interdiction mission are the F-14 and F/A-18, the F-15E Strike Eagle, the F-117 Stealth Fighter or Nighthawk, the AC-130, the Tornado (IDS version), the Jaguar, and the B-52 Stratofortress. (Data for the Strike Eagle, the Nighthawk, and the Stratofortress are available online at http://www.af.mil/news/factsheets/F_15E_Strike_Eagle.html, http://www.af.mil/news/factsheets/F_117A_Nighthawk.html, and http://www.af.mil/news/factsheets/B_52_Stratofortress.html.)



F-117 Nighthawk

Air defense suppression. Air defense suppression consists of "actions taken (by the friendly forces) to degrade fixed and mobile surface-based components of enemy air defense systems so that offensive air forces may effectively attack a target."[2] These actions can take the form of roll-back operations in which the opposing defensive forces are progressively destroyed or neutralized, starting at the periphery and working inward, to permit deeper penetration of succeeding defense positions. The air defense suppression mission is sometimes referred to as suppression of enemy air defenses (SEAD), an "activity that neutralizes, destroys, or temporarily degrades enemy surface-based air defenses by destructive and/or disruptive means"[2] (physical attack and/or electronic warfare). Lethal SEAD, or the destruction of enemy air defenses (DEAD), is the complete physical destruction of the enemy air defense elements using air-to-surface ordnance, such as bombs, cluster bomb units, and guided missiles. SEAD missions can be preemptive, for example, preplanned suppressive actions against the air defense, or reactive, for example, spontaneous actions taken as a result of air defense activity.

The defense suppression mission, also referred to as the Iron Hand mission, is conducted by aircraft specifically designed for this mission, for example, the EA-6B Prowler, or by operational aircraft that have been modified, for example, the F-16CJ (block 50). (Data for the Prowler and the F-16CJ are available online at http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-ea6b.html and http://www.af.mil/news/factsheets/F_16_Fighting_Falcon.html.) These aircraft, known as Wild Weasel or Iron Hand aircraft, have special equipment that allows them to locate, identify, and either jam or physically destroy ground-based enemy air defense systems that employ sensors that radiate electromagnetic waves (e.g., radar). U. S. Air Force aircraft that have conducted the SEAD mission are the F-105G Thunderchief and the F-4G Phantom II, both retired from service now.

F-16 Fighting Falcon (Viper)

Helicopters have also been used for air defense suppression. Eight AH-64A Apaches belonging to the U. S. Army's 101st Airborne Division were the first

Coalition aircraft to attack the enemy in Operation Desert Storm. The mission objective for the helicopters was to destroy two Iraqi air defense radars inside Iraqi territory using Hellfire missiles and rockets. The lethal suppression of these radars opened up a corridor for the strike aircraft. The latest version of the Apache, the Longbow AH-64D, has shown considerable promise as a SEAD aircraft.[4]

Antiship. The antiship mission consists of the search for and destruction of enemy boats and ships using bombs, missiles, rockets, and guns. This mission can be flown by ship-based helicopters, such as the SH-60B Seahawk, Lynx, and Ka-25B Hormone, carrying Penguin, Hellfire, Exocet, or Sea Skua antiship missiles, or by fixed-wing aircraft, such as the F/A-18, S-3B Viking, P-3 Orion, and B-52. (Data for the Seahawk, the Viking, and the Orion are available online at http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-sh60.html, http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-s3b.html, and http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-p3.html.)

Submarine detection and prosecution. This mission consists of a systematic search of a particular area for the purpose of locating and destroying a submarine known or suspected to be somewhere in the area. The weapons used against submarines include bombs and torpedoes. Aircraft that conduct this mission are known as antisubmarine warfare (ASW) aircraft and include the fixed-wing, land-based P-3 and carrier-based S-3, and the SH-60 helicopter.

S-3B Viking

P-3 Orion

3.1.1.3 Army aviation.[3]

Reconnaissance. "Reconnaissance operations obtain information by visual observation or other detection methods. This information might concern the activities and resources of an enemy or potential threat, or the meteorological, hydrographic characteristics of a particular area. Reconnaissance assets must possess the ability to develop the situation, process the information, and provide it to commanders in near real time. Army aviation's most modern assets, the OH-58D Kiowa Warrior and the AH-64 Apache, give the force commander a dramatically improved 24-hour air reconnaissance capability that can better develop the situation and rapidly send information to wherever it is most needed. No longer is the primary mission of attack helicopter assets within cavalry units to protect the scouts."[3]

Security. "The commander conducts security operations to provide maneuver space, reaction time, and protect the main body. Security is incorporated as part of the battlefield framework in planning all offensive or defensive operations. Although reconnaissance and security missions are associated with the corps cavalry regiment and the division cavalry squadron, attack helicopter battalions are well suited for these missions."[3]

Attack. "The primary purpose of attack helicopter operations is the destruction of enemy ground force at decisive points. Attack units can conduct deep operations or be used in conjunction with ground maneuver units during close battle operations. For cross-component support Army attack helicopters, usually tasked as units, can perform a close air support (CAS) function."[3]

Air assault. "Air assault operations are those in which air assault forces—employing the firepower, mobility, protection, and total integration of helicopter assets in their air or ground roles—maneuver on the battlefield, under the control of the air assault task force commander to engage and destroy forces or to seize and hold key terrain."[3]

Theater missile defense. "The theater missile threat is real and increasing in scope. Proliferation of theater ballistic missiles (TBMs) presents a serious threat to maneuver forces during many potential contingencies. Although the risks from fixed-wing aircraft might have decreased, the threat from TBMs, cruise missiles, and other unmanned aerial vehicles continues to grow. TBMs have many employment options. They offer various warhead choices, operate over extended ranges, and are relatively inexpensive. Theater missile defense (TMD) is a joint mission. It is accomplished by establishing an effective, interoperable battle management/command, control, communications, computers, and intelligence (BM/C4I) system that permits the joint force commander to integrate and enhance the joint force's capabilities to destroy incoming theater missiles in flight (active defense), reduce the vulnerability of friendly force and critical assets from the effects of theater missile attacks, and destroy hostile theater missile capability by offensive actions against missile launchers, command, control, communications, and intelligence (C^3I), logistics facilities, and other theater missile infrastructure (attack operations). Army aviation plays a key role in TMD by executing deep operations to attack all elements of the hostile theater missile system."[3]

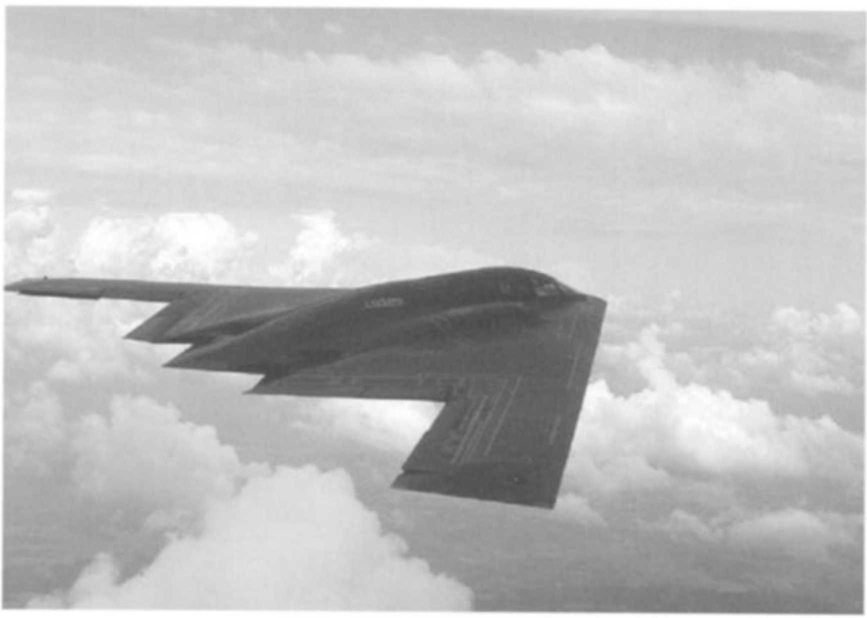
Special operations. "Special operations aviation (SOA) units are trained, equipped, and manned to support both special and conventional operating forces. Special operations cover a series of unique primary, collateral, and emerging missions that directly support a theater combatant commander. Army SOA assets are dedicated to conducting special operations missions across the full range of military operations. They provide a mix of short-, medium-, and long-range lift, and limited light-attack capabilities."[3]

Support by fire. "Support by fire (SBF) is a mission given to attack helicopters, directing them to establish a base of fire or an overwatch position. It can be used to engage a target while ground or air maneuver assets move to or bypass the same target area. It may range from suppression to destruction of the target; however, the primary mission is to fix the target so another force may maneuver. SBF positions are less restrictive than battle positions."[3]

3.1.2 Strategic Combat Missions (Strategic Attack)

The strategic, or strategic attack, mission typically involves bombing enemy targets at relatively long distances from the friendly forces. Examples of strategic targets are electrical generating plants and distribution centers, petroleum, oil and lubrication storage facilities, key manufacturing systems, sources of raw material, critical material stockpiles, transportation systems, and important command, control and communication centers. The essence of the strategic attack mission is that it affects the enemy's entire effort rather than just a single action, battle, or campaign. Strategic attack is a function of objectives or effects achieved, not forces employed.

The important attributes of aircraft designed for the strategic attack mission are essentially the same as those of interdiction aircraft, except the payloads (nuclear or high explosive) are usually larger, the distances are longer, and they stay at high altitude more often. Aircraft that fly this mission are the B-52 Stratofortress, B-1B Lancer, B-2 Spirit, F-117, and F-15E. (Data for the Lancer and the Spirit are available online at http://www.af.mil/news/factsheets/B_1B_Lancer.html and http://www.af.mil/news/factsheets/B_2_Spirit.html.) The general threat to aircraft on a strategic mission consists of any enemy aircraft on CAP or launched as air interceptors and the surface-based air defense along the routes to and from the target and in the vicinity of the target.



B-2 Spirit

3.1.3 *Combat Support Missions*

3.1.3.1 General.

Early warning, communications, and strike and traffic control. These missions are conducted by aircraft that are located in a position where they can observe and notify friendly forces of the launch or approach of unknown aircraft. They can also direct air interceptors toward the incoming threats. They are usually on station for long periods of time and can be a high priority target in the event of a surprise attack. U. S. aircraft employed in this role are the E-2C Hawkeye, the E-3 Sentry Airborne Warning and Control System (AWACS), and the E-8C Joint Surveillance Target Attack Radar System (Joint Stars or JSTARS). (Data for the Hawkeye, the Sentry, and the JSTARS are available online at http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-e2c.html, http://www.af.mil/news/factsheets/E_3_Sentry_AWACS_.html, and http://www.af.mil/news/factsheets/E_8C_Joint_Stars.html.) The general threat to aircraft on these missions consists of enemy fighters and very long range surface-based air defenses.

E-2C Hawkeye

Electronic support and countermeasures. Special purpose aircraft whose mission is to search for, detect, locate, and identify sources of radiated electromagnetic waves are known as electronic support measures (ESM), signal intelligence (SIGINT), or special electronic mission aircraft (SEMA). Special purpose aircraft whose role is to radiate electromagnetic energy that degrades or deceives hostile electronic equipment are referred to as electronic attack (EA) or electronic countermeasures (ECM) aircraft. The EA aircraft can protect a strike package by standing off of the target area and jamming the enemy radars, known as standoff jamming, or it can accompany the strike aircraft as they ingress to the target area and jam the radars from a close distance, known as escort, close support, or stand-in jamming. Examples of EA aircraft are the Navy's EA-6B Prowler and the Air Force's retired EF-111 Raven and RC-135 Rivet Joint, and the U. S. Army's C-12 Guardrail (Note 7). The general threat to aircraft on these missions consists of enemy fighters and very long-range surface-based air defenses. (Data for the Raven, the Rivet Joint, and the Guardrail are available online at http://www.au.af.mil/au/database/projects/ay1996/acsc/96-004/hardware/docs/ef111.htm, http://www.af.mil/news/factsheets/RC_135V_W_Rivet_Joint.html, and http://www.redstone.army.mil/pub_affairs/amcom_fact/aFACTGU~1.html.)

EA-6B Prowler

Forward air control. Aircraft on an airborne forward air control (AFAC) mission, known as a forward air controller (airborne) [FAC(A)], control other aircraft in close air support of ground troops. The fixed-wing aircraft that can provide this capability are the OA-10, and the F-14, F-16, and F/A-18 fast FAC. Helicopters, such as the AH-1, also can be used on the FAC mission. The general threat to aircraft on a FAC mission consists of enemy fighters and any surface-based air defenses in the vicinity of the fighting, including small arms (Note 8).

Surveillance and reconnaissance/observation/scouting. The surveillance mission consists of "the systematic observation of aerospace, surface, or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means."[2] Aircraft that can conduct this mission are the U-2 and several UAVs, including the Pioneer and the Global Hawk. (Data for the U-2, Pioneer UAV, and Global Hawk UAV are available online at http://www.af.mil/news/factsheets/U_2S.html, http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-uav.html, and http://www.af.mil/news/factsheets/global.html.) The reconnaissance/observation/scouting mission complements surveillance in obtaining, "by visual observation or other detection methods, information about the activities and resources of an enemy or potential enemy; or in securing data concerning the meteorological, hydrographic, or geographic characteristics of a particular area."[2] Helicopters that can be used on this mission include the OH-58D KiowaWarrior (http://www.redstone.army.mil/pub_affairs/amcom_fact/aFACTKI~1.html), the

AH-64, and the RAH-66 Comanche. The general threat to aircraft on any of these missions includes all of the enemy surface-based weapons in the vicinity of the aircraft and any enemy aircraft defending the enemy forces and territory.

OH-58D Kiowa Warrior

Long-range targeting. This mission, also known as over-the-horizon targeting (OHT), involves the location and identification of potential hostile targets and the subsequent relay of position information to a friendly command center. Naval versions of long-range targeting are the antiship surveillance and targeting (ASST) mission, which consists of enemy ship detection, classification, location, and damage assessment beyond the own ship's radar horizon, and the naval gunfire support (NGFS) mission. The general threat to aircraft on these missions consists of enemy fighters and very long-range surface-based air defenses.

Photoreconnaissance and tactical photoreconnaissance. The objective of this mission is to obtain photographs for the purpose of making maps or charts (photoreconnaissance) or for information on the results of bombing or on enemy concentrations and movements (tactical photoreconnaissance). The mission is conducted by a special purpose aircraft, such as the F-14 with the Tactical Air Reconnaissance Pod System (TARPS), sometimes with, and sometimes without, a fighter escort, and UAVs, such as Pioneer and Global Hawk. The general threat to aircraft on this mission consists of enemy fighters and the surface-based air defenses along the ingress and egress routes and in the vicinity of the target. Because the 'recce' assigned to obtain pictures for bomb damage assessment (BDA) is usually the last one over the target after a strike, the element of surprise is missing, and the enemy air defense can concentrate on this one aircraft. The mission is successful only if the aircraft returns with the film.

Combat search and rescue. The search and rescue (SAR) mission involves the search for and rescue of personnel in distress on land or at sea. If this mission is conducted in a hostile area, it is referred to as combat SAR (CSAR) by the U. S. Air Force, or strike rescue by the U. S. Navy, or tactical recovery of aircraft and personnel (TRAP) by the U. S. Marines. The mission is often conducted by fixed-wing aircraft, such as the C-130 Hercules, and helicopters, such as the HH-60G Pave Hawk, working together, with the fixed-wing aircraft providing air cover for the searching helicopter. (Data for the Hercules and Pave Hawk are available online at http://www.af.mil/news/factsheets/C_130_Hercules.html and http://www.af.mil/news/factsheets/HH_60G_Pave_Hawk.html.) The general threat to aircraft on the CSAR mission consists of enemy fighters and the surface-based air defense along the ingress and egress routes and in the vicinity of the downed personnel.

HH-60G

Airborne mine countermeasures. This mission includes minesweeping, mine neutralization, mine hunting, and floating mine destruction. The MH-53E Sea Dragon is typically used for this mission. (http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-mh53.html.) The general threat to aircraft on this mission consists of enemy fighters and any surface-based air defenses in the vicinity of the mined area.

MH-53E Sea Dragon

Transport of supplies, equipment, and personnel. This mission consists of the pickup, transport, and delivery of cargo, troops, and wounded or sick personnel from one zone to another. The pickup and delivery zones can be either intertheater (or strategic) or intratheater (or theater). The Air Force refers to this mission as airlift, which is the transportation of personnel and materiel through the air. The Marines refer to this mission as either amphibious or land assault support, depending upon the origin of the mission. The Navy refers to this mission as medical evacuation (MEDVAC) or vertical replenishment (VERTREP). Both large fixed-wing aircraft, such as the C-130, the C-141B Starlifter, the C-5 Galaxy, and the C-17 Globemaster III, and helicopters, such as the CH-46 Sea Knight, the CH-47 Chinook, the CH-53D Sea Stallion, the UH-60 Black Hawk, and the SH-60B can be used for this mission. (http:/www.af.mil/news/factsheets/C_141B_Starlifter.html, http://www.af.mil/news/factsheets/C_5_Galaxy.html, http://www.af.mil/news/factsheets/C_17_Globemaster_III.html, http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-ch46.html, http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-ch53d.html, and http://www.redstone.army.mil/pub_affairs/amcom_fact/afactbl~1.html.) The most recent addition to this category is the joint-service, multimission tilt-rotor V-22A Osprey. (http://www.chinfo.navy.mil/navpalib/factfile/aircraft/air-v22a.html.) The general threat to aircraft on these missions consists of any enemy fighters and surface-based air defenses located along the ingress and egress routes and in the vicinity of the pickup and delivery zones.

Special operations. Special operations are "operations conducted by specially organized, trained, and equipped military and paramilitary forces to achieve military, political, economic, or informational objectives by unconventional military means in hostile, denied, or politically sensitive areas."[2] (http://www.defenselink.mil/execsec/adr98/chap4.html) Special operations missions are performed by

C-17 Globemaster III

a Special Operations Force (SOF), such as the 75th Ranger Regiment and the 160th Special Operations Aviation Regiment (SOAR). The U.S. Air Force SOF "consists of uniquely equipped fixed and rotary wing aircraft operated by highly trained aircrews whose missions include insertion, extraction, resupply, aerial fire support, refueling, combat search and rescue, and PSYOP." (http://www.specialoperations.com/Focus/Official/Reference_Manual/Chapter_Five.htm) Aircraft operated by the Air Force Special Operations Command (AFSOC) include the MC-130E/H Combat Talon I/II, the AC-130H/U Gunship, the MC-130P Combat Shadow, the MH-53J Pave Low III, and the EC-130E Commando Solo. (http://www.specialoperations.com/Focus/Official/Reference_Manual/Chapter_Five.htm) (Data for the Combat Talon, the Combat Shadow, and Pave Low are available online at http://www.af.mil/news/factsheets/MC_130E_H_Combat_Talon_I_II.html, http://www.af.mil/news/factsheets/MC_130P_Combat_Shadow.html, and http://www.af.mil/news/factsheets/MH_53J_M_Pave_Low.html.)

Air refueling. Air or inflight refueling is usually performed by KC-10, KC-130, and KC-135 tankers using either a boom or probe and drogue to provide fuel to fixed-wing and rotary-wing aircraft.

3.1.3.2 *Army aviation.*[3]

Command, control, and communications. "Maintaining command, control, and communications (C3) is critical to any operation. Aviation units provide communication enhancement through airborne transmission or relay equipment."[3]

Air movement. "Air movement operations are conducted to reposition units, personnel, supplies, equipment, and other critical combat elements in support of current and/or future operations. These operations include both airdrops and air landings."[3]

Electronic warfare. "Electronic warfare (EW) is an essential component of C^2 warfare (C^2W). As part of C^2W, EW is used in conjunction with multidisciplined counterintelligence to protect friendly C^2 while attacking the enemy's C^2 structure. Effective use of EW requires coordination and integration of EW operations with the commander's scheme of maneuver and fire support plan. The integrated use of EW throughout the battlefield supports the synergy needed to locate, identify, damage, and destroy enemy forces and their structure. SEMA use the electromagnetic spectrum to locate and target enemy units and facilities, intercept enemy communications, disrupt enemy C^4I, and target acquisition capabilities."[3]

Combat search and rescue. "Aviation units must be prepared to conduct combat search and rescue in support of their own operations and to provide support at both the intra- and inter-service levels."[3]

Air traffic services. "Air traffic services (ATS) encompass two areas: Army airspace command and control (A^2C^2) and air traffic control (ATC). ATS units provide a range of support that spans the entire theater during deep, close, and rear operations. Also, ATS operations span the wide range of military operations servicing Army, service component, interagency, multinational, and host nation airspace users."[3]

Aerial mine warfare. "Aerial-delivered mines can support tactical operations by emplacing tactical minefield; reinforcing existing obstacles; closing lanes, gaps, and defiles; protecting flanks; and denying the enemy air defense (AD) sites. Aerial-delivered minefields also can be employed for flank protection of advancing forces and for operating in concert with air/ground cavalry units performing screen and guard missions."[3]

Go to Problems 3.1.1 to 3.1.17.

3.2 Air Defense Threat

The threats to aircraft are those elements of a man-made environment designed to reduce the ability of an aircraft to perform mission-related functions by inflicting damaging effects, forcing undesirable maneuvers, or degrading system effectiveness (http://www.arl.army.mil/slad/AWSS/SF-areas/combmaneu/threat.htm). This man-made hostile environment is known as the air defense environment. The air defense environment can be made up of numerous threat elements, each having a distinct set of characteristics and capabilities, such as a surface-to-air missile site with surveillance sensors, target tracking sensors, communication links to a command and control center, and several fire units or launch platforms; or it can be one soldier carrying a gun. The various types of surface and airborne weapon systems that pose a threat to aircraft are illustrated in Fig. 3.1. Assurance that all of the threat elements and their effects are completely and accurately considered in the survivability analysis, design, and operation of an aircraft requires more than a casual knowledge of current and anticipated hostile air defense systems.

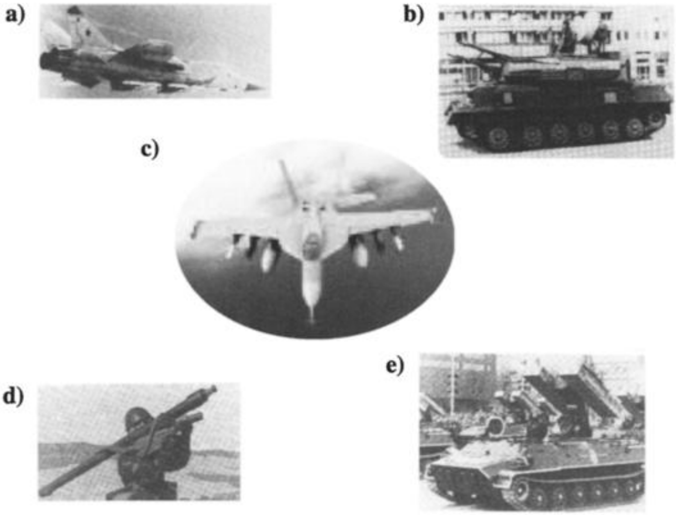


Fig. 3.1 Threats to aircraft.

3.2.1 What Is Air Defense?

Learning Objective	**3.2.1**	**Describe air defense, air defense weapons, air defense territories, layered air defense, and integrated air defense.**

Air defense (AD) is defined by the U. S. Joint Chiefs of Staff as, "all defensive measures designed to destroy attacking enemy aircraft or missiles in the earth's envelope of atmosphere, or to nullify or reduce the effectiveness of such attack."[2] Of interest here is the active enemy air defense that employs weapons systems which have the potential to encounter, engage, and destroy friendly aircraft. To the air defense the aircraft is a target (Note 9).

3.2.1.1 Air defense weapons. The air defense weapons considered here include large, surface-based guns known as antiaircraft artillery (AAA), surface-to-air missiles, and air-to-air guns and missiles (AAMs) carried by fighter and interceptor aircraft (Note 10). Smaller weapons (whose primary purpose is not air defense) that can be used against aircraft are referred to as non-AD weapons. Examples of non-AD weapons are small caliber rifles, automatic weapons, and machine guns; and antiarmor weapons, such as the TOW missile, rocket powered granades, and main tank guns. Some current AD weapons are listed in Table 1.1 (Note 11). Detailed descriptions of these systems, as well as many others, can be found in Refs. 5–11.

3.2.1.2 Air defense territories, layers, and integration. The AD forces are usually assigned to protect a specific territory from attacking aircraft or ballistic missiles. The AD of the assigned territory can be accomplished using ground-based AD forces, sea-based forces, airborne forces, or some combination of these forces. In general, two specific types of AD territories exist: point/organic air defense and area air defense. Layered air defense, or defense-in-depth, is a combination of these types in which one or more point and area defense weapons are assigned overlapping or contiguous AD areas. When the individual target sensors, weapon firing platforms, and command centers of the AD are linked together, the total AD system is referred to as an integrated air defense system (IADS).

Point, tactical, and organic air defense. An AD that is designed to protect assets in a limited area from aircraft that are heading directly toward those assets, or that pose a potential threat to those assets, is referred to as a point defense or tactical air defense, and weapon systems that are designed for this purpose are called point defense weapons. If the point defense weapon system is protecting the platform it is mounted on, it is a self-protection weapon. If the weapon is a short-range weapon, it can be referred to as a close-in weapon system (CIWS). If the point defense system is self-propelled or towed and moves with the maneuver forces on land, sea, or in the air, the system is said to provide an organic air defense. These systems are usually quick reacting, short- to medium-range systems with a relatively high rate of fire. They can usually engage only one target at a time, but might have the ability to rapidly slew to another target after assessing a kill of the engaged target. Examples of a point defense system are the organic Russian Federation 2S6 Tunguska, with its rapid firing, radar-directed, twin 30-mm barrel gun and SA-19 Grison missile system, and the UK Rapier missile system.

Area, region, and theater air defense. An AD that is designed to protect regional assets, such as large areas of land or sea, population centers, commercial and industrial areas, and fixed or floating high-value military units or facilities, is referred to as an area or regional air defense. Air defense of an area or region that is under the responsibility of the commander of a unified or specified commander is referred to as theater AD. Area AD weapons do not protect any one particular asset, but are responsible for killing any aircraft that attempt to penetrate the defended area; they attrite the air threat (Note 12). Area air defense can be provided by surface-based weapons, such as long- and medium-range SAMs, and by aircraft. Surface-based area AD systems may be nonmobile, or towed, or mounted on trucks, or on relatively large surface combatants. They have medium- to long-range capability and a relatively low rate of fire. These systems can cover a large volume of air space, maintain track files on many aircraft, and guide surface-to-air missiles toward several targets concurrently.

Area AD is typically organized into brigades, and each brigade has several battalions. An AD battalion consists of elements for command and control, administration, logistical support, and one or more firing batteries. Each firing battery has one or more firing platoons (fire control and launcher) or fire units located together or separated by several kilometers. Examples of surface-based area defense weapons are the Russian Federation SA-10 and the U. S. Patriot missile systems.

Aircraft that contribute to an area defense for the surface forces are known as airborne interceptors or combat air patrol aircraft. Airborne interceptors are launched when notified of an incoming attack against the defended forces.

Aircraft on CAP are stationed in the area they are assigned to defend, loitering, and performing maneuvers that maintain a proper alignment for their assigned sector or area. The time-on-station is significantly increased by the use of air-to-air refueling. Several aircraft are cycled out to the station and back to the home base in specific time-sequenced patterns that maintain a constant surveillance of the AD area and allow the on-station aircraft to return for rest and relaxation. Interceptor aircraft assigned to defend the outer edge of the area are typically on alert at the air base and await instructions to launch against an attacking force. These AD aircraft typically carry medium- and/or long-range missiles and have powerful radars that can detect incoming low-altitude aircraft at long range (Note 13). An example of an aircraft that can provide area or fleet air defense (FAD) for ships at sea in the outer air battle (OAB) is the U. S. Navy's F-14 Tomcat with the Phoenix missile.

Layered defense of ground-based forces. The air defense of ground-based forces can be accomplished using weapons with different range and altitude capabilities in a layered defense. A layered defense provides a defense in-depth, which usually has some overlapping mutual support in both range and altitude. In general, each weapon in the layered defense has an assigned weapon engagement zone (WEZ). The theater for ground-based AD can be divided into the three areas. In the area farthest forward the mission of the AD is to selectively kill and disrupt the air forces. In the area 10 to 15 km forward of the FLOT, the mission of the AD is to protect the maneuver assets, deny the air forces sanctuary, and give the ground forces the freedom to maneuver. In the vicinity of and behind the FLOT, the AD controls the air environment and protects key assets.

The high-to-medium-altitude air defense (HIMAD), at long to medium range from the assets to be protected, could be provided by long range SAMs, such as the Russian Federation S-400. The low-to-medium-altitude air defense (LOMAD) at medium range could be provided by medium-range SAMs, such as the Russian Federation SA-6 and U. S. Hawk missile systems. The low-altitude, short-range air defense (SHORAD) could be provided by mobile, fast reacting, high rate of fire weapons, such as small antiaircraft artillery and short-range missiles. Examples of SHORAD weapons are man-portable AD missiles, such as the U. S. Stinger and the Russian Federation SA-16 Gimlet, and gun systems, such as the U. S. Army's 20-mm, six-barrel Vulcan AD system and the Dutch Signaal's Goalkeeper 30-mm CIWS.

Layered defense of sea-based forces. Sea-based AD areas are either point defense for the self-protection of single ships or layered area defense for the protection of battle groups. The layered AD usually consists of combat air patrol aircraft and deck-launched interceptors (DLI) that fight the outer air battle with the approaching fighters and bombers in the outer zone known as the fighter engagement zone (FEZ), long- and medium-range SAMs that cover the middle or missile engagement zone (MEZ), and short-range point defense SAMs and guns that protect the individual ships against the leakers through the FEZ and MEZ (Note 14). The zone defended by the SAMs and guns is sometimes referred to as the inner defense zone. An example of a layered sea-based AD for a carrier battle group is shown in Fig. 3.2. In this example, an aircraft carrier, a high-value asset, is protected from air attack by a guided missile cruiser. An airborne early warning (AEW) aircraft on

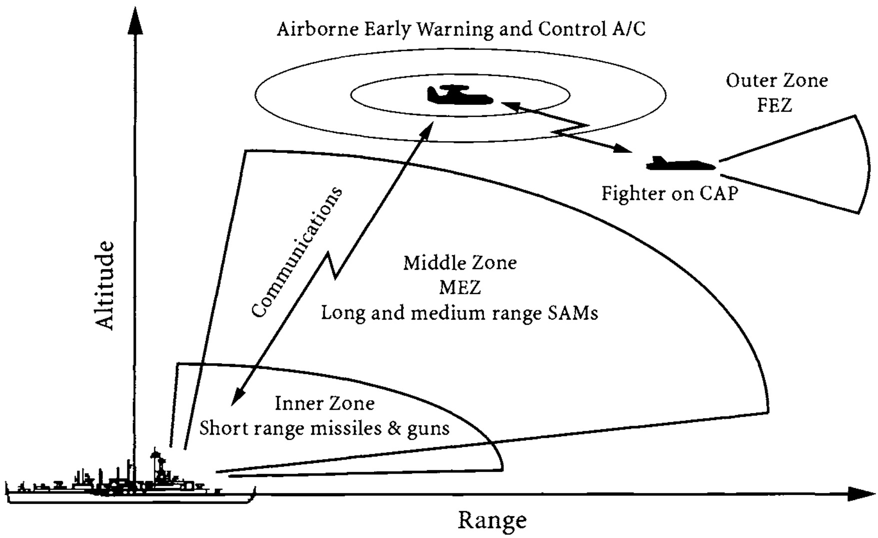


Fig. 3.2 Layered sea-based air defense.

orbit provides an advanced warning of a possible air attack. It also controls and directs (provides headings to or 'vectors') the AD aircraft, including the fighter aircraft on CAP and any interceptors launched when the attack was first detected, to intercept, identify, and kill, if necessary, the incoming attackers or bogeys (Note 15). The active air defense in the outer zone is provided primarily by the fighters on CAP. The primary mission of these CAP aircraft in the outer air battle is to destroy any missile-launching aircraft before they can launch their missiles. The middle zone is covered by the naval SAMs on the guided missile ship, and the inner zone is defended by the SAMs and guns on the ship being attacked.

Integrated air defense system. An IADS consists of 1) a number of surveillance sensors (surface-based, air-based, and space-based); 2) several weapon system installations or fire units, with their organic detection, tracking, and guidance sensors for fire control; 3) one or more data fusion nodes sometimes referred to as filter centers; 4) one or more decision nodes, sometimes referred to as command centers or command, control, communication, and information (C3I) centers; and 5) radio or hardwire communication links between the sensors, weapon sites, and centers.

Information gathered by the various surveillance sensors on any aircraft contacts and tracks within their field of view is passed as messages to a data fusion node. The sensor information on target location(s) collected at the node is correlated to determine the correct number and location of the targets. This process is known as track correlation. The correlated track data are used to create the composite air picture that is then sent to a decision node. There, decisions are made on which tracks are hostile (confirmed or tentative), unknown, or friendly. The hostile targets are evaluated and prioritized based upon such criteria as 'how likely the

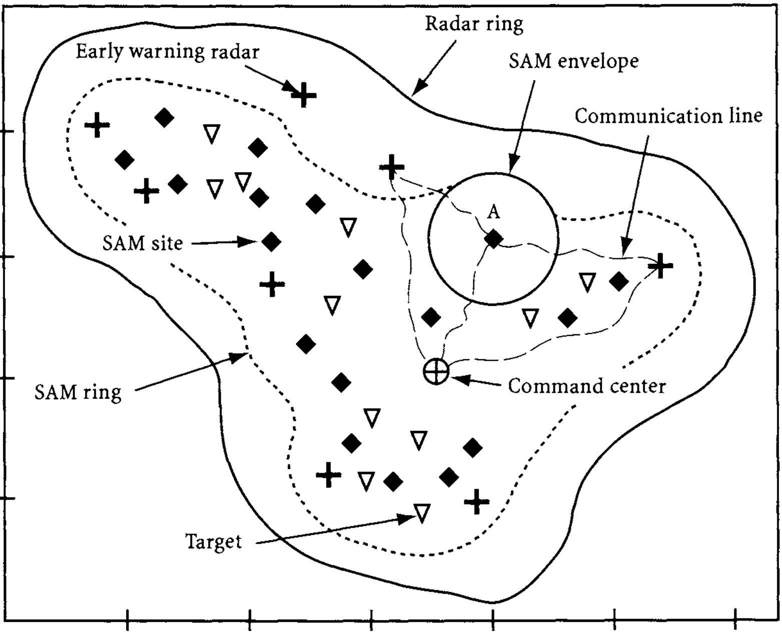


Fig. 3.3 Generic IADS (adapted from Ref. 13).

target is to attack the defended forces,' 'how soon a target can attack,' and 'how much damage the target can inflict.' Based upon the tactical picture and the target prioritization, one or more of the fire units under the control of the command center are assigned the highest priority targets. These assignments are based upon the availability, condition, and capability of the fire units and on any rules of engagement (ROE) in effect. Messages are then passed to these assigned units, which, when active, attempt to encounter, engage, and kill the assigned targets. The process of prioritizing targets and assigning fire units is known as classification. A generic integrated air defense system (IADS) is illustrated in Fig. 3.3. Reference 12 contains a description of the functions of the various IADS components and a long list of references.

Go to Problems 3.2.1 to 3.2.9.

3.2.2 Operational Functions of an Air Defense Weapon System

Learning Objective	**3.2.2**	**Describe the 14 operational functions of an air defense and their measures.**

Regardless of the level of complexity of the air defense, every antiaircraft weapon system has the same set of required operational functions to perform. These functions are given in Table 3.2. The probability of a successful outcome of each of the

Table 3.2 Air defense operational functions

Probability	Operational function
	Move to the assigned location and set up, if necessary.
P_A	Communicate with other units in the AD.
	Search for aircraft.
$P_{D\|A}$	Detect and acquire contacts.
	Track one or more contacts.
	Classify and identify the contacts
$P_{L\|D}$	Prioritize the hostile contacts as targets and assign fire units.
	Compute a fire control solution for each target.
	Fire a ballistic projectile or launch a guided missile.
$P_{I\|L}$	Fly the projectile or guide the missile to an intercept.
$P_{H\|I}$ or $P_{F\|I}$	Hit the target with the propagator warhead, or detonate (or fuze) the HE warhead.
$P_{K\|H}$ or $P_{K\|F}$	Kill the target with the propagator hit, or kill the target with the warhead detonation (fuzing).
P_K	Evaluate the outcome of the shot.
	Fire again, if necessary, or slew to another target.

six phases of the one-on-one single-shot scenario illustrated in Fig. 1.3 in Chapter 1 are associated with one or more of these operational functions listed in the table.

A general, big picture description of a one-on-one encounter between an aircraft and a surface-based missile system is given next to illustrate in more detail the AD functions that must take place if the threat is to kill the aircraft. Similar descriptions can be given for air-to-air encounters and encounters between aircraft and threat gun systems.

Go to Problem 3.2.10.

3.2.3 Big Picture for the One-on-One Encounter

Learning Objective 3.2.3 Describe the big picture of a one-on-one encounter.

Consider the ship and the attacking aircraft shown in Fig. 3.4. The ship is defending itself from the approaching aircraft using a medium-range, semiactive homing missile with a high-explosive warhead and proximity fuze (Note 16). An estimate of the extent of the effectiveness of the SAM system against the aircraft as it flies toward the ship is indicated in the figure by the two-dimensional envelope. The envelope is referred to here as the weapon envelope or launch envelope . When an aircraft is inside this envelope, it can be engaged and killed by the SAM with a

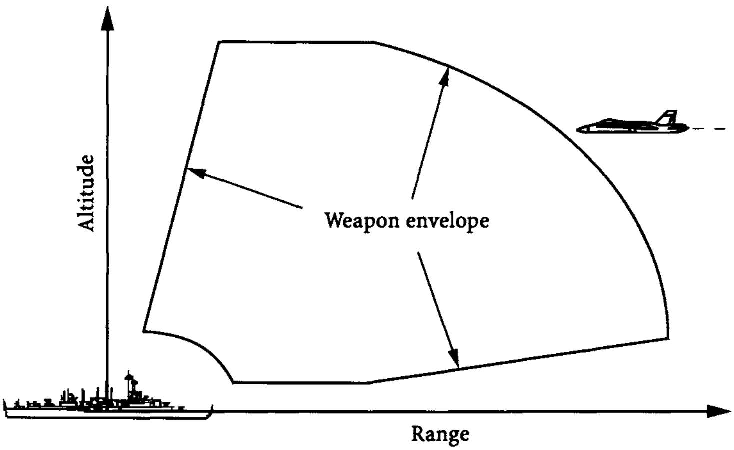


Fig. 3.4 One-on-one encounter.

'significant' probability. When it is outside of the envelope, the probability it can be engaged and killed is lower.

Similar two-dimensional envelopes exist for different approach directions or parallel flight path offsets from the ship. The three-dimensional extent of the two-dimensional envelopes around the ship defines the estimate of the volume of effectiveness of the weapon system against this aircraft for the defined scenario. Of interest here is the extent of the weapon envelope.

The sequence of events in the one-on-one encounter described in Chapter 1, Sec. 1.1.4, and the required operational functions listed in Table 3.2, such as detection of the aircraft and the subsequent missile launch, intercept, and warhead detonation, must occur if the ship's weapon system is to kill the aircraft. These events will occur at specific times referred to as time line events. The entire encounter from detection to kill assessment is described next in terms of the major events that occur during the encounter. Essentially the same events will occur for any other AD scenario.

3.2.3.1 Air defense. The ship's air defense includes a 360-deg, two-dimensional (bearing and range) air search/surveillance/early warning (EW) radar; a command and control center with communication links; and two missile launch platforms, one at each end of the ship. When the weapon system is searching for air targets and is ready and able to encounter and engage aircraft flying within its defended area, it is said to be active.

3.2.3.2 Target detection and acquisition. The capability of the radar to detect or discern the presence of a target at a given range and altitude is indicated by the detection envelope shown in Fig. 3.5. The envelope does not represent a demarcation line outside of which the aircraft cannot be detected and inside of which the aircraft is detected with absolute certainty. Rather, it is a representation of a particular probability of detection by the sensor, based upon a specific probability of false alarm P_{fa}, for example, $P_D = 0.90$ and $P_{fa} = 1 \times 10^{-8}$, respectively (Note 17). The extent of the envelope is a function of the radar parameters and

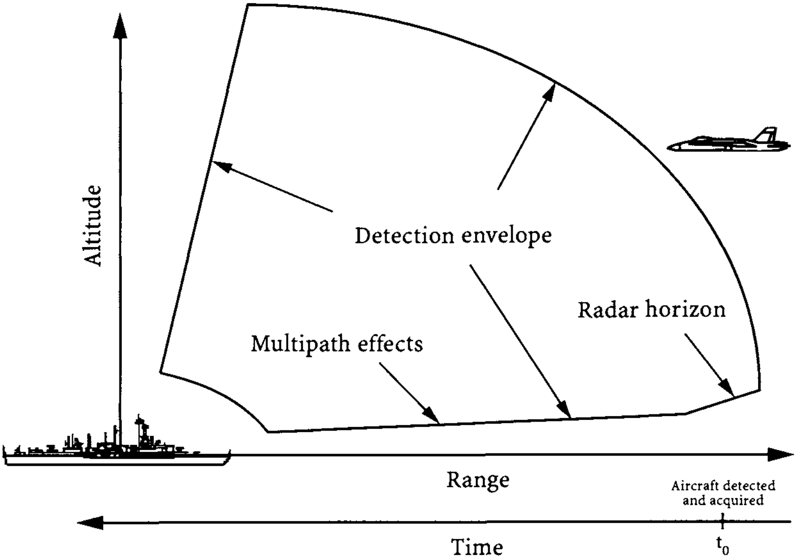


Fig. 3.5 Target detection and acquisition.

the aircraft's radar cross section. Other factors that influence the radar's detection envelope are the radar horizon, which depends upon the height of the radar antenna and the altitude of the aircraft; the weather conditions; the multipath phenomenon caused by reflections of the radar signal and target echo off of the ocean surface; and any constraints on the radar antenna movement or on-ship blockage of the radar beam.

As the radar antenna rotates, periodically sending out discrete pulses of electromagnetic radiation known as the radar signal, it 'listens' between the pulse transmissions for returning echoes from any aircraft within its search volume. When the aircraft is beyond the outer edge of the detection envelope, the echoes from the aircraft are too weak to be distinguished from the echoes from the nonaircraft scattering surfaces, known as clutter, and the noise level in the radar receiver. As the aircraft approaches the outer edge of the detection envelope, the echoes from the aircraft progressively get stronger, until they eventually exceed the noise and clutter by a certain amount and detection of the aircraft occurs, either automatically by the radar signal processor or manually by the radar operator. If the aircraft echo is detected a predefined number of times within a specific sequence of pulses, for example, at least three out of four, a contact is made, and the aircraft is said to be acquired or locked-on, and the location of the target in space can be determined. The detection and acquisition of the aircraft takes place on the time line at t_0.

3.2.3.3 Target tracking, classification, identification, and weapon assignment. A track file is established for the newly acquired contact, and the information on the contact is sent to a command post, central fusion center, or command and control (C^2) center, referred to on ships as the Combat Information Center (CIC) or Combat Direction Center (CDC). The CIC also collects information from several other aircraft detection and tracking sensors on the ship, such as a separate height-finding radar and passive electro-optic and electronic surveillance sensors, as well as tactical information provided by other AD units. The raw data provided by the individual sensors and data links are correlated in the CIC to determine if the contact is an aircraft or a missile, known as target classification, and to determine the correct number of contacts being tracked and the location and flight path(s) of the contact(s) (Note 18). The contact is then interrogated with an IFF (identification, friend, or foe) or IFFN (identification, friend, foe, or neutral) transmission to identify the contact. If no response is received or if the response does not correspond to a proper response, the contact is assigned an unknown status, referred to as a bogey, and tracking continues. If there are several tracks being followed, a prioritization is made for each of the tracks based upon some defined criterion, for example, the highest priority track is the one that will reach a keep-out boundary (KOB) first (Note 19). If the aircraft is believed to be hostile and attacking the ship, an available and capable weapon firing platform or fire unit is assigned, which in this example is the forward missile launcher.[14]

If the individual weapon control system or director for the firing platform has its own target detection and tracking sensor(s), such as a target acquisition radar (TAR) and a target tracking radar (TTR) or target engagement radar, it attempts to detect and track the incoming target, known as a hostile or bandit, after notification of the assignment. General position information, such as target bearing, range, and elevation or altitude, are provided by the three-dimensional air search radar. Once the weapon director sensor has detected and acquired the aircraft, the location, heading, and speed of the approaching aircraft are used by the weapon director to determine the appropriate launcher heading (Note 20). Other information, such as the remaining time, or time-to-go, before the aircraft reaches the KOB and a prediction of the probability the target would be killed if one or more missiles were fired, can be provided to the CIC. Eventually, when the target enters into a zone in which the missile is predicted to be sufficiently effective, based upon the current tactical situation, the decision is made to launch a missile. Commands can be sent to an onboard missile guidance package before launch, instructing it to perform some initial maneuver after it leaves the launch rail and to fly out to some predetermined position in space.

3.2.3.4 Missile engagement and flyout to midcourse position. The engagement phase of the encounter begins when the missile is launched at time t_1, as shown in Fig. 3.6. The length of time between t_0 and t_1 represents the reaction or delay time required by the system between initial target detection and acquisition and missile launch. Typically, this time can vary from a few seconds to perhaps many minutes, depending upon the weapon and the scenario.

The flyout of the missile from the launcher to the intercept with the approaching target is usually broken up into three phases: boost or launch, midcourse, and terminal, as shown in Fig. 3.6. The boost phase lasts from the time the missile leaves the launcher t_1 until the booster motor has burned all of its fuel.

The midcourse phase is usually the longest phase in both distance and time. During this phase, the missile can use inertial guidance to fly to a specific location or aim point in space, referred to as the midcourse position, or it can guide itself using target location information provided by its own onboard target sensors, or it

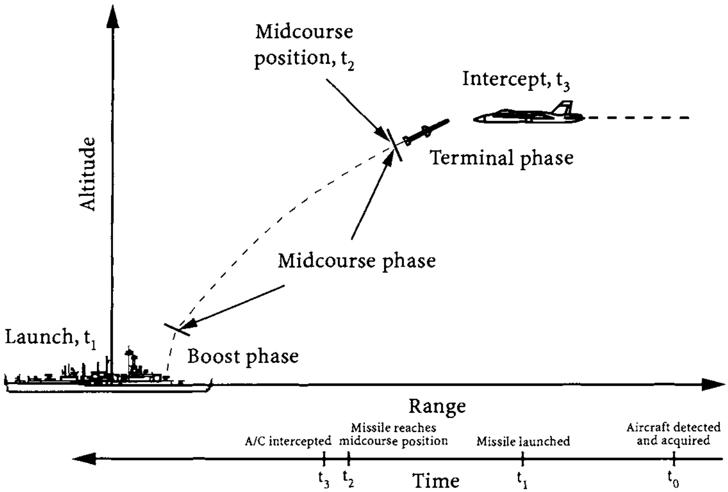


Fig. 3.6 Missile launch and flyout to intercept.

can receive guidance commands from the ship to change its direction as it flies out. If inertial guidance is used, the missile can fly to the initial aim point provided at launch, or it can receive updated aim points as it proceeds toward the interception. These updated aim points are the result of the most recent target track information. The midcourse position is not half-way to the target, but denotes the position at the end of the midcourse phase where the type of guidance can change to some type of homing guidance. At this position the distance from the missile to the target must be within the acquisition range of the missile's target sensor, and the missile must be pointed in the general direction of the target so that the target is within the sensor field of view. The missile reaches this midcourse point ontime line at t_2.

3.2.3.5 Terminal phase, target intercept, and endgame. The terminal phase of the flyout starts at the midcourse position and ends with the detonation of the warhead in the proximity of the aircraft, or a direct hit on the aircraft, or a flyby of the target. During this phase, the missile can guide itself to the target using some form of homing guidance, or it can continue to receive guidance commands from the ship. A successful intercept of the target by the missile occurs at t_3 if the warhead on the missile has a possibility of killing the target, and the endgame is that final, brief period of time in the engagement when the missile closes in on the intercepted aircraft, as illustrated in Fig. 3.7. The endgame conditions consist of the missile and target locations, velocities, and attitudes at t_3. The endgame events include aircraft detection by the proximity fuze's target detection device (TDD), the high-explosive warhead detonation, blast wave propagation, and fragment flyout, impact, and penetration through the aircraft, and the aircraft's response to the blast loading and fragment impacts.

The illustration in Fig. 3.7 is a snapshot of the scene shortly after the warhead detonated. All of the locations and paths in Fig. 3.7 are shown with respect to the target aircraft, that is, the aircraft is motionless in the figure, and the missile

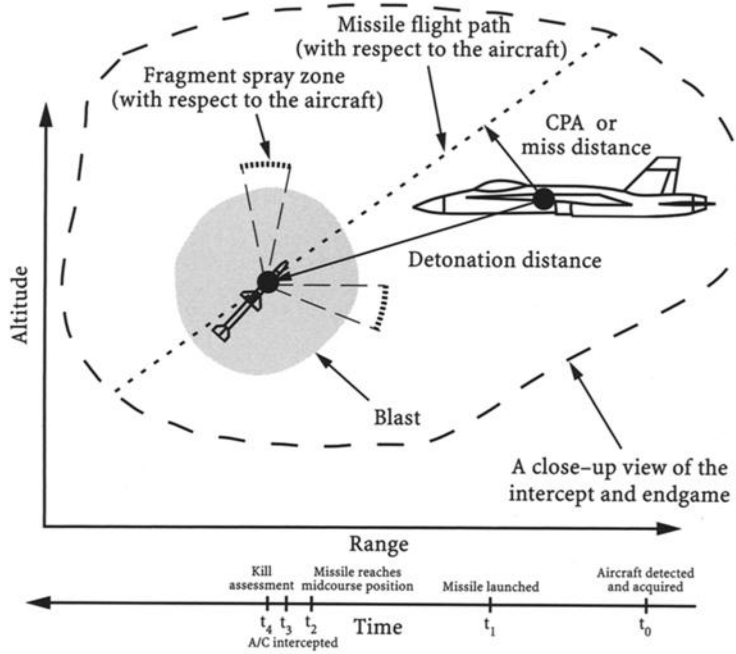


Fig. 3.7 Intercept and endgame.

and fragments move along the paths shown in the figure. The assumption is made here that neither the missile nor the target aircraft change directions or velocities during the end game. Thus, the missile and fragments move along straight lines with respect to the aircraft, as illustrated in Fig. 3.7 (Note 21). The theoretical closest point of approach (CPA) of the warhead on the missile to the center of the target is indicated in Fig. 3.7. The CPA is also referred to as the miss distance. However, the proximity fuze on the missile will most likely detonate the HE warhead before this location is reached, as illustrated by the detonation distance in Fig. 3.7 (Note 22).

The difference in time between t_1, missile launch, and t_3, target intercept, is the missile flyout time. Typical flyout times ($t_3 - t_1$) range from seconds to many minutes, depending upon the velocity of the propagator and the range to the aircraft when the propagator is launched or fired.

3.2.3.6 Target kill assessment. The attempt by the defense to determine the result of the missile shot is referred to as the target kill assessment. The time when the target is declared either killed or not killed is t_4. Thus, the total time for the encounter from detection to kill assessment is $t_4 - t_0$.

If the target were not killed by this missile, another missile might be fired in a shoot-look-shoot firing doctrine. The second missile will intercept an approaching target closer to the ship. If the interception occurs sufficiently close to the ship, explosion debris from the missile warhead or target aircraft could damage the ship. To increase the likelihood the target is killed further away and to reduce the time required to kill the target, a two missile shoot-shoot-look doctrine is sometimes used.

Go to Problems 3.2.11 to 3.2.17.

3.2.4 Warhead Lethality

Learning Objective	**3.2.4**	**Describe warhead lethality, the lethality functions for the contact warhead and the proximity-fuzed HE warhead, and the warhead lethal radius.**

The ability of a warhead to kill an aircraft depends upon the type of warhead. The two types of antiaircraft warheads considered here are the contact warheads and the proximity-fuzed HE warheads. The measure of warhead lethality is $P_{K|H}$ or A_V when a direct hit must occur to kill the aircraft and is $P_{K|F}$ when the propagator carries an HE warhead with a proximity fuze. The two probabilities are referred to as the warhead lethality or kill functions.

3.2.4.1 Contact warheads. The two metrics used to measure the lethality of a warhead against an air target are $P_{K|H}$ and the target's single-hit vulnerable area A_V. The contact warhead lethality function $P_{K|H}$ is usually defined as the probability the aircraft is killed, given a random hit on the aircraft area presented to the propagator A_P. Thus, $P_{K|H}$ is a uniform probability function over the extent of A_P. For the aircraft with nonoverlapping, nonredundant critical components illustrated in Fig. 3.8a,

$$P_{K|H} = \frac{A_V}{A_P} \tag{3.1}$$

Note that upper-case subscripts refer to the aircraft, and lower-case subscripts refer to the individual components on the aircraft.

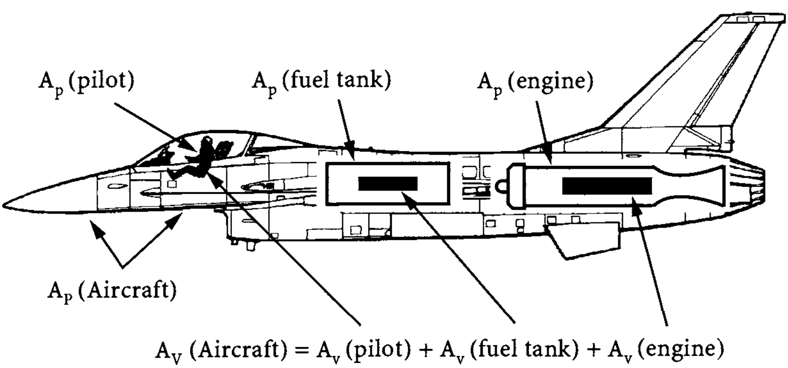


Fig. 3.8a Aircraft and component presented and vulnerable areas.

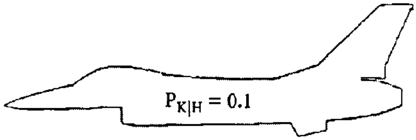


Fig. 3.8b Uniform $P_{K|H}$ functions.

In some vulnerability studies the $P_{K|H}$ function is considered to be dependent upon the location of the hit on the target. For example, for the aircraft shown in Fig. 3.8a $P_{K|H} = 1$ for a hit on the vulnerable area of the pilot, fuselage fuel tank, or engine, whereas $P_{K|H} = 0$ for any hit where there are no critical components. The lethality functions for the uniform $P_{K|H}$ (assumed to be equal to 0.1) and the location-dependent $P_{K|H}$ are illustrated in Figs. 3.8b and 3.8c, respectively. The general procedure for determining the single-hit vulnerable area and $P_{K|H}$ for any aircraft is described in Chapter 5, Sec. 5.3.4.

3.2.4.2 Proximity-fuzed warheads. The proximity-fuzed warhead lethality function $P_{K|F}$ depends upon the endgame conditions and the location of the detonation around the aircraft. For example consider the endgame conditions and the detonation location shown in Fig. 3.7 and repeated in Fig. 3.9a. Also shown in Fig. 3.9a is the zone of parallel missile flight paths (with respect to the aircraft) that would result in a direct hit by the missile on the aircraft if the warhead did not fuze first.

Note in Fig. 3.9a that the fragment spray zone from this particular detonation location does not hit the aircraft; the warhead detonated early. Assessment of the vulnerability of the aircraft to the fragments, blast, and missile debris generated by this warhead detonation results in a relatively low $P_{K|F} = 0.10$. If the blast and missile debris are neglected, $P_{K|F} = 0$ for this detonation location because no fragments hit the aircraft. If the detonation occurs further along the flight path, as shown in Fig. 3.9b, the $P_{K|F}$ increases to essentially 1.00 because of the relatively large number of fragments that hit and most likely kill many of the critical components on the aircraft.

The procedure for determing $P_{K|F}$ caused by fragments for any aircraft and warhead detonation location is presented in two parts. The number of fragments from the warhead detonation that hit the aircraft is determined in Chapter 4, Sec. 4.3.7.2, and the probability the aircraft is killed by the fragment hits is determined in Chapter 5, Sec. 5.3.4.4. The lethality of the proximity warhead can be presented

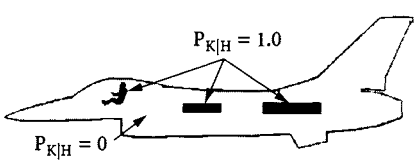


Fig. 3.8c Location-dependent $P_{K|H}$ function.

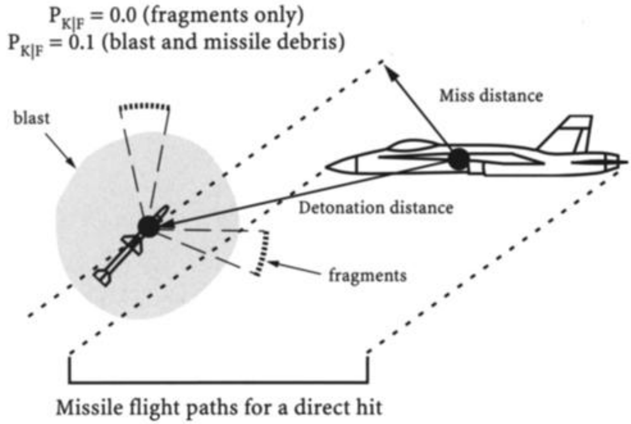


Fig. 3.9a $P_{K|F}$ **for one particular set of endgame conditions and detonation location.**

in a discrete form by determining the $P_{K|F}$ for an array of detonation locations around the aircraft with the same endgame conditions, such as the $P_{K|F}$ array shown in Fig. 3.10. Detonations are located above the aircraft for direct-hit flight paths because of the possibility that a missile along a flight path in the direct-hit zone could actually miss the relatively thin fuselage of the aircraft. Although the proximity fuze is designed to not function if a direct hit is possible, detonations are shown on direct-hit flight paths below the aircraft to account for the fact that a detonaton could occur.

The array of $P_{K|F}$ values shown in Fig. 3.10 assumes that a detonation occurs at each point in the array. However, when the proximity fuze is considered, warhead detonation, or proximity fuzing, is designed to occur within a proximity-fuzing region defined by the angles of the fragment spray zones. The procedure for determining the fragment spray zones is described in Chapter 4, Sec. 4.3.7.2. The proximity-fuzing regions for flight paths above and in front of the target (the early bird) and below and behind the aircraft (the late bird) are illustrated in Fig. 3.10. A detonation within either of these regions will result in one or more fragment hits on the target. Consequently, detonations within the proximity-fuzing regions have

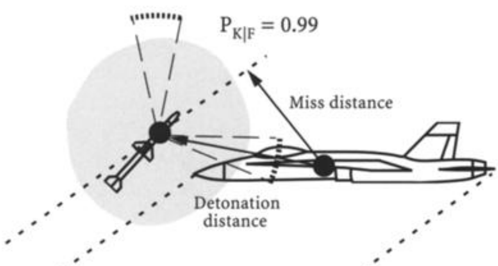


Fig. 3.9b **Much higher** $P_{K|F}$.

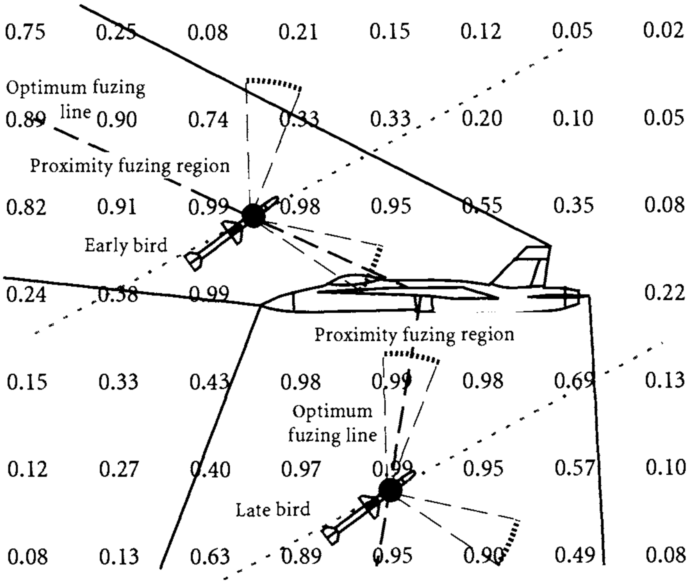


Fig. 3.10 Array of $P_{K|F}$ values for detonations around the aircraft with the same detonation conditions.

a larger $P_{K|F}$ than detonations outside of the regions. (A nonzero value of $P_{K|F}$ outside of the spray zones is caused only by blast and missile debris.) Thus, the values of $P_{K|F}$ within the proximity-fuzing region are of special interest because they are the locations where a detonation is designed to occur. The theoretical detonation locations within a proximity-fuzing region that result in the maximum value of $P_{K|F}$ at any detonation distance lay on the optimum fuzing line indicated by the dashed line in the middle of the two spray zones in Fig. 3.10.

To obtain a one-variable estimate of the lethality function for the proximity-fuzed HE warhead for any particular target aircraft and endgame, the two-dimensional array of $P_{K|F}$ values is simplified to a curve for $P_{K|F}$ with the detonation distance as the independent variable. In the terminal phase of the flyout as the missile approaches the target along the dashed-line flight path (relative to the aircraft) shown in Fig. 3.10, the fuze will detonate the warhead somewhere along the path. For a high estimate of the warhead's lethality, the assumption is made that the warhead will fuze on the optimum-fuzing line (Note 23). The set of $P_{K|F}$ values on the optimum-fuzing line can be averaged for detonations around the aircraft at a given detonation distance. For example, the two warhead detonations in Fig. 3.10 are at the same detonation distance, and hence the $P_{K|F}$ values for the two detonations would be averaged to obtain the average $P_{K|F}$ for that detonation distance. The averaging process is repeated for a number of detonation distances. A hypothetical plot of the optimum-fuzed $P_{K|F}$ as a function of the detonation distance is illustrated in Fig. 3.11. This curve is known as the $P_{K|F}$ function or warhead lethality function. To obtain a one-number estimate of the lethality of the proximity-fuzed HE warhead against a particular target, the warhead lethal radius can be defined

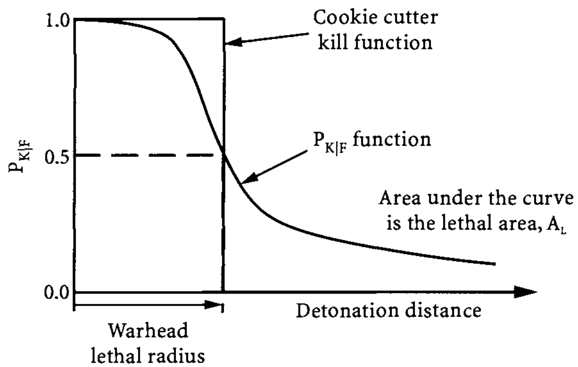


Fig. 3.11 Optimum-fuzed $P_{K|F}$ function and the warhead lethal radius.

to be that detonation distance where the average $P_{K|F}$ for all intercepts is 0.5 as shown in Fig. 3.11. In some analyses the term warhead lethal radius refers specifically to a sphere around the aircraft center within which $P_{K|F} = 1$. Outside of this radius, $P_{K|F} = 0$. This particular type of lethality function is referred to as a cookie-cutter kill function and is shown in Fig. 3.11 based upon the warhead lethal radius. Another one-number measure of the $P_{K|F}$ function is the lethal area A_L. The lethal area is the area (actually the volume) under the circularly symmetric $P_{K|F}$ function.

A simplification to the $P_{K|F}$ function that is sometimes made is to refer to, or equate, the detonation distance in Fig. 3.11 as the miss distance, which overestimates the warhead lethality because the miss distance is less than the detonation distance. However, there is a geometric relationship between the miss distance and the detonation distance. This relationship is shown in Fig. 4.26 and defined in Eq. (4.48a) for the two-dimensional intercept. This relationship can be used to convert from the detonation distance to the miss distance as the independent variable, and the warhead lethal radius is replaced with the lethal miss distance. This process is explained in more detail in Chapter 6, Section 2.

The array of $P_{K|F}$ values shown in Fig. 3.10 and the $P_{K|F}$ function shown in Fig. 3.11 are based upon one set of endgame conditions. In general, a different set of endgame conditions will exist for each new missile intercept. For example, the missile shown in Fig. 3.10 could have a different climb angle or a different velocity. This would affect the fragment spray zone angles, the value of $P_{K|F}$ at each detonation point, the direct hit and proximity-fuzing zones, and the relationship between the detonation distance and the miss distance. Thus, neither the value of $P_{K|F}$ at any particular detonation point nor the direct hit and proximity-fuzing regions are unique; they depend upon the endgame conditions. Consequently, if several endgame conditions are of interest several $P_{K|F}$ functions should be determined. A general curve for $P_{K|F}$ as a function of the detonation distance could be obtained by averaging the individual curves.

Go to Problems 3.2.18 to 3.2.20.

3.2.5 Weapon and Weapon System Effectiveness

Learning Objective	**3.2.5**	**Describe weapon system effectiveness, weapon effectiveness, the factors that affect effectiveness, the lethal and engagement envelopes, the footprint for a surface-to-air weapon, and the launch acceptability region for an air-to-air weapon.**

From the point of view of the enemy air defense, P_K is the measure of the effectiveness of their weapon system. The P_K of a weapon system in a one-on-one, multishot scenario can be estimated using Eq. (1.6a). Thus,

$$P_K = P_E P_{K|E} \tag{3.2a}$$

where

$$P_E = P_A P_{E|A} = P_A(P_{D|A} P_{L|D}) \tag{3.2b}$$

according to Eq. (1.5f), and

$$P_{K|E} = 1 - P_{S|E} = 1 - (1 - P_{K|SS})^N \tag{3.2c}$$

for N independent shots of a propagator, according to Eq. (1.6i).

The lethality of the weapon, or the effectiveness of the weapon in flight, is measured by $P_{K|SS}$, which is given by

$$P_{K|SS} = P_{SSK} = P_{H|SS} P_{K|H} \quad \text{or} \quad P_{K|SS} = P_{F|SS} P_{K|F} \tag{3.2d}$$

for propagators with contact warheads or proximity warheads, according to Eq. (1.5i), where $P_{K|H}$ or $P_{K|F}$ is the lethality of the munition or the warhead on the weapon. The procedure for determining $P_{K|SS}$ for both contact and proximity warheads is described in Chapter 6, Sec. 6.2.2.1.

3.2.5.1 Weapon capabilities that affect effectiveness. The specific capabilities of a weapon that affect its effectiveness depend upon the type of weapon considered. For guns the muzzle velocity of the round as it leaves the barrel, the size of the ballistic projectile, the aerodynamic characteristics of the projectile, the ballistic dispersion of the projectiles, the type of warhead, and the type of fuze, if any, influence $P_{K|SS}$. The distance between the gun and the aircraft, the aircraft's speed and flight path after the gun fires, the number of rounds that hit the aircraft, and the vulnerability of the aircraft to the warhead also affect the gun's effectiveness. The factors that affect gun system effectiveness, that is, P_K, include those that influence the weapon's effectiveness plus the aircraft detection, tracking, and fire control capabilities in terms of reaction times, fire control prediction accuracy, and the the rate and duration of fire.

For guided missiles the flight performance of the missile, the guidance type and navigation accuracy, the warhead design, the fuze, and the missile sensors and signatures are major factors that affect the effectiveness of the missile (Note 24). The flight performance includes such factors as the available acceleration from the motor in terms of magnitude and duration, the response of the missile to commanded accelerations, and the maximum acceleration capability of the airframe. The distance from the missile's launching platform to the aircraft at the time of launch, the aircraft's velocity and flight path after missile launch, and the vulnerability of the aircraft to the damage mechanisms generated by the warhead also influence the effectiveness of the missile. The effectiveness of the guided missile system is a function of the target detection and tracking capabilities, the fire control doctrine, the number of missiles fired at one target, and the effectiveness of the missiles.

3.2.5.2 Weapon envelopes. The measures of weapon system and weapon effectiveness, P_K and $P_{K|SS}$ given by Eqs. (3.2a) and (3.2d) respectively, are expected values for any given one-on-one scenario between the weapon system and an aircraft. Of greater interest to mission planners and the aircrews that fly the missions is the extent a weapon can reach out and kill aircraft. The extent of weapon system (or weapon) effectiveness is represented by the weapon envelope. The weapon envelope is a three-dimensional envelope that encloses one or more volumes of air space around the weapon location. Figure 3.4 is a general illustration of a two-dimensional slice through the three-dimensional envelope for an aircraft that is flying directly toward the weapon. Aircraft that are within the weapon envelope can be engaged and killed with a probability assumed to be significant by the weapon analyst, for example, $P_K \geq 0.5$ or $P_K \geq 0.8$. Aircraft that are outside of the envelope are killed with a probability that is less than significant, for example, $P_K < 0.5$ or $P_K < 0.8$. Several envelopes, each with a different minimum P_K, can be used to describe the weapon's extent of effectiveness, for example, one envelope extends out to the locations where $P_K = 0.5$ and another, smaller envelope extends out to the locations where $P_K = 0.8$.

Gun envelopes. The three-dimensional shape of the weapon envelope for surface-based guns is usually idealized as a hemisphere centered at the gun location. The radius of the hemisphere can be described by the open-fire range, the tactical range, the self-destruct range, or the maximum effective range. The open-fire range is the slant range from the gun to the target when the gun opens fire. The tactical range is the slant range from the gun to the target when, under normal circumstances, the target can expect to be hit by the gunfire. The self-destruct range is the slant range from the gun to the projectile when the time fuze on the projectile's HE warhead self-destructs. The maximum effective range is a subjective term that refers to either the hit probability or the kill probability for the gun.

Surface-to-air missile envelopes. Weapon envelopes for SAMs are more complex than those for guns. SAM weapon envelopes have been referred to in other publications as the lethal, effective, tactical, intercept, engagement, or performance envelopes. Only the terms lethal (launch) envelope, lethal (intercept) envelope, and the intercept or engagement envelope are used here. The terms *lethal (launch) envelope* and *lethal (intercept) envelope* are usually used when the vulnerability of the aircraft is considered in detail in the assessment, for example, the aircraft is more vulnerable in some directions than in others. The *lethal (launch) envelope* is based upon the location of the aircraft at the time of missile launch. The *lethal (intercept) envelope* is based upon the location of the aircraft at the time of the missile intercept. The term *intercept* or *engagement envelope* is usually used for SAMs with proximity-fuzed HE warheads when the vulnerability of the aircraft is represented by a sphere around the aircraft. The radius of the sphere, centered at the target center, is a simple estimate of the vulnerability of the aircraft to the particular threat warhead and is referred to as the lethal radius. When the miss distance is less than this radius, an aircraft kill is declared. When the miss distance is larger than the radius, the aircraft is said to survive.

Determining the three-dimensional extent of the weapon envelope can, in theory, be accomplished in two ways. In the first way a large number of realistic tests can be conducted using the actual weapon, live ammunition, and real aircraft. As the aircraft flies along a specified flight path through the territory defended by the weapon, the weapon begins firing at the aircraft as soon as possible and continues to fire until the aircraft is either killed or exits the defended territory. If the aircraft is killed, the location of the kill along the flight path is noted. Another aircraft is then sent into the test arena along the same path, and the weapon begins firing as soon as possible. Again, this aircraft is either killed at a particular location, or it survives. This process is repeated many times for this particular flight path in order to obtain a statistically significant set of data points for the locations of an aircraft kill. This process is repeated for many different flight paths through the defended territory. The results of these tests provide a three-dimensional (x, y, z) array of values for P_K around the weapon location. The weapon envelope is then drawn such that it encloses those locations where the P_K is defined to be significant.

Or a prediction of the extent of weapon system effectiveness can be made using survivability assessment methodologies and computer simulations, both analytical and hardware-integrated (Note 25). The first method just described is usually prohibitively expensive and very difficult to accomplish. The second method is much less expensive and is the only feasible method when a weapon is in the early design phases.[15]

Lethal (launch) envelope: Using computer modeling and simulation, P_K can be determined for the scenario where the approaching aircraft is at a certain altitude and flying a specified flight path at a selected horizontal offset with respect to the launching platform. Figure 3.4 is an illustration of the situation where the aircraft is flying straight and level, at a given altitude, directly toward the weapon location, that is, at a zero offset. The weapon is assumed to be active. Equations are developed that represent the aircraft detection, tracking, missile launch, missile flyout, warhead impact or proximity detonation, and the target vulnerability to the impact or detonation for reacting and nonreacting targets (Note 26). The equations following detection and through flyout to the intercept are usually deterministic, and consequently a single missile location at intercept is obtained for each shot. Accounting for the relative locations, velocities, and attitudes of the missile and target, the propagator's warhead and fuze, and the aircraft's three-dimensional vulnerability in the endgame yields a value for $P_{K|F}$ for the particular detonation location. This value is equal to both $P_{K|E}$ (or $P_{K|SS}$) and P_K for that shot because

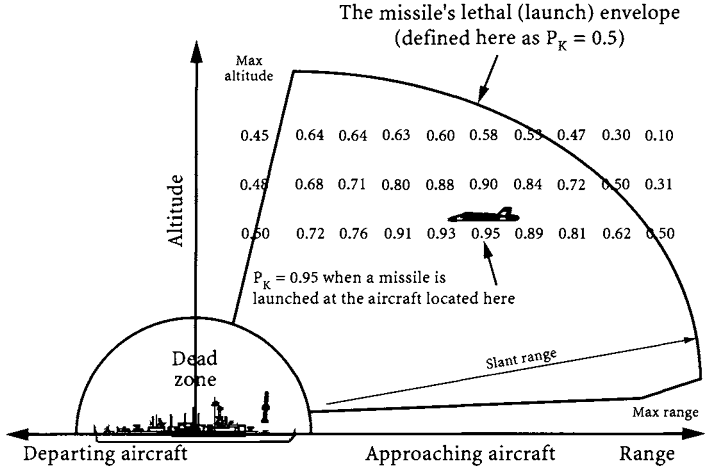


Fig. 3.12a Lethal (launch) envelope (aircraft flying straight and level, zero offset, no EA).

$P_E = 1$ is assumed. If the launch and flyout equations contain random variables, such as target tracking and missile guidance errors, the intercept location is a random variable, and the Monte Carlo solution technique can be used to determine the distribution of intercept or miss distance locations and the corresponding expected value for the P_K for each engagement (Note 27).

A series of trials for the specified flight path, at a given offset, can be conducted using several different target altitudes. In each trial, when the required conditions for a successful launch are satisfied, such as successful detection and continuous tracking, a missile is fired at the aircraft when the aircraft is located at a series of specific horizontal distances in front of, and behind, the location of the firing unit. The numerical result for the P_K obtained from each of the shots (or series of shots) can be presented in the two-dimensional array form shown in Fig. 3.12a for each offset for approaching aircraft. Each number in the array is the P_K obtained for a missile launch when the aircraft was at the location indicated by the position of the number in the array. If a missile cannot be launched when the aircraft is at a particular location because the aircraft has not been successfully detected and tracked, then $P_K = 0$ for that location because $P_E = 0$. When a missile can be fired, $P_E = 1.0$, and the subsequent P_K is equal to $P_{K|E}$. Repeating the simulation for other offsets provides the total, three-dimensional array of P_K values for the selected scenario. A definition of weapon effectiveness, such as $P_K \geq 0.5$, is made, and the $P_K = 0.5$ contour is drawn in the figure, as shown in Fig. 3.12a for the zero offset.

The maximum range and maximum altitude of the lethal (launch) envelope (not the missile) shown in Fig. 3.12a denote the furthest range and altitude of the aircraft from the launch site where a launched missile can fly out, intercept, and cause lethal damage to an approaching aircraft with a significant probability. The slant range is the longest straight-line distance from the launch site to the edge

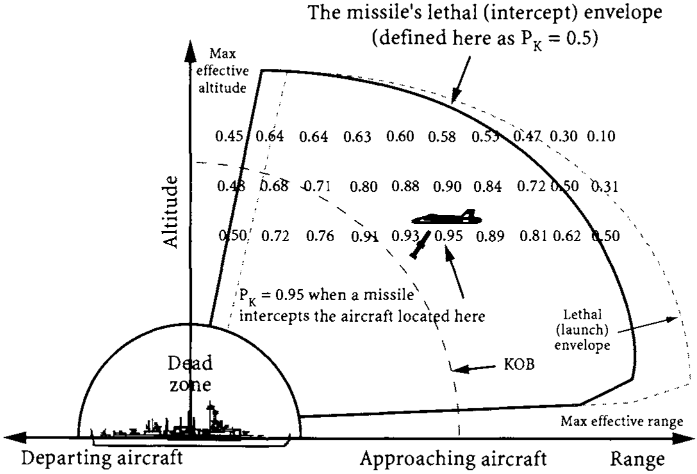


Fig. 3.12b Lethal (intercept) envelope (aircraft flying straight and level, zero offset, no EA).

of the envelope. The dead zone is that volume around the launcher in which the missile fuze is unarmed as the missile passes through, and many weapons have launcher elevation limits.

The shape and size of the lethal (launch) envelope depend upon the many factors that affect weapon effectiveness, such as the aircraft's signatures, speed, countermeasures, and vulnerability. As an aircraft's signatures are reduced, the maximum range is reduced as a result of delays in the time of detection and engagement, and the outer portion of the envelope shrinks around the launch site. As an aircraft's vulnerability is reduced, the envelope also shrinks because P_K is smaller for less vulnerable aircraft.

There is only one envelope shown in Fig. 3.12a, and it is for approaching aircraft. There is an envelope similar but smaller to the one shown in the figure for departing aircraft. The maximum range of a missile is usually shorter for egressing aircraft than for approaching aircraft because the missile must catch up with the departing aircraft. However, if the aircraft's signature is much lower from the front than from the rear the reverse might be true.

The P_K contour shown in Fig. 3.12a is referred to as the weapon's lethal (launch) envelope because the P_K values, and hence the envelope, are located with respect to the aircraft's location at the time of missile launch. Lethal (launch) envelopes are used by the air defense to determine when to launch a missile. If the aircraft is outside the envelope, no missiles are launched. If the aircraft is inside the envelope, one or more missiles can be launched. Lethal (launch) envelopes should be avoided by pilots, if possible.

Lethal (intercept) envelope: If the P_K value for each missile launch is located at the position of the aircraft at the time of propagator intercept (rather than at the aircraft location at the time of launch), the envelope is referred to as the lethal (intercept) envelope. Figure 3.12b presents the lethal (intercept) envelope corresponding to the lethal (launch) envelope shown in Fig. 3.12a and indicated in

Fig. 3.12a by the gray dashed line. The maximum range and maximum altitude to the aircraft at intercept are referred to as the maximum effective range and altitude of the missile, respectively. Lethal (intercept) envelopes are of interest to the air defense because they can be compared to the KOB shown in Fig. 3.12b. The intercepts outside of the KOB are locations of a possible aircraft kill before the aircraft can launch its weapons. In this example the weapon system is very effective outside of the KOB. Thus, the air defense has a high probability of killing the attacking aircraft before it can deliver its ordnance.

Intercept or engagement envelope: The intercept or engagement envelope for missiles is developed using the missile miss distance at intercept for each shot as the measure of lethality. The assumption is made that the aircraft is killed (sometimes referred to as hit) when the miss distance is less than the lethal miss distance (described above) and is not killed (or not hit) when the miss distance is greater. Thus, the cookie-cutter kill function shown in Fig. 3.11 is used with the lethal miss distance as the radius (Note 28). The miss distance for a shot is usually determined using the same or similar computer models and simulations used for the lethality envelopes. The miss distance computed for each of the missile shots in the one-on-one scenario illustrated in Fig. 3.12b is plotted in Fig. 3.13. Drawing the contour for the lethal miss distance of 20 m in the miss distance array shown in Fig. 3.13 gives the intercept or engagement envelope based upon the location of the aircraft at the time of missile intercept. Some published documents locate the intercept or engagement envelope at the location of the missile launch rather than at the location of the intercept.

Lethal missile footprint: Projecting the three-dimensional lethal (launch) envelope for a radar-directed SAM onto the defended surface gives the lethal missile footprint around the weapon site, as shown in Fig. 3.14a. Note the areas on both sides of the SAM site where this particular missile is not effective. The inability of this particular SAM system to kill aircraft located in these two areas is caused by its use of semiactive homing guidance, which uses the Doppler frequency shift of

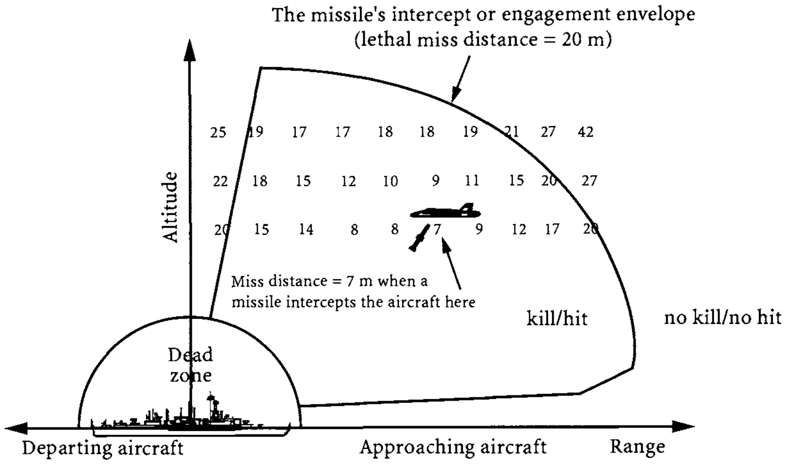


Fig. 3.13 Intercept or engagement envelope.

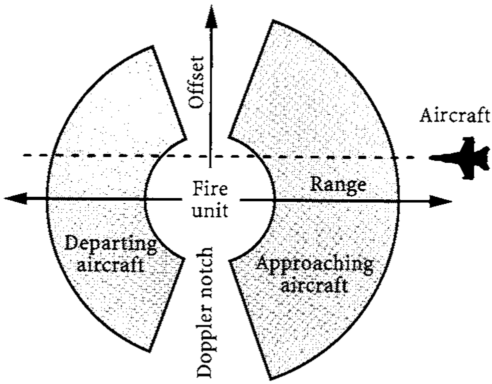


Fig. 3.14a Lethal missile footprint.

the echo from the aircraft (described in Sec. 3.6.2.3) to detect and track the aircraft. The Doppler frequency shift of the aircraft echo from aircraft moving within these areas is too small to be detected by the radar because of the relatively small radial velocity between the aircraft and the radar site. These notches in the footprint are referred to as Doppler notches.

The missile footprint for an infrared homing missile is shown in Fig. 3.14b. The lock-on envelope or boundary is the locus of points around the weapon where the aircraft can be detected by the IR seeker. The IR detectors used in the early IR homing missiles employed uncooled detectors, such as lead sulfide, with a useful sensitivity in the 1–3 μm, or hot metal emission and reflected sunlight, region. Although homing in on the aircraft-reflected sunlight from any direction is possible with an uncooled seeker, the early IR missiles were generally restricted to

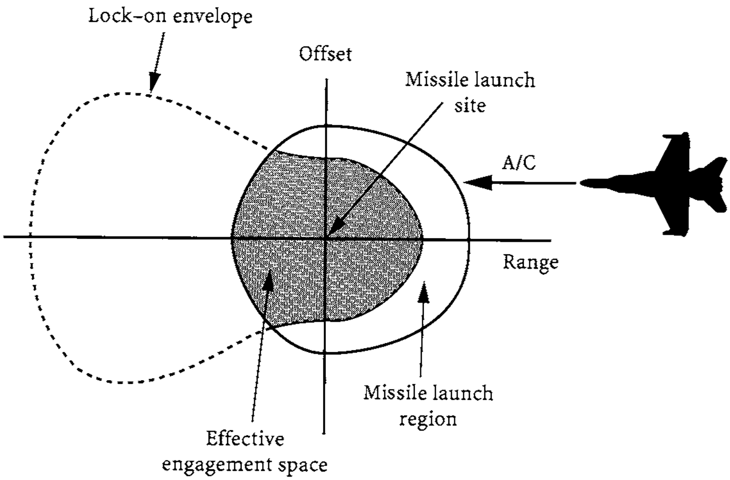


Fig. 3.14b Footprint on an IR missile.

launches from behind the target aircraft toward the exposed hot engine parts and tail pipe because these were the only parts of the aircraft that were hot enough to be detected. These launches at departing aircraft were often referred to as revenge shots. Using cooled detector materials, such as indium antiminide, in modern missiles enables the seeker to track the relatively low-level radiation in the 4–5 μm band that is emitted by the hot gases in the engine exhaust plume. Because the plume can be observed from all aspects around the aircraft, cooled-seeker IR missiles have the potential for detecting the aircraft from almost any direction. Any IR missile that can detect, track, and intercept an aircraft after a launch from any direction is referred to as an all-aspect IR missile (Note 29).

The effective engagement space of an IR missile, illustrated by the gray area in Fig. 3.14b, depends upon the ability of the seeker to detect and track the aircraft, which is defined by the lock-on envelope, and the ability of the launched missile to intercept the aircraft, which is defined by the missile's launch region (assuming the target can be detected and tracked). Hence, the missile is effective only when launched at aircraft located within the overlap of the lock-on boundary and the missile launch region. The aircraft cannot be seen outside of the lock-on envelope, and it cannot be intercepted outside of the launch region.

Air-to-air missile envelope. In the case of air-launched weapons, the shooter is relatively free to move around the target aircraft. Consequently, the envelope for air-to-air weapons defines those locations of the shooter with respect to the target aircraft where the P_K associated with a shot is significant, as opposed to the surface-to-air weapons where the locations of the target around the shooter are plotted. A typical weapon envelope for an air-launched, semiactive guided missile is shown in Fig. 3.15. The target aircraft is flying straight and level. The launching aircraft is approaching the target aircraft at the same altitude. Locations inside the envelope represent locations of the launching aircraft where a missile shot is predicted to result in a P_K larger than the defined lethal P_K (or a miss distance smaller than the lethal radius). The region inside the envelope is referred to as the launch acceptability region (LAR). The shape of the LAR is strongly dependent upon the relative target and shooter speeds and any evasive maneuvers performed by the target.

Typical values for the envelopes. The effective slant range for guns can be estimated from the rule of thumb that says the maximum slant range in kilometers

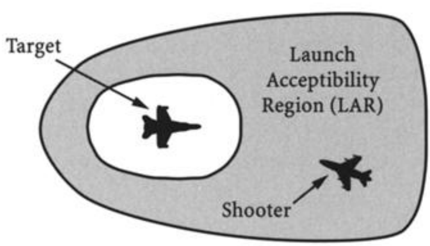


Fig. 3.15 Weapon envelope for air-to-air missiles.

is equivalent to the gun projectile diameter in millimeters divided by 10. Thus, the maximum effective slant range of a 30-mm gun is approximately 3 km. The maximum extent of the lethal (launch) envelope for missiles can vary from 1 to 5 nm for the small missiles (diameter <120 mm), from 3 to 10 nm for the medium missiles (120 mm $<$diameter $<$240 mm), and from 10 to 50 nm for the large missiles (diameter $>$240 mm).

Go to Problems 3.2.21 to 3.2.26.

3.2.6 Air Defense Effectiveness

Learning Objective	**3.2.6**	**Describe air defense effectiveness.**

The effectiveness of an AD weapon system refers to the ability of the weapon system to encounter aircraft, engage them with one or more weapons, and eventually kill one or more critical components on the aircraft that perform a function essential for either mission completion or flight. The effectiveness of the weapon system can vary from 'not effective' to 'extremely effective,' depending upon the particular weapon system, the target aircraft, and the scenario. The phrase 'air defense effectiveness' refers to the ability of the AD, which consists of one or more AD weapon systems, to encounter aircraft, to engage them, and to inflict damage sufficient to kill them.

Air defense effectiveness is influenced by the number of weapon systems available to engage the aircraft, the one-on-one effectiveness of each of the individual weapon systems, and the number of aircraft that can be encountered, engaged, and killed in one attack by each weapon system. As an example of the relationship between weapon system effectiveness and AD effectiveness, consider a helicopter flying into an area defended by one or more troops with assault rifles. The individual weapon system consists of a soldier with a rifle, the weapon is the rifle, and the AD consists of the number of soldiers that can fire at the helicopter.

Examining weapon system effectiveness, the weapon system consisting of a soldier with an assault rifle is probably not as effective against the helicopter as a weapon system consisting of the same soldier with a MANPAD. The MANPAD can kill aircraft at a longer range, and it has a higher P_K at any given range.

Examining AD effectiveness in point defense, the AD that consists of a single soldier firing an assault rifle at the helicopter is probably not as effective against the helicopter as the AD that consists of 50 soldiers, all firing away at the helicopter with assault rifles; and the most effective air defense might be the one soldier with the MANPAD.

Go to Problem 3.2.27.

3.3 Terminology

3.3.1 Aircraft Combat Survivability Terminology

Learning Objectives	**3.3.1**	**Describe ballistics, interior ballistics, exterior ballistics, and terminal ballistics, and the threat and aircraft response topical fields.**
	3.3.2	**Describe the terms damage mechanism, damage process, kill mode, terminal effect, and aircraft response measure, and use them to describe a damage incident.**

The scientific study of the firing of weapons, the flight of the weapon propagator toward the target, and the effects of the propagator and its warhead upon the target is known as ballistics. The firing phase is referred to as interior ballistics, the flight or trajectory phase is referred to as exterior ballistics, and the final phase consisting of the destructive effects of the weapon on the target is known as terminal ballistics (http://155.217.58.58/cgi-bin/atdl.dll/fm/1-140/CH4.HTM).

The terminology associated with the fields of ballistics and the air defense threat in general can be divided into two topical fields: the threat topical field and the aircraft response topical field. The threat topical field is shown in Table 3.3. This topical field contains two subfields that are used to describe the threat characteristics and the threat operations. Threat characteristics refer to the type of threat, such as antiaircraft artillery or surface-to-air guided missile systems; the type of warhead on the threat propagator, such as armor-piercing or high explosive; and the damage mechanisms associated with the warhead. The damage mechanisms, also referred to as threat or kill mechanisms, are the physical output of the warhead that cause damage to the target. Two examples of damage mechanisms are metallic fragments and incendiary materials. Threat operations refer to those inherent capabilities and factors that relate to the ability of the threat to perform its basic search, detection, track, firing/launching, and guidance functions.

None of the threat terms just given reflect any interaction between the threat and the aircraft or target, that is, the terminal ballistics. Rather, these descriptors relate to the inherent or possessed capabilities of the threats themselves. The aircraft response topical field, shown in Table 3.4, is the field that contains those terms which are used to describe the threat effects or interactions of the threat with the target aircraft and the response of the aircraft. The aircraft response field has three categories: damage processes, aircraft vulnerability, and response measures.

Table 3.3 Threat topical field

Threat characteristics	Threat operations
Threat types	Search/detect/track
Warhead types	Launch or fire
Damage mechanisms	Guide and navigate

Table 3.4 Aircraft response topical field

Damage processes	Aircraft vulnerability	Response measures
Impact and penetration	Terminal effects	Kill categories
Combustion	Kill modes	Kill levels
Blast loading	Kill criteria	

Damage processes, such as penetration and combustion, describe the interaction between the damage mechanisms and the target aircraft, for example, penetrators penetrate and incendiaries cause combustion. Aircraft vulnerability includes the qualitative and quantitative response of the aircraft components and systems to the damage processes. An aircraft's vulnerability to a hit is described by the terms terminal effects, kill or damage modes, and kill criteria. Terminal effects refers to the physical state of the various materials, components, and personnel in the aircraft when subjected to the damage processes, such as the hole in the fuselage skin caused by penetration by a fragment. When you take a picture of a damaged aircraft, what you see are the terminal effects. Kill or damage modes refers to the ways that components, systems, or the aircraft can be killed by the damage processes, such as an explosion inside a fuel tank that results in the loss of the integrity of the wing structure or the loss of the fuel supply in that wing. Component kill criteria are numerical measures that define when a component is killed or a component kill mode occurs. One kill criterion is the probability a component is killed given that it is hit $P_{k|h}$. The response measures are quantitative measures of the final results of the threat effects in terms of operational capability. They include kill categories, such as attrition and mission abort, and kill levels within

Table 3.5 Examples of damage mechanisms, damage processes, terminal effects, and kill modes

Term	Definition	Examples
Damage mechanism	Physical entity that causes damage to the aircraft	Metallic penetrator Incendiary material Blast wave
Damage process	Interaction between damage mechanism and aircraft's components	Penetration of control rod Combustion in wing fuel tank Blast loading on skin
Terminal effect	Damage state of components subjected to damage processes	Broken control rod Large hole in wing skin Crushed skin
Kill mode	Component or system response that results in a component or system kill and possibly an aircraft kill caused by loss of an essential function	Severed control path In-tank explosion Pressure overload

a category, such as the aircraft falls out of control within 30 s after suffering a hit (a K-level attrition kill).

The connection between the threat topical field and the aircraft response topical field is often difficult to grasp because of the misuse of many of the terms. The connection between the terms damage mechanism, damage process, terminal effect, and kill mode is one of the more confusing connections. Table 3.5 gives some example terms in these three subfields that in the past have been commonly, but erroneously, interchanged, with resulting ambiguity. Example 3.1 describes one possible sequence of events relating these terms.

Go to Problems 3.3.1 to 3.3.11.

Example 3.1 A Helicopter Gets Hit

An armor-piercing round from a machine gun (a metallic penetrator damage mechanism) hits the tail boom of a helicopter at an oblique angle. As the penetrator penetrates the tail boom skin (the penetration damage process), it slows down, tumbles, and changes direction. Small bits of tail boom skin from the entry hole (more metallic damage mechanisms) are ejected in several directions. After penetrating the skin, the penetrator hits and penetrates a rod in the flight control signal path from the pilot to the tail rotor, creating a jagged hole approximately 0.5 in. in diameter (a terminal effect). After penetrating the rod, the penetrator exits the skin on the opposite side of the tail boom. The rod breaks when the pilot attempts to maneuver the helicopter (a component kill mode and subsequent terminal effect), causing a disruption in the control signal path from the pilot to the tail rotor (a flight control system kill mode). The pilot's inability to control the tail rotor because of the broken rod (the loss of an essential function for flight) causes the aircraft to fall out of control (an attrition kill). Thus,

Damage Mech. → Damage Process → Comp Kill Mode
→ Sys Kill Mode → Aircraft Response

Penetrator → Penetration → Broken Rod → Severed Control Path
→ Attrition Kill

Suppose there was an electrical control path from the cockpit to the tail rotor, separated from the rod, that also can transmit the pilot's control signal. Thus, the pilot does not lose control of helicopter when the tail boom is hit and the control rod breaks because the electrical path also carries the control signal. Consequently, there is no attrition kill of the aircraft because of the redundancy and separation of the tail rotor control signal paths. Thus, when there are redundant and separated control paths to the tail rotor,

Damage Mech. → Damage Process → Comp Kill Mode → Sys Kill Mode
→ Aircraft Response

Penetrator → Penetration → Broken Rod → One Severed Control Path
→ No Attrition Kill

However, the pilot notices the hit and realizes that the control system has been damaged. Because of the nonessential nature of the mission, the pilot decides to abort the mission and return to base. This is a mission abort kill caused by safety of flight. Had the damage been more extensive, the pilot might have been forced to land immediately in order to prevent a crash, which would be a forced landing kill (Note 30).

3.3.2 Vulnerability/Lethality Taxonomy

Learning Objective 3.3.3 Describe the five levels in the Vulnerability/Lethality Taxonomy, their metrics, and the mapping operators.

In the late 1980s, in an attempt to improve the quality of the vulnerability modeling of live fire tests, the Survivability/Lethality Analysis Directorate, Army Research Laboratory, Aberdeen Proving Ground, Maryland, began the development of a vulnerability/lethality (V/L) taxonomy that would allow a rational scientific approach to the V/L assessment process for both land and air vehicles.[16–18] A brief description of the taxonomy and its relationship to the terminology used by the aircraft combat survivability discipline is given next.

The V/L Taxonomy is based upon the concept of a system or target, for example, an armored vehicle or an aircraft, and five sequential levels that describe the state of the system or its capabilities before and after a hit by, or proximity fuzing of, a warhead. Each of the five levels has a distinct set of descriptors or metrics that define the state or capability of the system. The system levels are related or mapped by operators. For example, the operator $O_{1,2}$ describes the transition of the state from level 1 to level 2. The five levels and their connecting operators are listed in Fig. 3.16, with examples based upon an encounter between an aircraft and a SAM.

The general V/L Taxonomy presented in Fig. 3.16 is in consonance with the terminology used in the ACS discipline. Note the sequential transition from level 0, the engagement of an aircraft by a weapon, to level 1, the beginning of the endgame, to level 2, the completion of the vulnerability phase. Levels 3 and 4 describe the remaining capabilities of the damaged target and the ability of the target to perform militarily useful functions, respectively. Thus, level 3 is the level that evaluates the ability of a damaged aircraft to continue to fly and fight, and level 4 describes the ability of the damaged aircraft to contribute to the mission objectives (Note 31).

Go to Problems 3.3.12 to 3.3.15.

3.4 Threat Characteristics

The threat characteristics of interest here are those descriptions that relate to the threat type, the warhead type, and the damage mechanisms associated with the warheads.

Level 0] Threat–Launch Initial Conditions

A two–engine target aircraft is on an interdiction mission. It is flying straight and level at 15K ft. All aircraft systems and components are functioning at full capability at the time of a missile launch.

↓ Operator $O_{0,1}$] The missile flies out to an intercept with the aircraft. The missile flight path can be determined by live fire testing or simulated using a missile flyout program, such as ESAMS.

Level 1] Threat–Target Interaction Initial Conditions

The missile is traveling at Mach 2 and is approaching the aircraft from the port side, below and behind the aircraft. The target is in a five–g turn in an attempt to avoid the missile. All systems and components are functioning at full capability at the time of a proximity detonation of the missile's HE warhead 30 ft from the left engine.

↓ Operator $O_{1,2}$] The fragments and some of the missile parts impact the aircraft skin and penetrate into the aircraft, and the blast from the HE warhead detonation engulfs the aircraft. The impact and penetration of the fragments and missile parts into the aircraft and the effects of the blast loading can be determined by live fire testing or simulated using an endgame program, such as AJEM.

Level 2] Target Damaged Components

The fragments, missile parts, and blast from the proximity detonation near the left engine result in major damage to, and a total loss of thrust from, that engine; the loss of hydraulic fluid from holes in the hydraulic lines attached to the left engine–mounted hydraulic pump; and 73 holes 0.5 in^2 or smaller in the target skin in the vicinity of the left engine.

↓ Operator $O_{2,3}$] The ability of the aircraft to continue to fly and perform mission essential functions after the warhead detonation can be determined by live fire testing on flying aircraft, or by live fire testing on stationary aircraft followed by flight testing, or by conducting a Failure Mode and Effects Analysis or Fault Tree Analysis. The FMEA or FTA will determine if the components that were killed or damaged by the detonation result in a loss of one or more flight or mission essential functions.

Level 3] Target Measures–of–Capability

The damaged aircraft can continue to fly because it still has the flight essential functions of structural integrity, lift, thrust, and control. However, its maximum speed is reduced by 25%, and its maneuverability is reduced by 40%. It still has full capability to perform mission–related functions, such as delivering ordnance, navigation, and communication.

↓ Operator $O_{3,4}$] The ability of the damaged aircraft to contribute to the battle can be determined by observing the contributions of real aircraft that have been damaged in actual combat, or by conducting a live fire test during a practice mission, or by simulating the mission using a mission model, such as SUPPRESSOR.

Level 4] Target Measures–of–Effectiveness (Utility)

Although all mission essential functions are fully capable, the pilot decides to abort the mission for safety of flight. Consequently, this becomes a mission abort kill, and the mission objectives are not achieved. Thus, the utility of this particular aircraft on this mission has gone from one to zero as a result of the encounter with the threat.

Fig. 3.16 V/L Taxonomy.

3.4.1 Types of Threats

Learning Objective 3.4.1 Describe the threat types, the firing platforms, their firing devices, and the threat propagators.

Threat type denotes the general classification of the threat element in terms of the functions it performs. In general, threat elements can be grouped into two types: nonterminal and terminal.

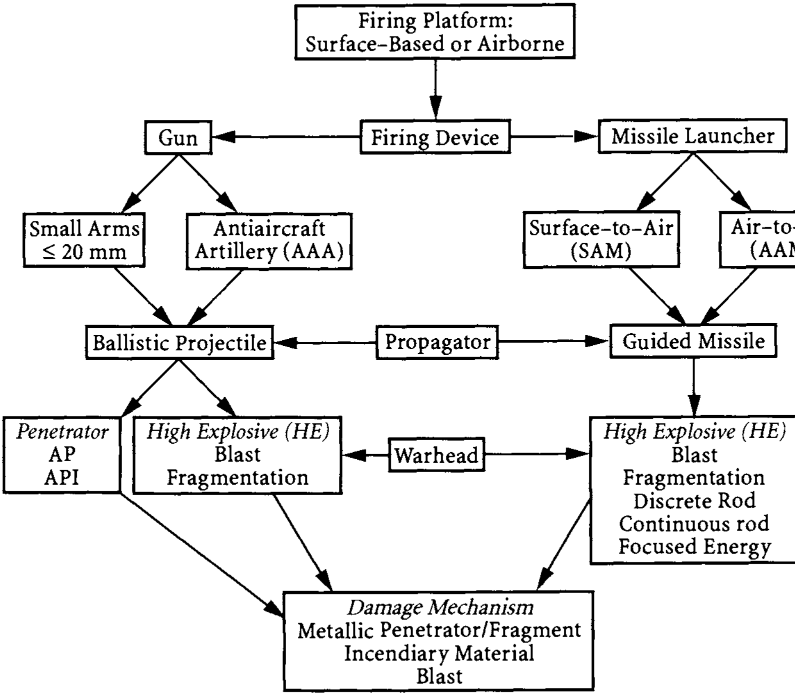


Fig. 3.17 Terminal threat elements.

The nonterminal threat elements do not in themselves possess a capability to inflict damage. They are the sensors, communications, and other electronic and optical systems used by air defense forces to support the terminal threat elements. These elements normally consist of target detection and early warning, target identification, target tracking, electronic counter-countermeasure (ECCM), fire or weapon control, missile guidance, and communication systems. They can be land-, sea-, or air-based and are normally an integrated part of the enemy's offensive and defensive forces. Their purpose is to supply target position, speed, and heading information to the terminal threat elements associated with the fire units.

In general, the terminal threat elements have the capability to cause damage to an airborne target. They consist of the firing platform, the firing device, and the threat propagator with its warhead and the associated damage mechanisms, as illustrated in Fig. 3.17.

3.4.1.1 Firing platforms. Terminal threat firing platforms are divided into two categories: surface-based and airborne.

Surface-based platform. The surface-based firing platforms include both ground-based stationary sites and mobile platforms, such as humans and wheeled and tracked vehicles, and marine vessels. These platforms can carry both guns and missile launching equipment.

Airborne platform. The airborne firing platforms include all air vehicles capable of carrying guns or missile launching equipment that can be used against aircraft.

3.4.1.2 Firing devices.

The devices that can launch propagators at aircraft from surface-based and airborne platforms consist of guns and guided missile launchers (Note 32).

Gun. A gun is a device, including any stock, carriage, or attachment from which projectiles, rounds, or high-explosive shells are propelled by the force of an explosive reaction. Guns come in various sizes, ranging from hand-held small arms (SA) to much larger transportable, airborne, or stationary antiaircraft artillery (Note 33). According to Ref. 2, small arms are man-portable, individual, and crew-served guns (weapon systems) that fire projectiles up to and including 20 mm in diameter (Note 34). Antiaircraft artillery (AAA) denotes that category of guns that fires projectiles greater than 20 mm in size. Guns larger than 12.7 mm are also referred to as antiaircraft (AA) guns, and a rapid firing gun that shoots high-explosive shells (usually 20 mm or larger) is referred to as a cannon. Table 3.6 presents the various types of guns within the small arms and suggested AAA categories.

Guns can be land-, sea-, or air-based and can employ one or more combinations of visual, optical, electro-optical, and radar target tracking. Land-based guns larger than 57 mm are usually located in fixed or prepared sites. Guns are fabricated in different barrel configurations, usually from one to six. Medium and heavy AAA are typically single-barrel weapons that fire single rounds continuously in slow succession. Light AAA and most small arms are automatic weapons that fire a number of rounds in rapid succession from one or more barrels, either continuously or in short bursts. Figure 3.18 shows a modern mobile gun system. (http://www.fas.org/man/dod-101/sys/land/row/tridon.htm.)

Missile launch and guidance equipment. This equipment is used to launch and guide missiles to an intercept point. The equipment is located on surface-based or airborne platforms and varies in size from a single hand-held launch tube or canister to a semipermanent complex containing numerous trailers, vans, and launch units.

Table 3.6 Types of guns and their projectiles

Gun	Projectile, mm
Small arms	$\leq$20
Pistols, shoulder-fired rifles, carbines, assault rifles, submachine guns	7.62
Mounted light and heavy machine guns	7.62, 12.7, 14.5, and 20
Antiaircraft artillery	>20
Light	21–59
Medium	60–99
Heavy	$\geq$100

Fig. 3.18 40 Mk3 Tridon gun system (Reproduced with permission of Bofors Defence Sweden; http://www.boforsdefence.com/eng/products/air3_tridon.htm).

The equipment can employ both optical and radar target tracking in conjunction with special missile tracking and guidance computers.

3.4.1.3 Threat propagators. The threat propagator is the physical entity that carries the warhead from the firing platform to the target aircraft. Threat propagators can be divided into two categories: ballistic projectiles and guided missiles (Note 35). A third category of propagator has recently been developed for killing helicopters, but this one does not travel from the firing platform to the helicopter. It just sits and waits for an unsuspecting helicopter to fly by. It is the antihelicopter mine.[19] (http://www.redstone.army.mil/cic/etv/animate/copter.htm and http://www.ukdf.org.uk/online_library_fs.htm.(FS18)) The target sensors are acoustic for detection and warhead aiming and possibly infrared for fuzing of the HE warhead with its explosively formed penetrators (EFPs).

Ballistic projectiles. A ballistic projectile is an object initially propelled by an applied exterior force and continuing in motion by virtue of its own inertia, such as a bullet or artillery shell. The term projectile is generally used to represent the physical entity that contains the warhead. This propagator is usually associated with guns, such as small arms and AAA, although grenades and mortars are also ballistic projectiles that have been used against aircraft at low altitude or on the ground.

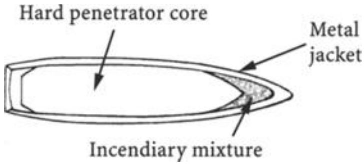


Fig. 3.19 Typical AP-I projectile.

The term bullet typically refers to projectiles 12.7 mm (0.50 cal) and smaller. Small arms projectiles include calibers 5.56 mm (0.22 cal), 7.62 mm (0.30 cal), 12.7 mm (0.50 cal), 14.5 mm, and 20 mm. Most SA projectiles are of the ball (B), armor-piercing (AP), or armor-piercing incendiary (AP-I) type, except for the 14.5-mm machine gun, which is also capable of firing a high-explosive incendiary (HE-I) and an incendiary tracer (I-T) projectile. Figure 3.19 shows a typical 7.62-mm AP-I projectile. This projectile consists of a hardened steel core with a gilding metallic jacket. An incendiary material designed to ignite upon impact with the target is located between the sharp core nose and the metallic jacket.

Light AAA generally includes diameters (or calibers) 23, 30, 37, 40, 45, and 57 mm; medium AAA includes 76 mm (3 in.) and 85 mm; and heavy AAA includes 100 mm and 130 mm (5 in.). The projectiles are usually AP or HE, and they can contain incendiary (I) material and/or a tracer (T) material that, when ignited, reveals the path of the projectile. Figure 3.20 shows a 23-mm HE-T projectile. Airborne guns or cannon typically fire 20, 23, 30, and 37 mm AP-I and HE-I projectiles, with and without a tracer.

Guided missiles. A guided missile is an aerospace vehicle, with varying guidance capabilities, that is self-propelled through space for the purpose of inflicting damage on a designated target. These propagators contain a propulsion system, a warhead section, a guidance system, and possibly one or more sensors for detecting and tracking aircraft. Movable control surfaces are deflected by commands from the guidance section to direct the missile in flight. Some missiles are dependent on off-board equipment for guidance commands, whereas others are able to guide themselves independently after launch (Note 36). Most missiles carry a high-explosive warhead. Two of the important aerodynamic parameters of missiles are the number of *g*s the missile can pull while maneuvering and the duration of propulsion. A sketch of a typical missile configuration is given in Fig. 3.21. The two types of missiles that pose a threat to airborne aircraft are the air-to-air missile and the surface-to-air missile (Note 37).

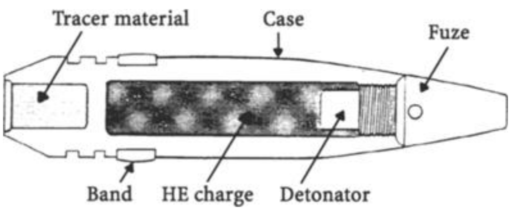


Fig. 3.20 Typical HE-T projectile.

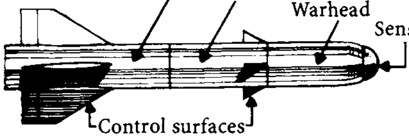


Fig. 3.21 Typical missile configuration.

Air-to-air missiles are launched from one aircraft toward another aircraft. Air-to-air missiles can employ various types of guidance techniques. However, some form of homing is the usual type of guidance used in order to minimize the missile system equipment weight in the launch platform and to lessen the maneuver restrictions on the shooter aircraft after missile launch. Weight constraints in the missile itself dictate the use of relatively small warheads.

Surface-to-air missiles are those launched from land- or sea-based platforms. The sea-based platforms are usually ships, but SUBSAMs could be launched from floating capsules deployed from completely submerged submarines or from submarines submerged to periscope depth. SAMs have varying guidance and propulsion capabilities. They can employ various, and in many cases sophisticated, ECCM schemes to enhance their effectiveness. Because weight is not as much of a problem for many of these SAMs, the missiles are often much larger than their air-to-air counterparts, and they can have larger warheads and longer ranges.

Antihelicopter mines. The antihelicopter mine is a stationary propagator. It contains an acoustic sensor and signal processors for detecting, tracking, and classifying fast-approaching helicopters and a gimbaled or pointable high-explosive warhead for the endgame. The warhead can be detonated on the ground, or it can be propelled into the air prior to detonation as the helicopter comes within range. An infrared sensor on the elevated warhead might be used for close-in aiming of the warhead at the time of detonation. The mine is small enough to be carried by hand or deployed from rockets or aircraft. (http://www.wood.army.mil/ENGRMAG/PB5984/schneck.htm.)

Go to Problems 3.4.1 to 3.4.6.

3.4.2 Types of Warheads and Their Damage Mechanisms

Learning Objective	**3.4.2**	**Describe the two types of warheads and the three types of damage mechanisms.**

3.4.2.1 Type of warheads. Another characteristic of the threat is the type of ordnance package carried by the propagator. The ordnance package consists of the warhead and possibly a fuze (Note 38). The purpose of the warhead is to provide or generate the damage mechanisms. Antiaircraft warheads in projectiles and missiles typically consist of either a solid metallic core or a HE charge surrounded by a metallic casing. A fuze is included when a HE core is employed. Solid core warheads are referred to as penetrator warheads, kinetic energy penetrators, or hittiles, and only cause damage when direct contact is made with the target. HE warheads are also referred to as chemical energy warheads (not to be confused with chemical warheads). They can cause damage when impacting the target or when detonated in the vicinity of the target. Both types of warheads can contain an incendiary material to increase the likelihood of a fire or explosion within the target aircraft. The interested reader is referred to Ref. 20 for an excellent reference on material devoted to tactical missile warheads. In particular, Refs. 21 and 22 consider the antiaircraft warhead. For a very thorough physical description of, and the mathematical and logical foundation for the design of, warheads to defeat the tactical ballistic missile, the interested reader is referred to Ref. 23. Much of the material in this reference is pertinent to aircraft targets.

3.4.2.2 Damage mechanisms. A damage mechanism is the output of the warhead that causes damage to the target. It is the physical description of the tangible instrument or measurable quantity designed to inflict damage upon the target. The three primary types of damage mechanisms associated with penetrator and HE warheads are 1) metallic penetrators and fragments, 2) incendiary materials, and 3) blast.

Most threat warheads utilize more than one damage mechanism when attempting to kill a target. For example, the damage mechanisms carried by the AP-I projectile are a metallic penetrator core and incendiary material. A proximity-fuzed surface-to-air missile can have metallic fragments, blast, and possibly incendiary materials as its primary damage mechanisms. The missile debris caused by the warhead detonation, such as the broken control surfaces, motor case, and other miscellaneous parts, are penetrator-like damage mechanisms that can make a major contribution to the lethality of the weapon. Any unspent rocket propellant on the missile is an incendiary damage mechanism that can significantly enhance the likelihood and magnitude of an onboard fire or explosion.

3.4.2.3 Types of penetrator warheads.

Learning Objective **3.4.3 Describe the three types of penetrator warheads.**

The penetrator warheads include the ball, armor-piercing, and armor-piercing incendiary projectiles. These warheads can also include a tracer material that burns along the projectile trajectory. The fiery path from the gun to the projectile is used by the gunner to improve the aim of the gun. The damage mechanisms associated with penetrator warheads are metallic penetrators and incendiary materials.

Ball-type projectiles (B). These are penetrators with relatively soft metallic cores, typically lead or mild steel, encased in a metallic jacket. They are typically used in small arms weapons against personnel and unarmored targets. The soft core flattens on impact, creating a larger hole than would normally be made by a harder substance of similar size and shape.

Table 3.7 Some AP projectile lethality factors

Projectile, mm	Core weight (grains) (Note 39)	Muzzle velocity, m/s	Intercept velocity m/s
7.62	120–170	700–900	300–500 at 1500 m
12.7	250–450	800–900	600–700 at 1500 m
14.5	400–600	≈1000	700–800 at 1500 m
23 (API-T)	≈2500	≈1000	700–800 at 1500 m

AP projectiles. The typical AP projectile is composed of a hardened steel core encased in a metallic jacket. A filler of lead or aluminum might be located at the nose or base of the projectile between the core and the jacket. The core is shaped in such a manner to give it maximum penetrability through the target. Although named an armor-piercing projectile, the AP projectile is not intended to penetrate thick armor. This type of projectile is normally associated with small arms and light AAA.

AP-I projectiles. This type of projectile is the same as the armor-piercing projectile, except that an incendiary mixture has been installed inside the metallic jacket, as shown in Fig. 3.19. The jacket is supposed to peel off upon impact with the aircraft skin or an internal component, allowing the incendiary materials to spread along the path of the projectile as it penetrates into the aircraft. The heat generated on impact can completely or partially ignite the incendiary mixture, causing a fireball that may burn for several seconds. This phenomenon is known as incendiary functioning and increases the probability of inducing a fire or explosion. These projectiles are also normally associated with small arms and light AAA.

Penetrator warhead parameters that influence warhead lethality. The parameters that influence the lethality of penetrator warheads include the weight of the penetrator core, the core material, the size and shape of the core, the projectile's muzzle velocity and its velocity at intercept, and the presence of any incendiary material in the projectile. The approximate weight, muzzle velocity, and intercept velocity at 1500 m are given in Table 3.7 for several penetrator warheads.

Go to Problems 3.4.7 to 3.4.17.

3.4.2.4 Types of HE warheads.

Learning Objective **3.4.4 Describe the five major types of HE warheads.**

An HE warhead typically consists of a metallic case around a high-explosive core. The shape of the metallic case can be circular cylindrical, convex, concave, or conical. The HE materials most often used in air target warheads are RDX and

HMX.[22] Incendiary materials that are ignited upon warhead impact or detonation also can be included in the warhead. Nearly all HE warhead types are fuzed. The fuze package includes a safety and arming device (S&A) to keep the warhead unarmed until the projectile is fired or the missile launched, the target detection device (TDD), and one or more detonators to initiate the detonation of the HE material. A booster can be used between the detonator and the high-explosive material to improve the detonation process.

There are five major types of HE warheads used against aircraft: the blast warhead, the fragmentation warhead, the discrete rod warhead, the continuous rod warhead, and the focused-energy warhead. The primary damage mechanisms carried or generated by these five HE warhead types are metallic penetrators and fragments, incendiary materials, and blast (Note 40). Each of the five warhead types is described next. This section ends with a presentation of the equations for the blast wave and the fragment initial velocity, spray angle, and velocity decay from an idealized warhead detonation and the results from experimental tests of two warhead detonations.

Blast warheads. Blast warheads consist of a high-explosive charge, such as TNT, RDX, HMX, PBX, or some combination of these materials, such as Comp B, enclosed in a relatively thin metallic case (Note 41). Because the case is relatively thin, the primary damage mechanism is the blast wave produced by the detonation of the HE charge. Although the blast warhead is relatively inexpensive, it has a relatively small lethal radius because of the rapid reduction in the blast wave overpressure with distance from the detonation point. Consequently, small blast warheads must detonate very close to, or inside, the aircraft in order to kill it.

Fragmentation warheads. Most of the current air target warheads are designed to kill the target with fragments from a contact or proximity detonation. This type of warhead, also known as a blast-fragmentation warhead, has been in existence since WWI. The metallic case around the HE core is designed to break into hundreds or thousands of high-velocity fragments upon charge detonation. Figure 3.22a contains a sequence of three still frames showing the approach and subsequent detonation of an HE warhead below an aircraft. Note the fireball and the ejection of the fragments around the warhead and in the direction of missile travel. Figure 3.22b shows a detonation above a stationary aircraft. Note the flashes from the impact of the fragments near the tail of the aircraft.

Figure 3.23 contains a photograph of the fragments ejected from the detonation of a large, stationary HE warhead. The warhead axis is horizontal in the figure. Note how the fragments appear to be concentrated in a ring-like pattern around the warhead and have separated radially as they propagate away from the detonation point as a result of the differences in initial velocity and velocity decay. Figure 3.24 is an idealized illustration of the detonation photograph in which the fragments are shown concentrated within a relatively thin (radial), narrow (azimuth) fragment spray band or zone around the detonation.

The size and shape of the fragments are determined by the type of case used. The two general types of cases are natural and controlled.

Natural fragmentation warheads: Natural fragmentation of a smooth case is random in size, with the structural configuration and material of the casing and

Fig. 3.22a Detonation of a proximity-fuzed HE warhead below a moving aircraft (courtesy of the U. S. Air Force).

Fig. 3.22b Detonation of a proximity-fuzed HE warhead above a stationary aircraft (courtesy of the U. S. Navy).

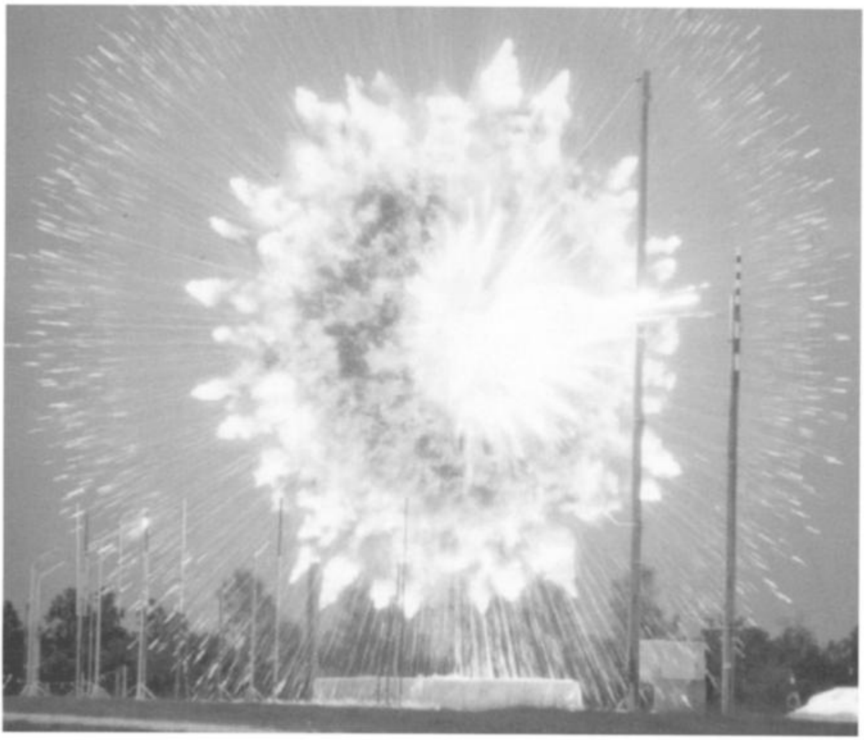


Fig. 3.23 Fragments from a stationary, horizontal HE warhead detonation (courtesy of the U. S. Air Force).

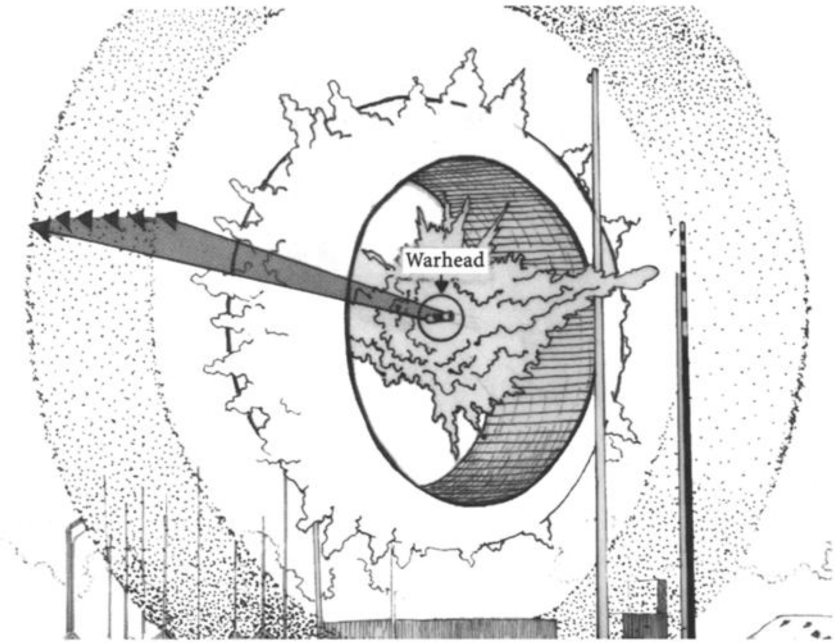


Fig. 3.24 Illustration of idealized fragment spray pattern.

the core contributing to the size variation of the fragments. An example of the fragments from a natural fragmentation case is given in Fig. 3.25. The fragment distribution for this case will usually contain a few fragments that are quite big and very destructive if they hit the target and many fragments that are too small to cause much damage even if they do hit the target. The mass distribution of the fragments from several natural fragmentation warheads is presented in Ref. 22.

Controlled fragmentation warheads: As a result of the ineffectiveness of many of the very small fragments from a natural fragmentation warhead, fragmenting cases are often designed to generate many fragments of a particular size and shape in order to optimize the effectiveness of the warhead against a particular type of target. There are two general types of controlled fragmentation cases: grooved or scored and preformed.

In the grooved or scored warhead the desired fragment dimensions and shape are obtained by cutting a groove on the inner and/or outer surface of the case. The grooves in the case cause a nonuniform stress field in the case at the time of detonation, and the case will break apart at locations of stress concentrations, such as the base of each groove. The grooves can be opposing diagonals on the inside of the case, as shown in the left-hand side of Fig. 3.26, or interior longitudinals and circumferentials. The opposing diagonal grooves result in diamond-shaped fragments, as shown in Fig. 3.27, and the orthogonal longitudinal and circumferential

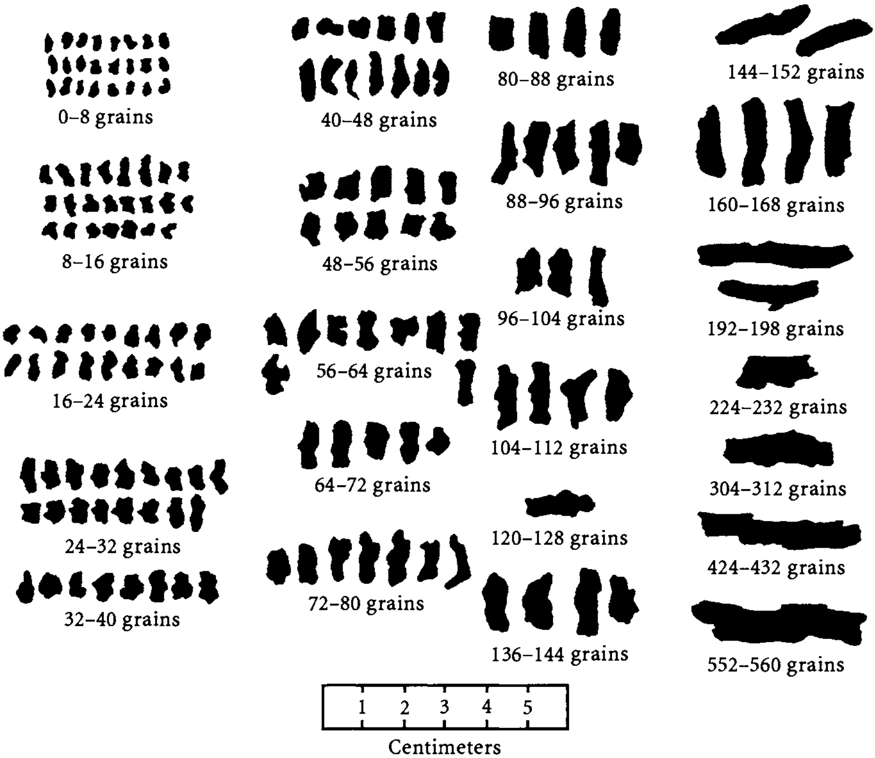


Fig. 3.25 Fragments from a natural fragmentation case (1 lb at sea level = 7000 grains; 1 ounce = 28.4 g; 1 g = 15.4 grains).

grooves yield rectangular rods. The fragments from a grooved case are known as fire-formed fragments (Note 42).

In the preformed fragmentation warhead the case is composed of one or more layers of preformed fragments, such as steel, tungsten, or titanium cubes, spheres, or right rectangular prisms, that are supported in a plastic matrix or between thin metallic shrouds. The right-hand side of Fig. 3.26 is an illustration of a preformed case with a single layer of rectangular fragments.

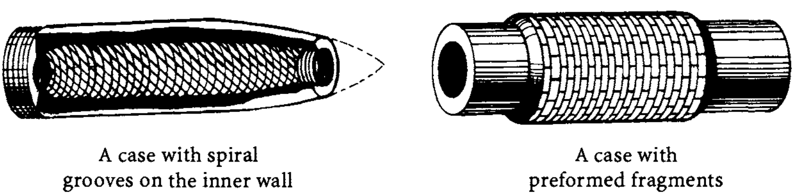


Fig. 3.26 Examples of controlled and preformed fragmentation warheads.

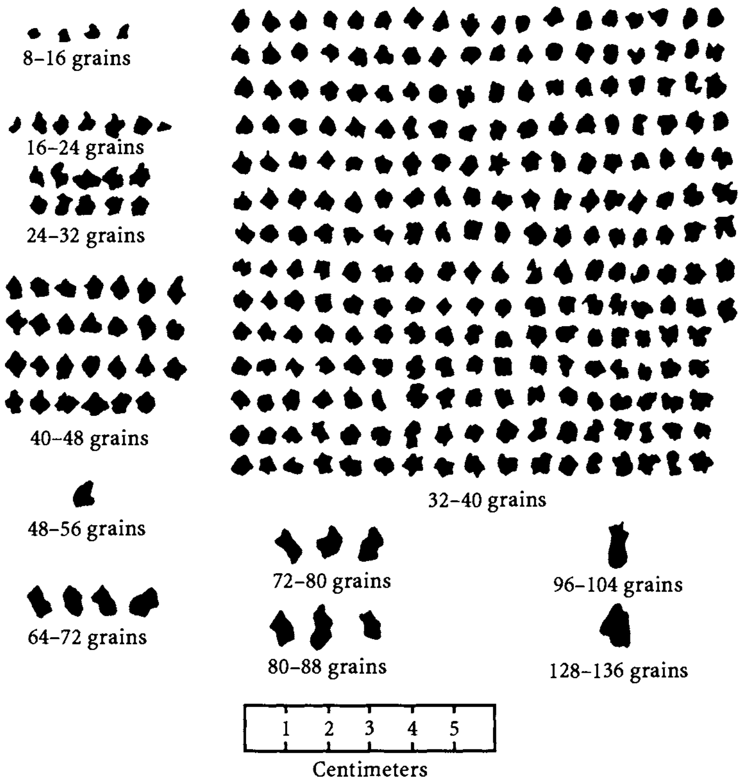


Fig. 3.27 Fragments from a controlled fragmentation case.

Aimable fragmentation warheads: In the conventional fragmentation warhead the fragment spray zone is symmetric about the missile axis. The aimable fragmentation warhead has the capability to detect the circumferential location of the target and control or aim the direction of the warhead fragments around the missile axis prior to detonation.[22] For example, suppose the target and the missile were approaching one another on displaced flight paths. If the target were detected below the missile, a detonated aimable warhead would eject more fragments downward toward the target and fewer fragments upward away from the target. In addition to increasing the number of fragments ejected toward the target, the velocity of the aimed fragments might be higher than the velocity of fragments from a symetrical detonation. The techniques for aiming the fragments include mechanical or detonative deformation of the warhead. According to Ref. 22, the aimable warhead concept has considerable potential for increasing the lethality of fragmentation warheads.

Factors that affect lethality: Some of the factors associated with the metallic case fragments that influence a fragmentation warhead's lethality are the number of fragments ejected by the charge detonation; the fragment material, weight, and shape; the initial velocity of the fragments; the spatial extent of the fragment spray zone; and the fragment velocity at target impact. The number of fragments ejected depends upon the weight of the case and the weight of each fragment. The fragment weight, shape, and material are chosen by the warhead designer to maximize lethality, considering such factors as target penetration, viscous air drag, fragment breakup, energy coupling at target impact, pyrophoric effects, and the relationship between the number of fragment hits on the target and the lethality of each hit.

Discrete rod warheads. The discrete rod warhead case, also known as a multirod or tumbling-rod warhead case, consists of a number of relatively short individual rectangular rods. The rods can be arranged in circumferential layers around the axis of the HE core, for example, eight rods form the circumference, and the layers are stacked longitudinally along the warhead axis. When the HE charge detonates, the rods are expelled away from the center of detonation in a tumbling manner. When a dual-ended detonation scheme is used, the rods initially converge on their way to the target. If the detonation is close to the target, a large number of closely spaced rods might hit the target, causing considerable damage.

In another version of the discrete rod warhead, relatively long, thin rods might be laid lengthwise or parallel to the missile axis around the circumference. Typically, the length of each rod is the same the length of the case. One or two layers of rods can be used.

Continuous rod warheads. The continuous rod warhead also consists of two layers of long rectangular rods arranged around the circumference of the case, as illustrated in Fig. 3.28a. However, in the continuous rod warhead the inner and outer rods are welded together at alternate ends so that upon detonation of the explosive core the rod bundle expands away from the blast center, creating the large

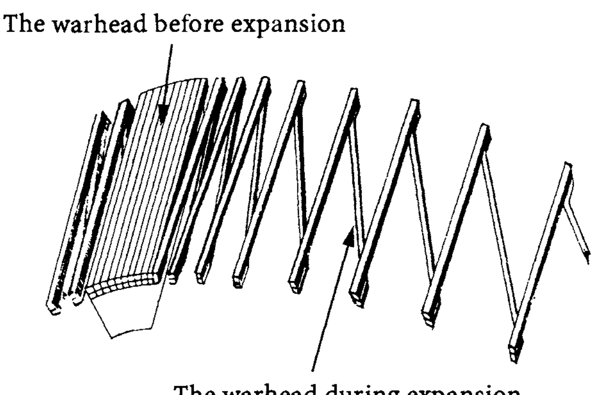


Fig. 3.28a Continuous rod warhead.

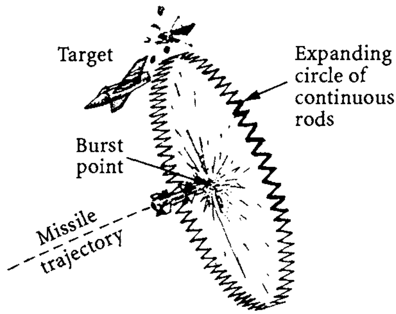


Fig. 3.28b Expanding rods.

jagged ring shown in Fig. 3.28b. The rods are the primary damage mechanism, and they have been likened to the blade of a knife that cuts deeply through target skin and structural members on contact.

Focused-energy warheads. Focused-energy warheads utilize a special geometry of the explosive charge and a soft metallic liner to focus the energy of the explosion in one or more desired directions. The explosive charge is shaped around the metallic liner such that the detonation pressure on the liner can hydrodynamically create one or more very high-velocity projectiles or jets of molten liner material. These projectiles or jets can cause much deeper target penetration than would be realized by a uniform detonation of the same mass of explosive in a fragmentation warhead. The energy of the explosive material can be focused along the warhead axis (the conical shaped charge) or in a desired array around the weapon (the multishaped charge) to increase the number of penetrators (Note 43).

Conical-shaped charge warheads: The conical-shaped charge, normally thought of as an antiarmor weapon, is part of the warhead on the Bofors RBS 70 SAM. The conical-shaped charge and the detonation of a conical-shaped charge warhead are illustrated in Figs. 3.29a and 3.29b, respectively. As shown in Fig. 3.29a, a cylindrical warhead is filled with an HE charge, except at the right end where it has been specially shaped. A solid conical prism of charge has been removed, and a soft, thin conical metallic liner, such as copper or aluminum, is inserted in

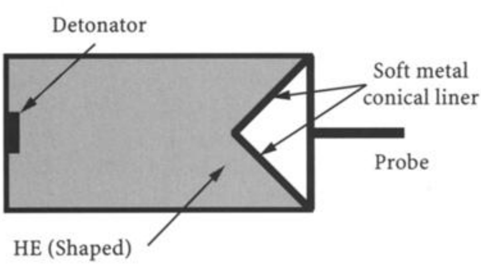


Fig. 3.29a Conical-shaped charge.

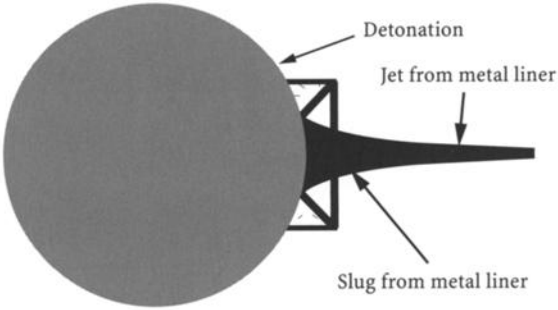


Fig. 3.29b Idealized detonation of a conical-shaped charge.

its place. A probe is attached at the front of the warhead to initiate detonation at a standoff distance from the target for increased effectiveness. When the probe strikes the target, the charge detonation takes place at the left end of the warhead, and the detonation wave proceeds through the explosive material toward the soft liner, as illustrated in Fig. 3.29b. As it passes over the apex of the conical liner, the overpressure in the wave acting on the liner is nearly hydrostatic. The liner at the apex melts and is thrust forward as a jet of molten metal by the difference between the extremely high, nearly hydrostatic detonation wave pressure on the left and the very low ambient pressure on the right. As the wave moves across the liner, the increasing size of the liner circumference is such that the overpressure cannot transform it into a thin jet, and a larger slug of molten metal emerges at the end of the jet. The velocity of the jet varies from 20,000 to 30,000 fps, depending upon the warhead design.

Multishaped charge warheads: Because the likelihood of hitting an aircraft at medium and long range with the single jet from a conical-shaped charge is remote, air target focused-energy warheads are usually multishaped (Note 44). Figure 3.30a illustrates the multishaped charge warhead with hemispherical liner inserts used on the Roland SAM and the detonation pattern from this warhead. The creation of the jets from the hemispherical liners is similar to the jet formation in the conical-shaped charge, except that the hemispherical shape of the liner prevents the formation of a thin jet and the velocity of the jet varies from 12,000 to 20,000 fps. The jet formation in a multishaped charge warhead is a very complex process, and the jets emerge with different velocities in different directions, as shown in Fig. 3.30a.

The multi-P-charge warhead is another example of the multishaped charge warhead. This warhead typically has many shallow, dish-shaped inserts, as illustrated in Fig. 3.30b. The detonation overpressure does not hydrodynamically compress the insert, but instead inverts the dish into a projectile by 'snapping' it through. This type of penetrator is referred to as an explosively formed projectile, an explosively formed penetrator, or a self-forging fragment.[22,24]

Go to Problems 3.4.18 to 3.4.29.

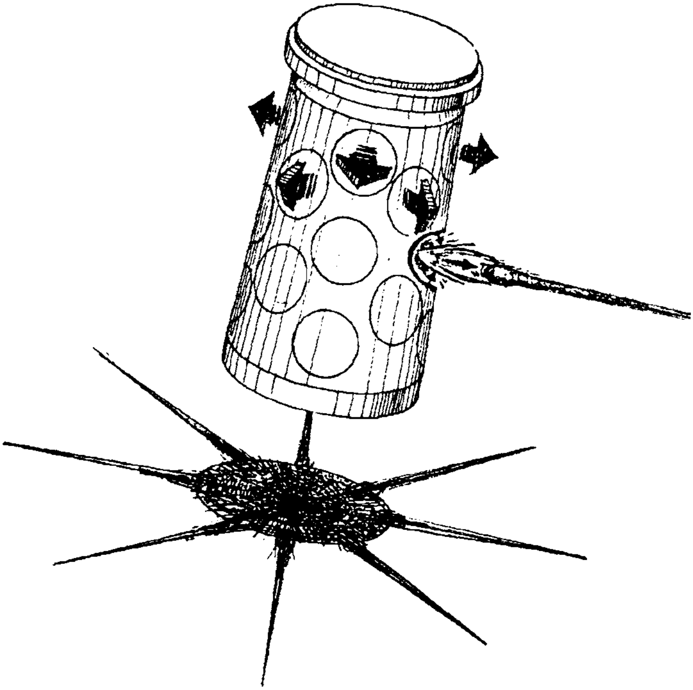


Fig. 3.30a Example of a multishaped charge warhead and detonation.

3.4.2.5 Blast and fragments from an HE warhead detonation.

Learning Objectives	**3.4.5**	**Describe the blast wave from an HE detonation, and determine the overpressure and impulse at any distance from the detonation as a function of warhead weight and detonation altitude.**
	3.4.6	**Describe the fragment spray zone from an idealized warhead detonation and an experimental warhead detonation, and predict the fragment initial velocity and spray angle.**

Blast from an idealized HE warhead detonation.

Blast wave: When a stationary, uncased, spherical HE charge detonates in air, the chemical energy of the charge is initially converted into a relatively small volume of gas at extremely high temperature and pressure known as the fireball. The spherical fireball expands supersonically. This expansion of the hot gas creates a spherical pressure wave in the surrounding air. The pressure wave is known as the shock wave, or blast wave, or air blast. The pressure of the ambient air surrounding the HE charge is P_a. The pressure in the blast wave above P_a is called the overpressure P. The peak overpressure in the wave occurs at the leading edge of the wave as it moves away from the detonation point and is denoted by P_o. The pressure ratio

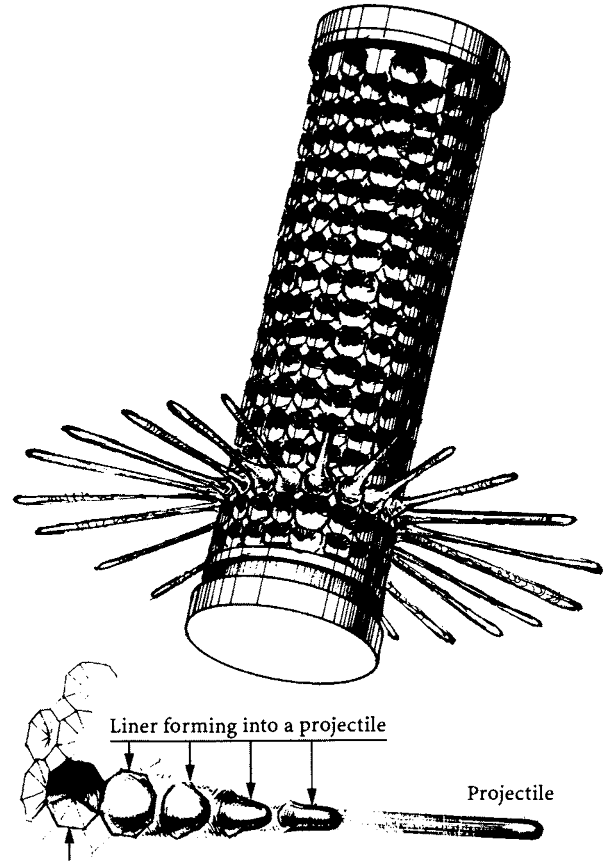
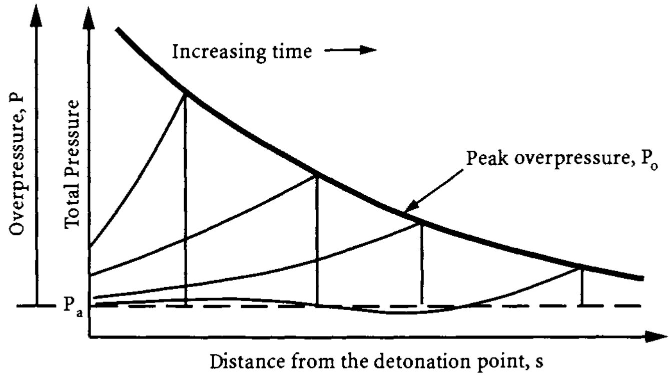


Fig. 3.30b Example of a multi-P-charge warhead.

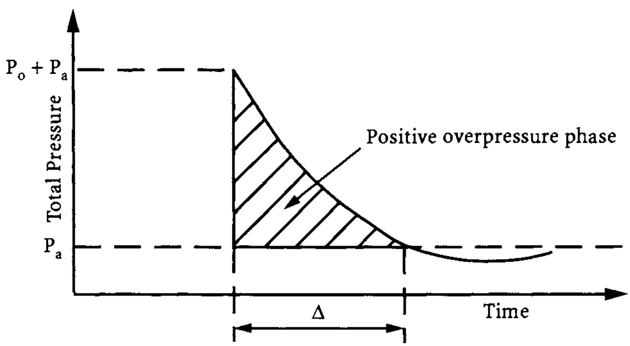
P_o/P_a is denoted by p. The front of the wave propagates away from the detonation point at a velocity U, and the air directly behind the front is in motion with a velocity u (Note 45).

The overpressure profile in the blast wave at several times after the detonation is illustrated in Fig. 3.31a as a function of distance from the detonation point s. Figure 3.31b illustrates the overpressure felt by an observer at a particular location as a function of time t.

Note in Fig. 3.31a that the peak overpressure in the wave decays as the wave moves away from the detonation point and that the overpressure in the wave at a given location becomes negative some time after the passage of the wave front. The area under the pressure-time curve during the positive overpressure phase Δ in Fig. 3.31b is the impulse per unit area of the blast I. There is also a dynamic pressure in the blast wave caused by the motion of the air, that is, a wind, behind the blast front.



(a) Overpressure in the blast wave at several instances of time



(b) Pressure at a particular distance from detonation as a function of time

Fig. 3.31 Blast wave from an HE warhead.

Blast wave parameters that affect lethality: The important parameters of the blast wave that affect lethality are the peak overpressure P_o, the duration of the positive phase Δ, the impulse per unit area associated with the positive phase duration I, and the peak dynamic pressure caused by the wind q_o. The peak overpressure P_o and the positive phase duration Δ are shown in Fig. 3.32 as a function of the distance from the detonation s for a reference explosion of one pound of TNT at sea level (SL) (Note 46).

The impulse associated with the positive overpressure phase can be approximated by

$$I \approx \int_0^{\Delta} P_o(1 - t/\Delta)e^{-(t/\Delta)}\,\mathrm{d}t \approx 0.37 P_o \Delta \tag{3.3}$$

where t is time.

Figure 3.32 shows the blast wave parameters P_o and Δ as a function of s for a reference explosion of 1 lb of TNT at sea level. To determine the values of P_o and Δ for different weights of TNT and different detonation altitudes, scaling

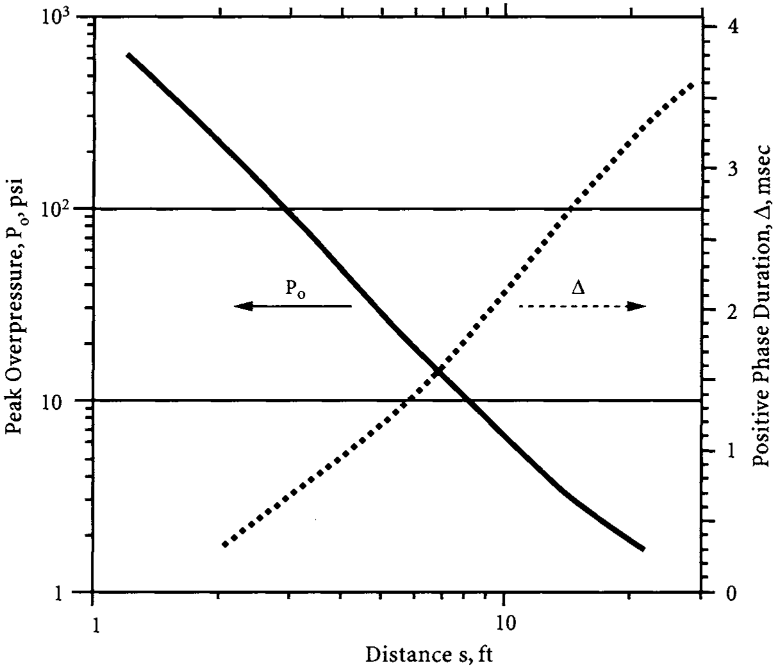


Fig. 3.32 Peak overpressure and impulse caused by 1 lb of TNT at SL. (Data for figure from Refs. 25 and 26.)

relationships must be used. The scaling relationships are based upon the pressure ratio p. The pressure ratio is defined as the ratio of the overpressure P_o to the atmospheric pressure P_a for a given weight of TNT and altitude. This ratio is the same for all combinations of altitude and weight of TNT. Thus, for W lbs of TNT at altitude H (with ambient pressure P_a and temperature T_a),

$$p = \frac{P_o(1 \text{ lb of TNT at SL})}{P_a(\text{at SL})} = \frac{P_o(W \text{ lb of TNT at alt } H)}{P_a(\text{at alt } H)} \tag{3.4}$$

P_o, s, and I at the larger weight and higher altitude are given by

$$\begin{aligned} P_o &= p P_a(\text{at alt } H) \\ s &= \alpha\beta s_{\text{ref}} \\ I &= \alpha\beta^2\gamma I_{\text{ref}} \end{aligned} \tag{3.5}$$

where s_{ref} and I_{ref} are the values of s and I obtained from Fig. 3.32 for the given value of p, and

$$\begin{aligned} \alpha &= (W \text{ lb of TNT}/1 \text{ lb of TNT})^{1/3} \\ \beta &= (P_a \text{ at SL}/P_a \text{ at alt } H)^{1/3} \\ \gamma &= (T_a \text{ at SL}/T_a \text{ at alt } H)^{1/2} \end{aligned} \tag{3.6}$$

Table 3.8 Ambient pressure, temperature, and weight density for several altitudes

Altitude, Kft	SL	5	10	15	20	25	30	35	40
P_a, psi	14.7	12.2	10.1	8.3	6.8	5.5	4.4	3.5	2.7
T_a, deg K	288	278	268	258	248	239	229	219	217
ρ_a, lb/ft^3	0.0765	0.0659	0.0565	0.0481	0.0407	0.0343	0.0286	0.0237	0.0188

Table 3.8 contains values of P_a and T_a for several altitudes based upon the International Civil Aviation Organization Standard Atmosphere. Also included in the table is the weight density of the atmosphere ρ_a, assuming a constant value of gravity.

The procedure for computing the peak overpressure is described in Example 3.2.

Go to Problems 3.4.30 to 3.4.32.

Example 3.2 Peak Overpressure for a 27-lb HE Blast Warhead at Sea Level and at 20,000 ft

A TNT warhead is detonated at SL and at 20,000 ft. Of interest here is the distance from the detonation where the peak overpressure is 10 psi.

According to Fig. 3.32, a peak overpressure of 10 psi occurs at $s_{\text{ref}} \approx 8$ ft from the detonation for the 1-lb TNT warhead at SL. At SL, $P_a = 14.7$ psi, according to Table 3.8. Thus, the overpressure ratio p at this location is

$$p = 10/14.7 = 0.68$$

according to Eq. (3.4). For the detonation of a warhead with 27 lb of HE at SL, the same overpressure ratio occurs at

$$s = (27)^{1/3}(1)^{1/3}8 \text{ ft} = 24 \text{ ft}$$

according to Eqs. (3.5) and (3.6). The overpressure at 24 ft caused by the detonation of 27 lb of TNT is 10 psi—the same as the overpressure for the 1-lb warhead at 8 ft because the atmospheric pressure is the same.

When the 27 lb of TNT detonate at 20,000-ft altitude where $P_a = 6.8$ psi, the overpressure ratio when P_o is 10 psi is

$$p = 10/6.8 = 1.47$$

according to Eq. (3.4). At SL this corresponds to

$$P_o = 1.47 \cdot 14.7 \text{ psi} = 21.6 \text{ psi}$$

according to Eq. (3.5). From Fig. 3.32, the distance from the detonation point for this overpressure is approximately

$$s = 5.5 \text{ ft}$$

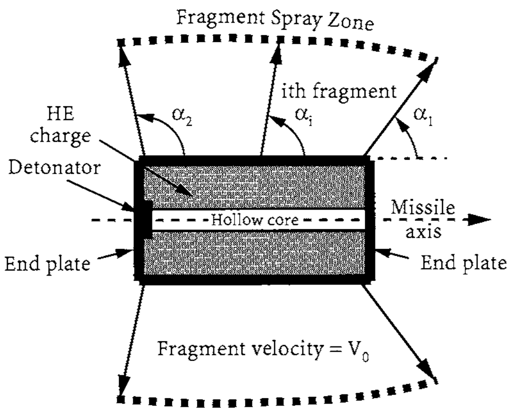
The corresponding distance where P_o is 10 psi because of a 27-lb TNT warhead detonation at 20,000 ft is

$$s = (27)^{1/3}(14.7/6.8)^{1/3}5.5 \approx 21 \text{ ft}$$

according to Eqs. (3.5) and (3.6).

Fragments from an idealized HE fragmentation warhead detonation. Figure 3.33 is a close-up illustration of an idealized static detonation of a circular cylindrical fragmentation warhead of length L and outer diameter D. The thickness of the case is h, and each case fragment is assumed to be identical. There are end plates at both ends of the warhead, and the detonator is located at the base end. A hollow core is located at the center of the warhead to allow other parts of the missile to pass through. If the fragments are preformed, they can be placed upon a relatively thin, internal metallic shell and covered with a thin layer of epoxy material to hold them in place.

Fragment initial velocity and spray angle for a static detonation: In the idealized static detonation shown in Fig. 3.33, each fragment is located within the radially thin fragment spray zone and has the same mass m_f and initial velocity V_0. The fragment spray angle, measured with respect to the missile axis, of the leading



Case length = L, Case outer diameter = D, Case thickness = h

Fig. 3.33 Idealized static detonation of a circular cylindrical HE warhead.

fragment in the zone is α_1, and the spray angle of the trailing fragment is α_2. The spray angles are influenced by the shape of the case and the location of the detonator(s). When the warhead is not cylindrical or consists of longitudinal zones of different fragment masses, the fragment spray is divided into polar zones, and each fragment within a zone is assumed to have the same mass and initial velocity.

Wide-angle diverging spray zones are used when the miss distance of the propagator is relatively large in an attempt to achieve at least several hits on the distant target in the same manner as an inaccurate shooter would use a shotgun when hunting birds. Wide-angle spray zones can be achieved using convex cases. Narrow-angle and converging (initially) spray zones are used on accurate missiles in order to achieve many closely spaced hits on the nearby target. The closely spaced hits have cumulative and synergistic effects that can result in more damage to the target than the same number of hits that are widely spaced. Narrow-angle and converging spray zones can be achieved using circular cylindrical cases and two detonators.

The initial fragment velocity as a result of the static detonation of the HE material can be estimated using the Gurney formula.[27] Consider the circular cylindrical case of length L, diameter D, and thickness h shown in Fig. 3.33. The mass of the metallic case and the high explosive is M and C, respectively. For a relatively long, slender case where the end effects can be neglected, the detonation velocity of each fragment in the case is approximated by

$$V_0 = \sqrt{2E}\left(\frac{C/M}{1 + 0.5\,C/M}\right)^{1/2} \tag{3.7}$$

where $(2E)^{1/2}$ is the Gurney constant for the type of explosive used. For many warheads $0.5 < C/M < 1.5$. Note that V_0 is independent of the individual fragment size (Note 47).

Equation (3.7) was derived for the case where $D \ll L$. For many warheads $1 < L/D < 3$. Consequently, corrections to Eq. (3.7) when $D \approx L$ have been developed. In general, they reduce V_0. For example, the reduction in V_0 for a case with $D = L$ is approximately 20%.

Typical values of the Gurney constant for TNT, RDX, and HMX are given in Table 3.9a. Also given in Table 3.9a are the weight density and the velocity of the detonation wave in the explosive V_D. Table 3.9b gives typical weight densities and sonic stress wave velocities of steel, tungsten, and aluminum cases (Note 48).

Table 3.9a Properties of some high explosives[25]

High explosive	Weight density or mass density, lb/in.^{3} or g/cm^3	Detonation velocity V_D, ft/s	Gurney constant $(2E)^{1/2}$, ft/s
TNT	0.0574 or 1.59	21,800	7,600
RDX	0.0600 or 1.66	26,800	9,300
HMX	0.0664 or 1.84	29,900	10,230

Table 3.9b Properties of some metallic cases[25]

Metallic case	Weight density or mass density, lb/in.^{3} or g/cm^3	Sonic velocity, ft/s
Steel	0.283 or 7.83	15,100
Tungsten	0.694 or 19.2	13,300
Aluminum	0.100 or 2.77	17,500

The spray angle of each fragment depends upon the shape of the case and the location of each fragment with respect to the detonator(s). The spray angle of the ith fragment α_i from a general warhead case with a detonator at the base end of the missile, as shown in Fig. 3.33, can be estimated using Shapiro's equation[25]

$$\alpha_i = 90\ \text{deg} - \tan^{-1}[(V_0 \cos \mu_i)/(2V_D)] \tag{3.8}$$

where $\mu_i = \pi/2 - \mu_{\text{ni}} + \mu_{\text{fi}}$. The angle μ_{ni} is the angle between the warhead axis and the outward normal to the case at the ith fragment (+ccw), and μ_{fi} is the angle between the warhead axis and the line from the detonator to the ith fragment (+ccw). For the circular cylindrical warhead shown in Fig. 3.33,

$$\begin{aligned} \mu_{\text{ni}} &= \pi/2 && \text{for all fragments} \\ \cos \mu_1 &= [1 + 0.25(D/l)^2]^{-1/2} && \text{for the ith fragment} \end{aligned}$$

where l is the axial location of the fragment. If the fragment is assumed to be far from the base end detonator, $l >> D$, $\cos \mu_i \approx 1$, and if $V_0/2V_D$ is small, Shapiro's equation for the ith fragment spray angle from the circular cylindrical case simplifies to Taylor's equation for the spray angle α for all fragments

$$\alpha = 90\ \text{deg} \pm \sin^{-1}(V_0/2V_D) \tag{3.9}$$

The $-$ sign in Eq. (3.9) is used when the detonator is located at the base end (Note 49).

The procedure for computing the fragment initial velocity and spray angle is described in Example 3.3.

Example 3.3 Fragments from an HE Warhead Detonation

Assume the dimensions of a circular cylindrical fragmentation warhead on a SAM are $L = 15$ in., $D = 7$ in., and $h = 0.4$ in.

The case is made of steel, and the high explosive is TNT. According to Tables 3.9a and 3.9b, the weight density of steel and TNT is 0.283 and 0.0574 lb/in.^{3}, respectively. The single detonator is located at the rear end of the warhead. Of interest are the number of fragments in the warhead case and the initial velocity and spray angle of each fragment.

The nominal circumference of the middle surface of the circular cylindrical case is $\pi(D-h)$ or $\pi(7-0.4) = 20.7$ in., and hence the case volume is approximately (20.7 in.) $\cdot$ (0.4 in.) $\cdot$ (15 in.) = 124.4 in.^{3}

Thus,

$$\text{steel case weight} = (0.283\,\text{lbs/in.}^3) \cdot (124.4\,\text{in.}^3) = 35.2\,\text{lb}$$

Assume the entire volume encompassed by the metallic case is filled with TNT. Thus, the volume of TNT is $\pi(3.5\text{ in.} - 0.4\text{ in.})^2 \cdot (15\text{ in.}) = 452.9\text{ in.}^3$ Hence,

$$\text{TNT weight} = (0.0574\,\text{lb/in.}^3) \cdot (452.9\,\text{in.}^3) = 26.0\,\text{lb}$$

Thus,

$$\text{total warhead weight} = 35.2\,\text{lb steel case} + 26\,\text{lb TNT} = 61.2\,\text{lb}$$

and

$$C/M = (26.0\,\text{lb})/(35.2\,\text{lb}) = 0.737$$

The metallic case consists of a single layer of preformed fragments. The warhead designer has selected 200 grains or 0.0286 lb (200 grains/7000 grains per lb) as the fragment weight that will result in the maximum lethality of the warhead. Thus, the number of fragments in the warhead case F is

$$F = (35.2\,\text{lb})/(0.0286\,\text{lb per fragment}) = 1231\text{ fragments}$$

The fragment thickness is 0.4 in., and thus the area of each fragment A_F is given by

$$A_F = (0.0286\,\text{lb})/(0.283\,\text{lb/in.}^3) \cdot (0.4\,\text{in.}) = 0.252\,\text{in.}^2$$

Thus, the size of each 200-grain preformed fragment is selected as $0.5 \times 0.5 \times 0.4$ in^3.

The Gurney constant $(2E)^{1/2}$ for TNT is 7600 ft/s according to Table 3.9a. Thus, the detonation velocity of each 200-grain fragment is

$$V_0 = 7{,}600\left(\frac{0.737}{1 + 0.5 \times 0.737}\right)^{1/2} = 5{,}577\,\text{ft/s}$$

according to Eq. (3.7).

The Shapiro spray angles $\alpha_1(l = 15 \text{ in.})$, $\alpha_{\text{center}}(l = 7.5 \text{ in.})$, and $\alpha_2(l = 0 \text{ in.})$ are

$$\alpha_1 = 90\,\text{deg} - \tan^{-1}\left(\frac{5577}{2 \cdot 21800\sqrt{1 + 0.25(7/15)^2}}\right) = 90\,\text{deg} - 7.1\,\text{deg}$$
$$= 82.9\,\text{deg}$$
$$\alpha_{\text{center}} = 90\,\text{deg} - \tan^{-1}\left(\frac{5577}{2 \cdot 21800\sqrt{1 + 0.25(7/7.5)^2}}\right) = 90\,\text{deg} - 6.6\,\text{deg}$$
$$= 83.4\,\text{deg}$$
$$\alpha_2 = 90\,\text{deg}$$

according to Eq. (3.8). Note the small difference between α_{center} and α_1. The Taylor spray angle for each fragment is

$$\alpha = 90\,\text{deg} - \sin^{-1}[(5577\,\text{ft/s})/(2 \cdot 21800\,\text{ft/s})] = 90\,\text{deg} - 7.3\,\text{deg} = 82.7\,\text{deg}$$

according to Eq. (3.9).

Comparison of theoretical fragment initial velocities and spray angles with experimental results: Some of the results from several circular cylindrical warhead arena tests described in Ref. 28 are presented in Figs. 3.34 and 3.35. The figures show the fragment velocity and spray angle for two detonator location schemes. The explosive was Octol (25% TNT and 75% HMX by weight), and the fragments were preformed 60-grain steel cubes laid directly on the bare explosive. The results shown in the two figures are from a warhead with $L = 9.9$ in., $D = 5.5$ ($L/D = 1.8$), and a $C/M = 0.94$. The warhead in Fig. 3.34 had a single detonator located at the left end, and the warhead in Fig. 3.35 had a detonator at both ends. The results from two tests are shown in Fig. 3.34, and one set of test results is shown in Fig. 3.35. The theoretical values for V_0 and the Taylor angle are indicated in the figures. Also shown are the fragment velocity and spray-angle results from an elastic-plastic model that includes the effects of gas leakage between the fragments.[28]

Note in the single-ended detonation scheme shown in Fig. 3.34 that the velocity and spray angle are not uniform along the case and that the Gurney velocity is an upper bound (Note 50). On the other hand, in Fig. 3.35 the center fragments exceed the Gurney velocity when detonators are used at each end. Also note the difference in spray angles for the two detonator schemes. The single detonator at the rear end causes most of the fragments to project forward at an angle less than 90 deg. Only a few of the fragments at the rear end are projected backward at an angle greater than 90 deg. Nevertheless, the spray zone diverges. An idealized diverging spray zone for the single-ended detonation is shown in the left diagram in Fig 3.36, where the fragments are assumed to be uniformly distributed between the two angles α_1 and α_2. A single detonator located at the center of the warhead would create a symmetric diverging spray zone similar to that shown in Fig. 3.36.

On the other hand, the simultaneous dual-end detonation scheme shown in Fig. 3.35 causes a Taylor spray angle less than 90 deg for the rear-end fragments

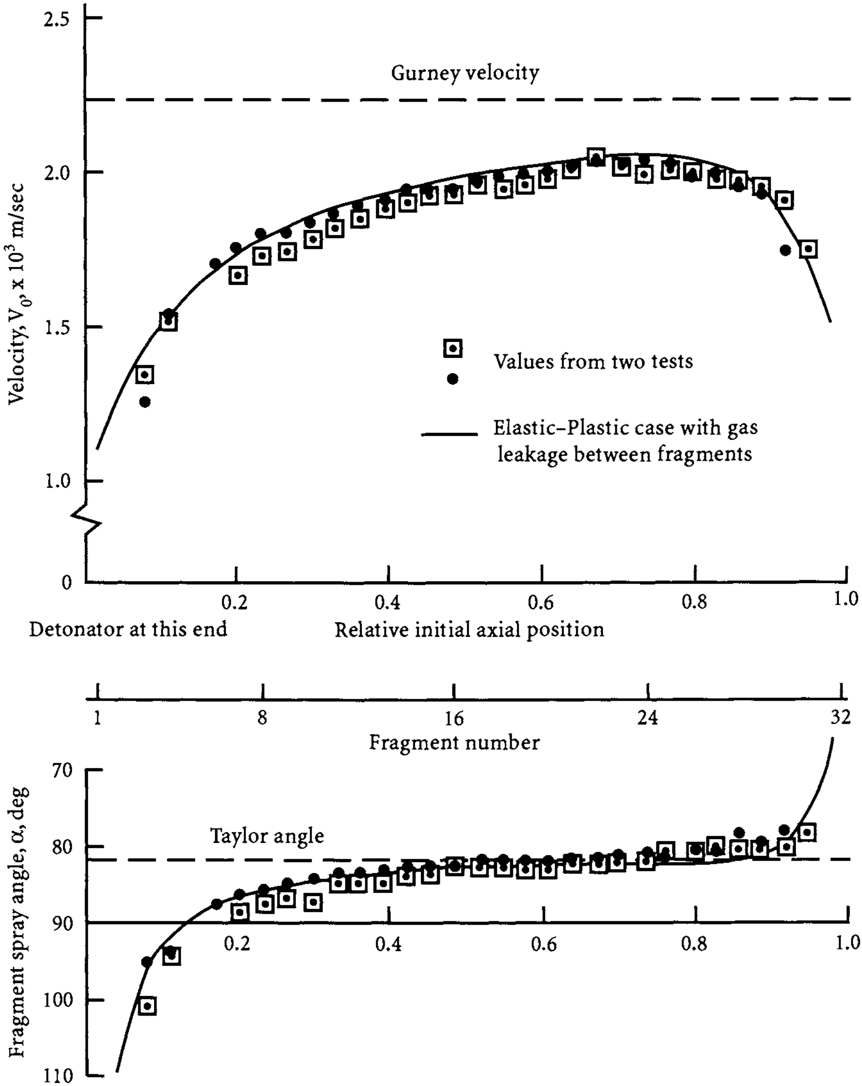


Fig. 3.34 Fragment velocity V_0 and spray angle α for a left-end detonator $L/D = 1.8$ (experimental data from Ref. 28).

and greater than 90 deg for the nose-end fragments. This converging spray pattern focuses the fragments into a central converging spray zone, as idealized in the right diagram in Fig. 3.36. Thus, a warhead with a detonator at both ends is sometimes referred to as a focused blast fragmentation warhead.

Comparison of the theoretical fragment weights and spray density with experimental results: In the idealized warhead detonation illustrated in Fig. 3.33, all fragments have the same weight, and the fragment spray density (the number of

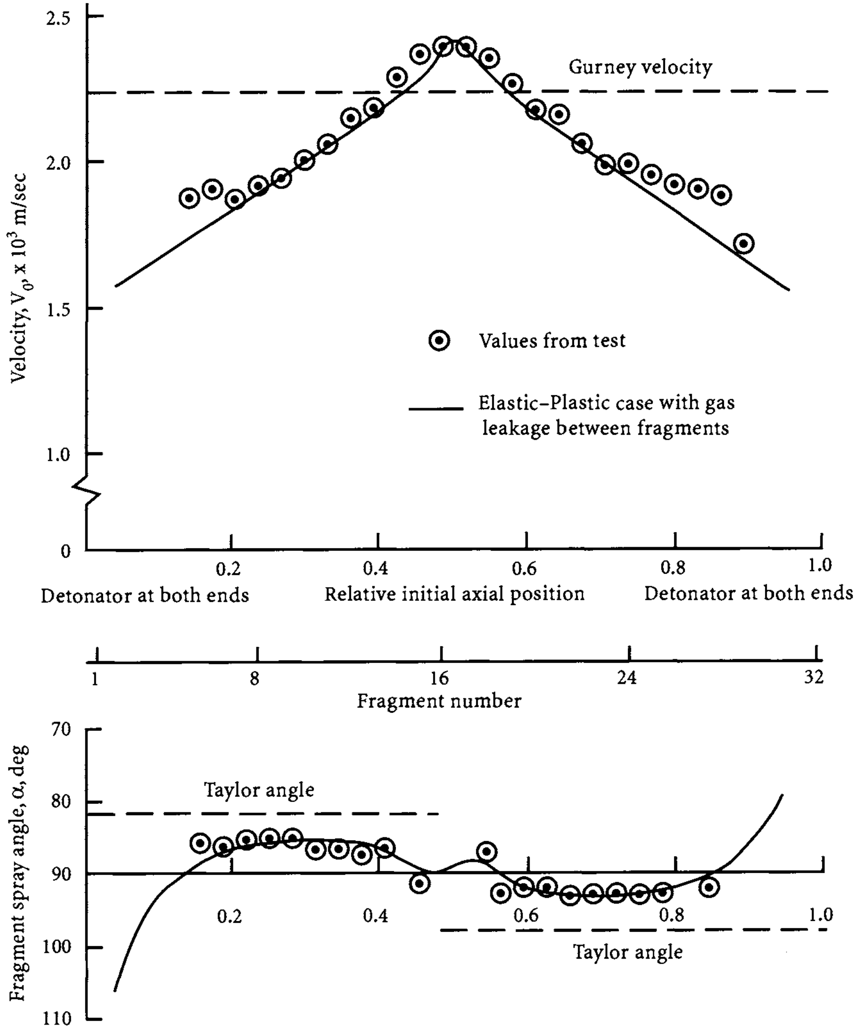


Fig. 3.35 Fragment velocity V_0 and spray angle α for a dual-ended detonation $L/D = 1.8$ (experimental data from Ref. 28).

fragments per unit area of the fragment spray zone) is uniform over the entire spray zone. In any real warhead detonation the fragments emanating from the detonation will have different weights, and the fragment spray density will not be uniform. To account for the nonuniformity of weight and spray density, the spatial distribution of fragments over the fragment spray zone can be described in terms of the polar angle. The polar angle is the angle between the missile axis and the fragment path, assuming that all fragments emanate spherically from a central point in the warhead. Thus, at typical detonation distances the polar angle of each fragment is

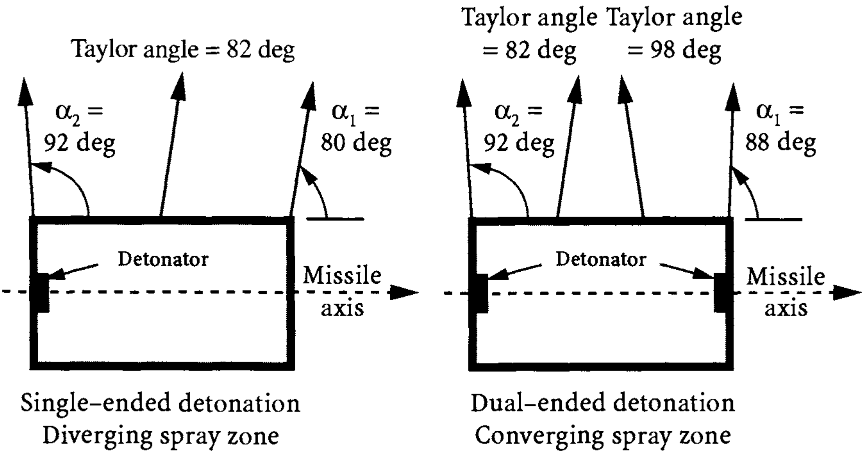


Fig. 3.36 Fragment spray zone for single-ended and simultaneous dual-end detonations.

essentially equal to the spray angle. Figure 3.37 is an illustration of the polar-angle distribution of the fragments from a single-ended detonation. The distribution is given in terms of the number of fragments emanating from the detonation within a polar-angle increment or polar zone. Five-degree increments are typically used. Thus, according to Fig. 3.37, approximately 980 fragments from the single-ended detonation shown in Fig. 3.33 have a spray angle between 80 and 85 deg. Also note in Fig. 3.37 that the fragments within each polar zone have been divided into several weight categories. According to the figure, approximately 700 of the 980 fragments in the 80–85-deg polar zone weigh between 55 and 65 grains.

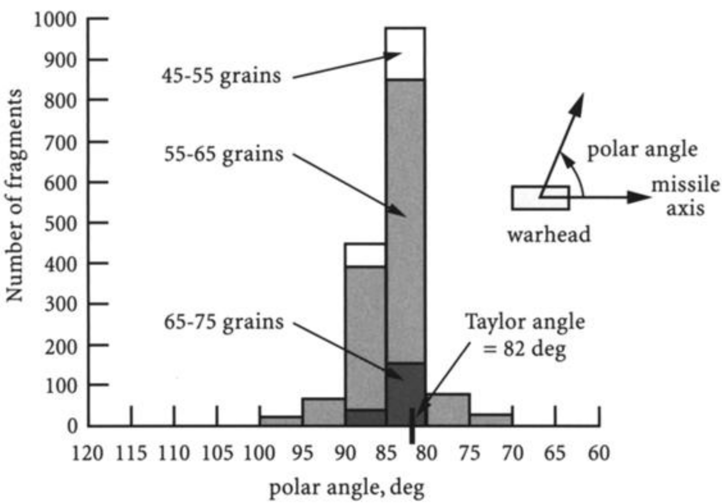


Fig. 3.37 Fragment distribution by polar angle.

Specification of fragment spray distributions in terms of polar-angle increments is desirable from two points of view. First, the fragments collected from an experimental warhead detonation in a warhead arena test, such as that shown in Fig. 3.23, can easily be grouped into polar-angle increments, and second, the fragment spray density within each polar zone is easily determined from the polar distribution of the fragments.

Go to Problems 3.4.33 to 3.4.38.

3.4.2.6 Fuzing.

Learning	**3.4.7**	**Describe the types of fuzes and their components.**
Objectives	**3.4.8**	**Describe how the active optical proximity fuze works.**

High-explosive warheads contain a fuze that detonates the warhead upon impact or in the vicinity of the target. The fuze package consists of a safety and arming device to keep the weapon safe until it is deployed and clear of friendly forces; a detonator, and possibly a booster, to initiate the HE charge detonation; a device that senses the presence of a target, known as the target detection device; and a logic circuit that initiates detonation at the proper time. Fuzing or charge detonation can be based upon the time required for the propagator to reach the vicinity of the target, or contact with the target, or in proximity to the target.

Time fuzing. Time-fuzed warheads are set to detonate at a predetermined elapsed time after launch. The predetermined elapsed time can be variable or fixed. The warhead's altitude or distance from the gun at the time of detonation can be set by selecting the appropriate variable time delay just before firing or as the projectile leaves the barrel. Medium and heavy AAA projectiles often employ time fuzing. High-explosive warheads with proximity fuzes carry time fuzes designed to self-destruct after a fixed time has elapsed to prevent a live HE warhead from returning to Earth.

Contact fuzing. Nearly all HE warheads have a contact or point detonating (PD) fuze. Contact fuzes, also known as impact fuzes, can detonate the charge either instantaneously upon target contact (a superquick or instantaneous fuze) or after a short delay (a delay fuze), depending upon whether the detonation is desired on the external surface of the target or within the target. High-explosive projectiles used by light AAA usually contain a contact fuze with a delay because the small amount of explosive used is most effective when the warhead is detonated inside the aircraft.

Proximity fuzing. Proximity fuzing, sometimes referred to as VT fuzing (a code name used during World War II to imply variable time fuzing), is used in all but the smallest missile warheads, and some medium and heavy AAA projectiles use proximity fuzing. In the category of small arms and light AAA projectiles, the 40-mm shell is the one most likely to contain a proximity fuze. With proximity

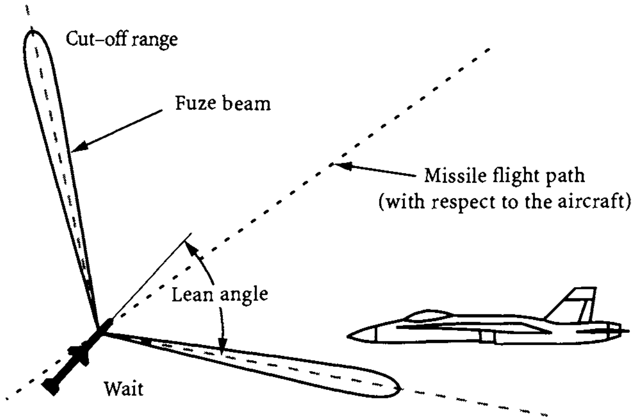


Fig. 3.38a Beam from an active optical TDD.

fuzing the warhead is detonated when the possibility of a direct hit is remote and the target is in the warhead fragment spray zone. The TDD can be active, semiactive, or passive. The active TDD can radiate an electromagnetic signal, such as a radio or radar wave (VT-RF) or an optical (laser) signal (active optical), and 'listen' for any returns from a nearby target. Or it can be a capacitance fuze that creates an electrostatic field around the propagator and senses perturbations in the field as a result of the presence of a target. A semiactive TDD detects electromagnetic energy reflected from a target that is being illuminated by another source. A passive TDD can detect electromagnetic energy radiated by the aircraft itself, such as infrared radiation (VT-IR). Some missile warheads can be command detonated by radio signals from the missile controller when the nonterminal tracking and guidance equipment displays indicate sufficient proximity to the target.

Figure 3.38a is an idealized illustration of the transmit/receive beam from an active optical target detector (AOTD). The beam is essentially symmetric around the missile axis and has a maximum cutoff range. Targets outside of this cutoff range are not detected, and consequently the warhead will not fuze before an intercept has occurred. The angle of the beam with respect to the missile axis is referred to as the fuze lean angle. The appropriate magnitude of this angle for maximum lethality depends upon the fragment spray angles α_1 and α_2 and the detonation conditions. As long as the target remains inside of the 'basket' created by the beam, as shown in Fig. 3.38a, target detection by the AOTD and subsequent warhead detonation will not occur. When a part of the target passes through the beam, as shown in Fig. 3.38b, an echo is received by the AOTD, and the warhead is detonated after either a fixed time delay or a time delay calculated using the missile and target velocities, attitudes, and separation distance at the time of detection.

The latest improvement in proximity fuzing technology is the aimable fuze on the aimable warhead. The TDD in the aimable fuze has the ability to sense the direction of the target with respect to the circumference of the warhead. When the warhead case is mechanically or explosively deformed in the proper direction

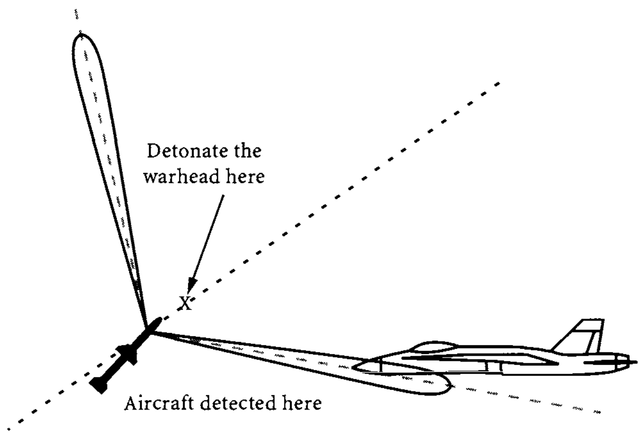


Fig. 3.38b Detection of the target by the TDD.

prior to detonation, the HE detonation can cause an increase in either the fragment velocity or the number of fragments ejected in the direction of the target, or both.

Go to Problems 3.4.39 to 3.4.43.

3.4.2.7 Several examples of SAM HE warheads.

Learning Objective **3.4.9 List some of the weights and diameters of current missile warheads.**

Figure 3.39 presents the diameter and weight for several surface-to-air missile blast-fragmentation warheads. The data were taken from Ref. 11. The missiles are listed by the name of the weapon system. All of the warheads listed can be detonated by a proximity fuze, except the Rapier and the SA-7, which only have a contact fuze (as of 1989).

Table 3.10 presents the warhead detonation parameters for three generic warheads.

Go to Problem 3.4.44.

3.5 Damage Processes and Terminal Effects

Damage mechanisms are the physical output of the warhead that cause damage to the target. There are three primary types of damage mechanisms associated with the warheads described in Sec. 3.4: metallic penetrators and fragments, incendiary particles, and air blast. A damage process refers to the interaction between a damage mechanism and the aircraft's components. The four damage processes considered here include impact and penetration through solids, impact and penetration

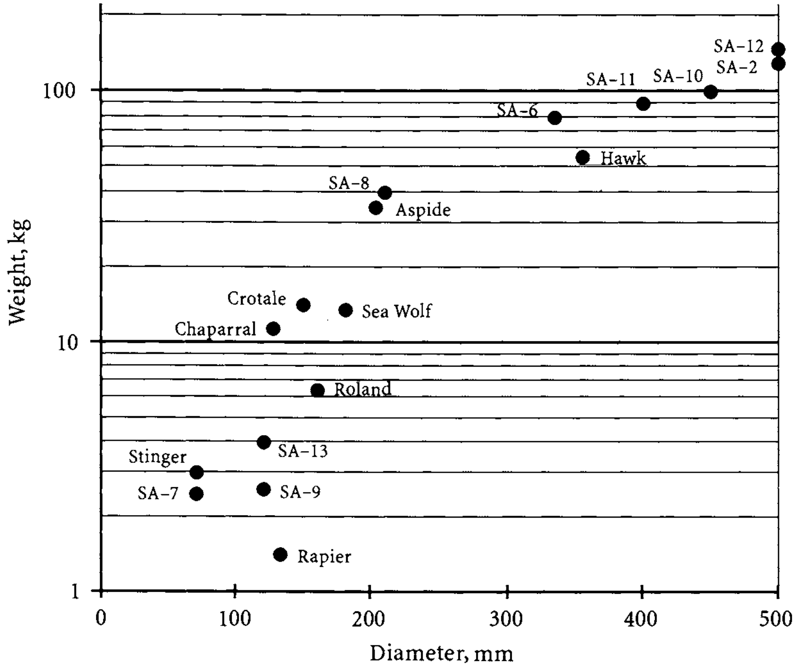


Fig. 3.39 Warhead diameter and weight on several surface-to-air guided missiles. (Data for figure from Brassey's Defence Publishers; Ref. 11.)

through fluids (hydrodynamic or hydraulic ram), combustion, and blast loading. The terminal or threat effects refer to the types and magnitudes of response or reactions of the various materials, components, and personnel in the aircraft when subjected to the damage processes, that is, the terminal effects describe the damage state of the aircraft.

To properly assess an aircraft's vulnerability and to make the design decisions required to reduce the vulnerability of the aircraft, the survivability engineer must be aware not only of the particular types of weapons that constitute the threat, but also of the nature of the damage processes and the terminal effects that are caused by the damage mechanisms generated by those weapons. Consequently, the following material describes in some detail the four major damage processes

Table 3.10 Parameters for three generic warheads

Parameter	Small warhead	Medium warhead	Large warhead
α_1, deg	75	80	85
α_2, deg	105	100	95
Fragment weight, grains	40	100	80
Number of fragments	2600	3200	8300
Fragment velocity, ft/s	5000	6000	9000

and the terminal effects that are associated with the three primary types of damage mechanisms.

3.5.1 Damage Mechanism—Metallic Penetrators and Fragments

A metallic penetrator can be the core of an AP projectile, a discrete rod, a continuous rod, a shaped charge jet, or chunks of missile debris from an HE detonation. Fragments are relatively small parts of a metallic case ejected by the detonation of the high-explosive core. Fragments that break up upon impact with the target and any pieces from the impacted target itself are referred to as secondary fragments. The primary damage processes associated with metallic penetrators and fragments are impact and penetration through solids and the internal pressure loading on fluid containing vessels as a result of impact and penetration through liquids, known as hydrodynamic or hydraulic ram (Note 51).

3.5.1.1 Damage process—impact and penetration through solids (Note 52).

Learning Objective	**3.5.1**	**Describe the impact and penetration damage processes for solids caused by metallic penetrators and fragments, including target spallation and the types of penetration.**

The impact on, and possible penetration through, a target by a penetrator is referred to as ballistic impact, and the phenomena associated with the impact and penetration are a part of the field referred to as terminal ballistics or penetration mechanics (Note 53). The two primary damage processes associated with ballistic impact on solids are impact and penetration. A phenomenon associated with impact that creates additional metallic fragments from the impacted target is known as spallation.

Impact and spallation. Impact refers to the situation where the penetrator hits but does not completely penetrate, perforate, or pierce the target skin or plate. The impact can partially 'bury' the penetrator in the impacted skin or plate, or the penetrator can ricochet off of the front face of the plate. The impact could also cause the penetrator to break up into several smaller pieces that ricochet in different directions. If the penetrator is relatively blunt, a high-velocity impact could result in the ejection of material from the back face of the impacted plate. This material is known as spall, and the ejection process is referred to as spallation. The impact damage process and spallation are described in the following paragraphs.

Consider the blunt penetrator or impactor striking the plate shown in Fig. 3.40. The impact on the plate generates an outward-traveling 'hemispherical' compression stress wave in the impacted plate and a plane compression wave in the impacting penetrator, as illustrated in Fig. 3.40, picture (1). The compression stress is maximum at the front edge of each wave. The compression wave propagates to the back surface of the plate, where it is reflected as a tension stress wave that travels backward toward the impacted plate surface, as illustrated in Fig. 3.40, picture (2).

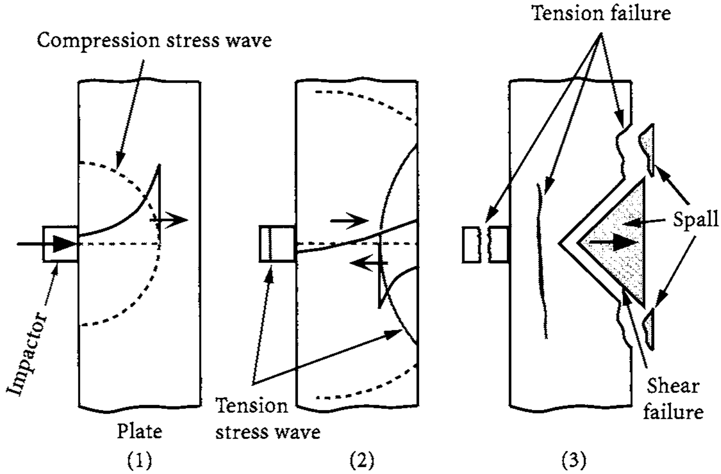


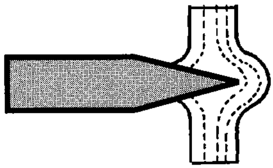
Fig. 3.40 Spallation.

The net effect of the overlapping backward-traveling tension wave and forward-traveling compression wave could be a relatively large tension stress within the plate. This tension stress can cause the plate material to fail in tension, resulting in either internal cracks parallel to the surface of the plate. Or it can result in the ejection of a layer of plate material from the back face at high velocity. Or it can cause the plate material to fail in diagonal shear, resulting in the high-velocity ejection of a relatively large conically shaped chunk of metal from the back of the plate (Note 54). These three types of impact damage are illustrated in Fig. 3.40, picture (3). In essence, the momentum of the impactor is transferred to the plate in the form of plate vibration and to the back face spall in the form of an ejection velocity.

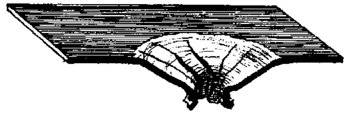
A similar compression stress wave and reflected tension wave are created in the impactor itself by the impact. The resulting tension stress within the impactor can reach a value sufficient to cause it to shatter, as illustrated in Fig. 3.40, pictures (2) and (3).

Any spall ejected from the back face of the impacted plate is capable of damaging components inside the aircraft, such as the aircrew in the cockpit. Furthermore, spall tends to disperse randomly from the point of impact and therefore can cause damage over a greater area than does a single penetrating round. Thus, spall must be considered as another type of metallic penetrator or fragment that can kill components (Note 55). Similar statements can be made for the shattered penetrator if the impact event occurs inside the aircraft.

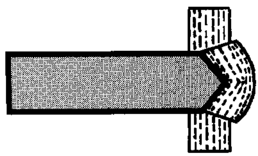
Penetration. The penetration damage process refers to the situation where the penetrator completely penetrates, perforates, or pierces the impacted plate. Penetration is dependent upon the impact conditions that include the penetrator material, impact velocity, weight, and shape; the angles of penetrator impact obliquity, and yaw; and the plate material and thickness (Note 56). Penetration can damage both the penetrator and the penetrated plate. Considering the penetration effects on the penetrator, hard, sharp penetrators impacting relatively soft plates suffer little



Piercing by a sharp, hard penetrator. The target material fails at the tip of the penetrator.



Petalling damage by a sharp, hard penetrator



Plugging by a blunt, hard penetrator. The target material in front of the penetrator (the plug) is pushed out by the penetrator.

Fig. 3.41 Penetration by piercing, with petalling, and by plugging (adapted from Ref. 29).

impact and penetration deformation, whereas relatively soft penetrators can suffer considerable deformation or erosion when penetrating harder plates. Penetrators can also break up as they impact and penetrate through the plate.

Types of plate penetration: When the penetrator is sharp and hard, the damage to the plate is confined to an area no more than two or three penetrator diameters. Sharp, hard penetrators penetrate by pushing the plate material aside. The penetrator must tear the plate during penetration, and a crown-shaped protrusion surrounded by radial cracks is formed, as shown in Fig. 3.41. This type of penetration is known as piercing, and the formation of the protrusion in the plate is referred to as petalling. Blunt, hard penetrators impacting relatively soft plates can produce a relatively clean hole by shearing out a portion of the plate known as a plug, as illustrated in Fig. 3.41. This type of penetration is termed plugging or punching. For relatively soft penetrators the penetrator generally flattens on impact and penetration and creates larger holes than the initial penetrator. The thickness of the impacted plate relative to the penetrator diameter has a significant effect on type of plate failure that occurs. For relatively slow impact velocities on relatively thin plates, the plate might deform into a relatively large dish-like shape as the permanent deformations extend beyond the local impact area.

Go to Problems 3.5.1 to 3.5.6.

Learning Objective 3.5.2 Define the V_{50} Protection Ballistic Limit and determine its value experimentally.

Impact velocity for complete penetration and the ballistic limit: A penetrator is about to impact a plate at a particular velocity, and the question arises, will the plate be completely penetrated? The first question to be answered is: what is meant by the

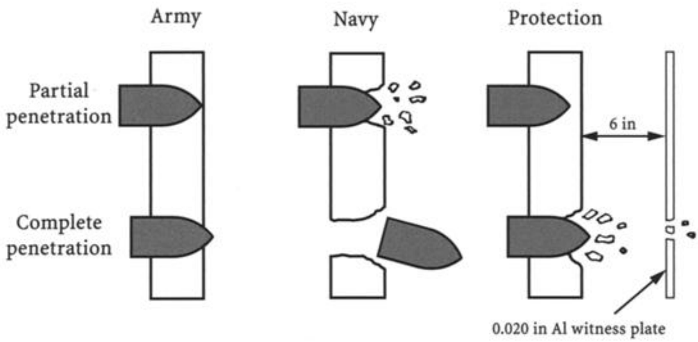


Fig. 3.42 Definitions of penetration.

term 'completely penetrated'? There are three definitions of complete penetration through target plates illustrated in Fig. 3.42. The Army definition, indicated in the diagram on the left side of the figure, requires the penetrator to pierce the rear surface of the plate. The Navy definition, in the center, requires the penetrator to pass completely through the plate. The Protection definition, indicated in the right diagram in Fig. 3.42, is the one most often used. There, complete penetration occurs when light can be seen through one or more holes in a 0.020-in. 2024-T3 aluminum alloy witness plate located 6 in. behind the target plate. The holes can be caused by either the impactor or any debris from the back face of the impacted plate.

The second question to be answered is: what is the penetrator velocity required for the complete penetrate of a plate? Is there a specific impact velocity below which the plate is not penetrated and above which it is penetrated? If so, let that particular velocity be defined as the ballistic limit. Thus, a penetrator that impacts a plate at a velocity at, or less than, the ballistic limit will not penetrate the plate, and a penetrator impact velocity above the ballistic limit will penetrate the plate. However, the actual penetration phenomenon is not so simple. In the real world, when a specific penetrator hits a given target plate at a particular impact velocity and angles of obliquity and yaw, the occurrence of complete penetration is a random outcome; it might occur, or it might not occur. Thus, associated with each impact velocity V is a probability of complete penetration, as illustrated by the solid curve labeled 'actual' in Fig. 3.43.

According to the data presented in Fig. 3.43, at relatively low impact velocities, where $V \leq V_0$, no hits penetrate the plate; hence, the probability of penetration is zero for these impact velocities. At relatively high velocities, where $V \geq V_{100}$, all hits penetrate; hence, their probability of penetration is unity. At the intermediate velocities the probability of penetration lies between zero and unity, as illustrated by the solid curve in Fig. 3.43. Associated with the probability of penetration of magnitude x is the V_x. For example, when a penetrator impacts a plate at the plate's V_{50}, the penetrator has a 0.5 probability of actually penetrating the plate. In most vulnerability studies any impact at a velocity at or above the V_{50} is assumed to completely penetrate the plate, and for impact velocities below the V_{50} the assumption is made that complete penetration does not occur. Thus, the smooth

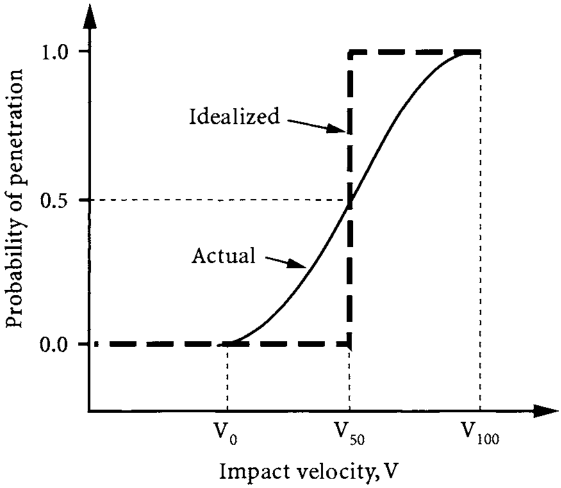


Fig. 3.43 Probability of penetration vs impact velocity.

curve relating the probability of penetration to the impact velocity shown in Fig. 3.43 is approximated by the dotted-line step function that passes through the V_{50} velocity, as illustrated in Fig. 3.43, and the V_{50} velocity is known as the V_{50} Ballistic Limit. When the Protection definition of complete penetration is used, the associated V_{50} is known as the V_{50} Protection Ballistic Limit (PBL).

The V_{50} PBL is a function of many parameters associated with the penetrator, the impacted plate, and the impact conditions. As a consequence of the many parameters, most experimental programs are designed to determine the V_{50} PBL as a function of the obliquity angle θ for a particular combination of penetrator and target plate. The experimental procedure to be used to determine the V_{50} as a function of θ is described in Ref. 30. According to Ref. 30,

> The V_{50} PBL may be defined as the average of an equal number of highest partial penetration velocities and the lowest complete penetration velocities, which occur within a specified velocity spread. The normal up-and-down firing procedure is used. A 0.020 inch (0.51 mm) thick 2024 T3 sheet of aluminum is placed 6-1/2 inch (165.1 mm) behind and parallel to the target to witness complete penetrations. Normally at least two partial and two complete penetration velocities are used to compute the PBL. Four, six, and ten-round ballistic limits are frequently used. The maximum allowable velocity span is dependent on the armor material and test conditions. Maximum velocity spans of 60, 90, 100, and 125 feet per second (ft/s) (18, 27, 30, and 38 m/s) are frequently used.

The highest partial penetration velocities are shots that, in effect, did not penetrate the plate. The up-and-down firing procedure referred to in Ref. 30 is based upon a bisection algorithm that assumes a normal probability distribution about the V_{50} within a narrow zone of mixed penetration results. The procedure is described in Ref. 31.

Example 3.4 illustrates the numerical procedure for determining the V_{50} PBL (Note 57).

Example 3.4 V_{50} Protection Ballistic Limit

Suppose a 100-grain steel cube is fired at a plate of 7075 aluminum alloy at an angle of obliquity of 20 deg off of the normal to the plate. This experiment is repeated (using a new plate) 10 times. Each shot has a different impact velocity. The outcomes of the 10 shots are given here: for velocity in feet/second—2300, 2310, 2320, 2330, 2340, 2350, 2360, 2370, 2380, 2390; and for penetration—no, no, yes, no, yes, no, yes, yes, no, yes.

Six velocities are used to determine the V_{50}. Thus, the highest three no penetration and the lowest three yes penetration lead to

$$\begin{aligned} V_{50}(\theta &= 20\,\text{deg}) \\ &= [2380(\text{no}) + 2350(\text{no}) + 2330(\text{no}) + 2320(\text{yes}) + 2340(\text{yes}) \\ &\quad +2360(\text{yes})]/6 = 2347\,\text{fps} \end{aligned}$$

Go to Problems 3.5.7 to 3.5.9.

Learning Objective 3.5.3 Describe the conditions that affect a penetrator's residual velocity, weight, and direction after penetration.

Penetrator's residual velocity, weight, and direction. Consider a penetrator of weight W that impacts the skin of an aircraft at the obliquity angle θ and the yaw angle ϕ with the velocity V. If the shape of the penetrator is sharp and the obliquity and yaw angles are small, the impact is said to be a sharp attack. Otherwise the impact is a blunt attack. If $V < V_{50}$ for the impact conditions, the penetrator is assumed to ricochet off the impacted plate in one or more pieces at a reduced velocity and in a different direction. If $V \geq V_{50}$, penetration is assumed to occur. After penetration the penetrator will have a reduced or residual velocity V_r and possibly a new or residual weight W_r and possibly a new direction of travel, represented by a residual obliquity θ_r. An equation for the residual velocity has been derived based upon an energy and momentum balance before penetration and after penetration. According to Ref. 32, the residual velocity can be given in the form

$$V_r = \frac{\sqrt{V^2 - V_{50}^2}}{(1 + w/W_r)} \tag{3.10}$$

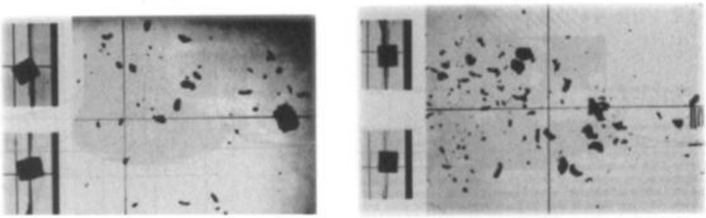
where w is the total weight removed or driven from the target plate by plugging or spallation (Note 58).

The direction of travel of the penetrator after penetration is affected by the structural arrangement in the vicinity of the impacted skin, by the angle of impact obliquity and by the ratio of the impact velocity V to the V_{50}. The change in direction typically reduces the original obliquity angle at impact, and the magnitude of the change is increased as the velocity ratio decreases and the obliquity angle increases. Thus, impacts on flat plates at a relatively high-velocity ratio and low angle of obliquity and yaw result in a relatively small change in direction of 10 deg or less. On the other hand, impacts at velocity ratios less than two and at large obliquity and yaw angles can result in a change of direction as large as the original obliquity angle, resulting in the penetrator traveling in a direction approximately normal to the impacted plate surface after penetration.

After the penetrator penetrates the aircraft's outer skin, a component beneath the skin in the (new) direction of travel will be subsequently hit by the (reduced velocity and mass) penetrator. If the residual velocity after penetration through the outer skin is above the V_{50} for the impacted component plate beneath the outer skin, penetration through that component plate is assumed to occur, and the velocity, and possibly the mass, of the impactor is again reduced according to Eq. (3.10), where V is the V_r after the first penetration. Again, the possibility exists that the direction of travel may change as a result of the second impact and penetration. A similar situation exists for any subsequent hits on components in the direction of penetrator travel. Eventually, the penetrator either exits the aircraft, or ricochets off of a plate and comes to rest somewhere inside the aircraft, or is buried inside a component.

The situation after penetration is complicated by the fact that any spall or plugs from the impacted plates behave as penetrators and can cause damage to subsequently impacted plates. Furthermore, the original impactor can break up or shatter into several smaller pieces during penetration, and if a gun projectile has a metallic jacket it, too, becomes a penetrator after being stripped away from the projectile core. Finally, the direction of travel of these secondary penetrators can be random.

Two examples of the penetration effects on a penetrator and the penetrated plate are provided by the flash radiographs shown in Fig. 3.44. In both examples a 0.375-in. cubic fragment, traveling at 5000 ft/s and 0-deg obliquity from left to right, impacts two, separated 0.063-in. steel plates. The radiographs show the



Corner on impact – little fragment shatter after impact

Side on impact – considerable fragment shatter after impact

Fig. 3.44 Cubic fragment and plate debris after impact of two plates.[32] (Reprinted with permission.)

fragment and plate debris after the penetration of both plates. In the left picture in Fig. 3.44, the fragment impacts the first plate corner on in a sharp attack. In the right picture the fragment impacts the first plate face on in a blunt attack. Note that the blunt impact at this velocity causes the fragment to shatter. Lower impact velocities face on might not result in fragment shatter into many small pieces.

Go to Problems 3.5.10 to 3.5.14.

Learning Objective 3.5.4 Determine the PBL V_{50}, and the penetrator/fragment residual velocity, weight, and direction after penetration using penetration equations.

Penetration equations. The term penetration equations refers to equations that predict the outcome of each of the impact and penetration events that can occur for particular combinations of penetrator and plate. The major events for the impact and penetration process for projectiles and fragments are shown in Fig. 3.45 (Ref. 29).

Several sets of penetration equations have been developed experimentally for the V_{50} and the residual velocity, weight, and direction of projectiles and fragments impacting the various materials found in aircraft. Two such sets are the equations contained in the 1985 JTCG/ME Penetration Equations Handbook[29] and the 1961 THOR equations presented in Ref. 33. These equations are in the form of regression equations. Each parameter in a regression equation consists of a combination of one or more of the primary variables raised to an empirically derived power.

The primary variables in the equations for projectiles are material, shape, total weight W, core weight W_c, and core diameter d. The primary variables in the equations for plates are material, weight density ρ, and thickness h. The primary variables in the equations for fragments are material; weight density ρ; weight W_f; length l; width w; breadth d; impact area A_f; and $A_f = C_f\, wd$, where $C_f =$ 0.354, 0.785, 1.50 for a diamond, sphere, cube. The primary variables in the impact conditions are impact velocity V, angle of obliquity θ, and yaw angle ϕ. The

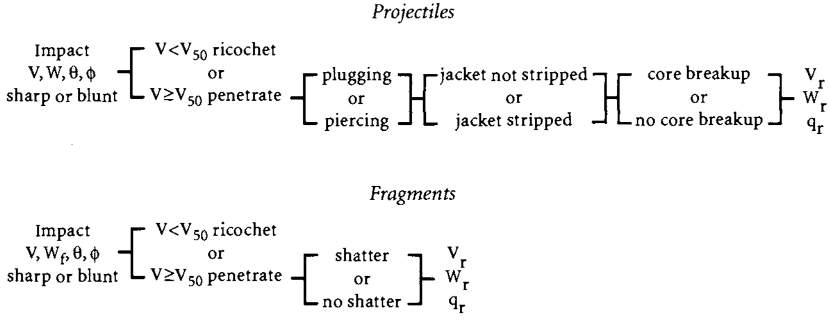


Fig. 3.45 Flow of penetration logic for projectiles and fragments (Adapted from Ref. 29).

Table 3.11 THOR coefficients for Eqs. (3.11–3.13) for aluminum alloy 2024-T-3

Coef	c	α	β	γ	λ
V_{50}	6.185	0.903	−0.941	1.098	——
V_r	7.047	1.029	−1.072	1.251	−0.139
W_r	−6.663	0.227	0.694	−0.361	1.901

equations are valid only for the range of parameter values used in the experiments. A third set of penetration equations is contained in the FATEPEN model.

JTCG/ME penetration equations: Equations are given in Ref. 29 for the V_{50}, V_r, and θ_r of thin plates impacted by sharp, steel core projectiles, with jacket stripped, at small yaw angles, and by blunt, mild steel fragments. The equations for core breakup, fragment shatter, and residual weight are also found in Ref. 29.

THOR penetration equations: From Ref. 33 the ballistic limit, taken here as the V_{50}, and the residual velocity V_r, and weight W_r, for general fragments can be given in the form (Note 59)

$$V_{50}\,(\text{ft/s}) = 10^c[h(\text{in.})\;A_f(\text{in.}^2)]^\alpha W_f(\text{grains})^\beta(\sec\theta)^\gamma \tag{3.11}$$

$$V_r\,(\text{ft/s}) = V(\text{ft/s}) - 10^c[h(\text{in.})\;A_f(\text{in.}^2)]^\alpha W_f(\text{grains})^\beta(\sec\theta)^\gamma V^\lambda \tag{3.12}$$

$$W_r\,(\text{grains}) = W_f\,(\text{grains}) - 10^c[h(\text{in.})A_f(\text{in.}^2)]^\alpha W_f(\text{grains})^\beta(\sec\theta)^\gamma V^\lambda \tag{3.13}$$

The values of the exponential coefficients c, α, β, γ, and λ in Eqs. (3.11–3.13) are given in Ref. 33 for several aircraft materials. Table 3.11 contains the values for the aluminum alloy 2024 T-3. These values were determined using fragment weights between 5 to 240 grains, an impact velocity between 1,200 and 11,000 ft/s, a target thickness between 0.02 and 2.00 in., and an angle of obliquity between 0 and 80 deg.

Example 3.5 illustrates the procedure for computing the residual velocity and mass of a fragment that penetrates an aluminum thin plate.

Example 3.5 Fragment Ballistic Limit, Residual Velocity, and Residual Mass

Suppose a 200-grain steel fragment with presented area of 0.25 in.^{2} impacts an aircraft plate made of 0.08 in. of 2024 T-3 aluminum alloy at an angle of obliquity of 20 deg and a velocity of 5000 fps. The V_{50} is

$$\begin{aligned} V_{50} &= 10^{6.185}\cdot(0.08\,\text{in.}\cdot 0.25\,\text{in.}^2)^{0.903}\cdot(200\,\text{grains})^{-0.941}\cdot[\sec(20\,\text{deg})]^{1.098} \\ &= 328\,\text{ft/s} \end{aligned}$$

according to Eq. (3.11) and Table 3.11. The residual velocity V_r is

$$\begin{aligned} V_r &= 5000\,\text{ft/s} - 10^{7.047}\cdot(0.08\,\text{in.}\cdot 0.25\,\text{in.}^2)^{1.029}\cdot(200\,\text{grains})^{-1.072} \\ &\quad\times[\sec(20\,\text{deg})]^{1.251}\cdot(5000\,\text{fps})^{-0.139} = 5000\,\text{ft/s} - 225\,\text{ft/s} = 4775\,\text{ft/s} \end{aligned}$$

according to Eq. (3.12) and Table 3.11. The residual weight W_r is

$$W_r = 200\,\text{grains} - 10^{-6.663} \cdot (0.08\,\text{in.} \cdot 0.25\,\text{in.}^2)^{0.227} \cdot (200\,\text{grains})^{0.694} \times [\sec(20\,\text{deg})]^{-0.361} \cdot (5000\,\text{fps})^{1.901} = 163\,\text{grains}$$

according to Eq. (3.13) and Table 3.11.

FATEPEN equations: The Fast Air Target Encounter Penetration Model (FATEPEN) is a set of fast running algorithms that simulates the penetration of and damage to spaced target structures by compact and noncompact warhead fragments and long rods at speeds up to 5 km/s. The model predicts penetrator mass loss, velocity loss, trajectory change, and tumbling throughout a target. The mass loss model includes an impact fracture model that, depending on impact conditions, transforms an incident intact warhead fragment into an expanding, multiparticle debris cloud that FATEPEN then tracks through the remaining target structure. FATEPEN also predicts multiparticle loading and damage to plate structures. The penetration algorithms are comprised of deterministic, analytical/empirical engineering models. The FATEPEN model is based as much as possible on fundamental principles of mechanics together with assumptions regarding the principal loading and response mechanisms involved. The latter derive directly from experimental observation. Empirical elements have been introduced either to obtain better agreement with available test data or to describe phenomena not readily amenable to first principle analytical modeling. The primary application of the code has been target vulnerability and weapon lethality assessments involving air targets and lightly armored surface targets. FATEPEN has been transitioned to use by all three services and is used as a submodel in a number of simulations. The point of contact for FATEPEN is Applied Research Associates, Inc., Rocky Mountain Division, 303-795-8106. (Data are available online at http://www.ara.com/fatepen.htm.)

Go to Problem 3.5.15.

Learning Objective **3.5.5 Determine the effects of multiple hits by penetrators or fragments.**

Multiple hits. The phenomena of impact, spallation, and penetration just described apply to the scenario where a single penetrator or fragment hits a target plate. When the threat is a rapid firing gun, the aircraft might receive several hits. When the threat is an HE warhead, the aircraft can receive many hits. If several penetrators or fragments hit a plate at locations that are relatively far apart and at times that are relatively different, each of the hits can be considered as an individual, independent event, that is, the outcome of each hit is unaffected by the outcomes of all of the other hits. When several hits occur within a local area, but at different times, the effects of each hit can be additive, and the final outcome of the

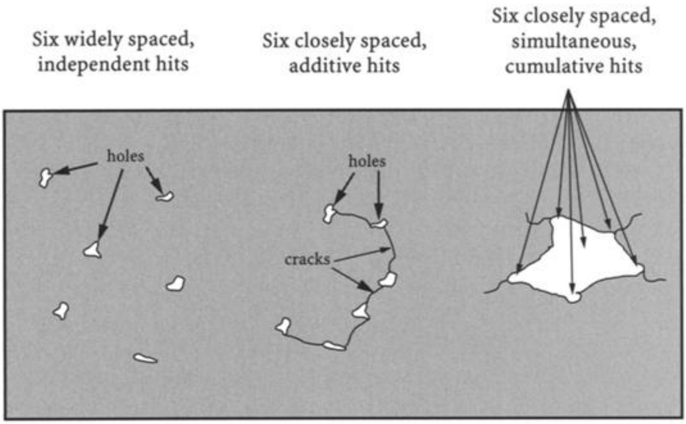


Fig. 3.46 Multiple-hit terminal effects.

hits is different because of the localized damage.[22] For example, suppose the total area removed from a plate by several closely spaced hits is equal to the sum of the areas removed by each of the individual penetrators. Because the area removed is localized, the plate may fail. If the individual hits were widely separated, the plate may not fail.

The situation where many fragments hit the plate nearly simultaneously within a local area requires special attention. Each of the impacting fragments creates a stress wave that emanates from the impact point. When the impact points are relatively close together, the stress waves overlap. The damage caused by the multiple overlapping stress waves can be much more severe than the damage caused by the individual, widely separated fragment hits considered alone, i.e., the damage caused by each of the closely spaced fragments is dependent upon the effects of the other fragment hits. Cracking between impact points might occur, and large areas of plate between several fragment hits might be removed. This situation is referred to as a cumulative or synergistic effect.[22]

For example, suppose six fragments, each with a presented area of 0.2 in.^{2}, simultaneously hit a target plate at widely separated locations with a velocity larger than the V_{50}, as illustrated on the left-hand side of the plate of Fig. 3.46. Each of the six hits would remove essentially 0.2 in.^{2} of target plate, for a total area removal of $6 \cdot 0.2$ in.^{2} $= 1.2$ in.^{2} If these same six fragments hit the plate at the locations indicated at the center of the plate in Fig. 3.46 at different times, cracking between the penetration holes could occur as an additive effect. If the six fragments hit the plate simultaneously in a relatively small area, as illustrated on the right-hand side of the plate in Fig. 3.46, the entire area of plate within the perimeter of the six hits could be removed as a result of cracking between the individual impact locations caused by the overlapping impact-caused stress waves.

Go to Problems 3.5.16 to 3.5.17.

Learning Objective	**3.5.6**	**Describe the terminal effects associated with impact and penetration through solids.**

Terminal effects. The terminal effects of impact and penetration depend upon the penetrator, the component that is penetrated, and the number of penetrations. In the case of structural members (e.g., spars, ribs, skin, and longerons), penetration can lead to major cracking, loss of material, and a subsequent loss of load-carrying ability. Aerodynamic surfaces (e.g., ailerons and rudders) can fail to perform their aerodynamic function after penetration. Mechanical components (e.g., hydraulic actuators, control rods, and helicopter tail rotor drive shafts and hanger bearings) can crack, jam, or sever when penetrated. Penetrated gear boxes and transmissions can jam because of gear damage or lose their lubrication, causing the box to overheat and seize up. Penetrated engine components (e.g., combustor case, turbine blade, and fuel valve) can lead to catastrophic engine failure, fuel leakage, and engine fire. Penetration through avionics components (e.g., computers and radar equipment) can cause a loss of signal or function and possibly a fire or explosion as a result of any electrical arcing. When penetrated, crew members tend to lose their ability to function, and penetration through the explosives or propellants in any bombs or missiles carried by the aircraft can result in a fire or explosion.

Go to Problem 3.5.18.

3.5.1.2 Damage process—penetration through liquids (hydrodynamic or hydraulic ram).

Learning Objectives	**3.5.7**	**Describe the hydrodynamic ram damage process for liquids caused by penetrating metallic penetrators and fragments.**
	3.5.8	**Describe the terminal effects associated with hydrodynamic ram.**

When a penetrator impacts and enters a compartment or vessel containing a fluid, a damage process called hydrodynamic or hydraulic ram is generated. Hydrodynamic ram refers to the internal fluid pressure that acts on the walls of the compartment and is caused by the impact and penetration of the penetrator through the fluid. It can be divided into three phases: the early shock phase, the later drag phase, and the final cavity phase, as illustrated in Fig. 3.47.

Phases of hydrodynamic ram. The shock phase is initiated when the penetrator impacts and penetrates the wall of the container or tank. As the energy of the impact and initial penetration is transferred to the fluid, a strong hemispherical shock wave centered at the point of impact is formed in the fluid, in a manner similar to the early spallation phenomenon in metals. This creates an impulsive load on the inside of the entry wall in the vicinity of the entry hole that can cause the entry wall to crack and petal away from the fluid in the opposite direction of the penetrator path. In the drag phase the penetrator travels through the fluid. It might tumble if it is oblong, and its energy is transformed into kinetic energy of fluid motion as the penetrator is slowed by viscous drag. An outwardly propagating

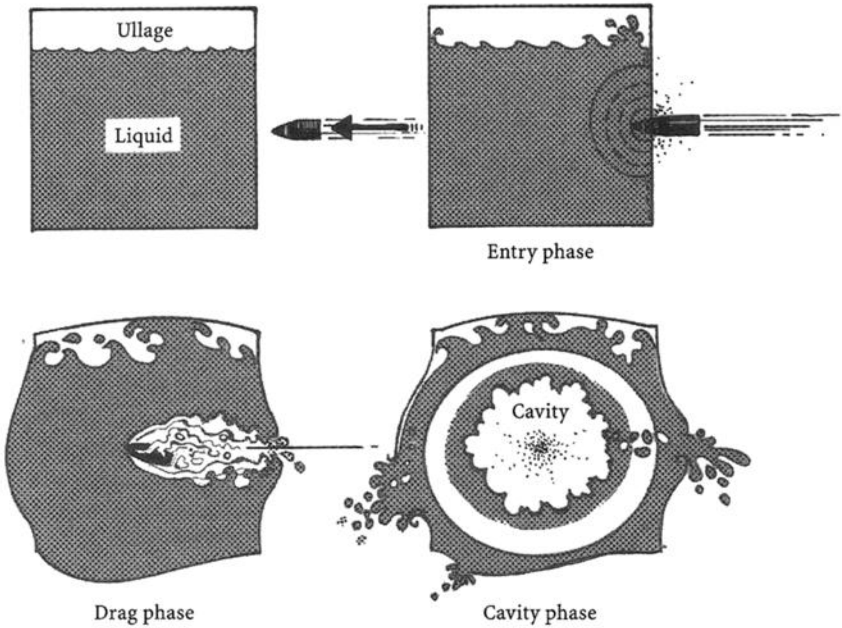


Fig. 3.47 Phases of hydrodynamic ram.

pressure field is generated along the penetrator path as fluid is displaced by the penetrator. In contrast to the very high fluid pressures developed in the shock phase, the fluid in the drag phase is accelerated relatively gradually, rather than impulsively, so that the peak pressure is much lower; however, the duration of the pressure pulse is considerably longer. A cavity develops behind the penetrator as it passes through the fluid, which is filled with liquid vapor evaporated from the cavity surface and with air that has entered the cavity through the entry hole. As the fluid seeks to regain its undisturbed condition, the cavity will oscillate. The concomitant pressures will pump fluid from any holes in the tank, and they may be sufficient to damage other system components. This cavity oscillation is called the cavity phase.

If the body penetrating the fluid is a ballistic projectile with an HE warhead and the warhead detonates while submerged, the explosive is converted to a high-temperature, high-pressure gas fireball, similar to that in air. However, depending upon the depth of the fluid surrounding the fireball, the fireball might be a bubble whose expansion is constrained by fluid rather than air. In addition, the heat generated by the detonation might vaporize some of the surrounding fluid. If the fluid is combustible, considerable energy can be added to that from the initial detonation. The bubble's spherical expansion into the surrounding fluid creates a spherical pressure or shock wave in the fluid similar to the blast wave in air, but with some significant differences. The similarities are that the overpressure is maximum at the front of the wave, and there is a negative phase in the wave. However, in a fluid the overpressure at a particular distance from the detonation is much higher than the corresponding overpressure in air at the same distance, the pressure wave

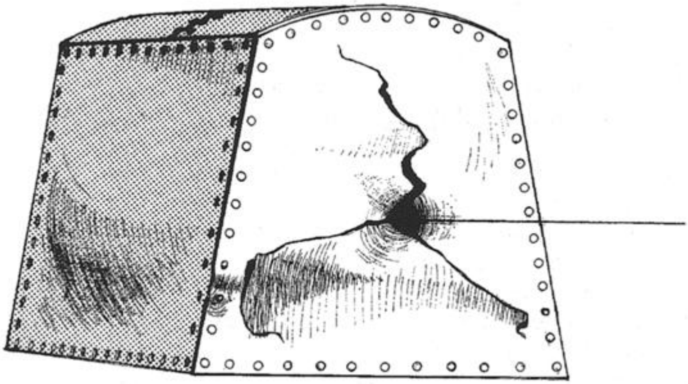


Fig. 3.48 Example of damage caused by hydrodynamic ram.

travels at a much higher velocity, and the positive phase duration is much shorter than that in air (Note 60).

Terminal effects. The penetrator-caused hydrodynamic ram loading on all of the wet walls of a fluid-containing tank can cause large-scale tearing and petalling, with openings very much larger than those made by the actual penetrator, as illustrated in Fig. 3.48. If the penetrator carries a high-explosive warhead that detonates within the fluid, the damage can be even more severe. The damaged wall shown in Fig. 3.48 could be the entry wall that received a major ram pulse caused by the impact of a tumbled penetrator or the rapid tumbling of the penetrator as soon as it entered into the fluid (Note 61). If the penetrator did not tumble as it passed through the fluid, or if the tank width was short, the damaged wall could be the exit wall, which received the ram loading as well as the impact from the penetrator on its way out of the tank.

The amount of structural damage caused by hydrodynamic ram can be significant, resulting in the failure of major load-carrying members and the connections between members. Wing tanks containing relatively high levels of fuel are particularly vulnerable to hydrodynamic ram damage, particularly when they are made of composite materials. If the composite members and the connections between members are not specifically designed to carry the very large transverse ram pressure, the damaged structure could fail, possibly under normal flight loads.

Another area of concern is any fuel tank located near an engine air inlet. Hydrodynamic ram loading on the wall of the tank next to the inlet can cause tears in the wall. These tears allow fuel to spew into the engine air inlet. This results in a rapid dump or steady stream of fuel into the front end of the engine, possibly damaging or killing the engine. The hydrodynamic ram loading can also be transmitted through attached lines, causing failure at fittings or other discontinuities in the lines. References 34–36 contain articles describing experimental and computer studies of the hydrodynamic ram phenomenon.

Go to Problems 3.5.19 to 3.5.23.

3.5.2 Damage Mechanism—Incendiary Materials

This damage mechanism includes those chemical agents or pyrophoric metals that are added to certain projectile and missile warheads to increase the probability of combustion in materials and in voids where flammable vapors can accumulate. Figures 3.20 and 3.21 show the location of the incendiary filler in a small-arms projectile and of the tracer material, also a source of incendiary material, in an HE-T AAA round, respectively. In the small-arms projectile the incendiary material is located in front of the passive core and is ignited upon contact with the target. In a high-explosive warhead any incendiary material is ignited when the warhead is detonated and is dispersed by the explosion. Secondary incendiary materials in the form of hot sparks can be generated by the impact of a metallic fragment on a metallic aircraft skin. The damage process associated with incendiary materials is combustion in the form of a fire or an explosion. Combustion can occur within the vapor space above the free surface of fuel in a fuel tank, known as the ullage and illustrated in Fig. 3.49, in the dry bays around the wing and fuselage fuel tanks, in the engine compartments, around lines carrying flammable fluid, and outside the aircraft.

3.5.2.1 Damage process—combustion.

Learning	**3.5.9**	**Describe the combustion damage process.**
Objectives	**3.5.10**	**Describe the terminal effects associated with combustion.**

Consider the fuel tank partially filled with fuel shown in Fig. 3.49. The tank is assumed to be in a steady-state, equilibrium condition. At sea level approximately 21% of the ullage volume is oxygen, approximately 78% is nitrogen, and there is a small amount of fuel vapor in the ullage that has evaporated from the surface of the liquid fuel. Suppose an ignition source, such as a spark, appears within the ullage. If the fuel vapor and oxygen concentrations in the vicinity of the spark are within certain limits, known as the flammability limit, the combustion damage process

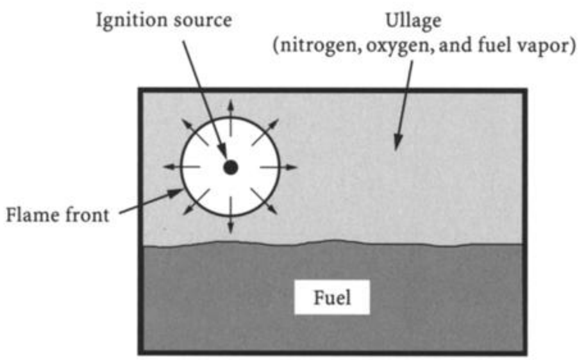


Fig. 3.49 Fuel tank under steady-state, equilibrium conditions.

can occur, and a flame front will propagate away from the source as shown in Fig. 3.49 until it reaches an area that will not support combustion.

Combustion can be defined as a sustained, exothermic chemical reaction of the form

$$C_NH_M + O_2 + N_2 \rightarrow H_2O + CO_2 + N_2 + \text{other products} + \text{energy released}$$

where C_NH_M is a hydrocarbon fuel, O_2 are oxygen molecules, N_2 are nitrogen molecules, H_2O is water, and CO_2 is carbon dioxide. The energy released is the heat of combustion. Combustion will only occur in a gaseous mixture when the concentrations of fuel vapor and oxygen are within certain limits. Fuel concentration, defined as the number of fuel molecules per unit volume, is measured by the fuel vapor pressure. In the partially full fuel tank the vapor pressure in the ullage is dependent only on the steady-state temperature of the fuel and ullage gas. The higher the temperature, the larger the number of fuel molecules the gas can hold, and the higher the fuel vapor pressure. The oxygen concentration in the ullage of a vented tank, defined as the number of oxygen molecules per unit volume, is dependent upon the aircraft's altitude; the higher the altitude, the smaller the number of oxygen molecules.

The relationship between the number of oxygen molecules (altitude) and the number of fuel molecules (temperature) determines whether combustion will take place. This relationship is illustrated by the flammability diagram shown in Fig. 3.50 for the three military aviation fuels, JP-4 (Jet B), JP-5, and JP-8 (Jet A-1). The extent of the combustible region is defined by the flammability limit for each of the three fuels (Note 62). Also shown in the figure is the flash point (Note 63). When the ullage condition is inside the flammability limit, combustion

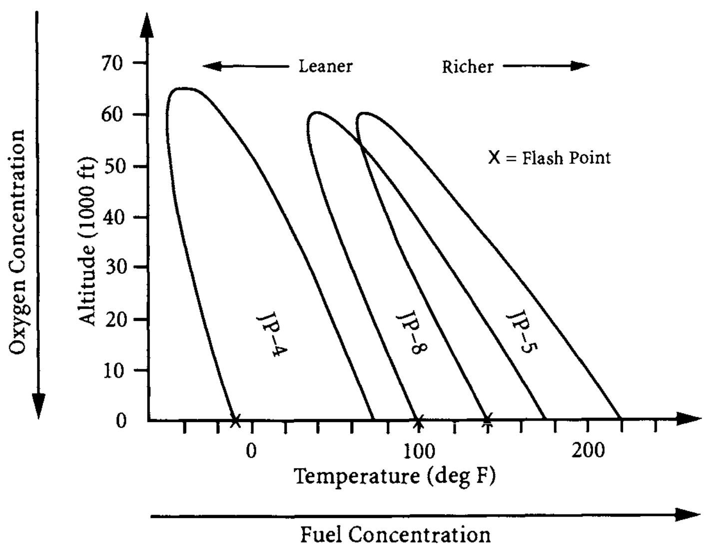


Fig. 3.50 Flammability diagram.

most likely will occur, and when it is outside the limit combustion most likely will not occur. If the ullage condition lies outside and to the left of the flammability limit for a particular fuel, the amount of fuel vapor is insufficient to support combustion, and the mixture is said to be too lean. If the condition lies to the right of the limit, there is too much fuel vapor to support combustion, and the mixture is said to be too rich. The limit shown in the figure for each fuel is not a unique dividing line, but instead represents an average limit.

The extent of the flammability limits shown in Fig. 3.50 depends upon the energy in the ignition source. Very energetic combustion sources might expand the limit. Furthermore, if the initial source of combustion is the detonation of a high-explosive material within the ullage combustion of the fuel vapor throughout the tank ullage is more likely to occur, even in ullages that are too lean or too rich under normal circumstances, as the products generated by the detonation of the HE material move through the ullage vapor.

The left-leaning shape of the flammability limits shown in Fig. 3.50 can be explained by considering an aircraft taking off with a partially full tank of JP-8 fuel. The temperature of the ullage in the tank depends upon many factors, such as the outside air temperature and any heat sinks or sources in the vicinity of the tank. If the oxygen/fuel relationship before takeoff lies outside and to the left of the flammability limit for a particular fuel, such as 80°F for JP-8, the mixture is too lean. Although the ullage temperature most likely will lower as the aircraft climbs, assume that it remains constant at 80°F (Note 64). The aircraft's ascent will result in a lower ullage pressure in the fuel tanks as the air in the ullage is vented to reduce the difference between the ullage pressure and the atmospheric pressure, and hence the ullage oxygen content will be reduced. According to the flammability limit for JP-8 shown in Fig. 3.50, this reduction in oxygen can result in a mixture in the 80-deg tank ullage above 15,000 ft that is flammable, that is, there are now enough fuel molecules for the reduced number of oxygen molecules. Similarly, if the ullage temperature is a flammable 160°F on takeoff the mixture will become too rich above 10,000 ft, assuming the temperature remains constant during the climb.

This explanation of the combustion process assumes the liquid fuel and the ullage gas are in steady-state equilibrium. However, penetration of fragments and projectiles into the fuel, fuel sloshing as a result of aircraft manuevers, the liberation of oxygen dissolved in the fuel, and fuel tank vibration might produce flammable fuel mists and vapors for some portions of the ullage for almost all flight profiles, and the detonation of an HE warhead in the ullage can significantly increase the size of the flammability limit as a result of the energy released by the detonation.

Given an ignition source in a flammable mixture, the flame front starts at the source and propagates throughout the mixture until either a solid boundary or a mixture that will not support combustion is reached. The velocity at which the flame front travels depends upon the amount and rate of energy released. A relatively large and rapid energy release by the combustion process causes a supersonic wave or flame front with a rapid rise and large increase in the pressure, called the overpressure. This phenomenon is referred to as a detonation. A relatively small and slow energy release causes a subsonic flame front with a slow rise and low increase in the pressure. This is called a deflagration. Aviation fuels typically deflagrate with overpressures normally less than 200 psi. Detonations and deflagrations may

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or may not lead to a fire. When the combustion overpressure inside the aircraft is sufficiently large to damage or destroy portions of the aircraft structure, the combustion process is referred to as an explosion.

3.5.2.2 Fires and explosions. Fire is a term used to denote deflagration with low overpressure. The effectiveness and wide use of incendiaries in antiaircraft weapon systems stems from the vulnerability of the aircraft fuel system to fire. Ignition and subsequent combustion can take place within the ullage or vapor space of a fuel tank. Fires can also occur in conjunction with a penetration damage process in which fuel spills out of holes punched in the tanks by penetrators and into adjacent void areas or dry bays. Incendiary materials igniting the vapors from these spilled fuels can lead to eventual loss of the aircraft because of the fire burning through structure, control rods, etc. Fuel is not the only combustible material onboard an aircraft. Incendiary materials can initiate fires in any flammable material or gas, such as air and vaporized liquid oxygen, and in other fluids, such as hydraulic fluid, brake fluid, and avionics cooling fluid, which could be particularly prone to combust.

Under certain conditions inside an aircraft, an explosion or rapid, high overpressure deflagration of a fuel-air mixture by incendiary materials can occur. This depends primarily on the composition of the fuel-air mixture and the intensity of the ignition source. Rapid deflagration of fuel vapors within a wing fuel tank ullage can cause an overpressure greater than 100 psi, which can rupture the fuel tank walls, destroy the surrounding structural elements, and result in a complete break up of major aircraft structure.

Go to Problems 3.5.24 to 3.5.29.

3.5.3 Damage Mechanism—Blast

Learning	**3.5.11**	**Describe the vaporific effect.**
Objectives	**3.5.12**	**Describe the blast damage process and the terminal effects.**

3.5.3.1 Blast damage mechanism. The blast from an HE warhead detonation is described in Sec. 3.4. The pressure loading on a target caused by the air blast from the detonation is called the blast loading. It is the damage process associated with blast and is the combined effect of the overpressure loading and the dynamic pressure loading (drag). In most externally detonating warheads the blast is a secondary damage mechanism. The blast is usually the last damage mechanism to reach the target, except for close detonations, and compounds or enhances the damage caused by the other damage mechanisms. If the pressure loading is sufficiently intense to significantly damage the aircraft, the other damage mechanisms probably have killed the target, provided they hit the target.

A blast can also be generated by a metallic penetrator that impacts an aluminum target. Impact at a velocity above 3000 fps can generate fine aluminum particles

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or vapor from the back surface of the impacted plate (very fine spall) that rapidly oxidize, emitting radiation in the form of light and heat. This phenomenon is referred to as the vaporific effect or flash. If the oxidation occurs in a relatively small enclosed space, such as a dry bay in an aircraft, any air in that space will be rapidly heated, creating a quasistatic overpressure or blast loading on the walls of the space and on any internal components. When many closely spaced penetrators hit an aluminum target nearly simultaneously, a very large number of fine aluminum particles can be created, and the cumulative effect of the nearly simultaneous oxidation of all of these particles can result in a very large internal overpressure. If the penetrator is itself pyrophoric, it, too, can oxidize and thus contribute to the overpressure. Pyrophoric penetrators that break up upon impact and penetration have more surface to oxidize, leading to more heating of the air and a larger overpressure. The terminal effects associated with vaporific blast can be large tearing and destruction of surrounding structure and the crushing of internal components.[22]

3.5.3.2 Damage process—blast loading.

Overpressure blast loading. This aspect of the blast damage process is the one that results from the effects of the overpressure in the blast striking and moving over the surfaces of the target. The terminal effects of the overpressure are crushing, buckling, or tearing of the skin and substructure of the aircraft. Note from the overpressure profile shown in Fig. 3.32 that the initial overpressure is eventually followed by a period of underpressure. Any semiclosed structures or containers in the aircraft (e.g., cockpit, fuel tanks, and hydraulic reservoirs) can experience a sudden compression/decompression cycle that could result in structural failure or loss of integrity even though they were not located directly facing the blast.

Dynamic blast loading. This loading is produced by the velocity of the air in the blast with respect to the aircraft. It's a drag loading on the target. The dynamic loading damage process causes structural deformation, bending and tearing of cantilevered structures (wings), and dynamic removal of any loosely secured attachments (e.g., canopy, panels, and antennas).

Go to Problems 3.5.30 to 3.5.32.

3.6 Radar and Infrared Systems and Fundamentals

Because an aircraft's susceptibility is primarily affected by the capabilities of the air defense's detection, tracking, and missile guidance elements, and because most of the these nonterminal threat elements use either radar or infrared devices, knowledge of radar and infrared systems and fundamentals is essential to the understanding of the procedures and techniques for susceptibility assessment and reduction. Consequently, background information on electromagnetic radiation and on radar and IR systems and fundamentals is given next. The list in Sec. 3.6.4 presents the important equations.

3.6.1 Electromagnetic Radiation

Learning Objectives	**3.6.1**	**List the electromagnetic signatures of an aircraft that can be used for detection and tracking.**
	3.6.2	**Describe the features of EM radiation as a continuous wave and as a stream of photons.**
	3.6.3	**Describe interference, reflection, refraction, transmission, absorption, and diffraction of EM radiation.**
	3.6.4	**Describe the source of EM radiation.**
	3.6.5	**Explain how an impinging radar wave is reflected by the surface of a body.**

Radar, infrared, and visual detection, tracking, and guidance systems are designed to sense electromagnetic (EM) radiation that is either reflected or emitted by an aircraft. Electromagnetic radiation can be thought of as orthogonal electric and magnetic (force) fields that propagate through a medium as harmonically oscillating, transverse waves. An EM wave at a particular instant in time is illustrated in Fig. 3.51a. The wave has a wavelength λ (meters), a frequency of oscillation f [cycles per second or hertz (Hz)], and a velocity of propagation c (meters per second). The power of the wave, in watts, is proportional to the square of the maximum electrical field strength, in volts per meter (Note 65). In the Earth's atmosphere the radiation wave velocity is nearly the same as the speed of light in a vacuum, which is approximately 300 m/μs (Note 66). In water it is approximately 25% slower. The frequency of the EM wave is equal to c/λ. Consequently, EM waves are approximately 25% longer in water than in a vacuum. EM wavelengths in a vacuum span the range from infinitely short to infinitely long. The EM spectrum for wavelengths from 10^{-9} to 10^5 m in a vacuum is presented in Fig. 3.51b, and the

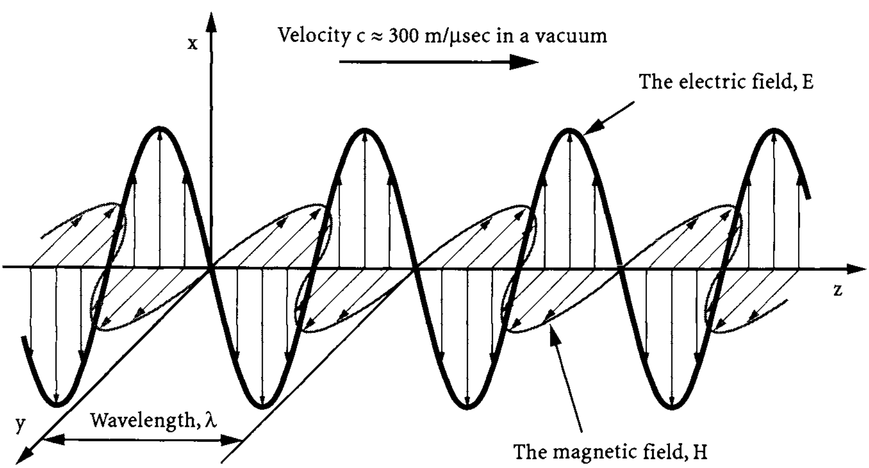

Fig. 3.51a Electromagnetic wave.

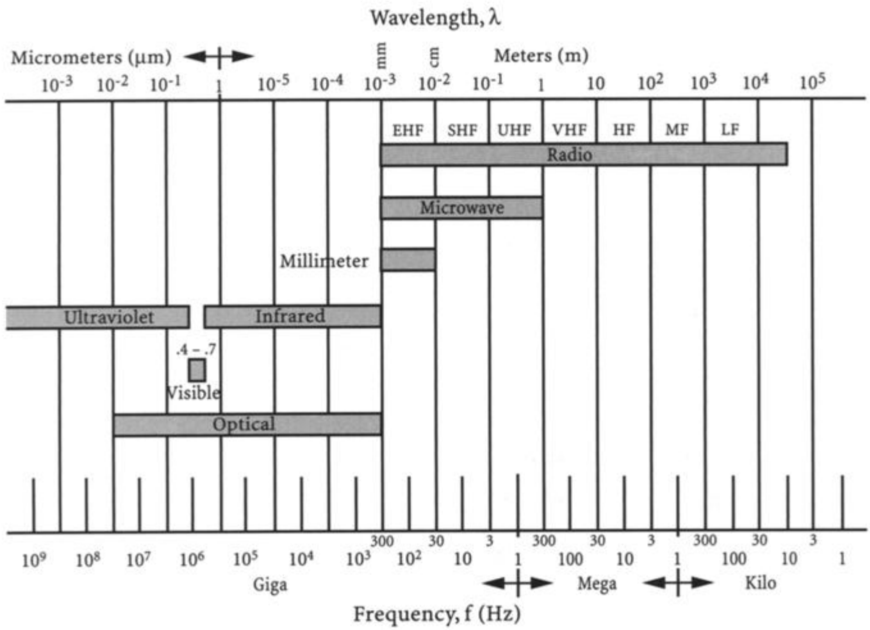

Fig. 3.51b Electromagnetic spectrum.

major bands of the spectrum of interest to the survivability discipline are indicated in the figure.

The orientation of the electric field of the wave with respect to a reference plane defines the wave's polarization. When the electric field of the propagating wave remains in one plane as the wave passes a particular location in space, the wave is said to be linearly polarized. A linearly polarized wave in which the electric field is in the vertical plane (with respect to the Earth or a scattering body) is said to be vertically polarized, and a wave with a horizontal electric field is horizontally polarized. Thus, the wave shown in Fig. 3.51a is a linearly polarized wave, and the polarization is vertical, assuming the x-z plane is vertical.

Multiple EM waves exhibit the phenomena of interference, in which the resultant electric and magnetic fields are the result of the vectorial addition of two or more waves. The EM wave resulting from the interference of two vertically polarized waves is illustrated by the solid line in Fig. 3.52. When the resultant wave is larger in magnitude than either of the contributing waves, the interference is said to be constructive; when it is smaller, the interference is destructive.

When an EM wave traveling in a medium, such as air, strikes the surface of a body or an aircraft skin, the phenomena of reflection, refraction, transmission, and absorption can occur. These phenomena are illustrated in Fig. 3.53. The impinging wave is denoted by 0-1 in the figure. Reflection refers to the scattering of all or part of the impinging wave and is illustrated by the reflected wave 1-2. Refraction, illustrated by the wave 1-3 in Fig. 3.53, is the bending of the remainder of the EM wave as it propagates across the boundary between two dissimilar media

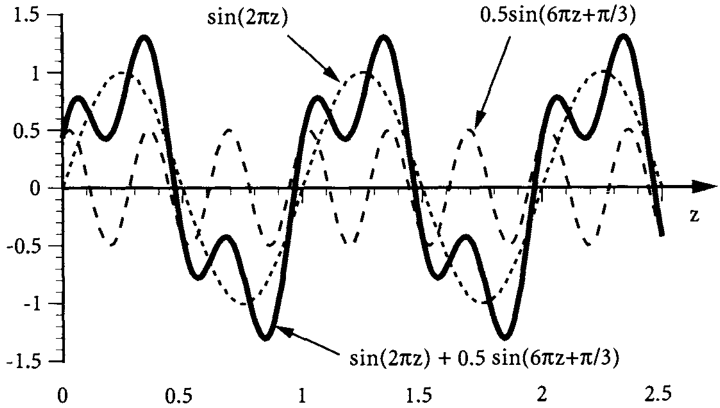

Fig. 3.52 EM interference.

(Note 67). Transmission refers to the passage of the EM wave through a medium or body, and absorption is the process in which the energy in the EM wave is converted into heat within the medium or body. Note in Fig. 3.53 that some of the refracted wave 1-3 reflects off of the rear surface as wave 3-4, and the remainder, wave 3-5, refracts as it crosses the rear surface and enters into the medium behind the body. This process of reflection, refraction, transmission, and absorption continues until the energy in the original wave has been scattered away from the body or converted to heat. As the wave passes over the body, the parts of the wave that strike an edge of the body undergo a slight bending as they pass by the edge. This phenomenon is known as diffraction, and longer wavelength waves diffract more around the body than short wavelength waves.

The description of EM radiation as a wave is not the only possible explanation of observed phenomena. Electromagnetic radiation can also be thought of as the propagation of a stream of discrete packets of energy, known as light quanta or photons, whose energy is directly proportional to the 'frequency' of the wave. The treatment of EM radiation as a wave appears to be more appropriate for the relatively long wavelengths, such as radar, whereas for the relatively short wavelengths, such as the infrared and visible portions of the EM spectrum, both the wave theory and the photon theory are used.

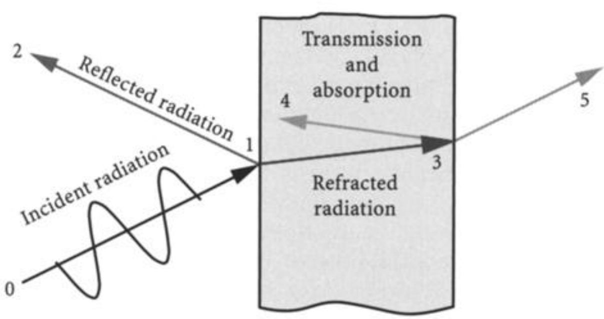

Fig. 3.53 EM radiation reflection, refraction, transmission, and absorption.

What is the source of EM radiation? Electromagnetic radiation is emitted by accelerating or decelerating charged particles, such as electrons. Thus, harmonically oscillating electrons emit an EM wave, and electrons that move from a higher energy level orbit to a lower energy level orbit within an atom give off EM waves in the form of photons. Oscillating electrons on the surface of an aircraft are the source of an aircraft's radar cross section. When an EM wave from a radar antenna impinges on a conducting surface of an aircraft, as illustrated by the wave 0-1 in Fig. 3.53, the oscillating electric field in the wave induces the free electrons on the surface of the skin at point 1 to oscillate. These oscillating free electrons emit an EM wave that propagates away from the surface as wave 1-2. Thus, the reflected signal is actually a reradiated signal. A perfect conductor will reradiate all of the impinging signal, whereas a surface that is not a perfect conductor will allow some of the impinging radiation to enter into the body, as illustrated by the wave 1-3 in Fig. 3.53. Both the accelerating/decelerating and the orbit jumping electrons are the source of an aircraft's IR signature, and the orbit jumping electrons are the source of the visible signature.

Online information on EM radiation is available at http://www.jpl.nasa.gov/basics/bsf6-1.html and http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec.html.

Go to Problems 3.6.1 to 3.6.11.

3.6.2 Radar

3.6.2.1 Generic radar systems, operations, and terminology.

Learning Objective **3.6.6 Describe the operations and terminology of CW and pulse radar systems.**

Radar (radio detection and ranging) systems are used by air defense forces to detect and track aircraft and to guide missiles. A typical detection and tracking radar system, such as the one shown in Fig. 3.54, includes a transmitter, one or more antennas, and a receiver. The transmitter generates electromagnetic radiation known as the radar signal, usually at a single frequency, known as the radio or radar frequency (RF). The signal is either a continuous wave (CW radar) or one or more short pulses (pulse radar), with each pulse containing many wavelengths. For radar systems with a reflecting (metal) antenna, such as the dish antenna shown in Fig. 3.54, the signal is sent from the transmitter to a feed horn in front of the antenna that illuminates the antenna, much like the light bulb in an ordinary flashlight illuminates the shiny metallic reflector. The signal from the feed horn is reflected from (reradiated by) the metallic antenna and becomes focused in space in either a fully focused 'pencil' beam or a semifocused 'fan' beam, depending upon the shape of the antenna. The signal then propagates into free space at the velocity of light, just like the light from a flashlight. If the signal strikes an electromagnetically reflecting object, such as an aircraft, or a mountain, or rain, or a duck, the incident signal can be reradiated or scattered in many directions. Some of the scattered signal from the aircraft will be in the direction of the radar receiver. This received signal is

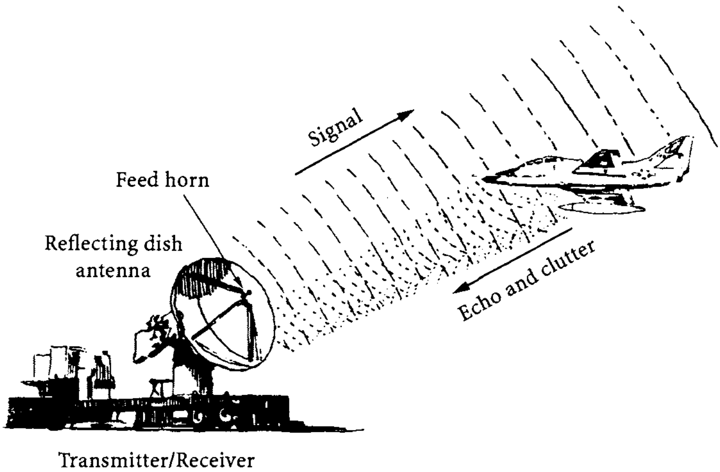

Fig. 3.54 Typical radar system in operation.

know as the target echo. Echoes from nonaircraft bodies, such as mountains, rain, and ducks, are called clutter. The antenna used by the receiver to intercept the echo can be the same as that used to radiate the signal, or it might be a separate antenna. Radar systems in which the receiving antenna is collocated with the transmitting antenna are called monostatic radars. Those systems that widely separate the two antennas are referred to as bistatic radars, and systems with multiple, separated receiving antennas are known as multistatic radar systems. The return signal is then processed by the receiver to extract information on the reflecting object, such as its its location in space, its relative radial velocity, and possibly the type of object.

In the past, air defense radars fell into three broad categories: surveillance radars, weapon or fire control radars, and illumination radars. In many modern, multifunction radar systems, such as the electronically scanning array (ESA) radar described next, one radar can perform all three functions. The surveillance radar is used to detect the presence of aircraft at long ranges and to provide the general view of the overall situation in the air needed to control the defense. It is also referred to as a search, surveillance, early warning, acquisition, or ground-controlled intercept (GCI) radar (Note 68). These radars normally operate as pulse radars at relatively low frequencies and long pulse widths and can use large, rotating antennas with fan beams with relatively wide beamwidths. Figure 3.55 is an illustration of a surveillance radar that is designed to determine the azimuthal location of the target. The target's azimuth and range are usually presented in polar coordinates to the radar operator on a plan position indicator (PPI) cathode ray tube, known as a PPI scope. Each time the aircraft is painted by the radar scan and the echo strength is larger than a selected value, a bright spot or blip appears on the PPI. Target tracking can be accomplished by surveillance radars as they continue searching by following the location of the target echo or blip on the PPI. This is known as track-while-scan; the target is tracked while the radar searches for other aircraft. As information on a target is collected, an attempt is made to classify it (determine the general type of target, such as an aircraft, mountain, or bird) and then identify it (determine the specific type of target, such as a fighter or bomber). When the decision is made

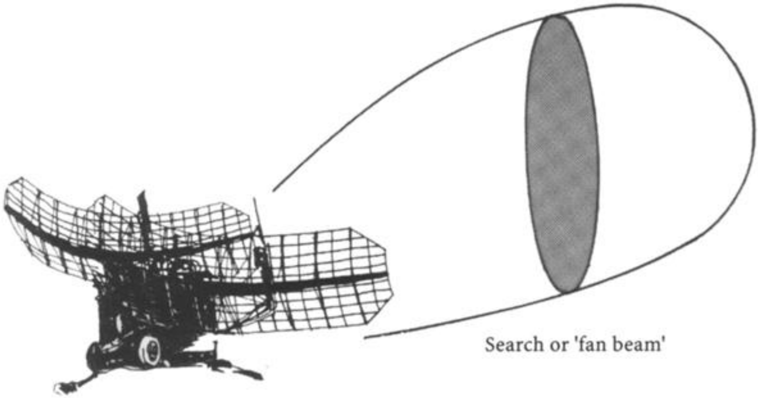

Fig. 3.55 Surveillance radar.

that the target is a threat and is within the range of a weapon control radar, the target track information is passed to the assigned weapon control radar.

Weapon control radars normally operate over a small volume of space and handle relatively few targets. They can be stationary, or they can be mounted on a mobile platform. Their function is to provide the information necessary to allow the weapon to be brought to bear on the target and to destroy it. The output from the weapon control radar is used by the fire control system to determine the target's flight path and to predict its future position so the weapon launch/firing platform can be pointed in the correct direction to cause an intercept. Consequently, these radars must provide accurate measurements of the target location in angle, and/or range, and/or velocity. Accurate measurements can be obtained using relatively short pulse widths, high signal frequencies, and narrow beamwidths. Figure 3.56 is an illustration of a weapon control radar.

The illumination radar system is used by semiactive homing systems. The target is illuminated by the radar signal, which can be a CW signal or a pulsed signal.

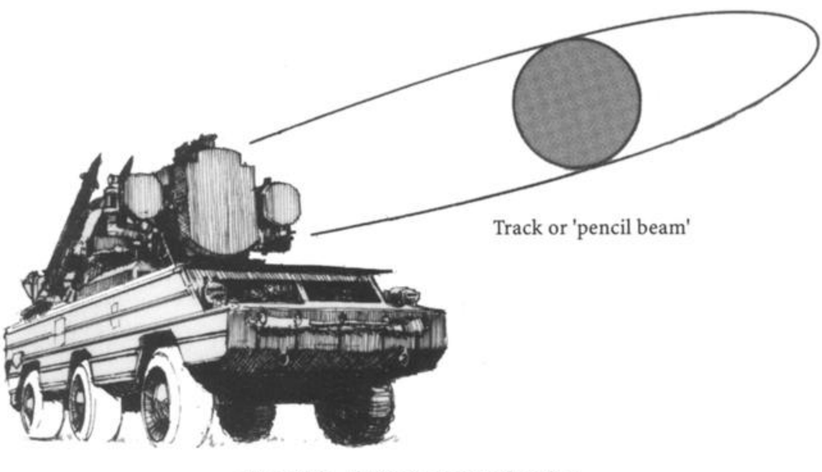

Fig. 3.56 Weapon control radar.

The time of illumination can range from continuous to a short duration during the final phase of the missile flyout.

Go to Problems 3.6.12 to 3.6.20.

3.6.2.2 Target location in space.

Learning Objective	**3.6.7**	**Describe how a radar locates a target in space.**

Radars are referred to as two-dimensional if they determine a target's range and one angle, such as the target's bearing, and three-dimensional if they determine range and both bearing and elevation angles. For monostatic, pulse radars the slant range of an aircraft from the radar R can be obtained by measuring the time delay Δt between the time a pulse is transmitted and the time when the echo is received. The pulse travels a total distance of $2R$ from the antenna to the aircraft and back at the speed of light. Thus, the range to the aircraft is given by

$$\text{Target range} = R = c(\Delta t)/2 \tag{3.14}$$

The general angular location of the aircraft with respect to the antenna main axis or boresight is provided by the direction the antenna is pointing when the echo is received. As the radar continues to transmit pulses and receive echoes, the aircraft's flight path can be tracked. Additional processing of the echoes can provide more accurate tracking and other information, such as the aircraft's radial velocity with respect to the radar antenna and the discrimination of a moving target from stationary clutter (Note 69).

Go to Problems 3.6.21 to 3.6.22.

3.6.2.3 Radar signal parameters.

Learning Objectives	**3.6.8**	**Use the decibel metric for radar power and other radar parameters.**
	3.6.9	**Describe the radar signal characteristics, including period, wavelength, and the microwave frequency spectrum.**
	3.6.10	**Describe the parameters of pulse radars, and determine the maximum unambiguous range, the target resolution range, and the radar's duty cycle.**
	3.6.11	**Explain the Doppler phenomenon; determine a target's radial velocity, the maximum unambiguous velocity, and blind speeds; and describe MTI and pulse-Doppler radars.**
	3.6.12	**Describe pulse compression and why it is used.**

Some important parameters of the radar signal are the units of signal power, normally watts or decibels, the signal characteristics of frequency and wavelength, the parameters associated with pulse and CW radars, and the features of Doppler and pulse compression.

Decibels. One common unit of measurement in radar is the decibel. The decibel is related to the common (base 10) logarithm. The measure of a nondimensional number α in decibels is given by

$$\alpha \text{ measured in dB} = 10 \times \log_{10}(\alpha) \tag{3.15}$$

The decibel, named for Alexander Graham Bell, was developed to measure the ratio of two powers, such as the power out P_2 to the power in P_1, that is, $\alpha = P_2/P_1$. It also can be used to express the magnitude of a parameter, such as power. To measure power using the decibel, $P_1 = 1$ W, and the notation dBW is used. For example, 100 W of power is also $10 \cdot \log_{10}[(100\text{ W})/(1\text{ W})]$ or 20 dBW of power. In electronic countermeasure work the power levels are relatively low, and hence the standard reference level for power is 1 mW (10^{-3} W) instead of 1 W. When a signal power level is compared to a standard of 1 mW, it is written here with the units dBmW, or decibels with respect to 1 mW (Note 70).

Some common increments in decibels should be memorized to allow easier and quicker comprehension of the magnitudes involved. Because the base of the common logarithm is 10, the following relationships shown in Table 3.12 should be committed to memory.

Two other important values to memorize are the 3 dB value, which is equal to 1.995, which is nearly 2, and the −3 dB value, which is equal to 0.5012, which is nearly 0.5. When a signal power is twice as large as another signal power ($P_2/P_1 = 2$), it is said to be larger by 3 dB, or up 3 dB. When the signal power is half as large as another ($P_2/P_1 = 0.5$), it is said to be smaller by 3 dB, or down 3 dB.

The decibel unit of measurement is convenient to use in radar equations to compute numerical values because the addition of decibels corresponds to the multiplication of numbers and the subtraction of decibels is equivalent to division. Example 3.6 demonstrates the use of this method of measurement and calculation for nondimensional numbers.

Table 3.12 Some important decibel values[a]

Ratio α	Decibels
0.001	−30
0.01	−20
0.1	−10
1.0	0
10.0	10
100.0	20
1,000	30
1,000,000	60

[a]Values in left-hand column correspond to values in right-hand column.

Example 3.6 Calculating Using Decibels

Consider the following equations:

$$\begin{aligned} 10 \cdot 10 &= 100 \\ 2 \cdot 2 &= 4 \\ 10 \div 2 &= 5 \\ 2 \cdot 10 \cdot 4 \div 100 &= 0.8 \end{aligned}$$

Replacing each number in these equations with its equivalent in decibels results in the following:

$$\begin{aligned} &10\,\text{dB} + 10\,\text{dB} = 20\,\text{dB} = 100 \\ &3\,\text{dB} + 3\,\text{dB} = 6\,\text{dB} = 3.981 \approx 4 \\ &10\,\text{dB} - 3\,\text{dB} = 7\,\text{dB} = 5.0112 \approx 5 \\ &3\,\text{dB} + 10\,\text{dB} + 6\,\text{dB} - 20\,\text{dB} = -1\,\text{dB} = 0.7943 \approx 0.8 \end{aligned}$$

When the parameters in the equation to be solved have dimensions, each dimensional parameter must first be converted to a nondimensional number by dividing by a reference value of unity with the same dimension. This procedure is presented in Example 3.7.

Example 3.7 Solving Equations Using Decibels

Consider the power equation for a resistor

$$P = V^2/R$$

where P is the power of the resistor, measured in watts, V is the voltage, measured in volts, and R is the resistance, measured in ohms. Assume that $V = 110$ V and $R = 121\ \Omega$. Solving the power equation using a decimal calculator results in

$$P = (110\,\text{V})^2/(121\,\Omega) = 100\,\text{V}^2/\Omega = 100\,\text{W}$$

Before using the decibel approach to solve this equation, reference values must be chosen for each dimensional parameter in the equation. Here, select 1 V and 1 Ω as the reference values. Thus,

$$P(\text{W}) = \frac{(110\,\text{V})^2}{(121\,\Omega)} = \frac{\left[\frac{(110\,\text{V})^2}{(1\,\text{V})^2}\right]}{\left[\frac{(121\,\Omega)}{(1\,\Omega)}\right]}\left[\frac{(1\,\text{V})^2}{(1\,\Omega)}\right] = \frac{(110)^2}{121}\left[\frac{(1\,\text{V})^2}{(1\,\Omega)}\right] = \left[\frac{(110)^2}{121}\right] \times 1\,(\text{W})$$

Dividing both sides of this equation by 1 W and converting the nondimensional numbers to decibels leads to

$$\frac{P\,(\mathrm{W})}{1\,\mathrm{W}} = 2 \times 10 \times \log_{10}(110) - 10 \times \log_{10}(121) = 40.827 - 20.827 = 20\,\mathrm{dB}$$

Note that 20 dBW and 100 W are equivalent.

Care must be taken when nondimensionalizing equations in which the units of a particular dimension are mixed, such as when the length metrics or units of meters, centimeters, and micrometers appear in the same equation. Each parameter in the equation with the same dimension must be converted to and nondimensionalized with the same unit, such as meters. For example, a radar wavelength of 10 cm must be converted to a wavelength of 0.1 m when 1 m is the reference length.

Go to Problems 3.6.23 to 3.6.24.

Signal characteristics. An important aspect of the operation of radar systems is the ability to compare, classify, and quantify the differences and similarities in signals emitted from various radars. Each radar signal has a characteristic "fingerprint" that specifically identifies it and categorizes it as belonging to a particular group or radar type. The first characteristic is the signal or carrier frequency f, which is a measure of the number of harmonic oscillations in the signal within a specified time interval, typically 1 s. The period of the signal frequency is T, the time interval for one cycle of oscillation, and is given by

$$\text{Wave period} = T = 1/f \text{ (seconds per cycle)} \tag{3.16}$$

The two standard terms commonly used to denote the carrier frequency are megahertz (MHz, equivalent to 10^6 cycles/s) and gigahertz (GHz, equivalent to 10^9 cycles/s).

Another important parameter used in defining signals is the wavelength of the signal frequency λ. It can be defined either as the distance the radiated signal travels during one period of the carrier frequency or as the physical length of the wave at one instant in time, as illustrated in Fig. 3.51a. The wavelength can be computed from

$$\text{Wavelength} = \lambda = cT = c/f \tag{3.17}$$

Modern radars can operate in a frequency range from as low as 30 MHz to as high as 300 GHz. The radar signals between 300 MHz and 300 GHz are referred to as microwaves, where the microwave region is defined as that region of the electromagnetic spectrum with wavelengths falling between the limits of 1 m (300 MHz) and 1 mm (300 GHz). The microwave portion of the electromagnetic spectrum is presented in Fig. 3.57. The specific frequency ranges or bands shown in Fig. 3.57 can be denoted using either one of two standards of reference. Radar engineers

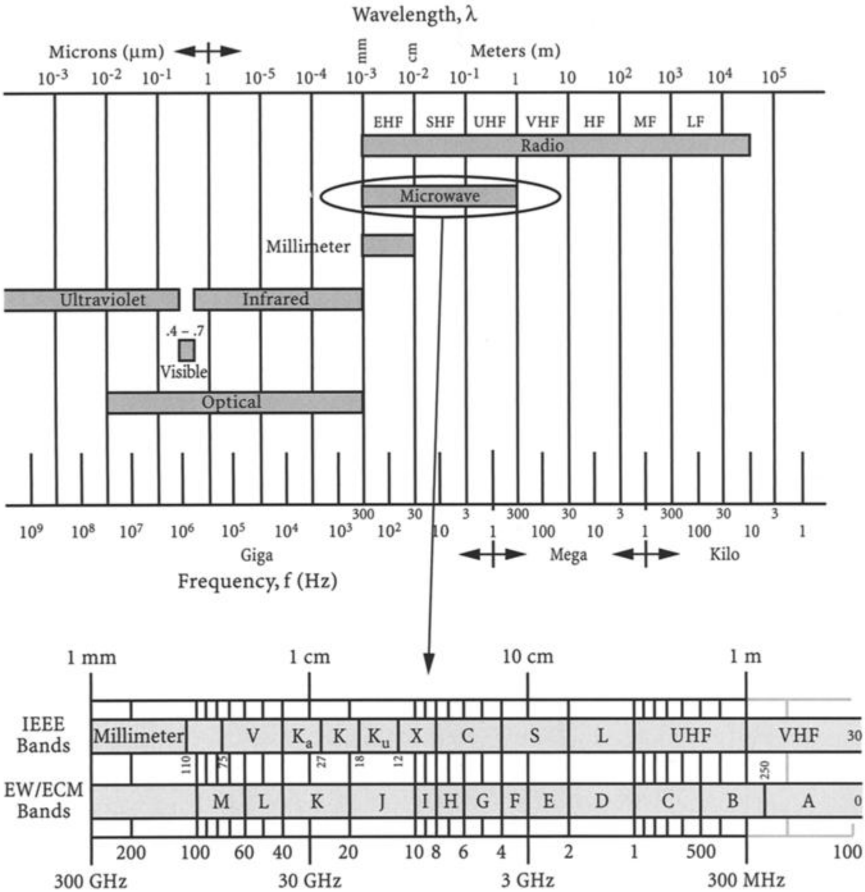

Fig. 3.57 Microwave frequency spectrum.

use a standard developed and agreed upon by the Institute of Electrical and Electronic Engineers (IEEE) known as ANSI STD 527. The electronic warfare band designations, shown in Fig. 3.57 under the heading EW/ECM, have been assigned by the military to facilitate the operational control of electronic countermeasures techniques. The military designations are the ones primarily used when discussing countermeasures and are the most recent of the two designation systems. Care should be taken when referring to a signal by its band designator because certain letters of the alphabet (L, C, and K) refer to different bands, depending upon the system being referenced.

Continuous wave radar and pulse radar. In the past, radars have been divided into one of two general categories; continuous wave radars and pulse radars. Both types of radar have advantages and disadvantages. The CW radar, whose signal is shown in Fig. 3.58a, is generally used to illuminate aircraft targets for semiactive

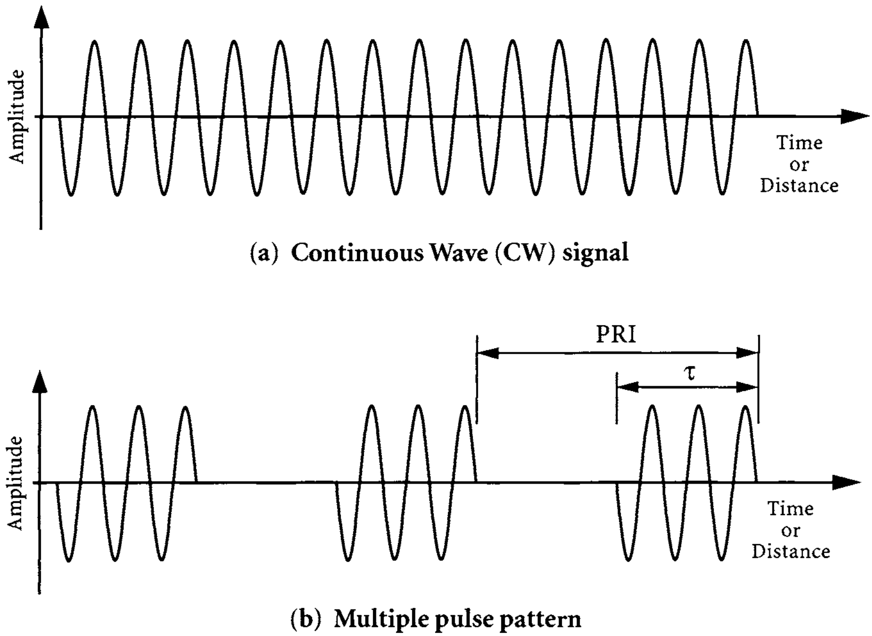

Fig. 3.58 CW and pulse radar signals.

homing missiles, and the pulse radar, whose signal is shown in Fig. 3.58b, is usually used to detect and track aircraft. A new type of radar that might have the potential to track aircraft, particularly those with a low radar cross section is the impulse radar, which is a form of ultrawideband (UWB) radar[37] (Note 71).

The pulse from a pulse radar can have any type of a waveform from a simple single short burst, obtained by 'switching' the carrier frequency on and then off, to multiple-pulse patterns. Figure 3.58b shows the time history of the output of a multiple-pulse radar signal. Three parameters that apply to pulse radar signals are appropriately named the pulse repetition frequency (PRF) f_r, measured in pulses per second (PPS); the pulse repetition time interval (PRI), where PRI = 1/PRF and is measured in milliseconds per or between pulses; and the pulse width or duration τ, measured in μs. The physical width, or length, of the pulse shown in Fig. 3.58b is equal to the distance traveled by the leading edge of the pulse during the time of the pulse transmission, or $c\tau$.

When multiple pulses are transmitted, the pulse repetition frequency limits the maximum unambiguous range of the radar R_u. The first pulse echo that returns from a distant target after a second pulse is transmitted could be interpreted as the echo from the second pulse from a close target, hence the term maximum unambiguous range. Is the echo from a close target (second pulse) or a distant target (first pulse)? Because the radar sends out a pulse of energy and then listens for the echo until a new pulse is sent out, the maximum time allowed for the first pulse to make the round trip from the radar to the aircraft and back is determined by the time interval between pulses or the pulse repetition interval. This time can be expressed approximately as

$$\text{Maximum time for round trip} = \text{PRI} = \frac{\text{Round trip distance}}{\text{Velocity of propagation}} = \frac{2R_u}{c} \tag{3.18a}$$

Hence, the maximum unambiguous range is given by

$$\text{Maximum unambiguous range} = R_u = \frac{c\,(\text{PRI})}{2} \tag{3.18b}$$

Fire control radars that track targets at relatively close ranges use very high pulse repetition frequencies compared with those of the search, early warning, and GCI radars, which normally operate at long ranges.

Pulse width is an important radar parameter for two reasons. First, it determines the amount of energy in the signal. If the output power of a radar is constant, the total energy in the signal can be increased by leaving the power on for a longer period of time, thus increasing the pulse width. For radars with very short pulse widths, a large power level is required to get sufficient energy into the signal in the short time that the transmitter is turned on. Conversely, the CW radars normally operate at a much lower power level because they are transmitting continuously.

A second factor affected by the pulse width is the target resolution in range ΔR, or how far apart in slant range do two targets have to be in order to be resolved as two distinct targets? When the pulse of electromagnetic energy transmitted into space is returned from the target, it may be sampled in the receiver by an electronic circuit called a range or tracking gate. A range gate is a switch that opens at a time after the pulse is sent coinciding with a prescribed range and closes at a set time later corresponding to a longer range. The time, and corresponding range, interval between the opening and the closing of the switch is called the range bin. Because the receiver wants to receive the entire pulse width within one range bin, the sampling circuit must be divided by the range gates into range bins that will sample the echo for an equal length of time. This sample time is the target range resolution cell. The minimum range resolution cell size that can receive an entire pulse width is $c\tau$. Now consider two closely spaced aircraft. Any pulse that strikes both aircraft will cause two echoes. The two echoes can be resolved as two targets provided that the leading edge of the second echo does not overlap the trailing edge of the first echo. Thus, twice the distance between the two aircraft in the direction of the radar must be greater than the pulse length, or

$$\text{Target resolution distance} = \Delta R = c\tau/2 \tag{3.19}$$

for the minimum target resolution range. This equation also defines the minimum range at which a target can be detected. The equation shows that as the pulse width increases, the resolution in range degrades because the range bins must be proportionately larger. The extreme case is that of the continuous wave radar, which theoretically has no range resolution capability because the pulse width is infinite. However, CW radars can be designed to give target range and resolution information by the use of special frequency modulation techniques.

Another pulse radar signal parameter is the duty cycle, which is defined as the ratio of the time the radar is transmitting to the pulse repetition interval. Thus,

$$\text{Duty cycle} = \tau/\text{PRI} \tag{3.20a}$$

The duty cycle is expressed as a decimal, or as a percent, or in decibel measure. The duty cycle for a CW radar is 100%. Normal fire control radar duty cycles are on the order of 0.001. The average power level of a radar is defined as the peak power level, which is the level during the transmitting cycle, times the duty cycle. Thus,

$$P_{\text{av}} = P_{\text{peak}} \cdot (\text{duty cycle}) \tag{3.20b}$$

Doppler. When an aircraft is moving radially with respect to the radar, the frequency of the echo is shifted from the original carrier frequency by an amount that is dependent upon the relative radial velocity of the target with respect to the radar antenna V_r. This change in frequency is called the Doppler frequency shift, Doppler frequency, or Doppler shift f_d. Like the sound waves from the whistle of a passing train, the Doppler shift is higher than f for approaching targets and is lower than f for the ones that are receding. The geometric relationship for the Doppler phenomenon for a stationary radar is illustrated in Fig. 3.59 a) for the stationary aircraft, b) for an aircraft approaching the radar site, and c) for an aircraft departing from the radar site.

Consider the two views of the stationary aircraft shown in Fig. 3.59a. In the upper view, where time = 0, the leading edge of the signal wave is on the nose of the aircraft. In the lower view, where time = T, the trailing edge of the wave has moved to the nose of the aircraft. Because the aircraft is stationary, the electrons on the nose of the aircraft will go through one complete cycle over the period T of the incident signal as the wave passes. Hence, the reflected echo will have the same frequency as the incident radar signal, and there is no Doppler shift. Now consider the two views of the incoming aircraft shown in Fig. 3.59b. Again, in the upper view the leading edge of the wave is on the nose of the aircraft at time = 0. However, in the lower view the aircraft has moved forward toward the radar, and the trailing edge of the wave reaches the aircraft's nose when time = T_d. Because of the motion of the aircraft toward the radar, the electrons in the nose of the incoming aircraft will go through one complete cycle in a time T_d that is less than the period of the incident signal T. Furthermore, because the aircraft is continuously radiating the echo as it approaches the radar the period of the echo observed by the receiving radar will be

$$T_d = \frac{\lambda - 2V_r T_d}{c} = \frac{1}{f + f_d} \tag{3.21a}$$

Usually, f_d is much smaller than f, and T_d is approximately equal to T. Under these conditions, Eq. (3.21a) can be solved for the Doppler shift, resulting in

$$\text{Doppler shift} = f_d = 2fV_r/c = 2V_r/\lambda \tag{3.21b}$$

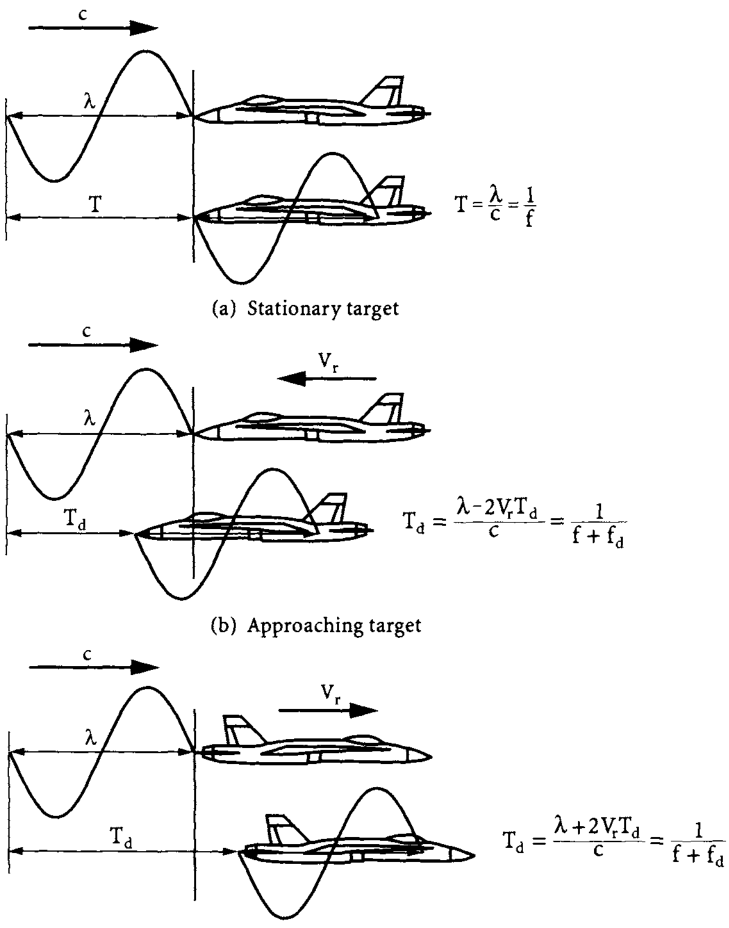

Fig. 3.59 Doppler phenomenon.

Solving Eq. (3.21b) for the relative radial velocity of the target results in

$$V_r = cf_d/(2f) = \lambda f_d/2 \tag{3.21c}$$

In the departing aircraft shown in Fig. 3.59c, the period of the echo is longer than the signal period because the aircraft is moving away from the wave. The relative radial velocity away from the radar V_r is also given by Eq. (3.21c), assuming f_d is a positive number for the departing aircraft.

If the target is moving in an arbitrary direction with respect to the radar, V_r is the radial or line of sight velocity of the target with respect to the stationary radar. Thus, $V_r = 0$ for aircraft that are moving in a circular path around the radar. If the radar is moving, for example, an airborne radar, and the target is stationary, Eqs. (3.21a to 3.21c) apply, and V_r is the relative radial velocity of the radar with respect to the stationary target. If both the radar and the target are moving, for example, an airborne radar and aircraft target, again Eqs. (3.21a to 3.21c) apply, and V_r is the relative radial velocity between the moving radar and the moving target.

The Doppler shift can be used to detect and track a moving target, particularly in the presence of strong echoes from stationary reflectors such as ground clutter. In a pulse radar the echo is detected when it is above a set level determined by the internal noise and background clutter. Because strong echoes from stationary objects do not exhibit a Doppler shift (for a stationary radar) and the weak echo from the moving target does, special circuitry can filter out the stationary clutter from the returned signal and reveal the moving target. A radar Doppler or velocity tracker can use banks of frequency filters or velocity gates and a circuitry that indicates which filter 'rings' when an echo is received. Continuous wave radars are theoretically able to determine Doppler shift most accurately because of their long sampling time and are therefore the type used when extremely accurate frequency shift measurements are required.

In general, the ability of pulse radars to measure accurately the Doppler shift varies with the pulse width and duty cycle. To increase the Doppler processing time of a pulse radar, a multiple-pulse waveform is used to obtain the Doppler shift, and many pulses are processed over an interval known as the coherent processing interval. However, when the echo from more than one pulse is processed an ambiguity in velocity can occur, just as in the case of range ambiguity. For unambiguous velocity measurement (the Doppler shift measured is the actual radial velocity of the target)

$$(f_d)_{\max} \leq 1/\mathrm{PRI} = \mathrm{PRF} \tag{3.22}$$

Also, blind speeds (Doppler shifts, and hence targets, not seen by the radar because of the periodicity of the echos) occur when f_d is equal to PRF, $2 \cdot$ PRF, $3 \cdot$ PRF, etc. Range ambiguity given by Eq. (3.18b) is directly proportional to the PRI (or inversely proportional to the PRF), whereas velocity ambiguity is inversely proportional to the PRI (or directly proportional to the PRF). Thus, the designer of a pulse radar that uses the Doppler phenomenon to detect and track aircraft must compromise between the two ambiguities. One technique to avoid this problem is to rapidly change, stagger, or jitter the PRF. However, this requires additional circuitry to transmit the pulses and process the echoes. Consequently, one or more of three PRF bands are often employed: low PRF (unambiguous in range), medium PRF (ambiguous in both range and Doppler), and high PRF (unambiguous in Doppler).[38,39] Pulse radars that use the Doppler shift to detect and track aircraft are known as moving target indicator or indication (MTI) radars when a low PRF is used, and as pulse-Doppler (PD) radars when a medium or high PRF is used.[40,41]

Pulse compression. Pulse compression refers to a modulation of the transmitted signal in order to obtain a relatively low-power, long pulse width signal with large radiated energy, without sacrificing the target range resolution. Normally this is accomplished using either frequency or phase modulation. In frequency modulation, known as chirp, the transmitted signal frequency is changed linearly from the leading edge of the constant amplitude pulse to the trailing edge. Upon reception of the scattered signal, the echo is passed through a pulse compression filter that slows down the leading edge of the pulse and speeds up the trailing edge. This procedure decreases the pulse width and hence increases the peak power of the echo. By comparing the overlapping echoes from two targets with a stored replica of the transmitted signal the targets can be accurately resolved.

Go to Problems 3.6.25 to 3.6.35.

3.6.2.4 Radar antennas.

Learning Objective	**3.6.13**	**Describe the antenna parameters of gain and beamwidth, the antenna types and shapes, and polarization.**

The antenna on a radar serves two primary purposes. First, it can direct and shape the radar beam, and second, it can provide a gain in power to the signal.

Gain. Antenna gain G_r is the ratio of the maximum power density in the beam radiated by the antenna to the power density that would have been radiated had the antenna been omnidirectional. The power density of the beam is the power per unit area in the beam and is usually measured in watts/square meter. The gain is related to the antenna size and signal wavelength by

$$\text{Antenna gain} = G_r = 4\pi\rho A/\lambda^2 = 4\pi A_e/\lambda^2 \tag{3.23}$$

where A is the physical aperture or the total frontal (planar) area of the antenna and ρ is the antenna efficiency factor. A nominal value for ρ is 0.6. These two quantities are sometimes multiplied together and called the effective aperture A_e. Two features that should be noted are that gain is directly proportional to the area and inversely proportional to the wavelength squared (or directly proportional to the frequency squared). Thus, to get appreciable gain one of two choices must be made; either a very large antenna or a relatively high frequency must be used.

Beamwidth. An antenna does not radiate all of the signal power in just one specific direction. Small amounts of signal are radiated in nearly all directions, and the distribution of the radiated power around the antenna is called the antenna radiation pattern. A typical antenna radiation pattern in azimuth is shown in Fig. 3.60. Note that the power measurement is in decibels, and the maximum power on the boresight of the main lobe is the reference power level. Note also the presence of nulls and secondary lobes, called side lobes, in the pattern. Side lobes are undesirable because of the ambiguity in angle they cause; any echo, or jamming or deceiving signal, taken in by a side lobe is interpreted as arriving in the main beam. The side-lobe gain of a reflecting antenna can be reduced by weighting or tapering the feed horn illumination pattern to reduce the illumination at the edges of the

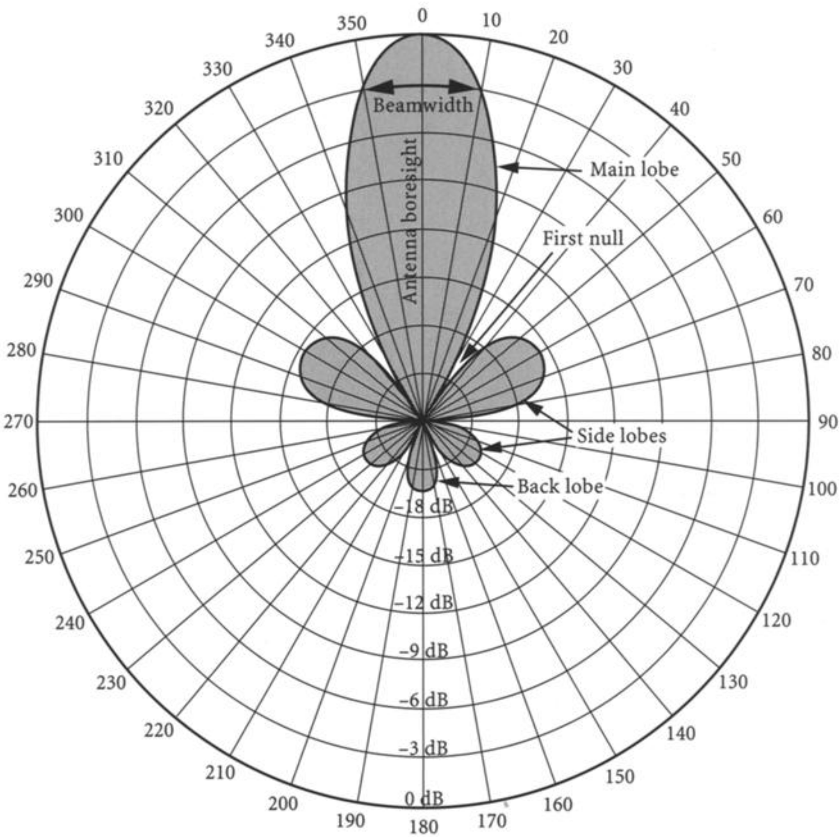

Fig. 3.60 Typical antenna radiation pattern.

antenna. However, this also reduces the efficiency of the antenna. The side-lobe gain on a phased-array antenna (described next) is reduced by the selection of the phasing pattern.

The beamwidth of the transmitted signal is usually defined as the width of the beam between the half-power or −3 dB points. Thus, the beam in Fig. 3.60 has a beamwidth of about 20 deg. In general, the beamwidth is inversely proportional to the aperture width of the antenna. The equation for the beamwidth of a parabolic dish antenna is

$$\text{Antenna beamwidth (in degrees)} = b\lambda/D \tag{3.24}$$

where D is the frontal diameter of the dish and b varies from about 50 for a uniform feed horn illumination function to 80 for a cosine squared illumination. The cosine squared illumination, which results in a larger beamwidth, is used to reduce the gain in the side lobes.

Antenna types and shapes. The two general types of air defense radar antennas are reflecting and phased array. Different reflecting antenna shapes are used to obtain beam patterns optimized to a specific function. Surveillance radar antennas are usually much wider than they are tall so that the radiated pattern is a vertical fan beam that provides narrow azimuth resolution while covering a large sector in elevation. Figure 3.55 shows a search radar antenna with a vertical fan beam. Note that the surveillance radar in Fig. 3.55 has two vertical fan beams. Some weapon control radars use two orthognal fan-shaped antennas to create a vertical fan beam for azimuth tracking and a horizontal fan beam for elevation tracking.

Weapon control radars that use a symmetrical, dish-shaped reflecting antenna have the narrow, high-resolution beam pattern referred to as a pencil beam. These pencil beams are so narrow they normally cannot be used to scan large areas for a target, but once 'locked on' they provide accurate directional information. Occasionally, a symmetrical antenna will be used as a target illuminator rather than as a target tracker. In those instances, normally associated with semiactive missile guidance systems, the radar does not have to supply accurate guidance information, but it might have to maintain a continuous target echo for the missile to home in on. Consequently, a wider symmetrical beam can be utilized.

Another important type of radar antenna is the phased-array antenna. This antenna consists of a multitude of individual radiating antennas or elements rigidly mounted in a regular one-dimensional (linear array) or two-dimensional (planar array) pattern. The elements themselves can be dipoles (a straight length of wire split in two equal lengths with an electrical connection at the split), open-ended waveguides (a rectangular metal cylinder open at the antenna face), or any other type of radiating element. One special type of planar array is the electronically phased array (EPA), or electronically scanning array (ESA), antenna shown in Fig. 3.61. The signal from each element in the array is either provided by a corporate feed horn, Fig. 3.61, or each element in the array can generate its own signal. The latter type is referred to as an active array or active electronically scanning array (AESA). By controlling the phase shift and amplitude of the individual signals from each of the antenna elements (with phase shifters), the radar beam can be electronically shaped and scanned back and forth and/or up and down at speeds unlimited by the mechanical inertia of the traditional scanning antenna. For example, in Fig. 3.61, there are seven antenna elements. Element 1 was the first element to send out a signal. A short time later, element 2 emitted its signal. This was followed by a delayed signal from antennas 3, 4, 5, and 6. Antenna 7 is on the verge of emitting its signal. The signal from each element propagates hemispherically, as shown in the figure. The seven signals from the seven antennas interfere as they propagate away from the antenna. The location where the interference of all seven signals is constructive forms the wave front of the composite signal from the antenna, as illustrated in Fig. 3.61. The beam shape and signal direction from a phased-array antenna can be changed so rapidly that the radar can track several targets, search for other targets, and guide missiles simultaneously. The gain pattern of the array can also be adjusted to null out any interference or noise coming from a direction different than the direction to the targets being tracked.

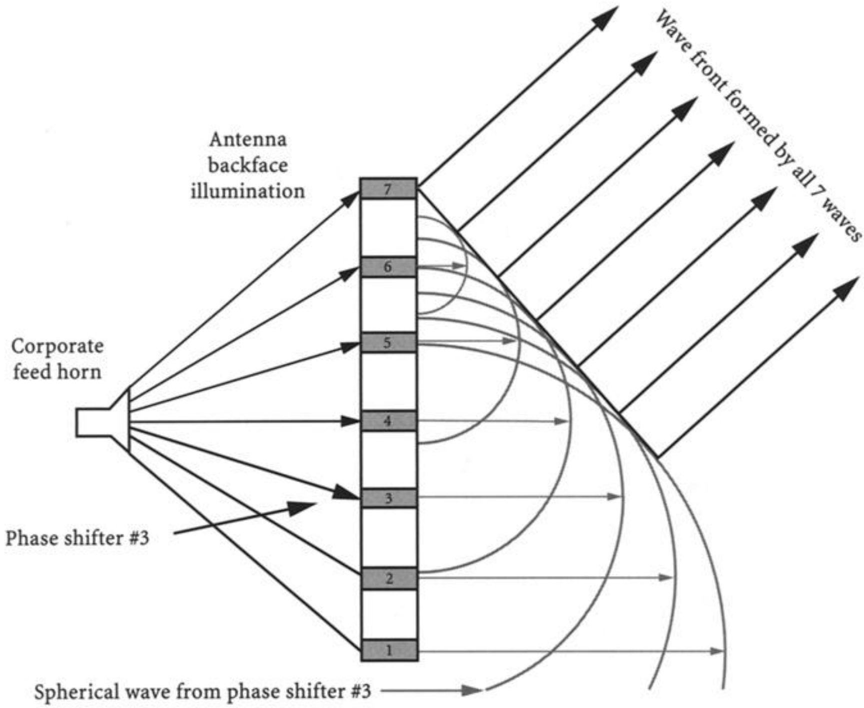

Fig. 3.61 Planar electronically phased array.

Polarization. The electromagnetic waves radiated by an antenna are polarized according to the antenna design. For example, conventional feed horns radiate linearly polarized waves, and a combination of two orthogonal feed horns will produce a circularly polarized composite wave when the signals from each horn are equal in strength and separated in phase by 90 deg (Note 72). The composite wave is elliptically polarized when the phase difference is less than 90 deg and greater than 0 deg. When the polarized signal strikes a scatterer, the polarization of the echo can be changed from that of the signal according to the geometry of the body. This phenomenon is called depolarization or cross-polarization. An antenna will effectively receive or detect only those echoes that are polarized in the same manner as the transmitted signal. For example, antennas that transmit horizontally polarized signals will only effectively receive horizontally polarized echoes. Thus, if the signal is horizontally polarized and the echo is vertically polarized the antenna will not receive the echo. By transmitting an elliptically or circularly polarized signal, the antenna will be able to receive some portion of the echo from a depolarizing body.

Go to Problems 3.6.36 to 3.6.42.

3.6.2.5 Propagation of radar signals through the atmosphere.

Learning Objective 3.6.14 Determine the attenuation of a radar signal as it propagates through the atmosphere.

Radar signals are attenuated by the oxygen and water vapor in the Earth's atmosphere. The attenuation becomes significant at frequencies above 10 GHz. The attenuation over a distance R can be expressed in the form $\exp(-R\alpha)$, where α is the rate of attenuation per unit distance. Converting the attenuation to a dB/km format, the approximate values of attenuation in terms of dB/km for a particular atmospheric condition are approximately −0.006 dB/km at 3 GHz, −0.01 dB/km at 10 GHz, and −0.07 dB/km at 30 GHz.[42] The corresponding attenuation over a distance of 100 km is −0.6, −1.0, and −7 dB.

Precipitation in the atmosphere in the form of rain, snow, and fog can significantly attenuate radar signals as well as contribute to background clutter. Generally, the higher the radar frequency, the more attenuation. The rate of attenuation for both a moderate rain and a heavy fog is approximately 0.1 dB/km for a 10 GHz radar signal. Consequently, the signal will be attenuated by 10 dB after traveling 100 km in a moderate rain or heavy fog.[43]

Go to Problems 3.6.43 to 3.6.44.

3.6.2.6 Surveillance and weapon control radar descriptions. Some of the attributes of effective air defense radars are all-weather capability, early and reliable detection (few false alarms) particularly for low-altitude targets, discrimination (the ability to detect and track a target in the presence of a high clutter environment), accurate target tracking, rapid automatic target acquisition, and countermeasures immunity. Table 3.13 lists estimated values for some of the major parameters of surveillance and weapon control radars, Example 3.8 contains the computations for several of the important radar parameters, and Refs. 44 and 45 contain descriptions of some current radar systems. Data on radar and radar systems is available online at http://www.aeronautics.ru/radru.htm, http://www.fas.org/man/dod-101/sys/ship/weaps/an-sps-49.htm, http://www.acronet.net/~target/products/misc/AN_SPS-55.html, http://www.periscopeone.com/demo/weapons/sensors/grdradar/index.html, http://webhome.idirect.com/~jproc/sari/sarintro.

Table 3.13 Estimated values for surveillance and weapon control radar parameters

Parameter	Surveillance	Weapon control
Power P_r	≥250–1000s kW	5–250 kW
Frequency f	VHF, UHF, L and S	S, C, X, K_u, K
Pulse width τ	5–10,000 μs	0.1–5 μs
Pulse repetition frequency	200–1,000 PPS	1,000–10,000 PPS
Beamwidth	1–10 deg	less than 1 to 2 deg

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Example 3.8 Determination of Several Radar Parameters

An MTI weapon control radar system has a parabolic dish antenna with a 1-m diameter, a uniform feed horn, and an efficiency of 90%. The signal is vertically polarized. Given the following parameters, determine the radar wavelength, the antenna gain, the beamwidth, the maximum unambiguous range, and the target resolution distance:

$$P_r = 200\,\text{kW} \quad f = 9\,\text{GHz (X band)}$$
$$\tau = 0.5\,\mu\text{s} \quad \text{PRF} = 2000\,\text{PPS}$$

The wavelength is given by Eq. (3.17):

$$\lambda = c/f = (300\,\text{m}/\mu\text{s})(10^6\,\mu\text{s/s})/(9 \cdot 10^9\,\text{Hz}) = 0.0333\,\text{m} = 3.33\,\text{cm}$$

According to Eq. (3.23), the gain of the antenna is

$$G_r = 4\pi\rho A/\lambda^2 = 4\pi \cdot 0.9[\pi \cdot (1\,\text{m})^2/4]/(0.0333\,\text{m})^2 = 8{,}010 \text{ or } 39.0\,\text{dB}$$

The beamwidth for the parabolic dish antenna is

$$\text{Beamwidth (in degrees)} = b\lambda/D = 50(0.0333\,\text{m})/(1\,\text{m}) = 1.67\,\text{deg}$$

according to Eq. (3.24).

The maximum unambiguous range is given by Eq. (3.18b). Using the fact PRI = 1/PRF results in

$$R_u = c(\text{PRI})/2 = c/(2\text{PRF}) = (3 \cdot 10^8\,\text{m/s})/(2 \cdot 2000\,\text{PPS}) = 75\,\text{km}$$

The range resolution of this radar is given by Eq. (3.19),

$$\Delta R = c\tau/2 = (300\,\text{m}/\mu\text{s})(0.5\,\mu\text{s})/2 = 75\,\text{m}$$

Suppose an aircraft approaches this radar at 200 m/s. What is the Doppler shift f_d?

Rearranging Eq. (3.21c) to solve for f_d leads to

$$f_d = 2V_r/\lambda = 2(200\,\text{m/s})/(0.0333\,\text{m}) = 12.0\,\text{KHz}$$

Will the velocity be ambiguous, and what are the blind speeds?

According to Eq. (3.22),

$$(f_d)_{\max} \leq 1/\mathrm{PRI} = \mathrm{PRF} = 2\,\mathrm{KHz}$$

Hence, $f_d \geq (f_d)_{\max}$, so the velocity is ambiguous. According to Eq. (3.21c), with $f_d = n\mathrm{PRF}$ the blind speeds are

$$\begin{aligned} \text{Blind speeds} &= V_r = \lambda(n\mathrm{PRF})/2 = (0.0333\,\mathrm{m})(2{,}000n\ \mathrm{PPS})/2 \\ &= 33.3,\ 66.6, \ldots 200,\ \text{etc. m/s} \end{aligned}$$

Because the design target velocity is equal to one of the blind speeds, the use of staggered PRFs is recommended.

3.6.3 *Infrared*

Learning Objective	**3.6.15**	**Describe the IR portion of the EM spectrum.**

Infrared radiation, like radar, is a band of the electromagnetic spectrum. The IR band lies within the optical band and encompasses wavelengths from 0.7 to 1000 μm. Radiation in this band is referred to as heat or thermal radiation. The IR band has been subdivided into many different subbands by various authors and organizations, and there is no standard. Here, the IR band is subdivided into the shortwave (SWIR) or near (1 to 3 μm) band, the midwave (MWIR) or middle (3 to 5 μm) band, the longwave (LWIR) (8 to 16 μm) band, and the far or extreme (16 to 1000 μm) band.[46] The locations of these IR subbands within the optical band are shown in Fig. 3.62 (Note 73).

Infrared radiation is used by air defense thermal imaging (TI) systems, by infrared search and track (IRST) systems, and by missile guidance systems. The thermal or infrared imaging systems, such as the IR camera, produce a two-dimensional picture or image of the radiation from a scene viewed by an optical device. The radiation sensed is usually in either the MWIR band or the LWIR band. (http://www.x20.org/thermal/.) The IRST is used by the air defense forces to search, detect, and track aircraft or missiles based upon their IR signature, typically in the LWIR band. The IRST can be surface-based or carried by enemy aircraft. (http://www.optronics.co.uk/irst.htm.)

Infrared systems can be used in the guidance of missiles that employ command guidance, beam rider guidance, or passive homing. Missiles with command guidance can carry an IR beacon in the tail. The beacon is passively tracked by an IR sensor in the target tracking device while an operator attempts to track the aircraft, usually with the aid of either direct-view optics or electro-optics. The tracking system notes the difference in the target and missile positions and generates the

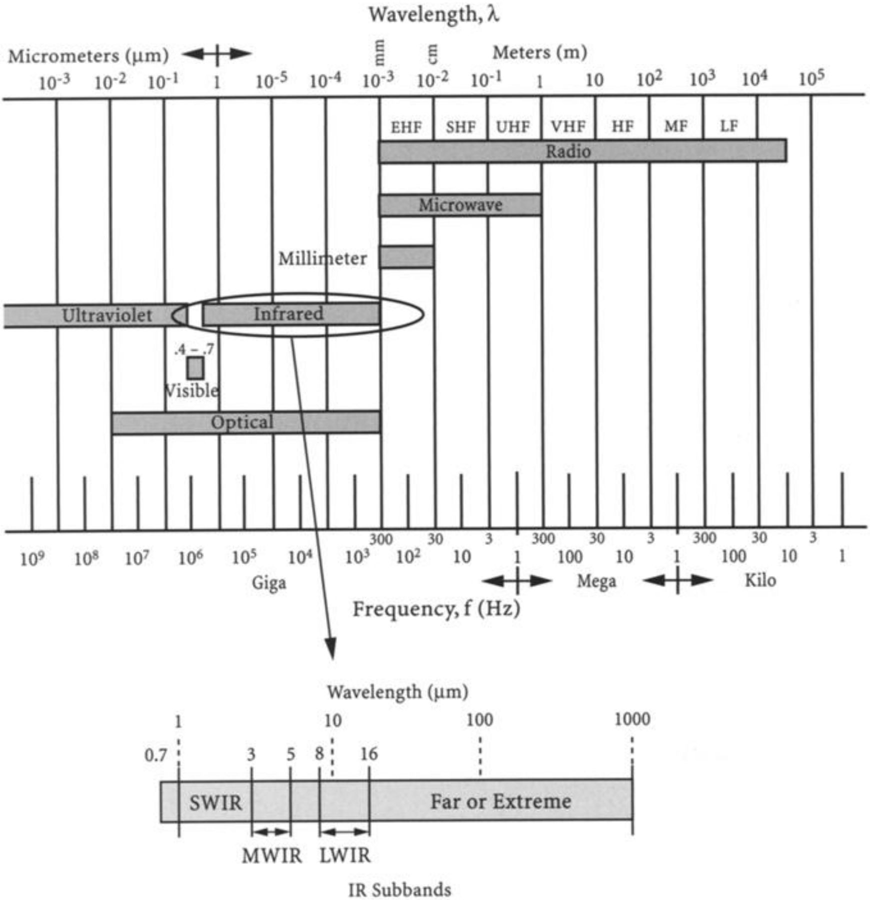

Fig. 3.62 IR band within the optical portion of the EM spectrum.[46]

necessary commands to direct the missile to an intercept. The command-to-line-of-sight navigation technique is usually used when the target range information is not available. Missiles employing the beam rider method of guidance and a laser that operates in the IR band will have an IR sensor in the tail of the missile that can see the approaching laser beam. A missile that uses passive homing most likely will have an IR detection and tracking system, known as an IR missile seeker, located in the nose of the missile. The IR radiation emitted by the target aircraft and its engine exhaust plume provide the IR signature sensed by the seeker (Note 74).

Infrared topics of interest to the survivability engineer include the operation of IR missile seekers, the emission, transmission, and absorption of IR radiation by bodies and gases, the effects of the atmosphere upon the transmission of IR radiation, and the capabilities of IR detectors. These topics are presented in the following sections. Material on the IR signature of an aircraft is presented in Chapter 4, Sec. 4.3.2.

Go to Problems 3.6.45 to 3.6.46.

3.6.3.1 IR missile seekers.

Learning Objective **3.6.16 Describe the operation of IR missile seekers.**

The IR detection and tracking system on a passive homing missile is located on the nose of the missile, as illustrated in Fig. 3.63. The IR seeker or tracker typically consists of a hemispherical seeker dome that is transparent to the IR wavelengths of interest, a gimballed platform that contains optical components for collecting and focusing the target radiation, an IR sensor or detector that converts the incident radiation to one or more electrical signals, and a servo and stabilization system to control the position of the tracking platform.

The seeker may have a single element IR detector, several colocated elements with different orientations, a one-dimensional or linear array of elements, or a two-dimensional array of elements known as a focal plane array (FPA). Seekers are generally categorized as reticle, scanning, or imaging, depending upon the method of tracking used. The nonimaging seekers require some sort of scanning

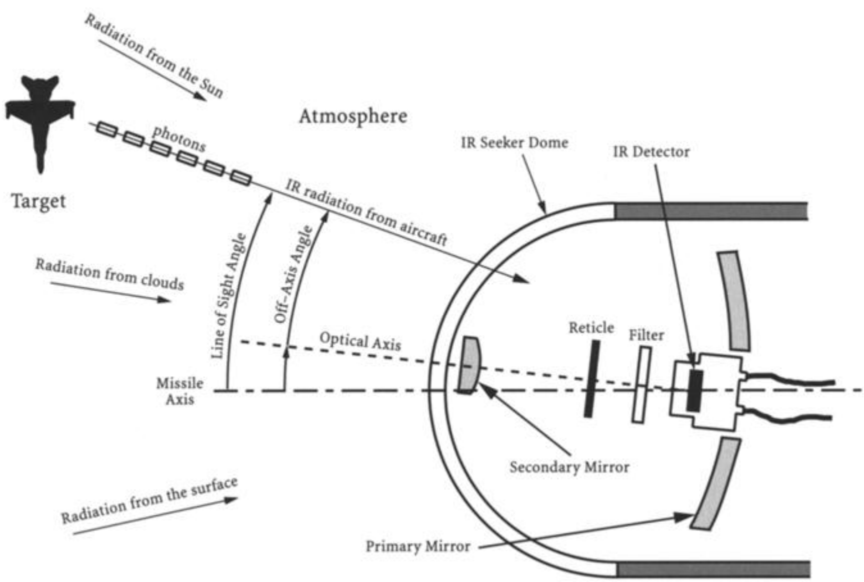

Fig. 3.63 One type of an IR missile seeker.

or signal modulation technique to generate a signal that can be used to determine the line-of-sight to the target. For example, many IR homing missiles use a single element detector in combination with a reticle. In the reticle-based seeker design shown in Fig. 3.63, infrared radiation from the target, sun, clouds, and the Earth's surface pass through the atmosphere and impinge on the seeker dome. The incident radiation passes through the dome and strikes the primary mirror, which redirects the incident radiation to the secondary mirror. This mirror focuses the radiation on a reticle that can be stationary or spinning. The reticle periodically interrupts or modulates the incoming radiation or signal for the purpose of target discrimination and tracking. The modulated signal passes through a spectral filter designed to eliminate much of the background radiation and improve the signal-to-noise ratio. Finally, the signal impinges upon the IR detector or sensor, which in this example is a single element. If the radiation is sufficiently intense within the bandwidth of the detector, an electrical signal is generated and processed to determine the LOS to the target aircraft.

There are two or three fields of view of a seeker, depending upon the seeker design; the field of regard (FOR), the field of view (FOV), and the instantaneous field of view (IFOV). The FOR defines the limits of the side-to-side movement of the optical axis within the seeker head shown in Fig. 3.63. The FOV is the angular extent of the seeker optics with respect to the optical axis. The IFOV is the relatively small field of view at any instant in time within the seeker field of view or field of regard and applies to seekers that use a scanning technique (Note 75).

Go to Problems 3.6.47 to 3.6.48.

3.6.3.2 Emission, reflection, and absorption of IR radiation by bodies and gases.

Learning Objectives	**3.6.17**	**Describe the three types of electron acceleration that produce IR radiation.**
	3.6.18	**Describe the continuum emission, reflection, and absorption of IR radiation, including the IR terminology and notation.**
	3.6.19	**Describe the emission, reflection, and absorption of IR radiation by gases.**

Electromagnetic radiation in the infrared band is emitted by any body or gas that has a temperature above absolute zero. This radiation is a form of power known as thermal radiation and is caused by the accelerations and decelerations of electrons. Electrons can be accelerated and decelerated by the rotation of molecules, by the vibration of atoms within molecules, known as molecular or atomic vibration, and by electron transition or orbit jumping. As the temperature of a body is increased above absolute zero, the molecules begin to rotate and emit radiation in the extreme IR band. As the temperature increase continues, atomic vibrations become important, and the IR radiation is in the midwave and longwave bands. A further increase in the temperature causes electron transitions and radiation in shortwave, visible, and ultraviolet bands. The total amount of thermal power radiated by a

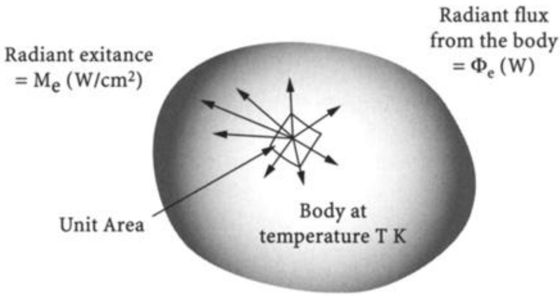

Fig. 3.64 Radiation from a solid body.

body and the distribution of the power over the wavelength spectrum are functions of the body material, surface condition, and temperature. For a continuum or solid, such as the tail pipe of an aircraft engine, the power is smoothly distributed over a relatively broad band of wavelengths, whereas in hot gaseous mixtures, such as engine exhaust plumes, the power is radiated only within very small bandwidths centered at discrete wavelengths. The solids are known as continuum radiators or emitters, and the gaseous mixtures are called line radiators or emitters.

Continuum radiators. Consider the solid body at the temperature T Kelvin (K) illustrated in Fig. 3.64. The total EM radiation or power emitted by the body over its entire surface is referred to as the radiant flux Φ_e and is measured in watts, for example, a 100 W light bulb. The radiation emitted by a unit area of the body, such as the unit area with the radiation arrows shown in Fig. 3.64, is called the radiant exitance M_e. For a perfect emitter, called a blackbody, the radiant exitance is given by the Stefan–Boltzmann law:

$$M_e = \sigma T^4 \quad (\mathrm{W/cm^2}) \tag{3.25}$$

where σ (not to be confused with the RCS) is the Stefan–Boltzmann constant, whose value is[47]

$$\sigma = 5.6697 \times 10^{-12} \quad (\mathrm{W/cm^2 - K^4})$$

Note in Fig. 3.64 that the radiation from the unit area is emitted diffusely in all directions above the surface. When the radiation is emitted in the form $\cos\theta$, where θ is the angle from the normal to the surface, the surface is referred to as a Lambertian surface.

Real bodies are never perfect radiators and consequently are called either gray bodies or spectral radiators. The radiant exitance of a gray body is given by

$$M_e = \varepsilon\sigma T^4 \quad (\mathrm{W/cm^2}) \tag{3.26}$$

where ϵ is the effective emissivity (for all wavelengths) and is equal to unity for the blackbody and is less than unity for the gray. For spectral or selective

Table 3.14 Emissivity of some common materials[48]

Material	Temperature, °C	Emissivity
Aluminum (unoxidized)	25	0.02
Aluminum (polished sheet)	100	0.05
Aluminum (anodized sheet)	100	0.55
Steel (polished)	100	0.07
Steel (oxidized)	200	0.79
Brick (red common)	20	0.93
Wood (planed oak)	20	0.90
Carbon (graphite, filed surface)	20	0.98
Paint (oil, average of 16 colors)	100	0.94
Skin (human)	32	0.98
Water (distilled)	20	0.95
Water (snow)	−10	0.85

radiators the emissivity is a function of wavelength, denoted by ε_λ, and Eq. (3.26) is not applicable. The emissivity of some common materials is given in Table 3.14 (Note 76).

Note in Table 3.14 that the emissivity of aluminum and steel is very strongly dependent upon the condition of the surface. A polished, and hence shiny, surface has a very low emissivity, whereas a rough surface has a relatively high emissivity and consequently emits considerably more radiation. Furthermore, note that human skin is a very efficient radiator of heat.

The radiant exitance from a continuum emitter is composed of radiation in all wavelengths and consequently is given by the integral relationship

$$M_e = \int_0^\infty M_\lambda \, \mathrm{d}\lambda \tag{3.27}$$

where M_λ is known as the spectral radiant exitance (the radiant exitance per unit wavelength). The spectral radiant exitance of a general body is given by Planck's law

$$M_\lambda = \frac{\varepsilon_\lambda C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \quad (\mathrm{W/cm^2/\mu m}) \tag{3.28}$$

where ε_λ is the spectral emissivity for the wavelength λ (in micrometers), and

$$C_1 = 3.74177 \times 10^4 \quad (\mathrm{W - \mu m^4/cm^2})$$

$$C_2 = 1.43877 \times 10^4 \quad (\mathrm{\mu m - K})$$

The black body spectral radiant exitance ($\varepsilon_\lambda = 1$ for all λ) is given in Fig. 3.65a as a function of wavelength for several values of temperature. Also shown in the figure is the visible bandwidth (0.4–0.7 μm) (Note 77). As the temperature increases,

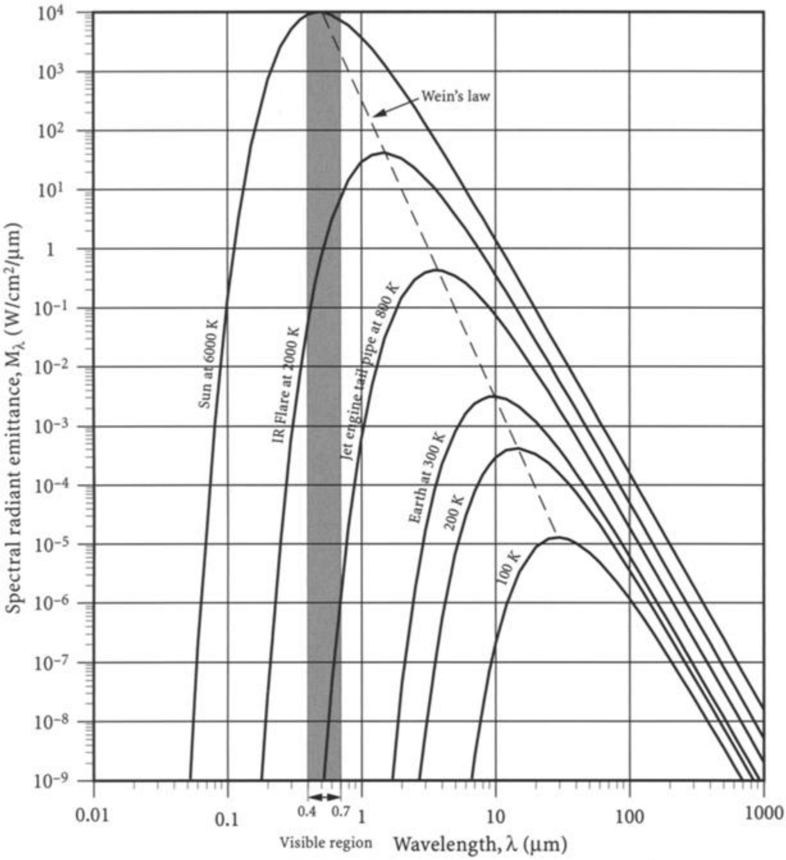

Fig. 3.65a Spectral radiant exitance from a blackbody.

the peak value of the spectral radiant exitance occurs at shorter wavelengths. For example, a body at room temperature (300 K) emits most of its energy at about 10 μm, whereas an 800 K aircraft tail pipe emits the maximum radiation at about 3.7 μm. Furthermore, note that the peak spectral radiant exitance of the sun is right in the middle of the visible band. An estimate of the wavelength associated with the peak spectral radiant exitance (denoted by the dashed line in Fig. 3.65a) is given by Wein's displacement law:

$$\lambda = 2898/T \approx 3000/T \quad (\mu\text{m}) \tag{3.29}$$

where T is in degrees Kelvin.

In general, IR detectors can only sense radiation within a narrowband of wavelengths, λ_1 to λ_2. Thus, the radiant exitance in the detector bandwidth

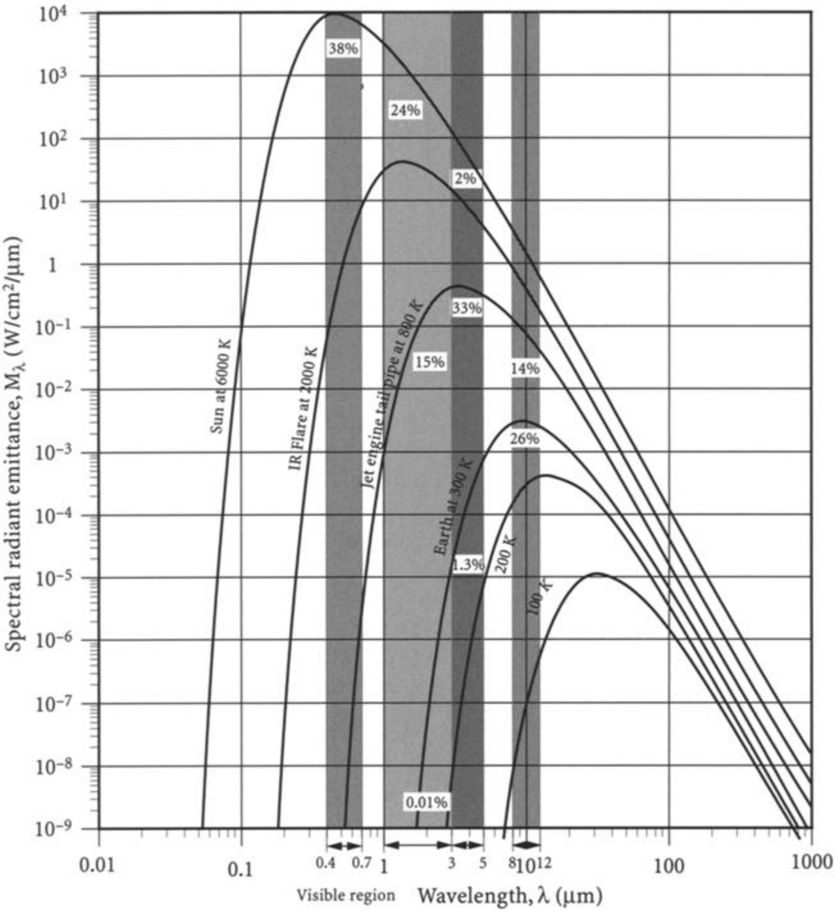

Fig. 3.65b Radiant exitance in bands 1–3 μm, 3–5 μm, and 8–12 μm.

is given by

$$M(\lambda_1 \leq \lambda \leq \lambda_2) = \int_{\lambda_1}^{\lambda_2} M_\lambda \, \mathrm{d}\lambda \tag{3.30}$$

According to Eqs. (3.28) and (3.30), the amount of power per unit area radiated by a body within the detector bandwidth depends upon the temperature, the emissivity, and the lower and upper wavelengths considered. The vertical gray bands in Fig. 3.65b show the extent of the wavelength bands 1–3 μm, 3–5 μm, and 8–12 μm for the blackbody spectral radiant exitance. The 1–3-mm and 3–5-mm bands are typical bands for early generation and later generation IR missile detectors, respectively. The 3–5-mm and 8–12-mm bands are often used in forward-looking infrared systems.

An Infrared Radiation Calculator (made of cardboard) has been developed that can be used to determine the radiant exitance and the percentage of radiant exitance within the wavelength band λ_1 to λ_2 (Note 78). The calculated percentage of the radiant exitance from a blackbody in the 1–3-μm, 3–5-μm, and 8–12-μm bandwidths is indicated in Fig. 3.65b for the 300, 800, and 6000 K temperatures. Note that the later generation IR missile detectors (3–5 μm) capture more of the radiation from the hot engine tail pipe at 800 K than do the early generation detectors (1–3 μm); 33% vs 15%. Furthermore, note that the 8–12-μm bandwidth is the most efficient bandwidth for sensing radiation from bodies near room temperature. Another feature to note is the radiant exitance sensed by an IR detector can have a proportionality much higher than the temperature to the fourth power. For example, the radiant exitance from the blackbody at 800 K is approximately 50 times greater than that from the blackbody at 300 K according to Eq. 3.25. Note in Fig. 3.65b that for the 3–5-μm detector 33% of the radiant exitance from a blackbody at 800 K is captured, whereas only 1.3% of the radiant exitance at 300 K is captured by the detector. Thus, the 3–5-mm detector senses $(0.33/0.013) \cdot 50$ or 1269 times more radiant exitance at 800 K than it does at 300 K, as illustrated in Fig. 3.65b.

The radiation from a body, such as an aircraft, can also be expressed as the power emitted per unit solid angle [the steradian (sr)] and is referred to as the radiant intensity I_e (W/sr) (Note 79). The radiation from a unit area on the body is similarly expressed as the power emitted per unit area per unit solid and is referred to as the radiant sterance or radiance L_e (W/cm^2/sr). Both I_e and L_e are illustrated in Fig. 3.66. The numerical values of I_e and L_e will depend upon the angle of the radiation arrow. The advantage of these two metrics is they remain a constant value as the radiation propagates away from the body. Consequently, I_e (in the bandwidth of an IR detector) is the usual metric used for aircraft IR signatures.

The infrared radiation emanating from a body is made up of the radiation emitted by the body as a result of its temperature and any incident radiation reflected by the body. Radiation incident upon the surface of a body is referred to as the radiant incidence or irradiance and is denoted by E_e (W/cm^2). In general, given any radiant incidence from an external source, such as the sun, a fraction of the radiation α is

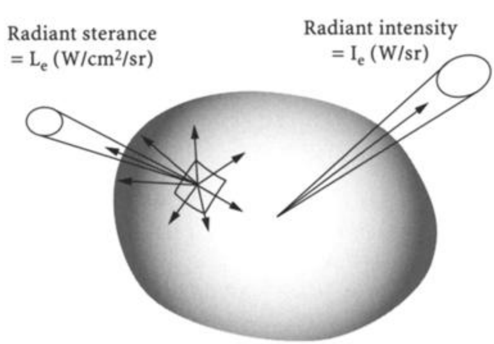

Fig. 3.66 Radiant intensity and radiant sterance.

absorbed by the body, thus raising its temperature, a fraction ρ is reflected at the incident surface, and a fraction τ is transmitted completely through the body, as illustrated in Fig. 3.53. For metals and opaque materials there is no transmission. Thus,

$$\alpha + \rho = 1 \tag{3.31}$$

That is, the relative amount of incident radiation absorbed plus the relative amount reflected is equal to unity, the relative amount of incident radiation. For a blackbody no incident radiation is reflected (hence the name), and $\rho = 0$. For gray bodies and spectral radiators $\rho \neq 0$. Under isothermal equilibrium (steady-state) conditions Kirchoff's law states that the ratio of the spectral radiant exitance of a body to that of a blackbody at the same temperature is equal to the absorptance. Thus, $\varepsilon_\lambda = \alpha_\lambda$, and consequently bodies that are efficient emitters at a given wavelength are also efficient absorbers at the same wavelength; the blackbody being the perfect emitter and absorber.

When a body at temperature T is placed in a medium that has a background temperature of T_0, radiation will be emitted and absorbed by both the body and the surrounding medium. If the body is at a higher temperature than the medium, the radiant exitance from the body will exceed the radiant illumination or irradiance on the body from the surrounding medium, and the body will lose thermal energy. If no additional thermal energy is added to the body, the temperature of the body will decrease and approach that of the medium until thermal equilibrium is reached, when the exitance and irradiance become equal. If the body is cooler than the medium, the reverse process occurs.

To aid the reader in keeping track of the IR terminology presented here, definitions of the common IR terms, symbols, and units are given in Table 3.15. The first five terms are associated with the emission of infrared radiation from the target, and the last term relates to the incidence of radiation on an IR sensor.

Line radiators. For hot gases under low to moderate pressure, such as the exhaust from an aircraft engine, the intermolecular spacing is relatively large, and hence molecular rotations and (atomic) vibrations are not constrained as they are

Table 3.15 Infrared terminology and notation[47]

Physical quantity	Term	Symbol	Unit
Power emitted	Radiant flux	Φ_e	W
Power emitted per unit surface area	Radiant exitance	M_e	W/cm^2
Power emitted per unit surface area per unit wavelength	Spectral radiant exitance	M_λ	$(W/cm^2)/cm$
Power emitted per unit solid angle	Radiant intensity	I_e	W/sr
Power emitted per unit surface area per unit solid angle	Radiant sterance	L_e	$(W/cm^2)/sr$
Power incident per unit surface area	Radiant incidence	E_e	W/cm^2

for solids. Consequently, radiant energy is emitted and absorbed by the gas only at discrete wavelengths associated with specific rotation and vibration frequencies, called spectral lines, that depend upon the particular type of molecule. These spectral lines are clustered into very tightly spaced sets called bands. The emissivity of the gas is essentially zero outside of these bands and is dependent upon the line spacing and intensity within the bands. For example, the primary lines or bands of radiation from an engine exhaust gas are caused by vibration of the atoms in the hot carbon dioxide (at frequencies corresponding to 2.7-μm and 4.3-μm wavelengths) and the hot water vapor (at 2.7 μm). Most of the exhaust gas radiation is caused by the CO_2 and occurs at 4.3 μm with a typical bandwidth of approximately 0.4 μm (Note 80).

Go to Problems 3.6.49 to 3.6.54.

3.6.3.3 Atmospheric transmission and absorption of IR radiation.

Learning Objective 3.6.20 Describe the effect of the atmosphere upon the transmission of IR radiation.

When IR radiation propagates through the atmosphere, which is a gas, some of it will be reflected or scattered, some of it will be absorbed, and some of it will be transmitted. The first two processes cause an attenuation or extinction of the radiation. For gases, the amount of reflectance or scattering of the incident IR radiation depends upon the molecules, haze, and fog in the atmosphere, but is generally small, whereas the transmittance and absorption are usually more important. Thus,

$$\alpha + \tau = 1 \tag{3.32}$$

Both α and τ are very strongly wavelength and temperature dependent for a specific gas. Because gases emit radiation in discrete bands, they also absorb radiation only in those same discrete bands. Higher temperature and/or pressure in the gas causes the emissivity within the bands to increase and the bands to become broader.

Figure 3.67 is an illustration of the percentage of radiation transmission over a 1-nautical-mile path for a given sea-level atmosphere and temperature as a function of wavelength. The absorbing molecules of the atmosphere are also indicated in the figure. Those spectral regions where the transmittance is high are called windows. Note that the absorption bands that separate the windows are mainly a result of the presence of carbon dioxide (CO_2) and water vapor (H_20) in the atmosphere. The major absorption bands caused by the water vapor occur at 1.4, 1.9, 2.7, 3.2, and 5.5 to 7.5 μm, and those caused by carbon dioxide occur at 2.7, 4.3, and 14 to 16 μm. The absorption of the EM radiation from Earth by these atmosphere gases and the subsequent warming of climate is known as the greenhouse effect (Note 81).

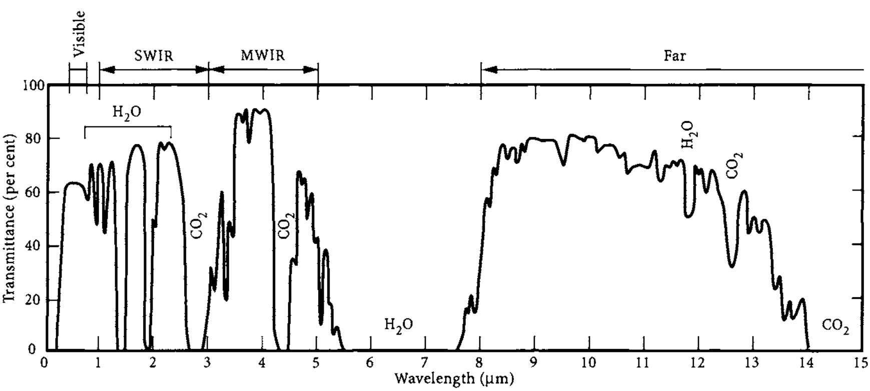

Fig. 3.67 Atmospheric attenuation of IR radiation.[49]

The altitude at which the radiation propagates also has a major effect on the amount of atmospheric absorption by the CO_2 and H_2O molecules. At sea level the water vapor level is relatively high, and the attenuation is significant, as shown in Fig. 3.67. However, as the altitude increases the H_2O level decreases rapidly. At 20,000 ft the amount of water vapor is less than 20% of the sea-level value, and at 40,000 ft the IR attenuation caused by H_2O is quite small. Fog and clouds, because they are heavy concentrations of water vapor, are strong absorbers of IR radiation. Transmittance of 1-μm IR radiation through a typical cloud is estimated to be only 1% for a path length of approximately 400 ft (Refs. 50 and 51).

The absorption caused by CO_2 also decreases as the altitude increases, but not as drastically as the change caused by H_2O. The relative concentration of CO_2 molecules in the atmosphere remains essentially constant with respect to altitude. Thus, the absorption by CO_2 decreases only because the atmospheric density decreases. When the absorption by CO_2 is nearly total at sea level, it will be less than 20% per nautical mile at 40,000 ft.

Scattering of IR radiation occurs as a result of the presence of molecules, haze, fogs, and aerosols in the atmosphere. Rayleigh scattering is caused by atmospheric particles that are small with respect to the wavelength. The effect of these small particles on IR radiation scattering usually is small. Mie scattering refers to scattering by particles that are large compared with the wavelength, such as water droplets. This type of scattering is essentially independent of the wavelength when the particle is very much larger than the wavelength.

Several computer programs have been developed that predict the extinction of radiation as it propagates through the atmosphere. Perhaps the most widely used models are the original Low Resolution Atmospheric Transmission Code (LOWTRAN), the improved Moderate Resolution Atmospheric Transmission Code (MODTRAN),[52] and the Moderate Spectral Atmospheric Radiance and Transmittance code (MOSART).[53]

Go to Problems 3.6.55 to 3.6.58.

3.6.3.4 Infrared detectors.

Learning Objective **3.6.21 Describe the operation of IR detectors.**

An IR detector is typically a small, thin film or plate of IR sensitive material that is thermally isolated from its surroundings and whose electrical properties change when subjected to IR radiation. Detectors sensitive to radiation within the 1–14-μm band are the most common. There are two major categories of detectors: thermal detectors and photon detectors.

Thermal detectors. Thermal detectors require a change in temperature to function and include devices such as bolometers and thermopiles. A bolometer can be a semiconductor or thermistor that exhibits a change in an electrical property when it is heated by IR radiation. A thermopile consists of two dissimilar metals joined together. When the thermopile is heated by IR radiation, a voltage across the metals is produced. Thermal detectors are generally slower to respond and are less sensitive than the photon detectors. However, they are usually nonselective with respect to wavelength.

Photon detectors. Photon detectors do not require a temperature change to function. Consequently, they are more sensitive and are faster to respond than thermal detectors. However, their output is usually strongly dependent upon the wavelength of the IR radiation. They normally function somewhere within the 2–14-μm band. The photon detector is usually a semiconductor and works on the quantum effect. There are several types of photon detectors, such as the photoconductors, photovoltaic detectors, charge-coupled devices, and charge-injection devices.

An idealized spectral response of an uncooled photon detector at room temperature is shown in Fig. 3.68. When the incident radiation wavelength is long, the photons do not have enough energy to knock an electron from the valence band of the atom across the forbidden gap to the conduction band, so there is no change in the electrical properties (Note 82). When the wavelength reaches a value known as the cutoff value, the photons have enough energy to knock the free electrons across the forbidden gap and into the conduction band, resulting in either a change in electrical voltage, conductivity, or current. The downward slope of the response curve for wavelengths shorter than the cutoff value is due to the fact that the power in the incident radiation is the same for all wavelengths; consequently, the number of photons per unit of time reduces as the energy per photon increases. Some photon detectors are cooled in order to lower the noise level in the detector. Furthermore, cooling the detector reduces the photon energy required to free the electrons and consequently extends the sensor bandwidth into the longer wavelengths. The consequences of cooling the detector are illustrated in Fig. 3.68. Note that the cooled detector, also known as a cooled seeker, has an increased response and can 'see' longer wavelengths.

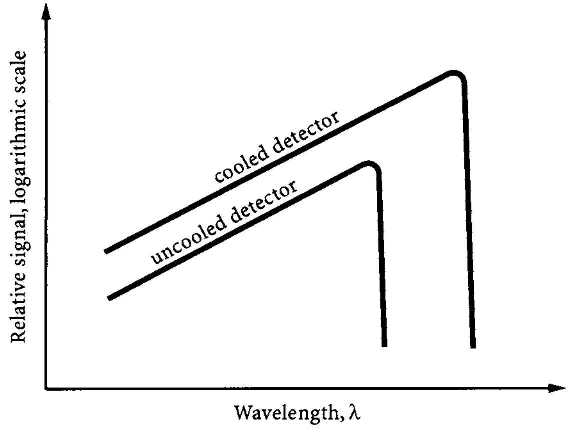

Fig. 3.68 Idealized spectral responses of uncooled and cooled photon detectors.

Figure 3.69 shows the spectral response of three IR detector materials: lead sulfide (PbS), cooled indium antimonide (InSb), and cooled mercury cadmium telluride (HgCdTe). The IR detectors used in the first generation IR missiles most likely included PbS, which peaks at 2 μm. Radiation in the 1–3-μm band comes mainly from very hot parts on the aircraft, from the solar reflection from the airframe and canopy, from the sun, and from the solar reflection from clouds, trees, snow, Earth, etc. More recent generations of IR missiles might use InSb. When cryogenically cooled to 77 K, InSb is most sensitive at 5 μm and can detect radiation in the 3–6 μm band (Note 83). Radiation in this band comes from the hot parts on the aircraft and from the hot CO_2 in the engine exhaust. The HgCdTe detector

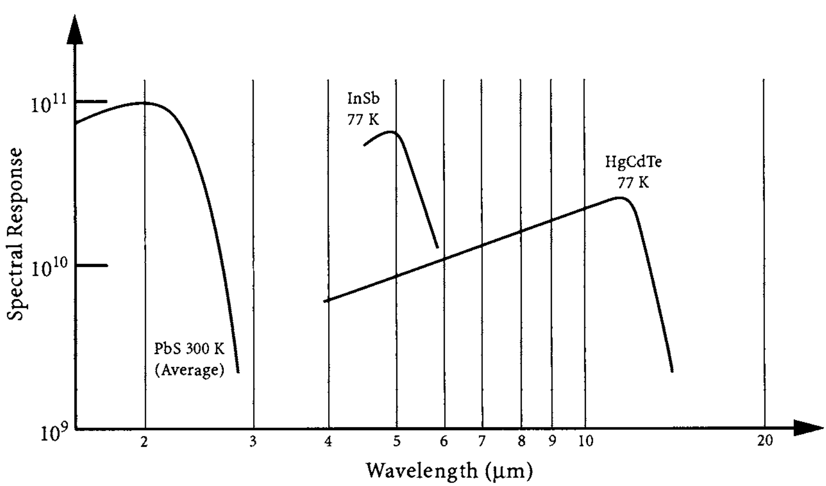

Fig. 3.69 Spectral response of three IR detector materials.[56]

material is a relatively recent development that, when cooled, responds to radiation in the 8–12 mm band and is used in two-dimensional FPAs.[54,55] (More data are available online at http://www.frost.com/prod/servlet/fcom?ActionName=DisplayReport&id=A020-01-00-00-00&ed=1&fcmseq=1026421612867, http://www.usdoj.gov/atr/cases/f7100/7132.pdf, and http://ewhdbks.mugu.navy.mil/EO-IR.htm.)

Modern IR detectors may be composed of two materials that have different bandwidths. Because each bandwidth is a different 'color,' these detectors are known as two-color detectors. The ability to sense radiation in two different bands, such as the 1–3-μm and the 3–5-μm bands, gives them the potential capability to distinguish an aircraft from surrounding radiators. For example, the radiation from the sun or other very hot body, such as an IR flare, has considerably more power in the 1–3-μm band than the 3–5-μm band. On the other hand, an aircraft has considerably more radiation in the 3–5-μm band than the 1–3-μm band (http://www.spie.org/web/oer/april/apr99/cover2.html).

Go to Problems 3.6.59 to 3.6.63.

3.6.3.5 More information on IR radiation. More information on IR radiation can be found online at http://www.omega.com/literature/transactions/volume1/historical1.html and http://www.infoplease.com/ce6/sci/A0825202.html.

Finally, a special center, known as the Infrared Information and Analysis Center (IRIA), has been set up by the Department of Defense as a focal point for the collection of infrared and electro-optical information. The IRIA is currently operated by the Systems Division, Veridian. The IRA is online at http://www.iriacenter.org/iriaweb.nsf?open. The following description is taken from the "About IRIA" link.

> The IRIA was established in 1954 at the Willow Run Laboratories to facilitate the exchange of information within the Department of Defense infrared community. The center is now a DoD Information Analysis Center sponsored by the Defense Technical Information Center and monitored by the Associate Director for Science and Technology, Army Night Vision and Electronic Sensors Directorate. IRIA's mission is to collect, analyze, and disseminate information on infrared and electro-optical (IR/EO) technology with an emphasis on military applications. IRIA administers the following symposia: National Military Sensing Symposium (MSS, formerly IRIS); Active Systems; Infrared Countermeasures; Infrared Detectors; Infrared Materials; Passive Sensors; Missile Defense—Models, Environment, and Atmospheres (formerly Targets, Backgrounds, and Discrimination); National Symposium on Sensor and Data Fusion; Camouflage, Concealment, and Deception; and Battlefield Acoustic and Seismic Sensing.
>
> In addition to core functions and MSS administration, IRIA performs a wide variety of technical area tasks to meet the needs of the DoD, other government agencies, and commercial sponsors. IRIA also operates a comprehensive library holding approximately 60,000 infrared/electrooptical technical documents. An associated bibliographic database is maintained to respond to technical and bibliographic inquiries from qualified users. Subject coverage in the electro-optical technology area includes the following: sources of electromagnetic radiation from the ultraviolet through far infrared spectral regions; radiation characteristics of

natural and human-made targets; optical properties of materials; detection materials and elements; information processing as it pertains to sensory collection of data; masers (microwave amplification by stimulated emission of radiation) and lasers (light amplification by stimulated emission of radiation); imaging systems such as forward looking infrared, scanners, staring systems, and image tubes; optical systems and components; detector and system coolers; atmospheric absorption, emission, and scattering; and search, homing, tracking, ranging, countermeasures, reconnaissance, and other military infrared and laser systems.

IRIA prepares and disseminates a variety of special publications, including handbooks, data books, state-of-the-art reports, critical reviews, technical assessments, newsletters, and announcements. *The Infrared and Electro-Optical Systems Handbook*, an eight-volume, unclassified document released by the IRIA Center in July 1993, is the foremost publication in the IR/EO technical area. IRIA collects and publishes the minutes and proceedings of the annual IRIS and the meetings of the specialty groups of IRIS just listed. The proceedings of these meetings constitute a comprehensive record of recent scientific and technical advances in the military infrared and electro-optical fields. IRIA also provides associated incidental technical and administrative support for these meetings.

3.6.4 List of the Important Radar and Infrared Equations

The following subsection present lists of the important equations developed in this section.

3.6.4.1 Decibels.

$$\alpha \text{ measured in decibels} = 10 \times \log_{10}(\alpha) \tag{3.15}$$

3.6.4.2 Radar equations.

$$c = \text{velocity of EM radiation in a vacuum} = 300\,\text{m}/\mu\text{s}$$

$$f = \text{radar wave frequency (cycles per second)}$$

$$\text{Target range} = R = c(\Delta t)/2 \tag{3.14}$$

$$\text{Wave period} = T = 1/f \text{ (seconds per cycle)} \tag{3.16}$$

$$\text{Wavelength} = \lambda = cT = c/f \tag{3.17}$$

$$\text{Pulse width} = \tau$$

$$\text{Pulse repetition frequency} = \text{PRF (pulses per second)}$$

$$\text{Pulse repetition interval} = \text{PRI (seconds per pulse)} = 1/\text{PRF}$$

$$\text{Maximum unambiguous range} = R_u = \frac{c\,(\text{PRI})}{2} \tag{3.18}$$

$$\text{Target resolution distance} = \Delta R = c\tau/2 \tag{3.19}$$

$$\text{Duty cycle} = \tau/\text{PRI} \tag{3.20a}$$

$$\text{Average power} = P_{\text{av}} = P_{\text{peak}} \cdot (\text{duty cycle}) \tag{3.20b}$$

$$\text{Doppler shift} = f_d = 2fV_r/c = 2V_r/\lambda \tag{3.21b}$$

$$\text{Relative radial velocity} = V_r = cf_d/(2f) = \lambda f_d/2 \tag{3.21c}$$

$$\text{For unambiguous velocity, } (f_d)_{\max} \leq 1/\text{PRI} = \text{PRF} \tag{3.22}$$

$$\text{Antenna planar area} = A, \quad \rho = \text{antenna efficiency}$$

$$\text{Antenna gain} = G_r = 4\pi\rho A/\lambda^2 = 4\pi A_e/\lambda^2 \tag{3.23}$$

$$\text{Antenna beamwidth (in degrees)} = b\lambda/D \tag{3.24}$$

3.6.4.3 IR equations.

$$\text{Blackbody radiant exitance } M_e = \sigma T^4 \quad (\text{W/cm}^2) \tag{3.25}$$

$$\sigma = 5.6697 \times 10^{-12} \quad (\text{W/cm}^2 - \text{K}^4)$$

$$\text{Gray-body radiant exitance } M_e = \varepsilon\sigma T^4 \quad (\text{W/cm}^2) \tag{3.26}$$

$$\text{Emissivity} = \varepsilon \quad (\text{Table 3.14})$$

$$\text{Planck's law (Fig. 3.65a)}$$

$$M_\lambda = \frac{\varepsilon_\lambda C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \quad (\text{W/cm}^2\mu\text{m}) \tag{3.28}$$

$$C_1 = 3.74177 \times 10^4 \quad (\text{W} - \mu\text{m}^4/\text{cm}^2)$$

$$C_2 = 1.43877 \times 10^4 \quad (\mu\text{m} - \text{K})$$

$$\text{Wein's displacement law, } \lambda = 2898/T \approx 3000/T \quad (\mu\text{m}) \tag{3.29}$$

$$\text{Radiant exitance in detector bandwidth (Fig. 3.65b)}$$

$$= M(\lambda_1 \leq \lambda \leq \lambda_2) = \int_{\lambda_1}^{\lambda_2} M_\lambda \, d\lambda \tag{3.30}$$

3.7 Threat Operations

Learning Objective **3.7.1 Describe the threat operations subfield.**

Threat operations are influenced by those environmental factors and inherent capabilities that relate to the ability of the threat to perform its basic search, detection, track, fire or launch, and guidance and navigation functions. The sequence of threat operational functions and events in almost any encounter between an aircraft and a threat is somewhat the same, regardless of the type of threat. This sequence of functions and events has been described in some detail in Secs. 3.2.2 and 3.2.3. Some of the important factors and elements of threat operations not presented there are described in the following Section.

Go to Problem 3.7.1.

3.7.1 Environmental Factors

Learning Objective 3.7.2 Describe the environmental factors associated with threat operations.

These factors include the mobility of the threat, its locational adaptability, and its day/night and weather capability.

3.7.1.1 Mobility. Mobility refers to the ease with which a threat can be moved. Factors involved are the effort required for disassembling, loading, transporting, and setting up a new location so that effective firing or launching can be achieved. The measures of mobility are the operational time at one location and the downtime required to move from one operating site to another. Many gun systems and some missile systems are mounted on wheeled or tracked vehicles and can fire on the move or shortly after stopping.

3.7.1.2 Locational adaptability. This refers to the ability of a threat to adapt to the sites at which its operation is desired in a combat environment. Factors that must be considered in site selection for the threats are the area required, the smoothness of terrain, access to a road or highway, the class of highway required for transporting the threat, etc.

3.7.1.3 Day/night and weather capability. Weather capability refers to the ability of a threat to track and deliver the propagator to an aircraft during specified variations in visibility, cloud cover, or light conditions. Generic measures of weather with respect to tracking capability include clear day, clear night, hazy, and all weather.

Clear day. The ability to maintain track under daylight conditions with no intervening clouds and with required visibility.

Clear night. The ability to maintain track with no cloud or visibility constraints, but with reduced light level (i.e., half-moon, quarter-moon, etc.).

Hazy. A qualifier for day or night capability to indicate an increased amount of particulate matter in the air (i.e., smoke, dust, etc.), which will degrade the tracking effectiveness.

All weather. The ability to maintain track with extremely low light levels, complete cloud cover, or minimal visibility.

Go to Problem 3.7.2.

3.7.2 Search, Detection, and Tracking Capabilities and Methods

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Learning Objective **3.7.3** **Describe the search, detection, and tracking capabilities and methods of the threat sensors.**

One goal of the nonterminal threat elements is the detection, identification, and accurate tracking of aircraft, and possibly the propagator, too. The desired information on each aircraft consists of its azimuth, elevation, range, heading, and airspeed. The ability of the threat to obtain some or all of this information in sufficient time to launch or fire a propagator is dependent upon the equipment used, the target, and the scenario. Searching and tracking can be done with radar, the human eye (with or without the assistance of either direct-view optical or electro-optical devices), the human ear (aided or unaided), lasers, IR missile seekers, and forward-looking IR and IR search and track devices. Some of the important search, detection, and tracking capabilities are the initial reaction time, maximum slew rate, target detection range, acquisition time or time to acquire the target, and the maximum tracking rate as described in the following subsections. The method of tracking used by the threat system has a major effect on the ability of the system to accurately locate the target. Consequently, several of the tracking methods used by radar, infrared, and visually directed systems are also described in the following Subsections.

3.7.2.1 Initial reaction time. This is the time interval that elapses between the time an air defense element is made aware of a need to be fully operational and the time the element is ready to begin its normal operational mode against the target aircraft. The functions that can be accomplished in parallel during this time interval consist of getting personnel in "combat ready" positions and transferring the equipment from a standby alert status to a fully operational status.

3.7.2.2 Maximum slew rate. This is the maximum angular velocity in both azimuth and elevation at which the tracking carriage of the threat can be rotated in order to begin tracking and engaging an aircraft that was in a different sector of the sky than the carriage had been initially pointing. The parameters that influence the maximum slew rate include the mass or weight of the equipment to be rotated and the electrical, mechanical, or hydraulic power available to rotate the equipment.

3.7.2.3 Target detection range. The target detection range is the maximum range a target can be detected with a certain probability and an associated probability of false alarm. It is expressed numerically with respect to a target signature of a standard size. For example, the maximum detection range of a radar system is usually given for a target with a 1-m^2 radar cross section.

3.7.2.4 Acquisition time. This is the elapsed time from the time of alert to the time the tracker has detected and acquired the target.

3.7.2.5 Maximum tracking rates. These are the maximum rates in azimuth and in elevation that the tracking carriage can be rotated while measuring the aircraft's position vs time.

3.7.2.6 Radar tracking methods.

Track-while-scan. Aircraft at long distances are usually tracked by pulse radars using the track-while-scan method of tracking. Track-while-scan radars scan an unlimited or limited angular sector in a regular manner and develop one or more target tracks with data obtained at the (sector) scan rate rather than continuously, as in the case of a single-target tracking. The scan can be accomplished using a single-beam antenna or two orthogonal fan beams. During each scan, the target will be illuminated for a brief period of time. Keeping track of the target's position during each scan provides the history of the target's flight path.

Tracking by weapon control radars. When the decision is made that the aircraft is a threat and is within the range of a weapon control radar, the current aircraft or target information is passed to the assigned radar. Weapon control radars are pulse radars or pulse-Doppler radars and normally operate over a small volume of space and handle relatively few targets. They mechanically or electronically move the radar beam using circular, spiral, sawtooth, helical, raster, or random types of scanning. The output from the weapon control radar is used to determine the target's flight path, and a prediction of the target's future position is then made, usually by a computer, so that the threat platform or propagator can be pointed in the correct position to cause a propagator intercept. The weapon control radar usually must obtain an accurate measurement of the target location in both range and angle in order to generate a small propagator miss distance. There are two general techniques used by weapon control radars to track a single target in angle: conical scan and monopulse.

Conical scan tracking: A conical scan or con-scan tracker can use a feed horn that moves in a circular path around the boresight of a parabolic dish antenna. This circular movement causes the axis of the pencil beam from the parabolic antenna to rotate around the axis or boresight of the antenna, as shown in Fig. 3.70. The progression of echos from a target that is not located on the boresight will be modulated in amplitude as the horn rotates. When the beam axis is closest to the target, the echo is the strongest; and when it is farthest, the echo is the weakest, as illustrated in the diagram at the bottom of Fig. 3.70. Adjusting the antenna boresight until there is no modulation of the target echo centers the target on the boresight, provided the target echo is constant for each pulse. If the aircraft's signature changes significantly between pulses, known as scintillation, the radar will have difficulty determining exactly when the aircraft is on the boresight.

Monopulse tracking: Monopulse, also known as simultaneous lobing, is a very accurate tracking technique that uses a cluster of several antennas or feed/receive horns, as shown in Fig. 3.71. A single composite pulse or beam is transmitted by the cluster (A, B, C, and D). The composite pulse strikes an aircraft, and each antenna in the cluster subsequently receives a different echo, as illustrated by the amplitude data shown in Fig. 3.71, because the different return path from the target to each

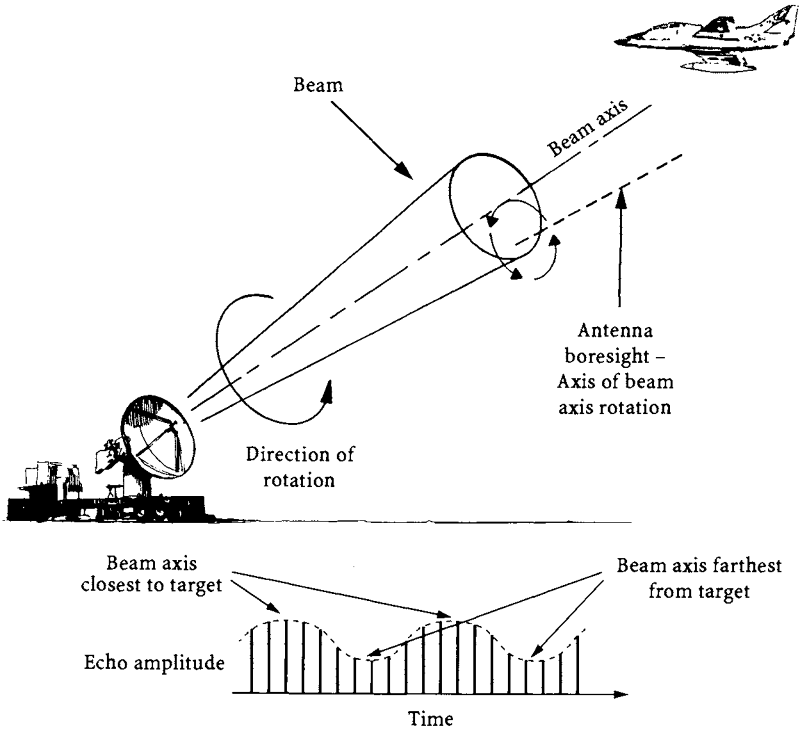

Fig. 3.70 Conical scan tracking.

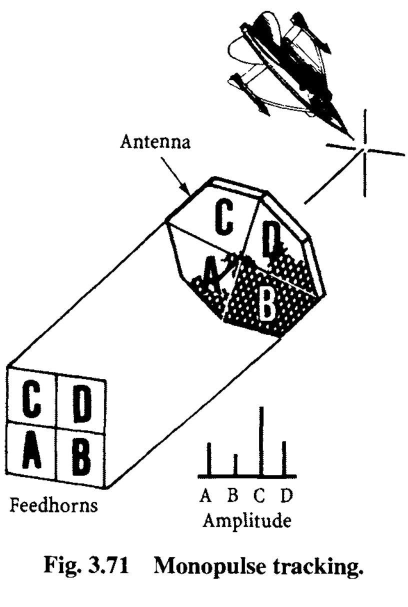

Fig. 3.71 Monopulse tracking.

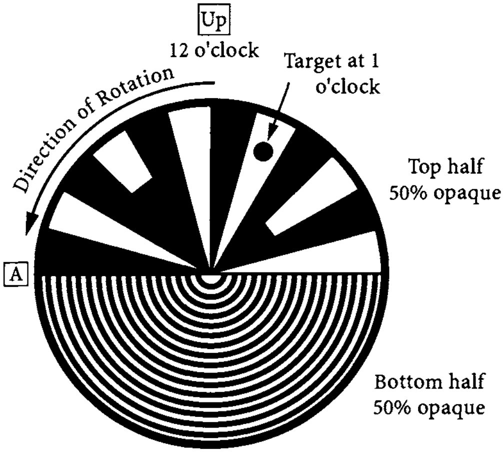

Fig. 3.72a Pattern for a spinning multiple-frequency reticle.

antenna. The range to the target is determined using the transit time of the sum of the returns from each antenna Δt and Eq. (3.14). The direction or angle to the target is determined by comparing the signals either in phase or in amplitude. The target is tracked by moving the beam until the difference between either the phase or the amplitude of the echoes received simultaneously at pairs of antenna locations is minimized or nulled. Arrangements of four orthogonal antennas or feeds (as shown in Fig. 3.71) can be used to determine both azimuth and elevation. For the antenna illustrated in Fig. 3.71, the difference between the sum of the echoes in C and A and the sum of the echoes in D and B is a measure of the azimuth error, and the difference between the sum of the echoes in A and B and the sum of the echoes in C and D is a measure of the elevation error. This method can be much superior in accuracy to the conical scan, and because it does not require repeated pulses to locate the angular position of the target (hence the name monopulse) it is much more difficult to deceive with countermeasures. A less sophisticated version of monopulse, known as lobe-on-receive-only (LORO) or scan-on-receive-only (SORO), transmits a burst of composite pulses and examines the individual echoes in each antenna location (the lobe) one at a time (the first pulse echo is received in A, the second pulse echo is received in B, the third pulse echo is received in C, and so on), as opposed to the simultaneous single-echo/multiple-antenna processing of monopulse.

3.7.2.7 IR tracking methods. Aircraft can be tracked by IR seekers by modulating the incident radiation with reticles, by scanning, and by using imaging devices.

Reticle trackers. A reticle tracker is a seeker that has a reticle placed in front of a single detector, as shown in Fig. 3.63. The reticle has a spatial pattern of varying IR transmission. The reticle can either be spinning (spin-scan), or it can be stationary, and the incident illumination is rotated about the center of the field of view

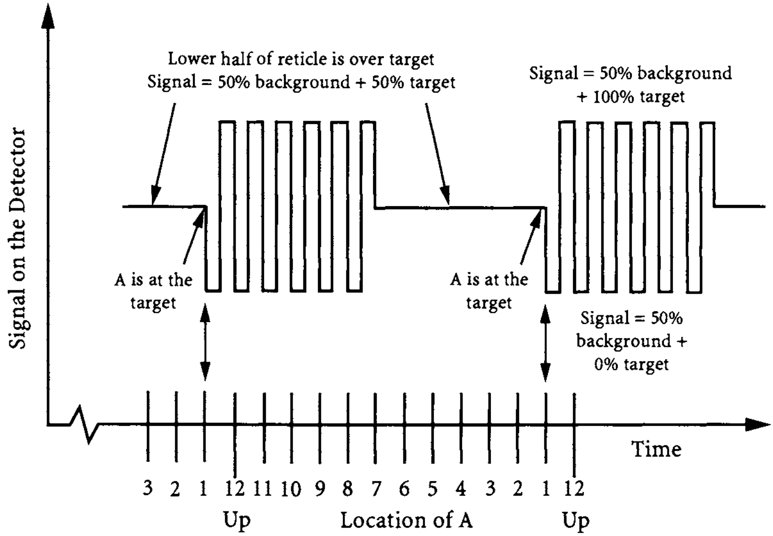

Fig. 3.72b Radiation on the detector vs time.

(con-scan). Both types modulate or chop the incident radiation. This modulation can be used both to track the target in polar angle (and possibly radius) and to exclude the background, thus improving the signal-to-noise ratio. Spinning reticles are often referred to as amplitude modulation, frequency modulation, or multiple-frequency. One simple example of a spinning multiple-frequency reticle is shown in Fig. 3.72a.

The assumption is made that the target is sufficiently far away so that it appears to be a small source. Consequently, the radiation from the target is represented by the dot at 1 o'clock in Fig. 3.72a. Both halves of the reticle allow approximately 50% of the incoming radiation to pass through. Consequently, the radiation from a nonuniform background in the field of view of the seeker (which is noise to the tracker) will be essentially constant as the reticle spins, whereas the radiation from the small source target will be chopped or modulated over one-half of the reticle and will be constant at the 50% value over the other half. The radiation on the detector is shown in Fig. 3.72b as a function of time and hence of the angular position of the reticle. The peak values occur when the target is in the open spaces between the opaque spokes, and the minimum values occur when it is behind the opaque spokes. Only the modulation of the signal is of interest. The steady noise caused by the background radiation can be eliminated by signal processing. Although the signal chopping improves the signal-to-noise ratio, it also reduces the efficiency of the seeker because only the modulated signal is available for processing.

For the reticle shown in Fig. 3.72a, the directional or polar location of the target with respect to the optical axis of the field of view can be determined by noting the timing of the initiation of the sequence of modulations. For example, a magnet pickup could be located on the body of the missile at 12 o'clock, or the up position, as shown in Fig. 3.72a. If a magnet is located on the reticle at location A, a timing signal will be generated every revolution when A is up. The polar angle to the target with respect to the optical axis can be determined by noting the time difference between the initial drop in signal strength when A passes in front of the target and when A is up, as illustrated in Fig. 3.72b. Because the drop in signal occurs at a time corresponding to 1/12 of a revolution before A is up, the target is at 1 o'clock. The radial location can be determined by examining the number of modulations during each revolution. This particular reticle has three radial bands, the inner band with four windows, the middle band with five windows, and the outer band with six windows. When the target is centered on the optical axis, no modulations occur; consequently, this particular reticle is called a null tracker. As the target moves off of the optical axis, modulations will occur. There are six modulations in Fig. 3.72b because the target is in the outer band. Thus, the number of the modulations and their timing determine the angular and radial tracking signal for the missile. The tracking platform can be moved in an attempt to position the target on the optical axis. Once the target is on the optical axis, the angle between the optical axis and the missile axis becomes the line-of-sight angle.

Another type of reticle tracker uses the wagon wheel reticle shown in Fig. 3.73a. In this tracking scheme the reticle is stationary, and the seeker optics projects the radiation from the target along a circular path over the reticle. Two paths are shown in Fig. 3.73a. When the target is on the optical axis, the circular signal path (denoted by the solid line) is centered at the center of the reticle. When the target is off of the optical axis, the circular path (denoted by the dashed line) sweeps over an asymmetrical area of the reticle. The signal incident upon the detector for both the on-axis and off-axis targets is shown in Fig. 3.73b. Note that the signal strength and the duration of the signal are constant for each of the tranparent portions of the reticle when the target is on the optical axis. However, when the target is off axis the signal strength in each portion is constant, but the duration differs. The irregular durations can be processed by the tracker to determine the location of target within the seeker's field of view. This particular tracking scheme is analogous to the conical scan tracking used by a radar tracking system; in radar

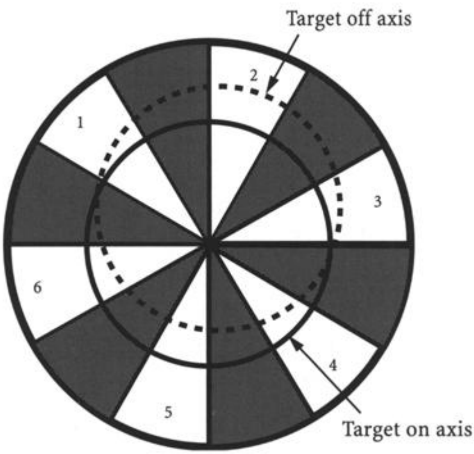

Fig. 3.73a Wagon-wheel reticle.

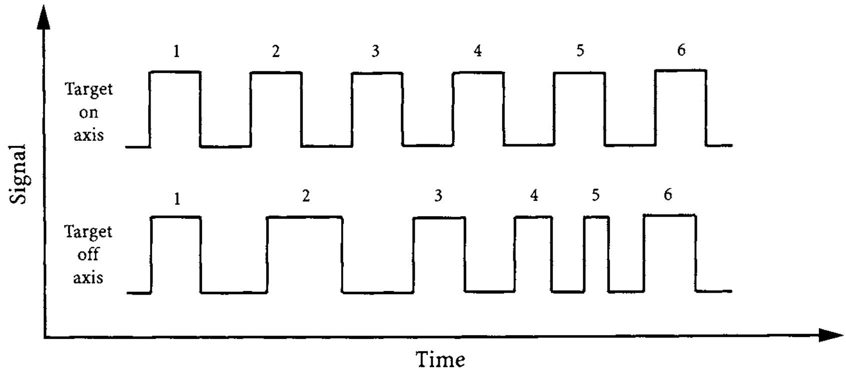

Fig. 3.73b Radiation on the detector vs time.

conical scanning the signal strengths from the echoes are compared, whereas the signal durations are compared in IR tracking. One advantage of the wagon-wheel reticle over the reticle shown in Fig. 3.72a is that the signal is 'strongest' when the target is on axis. The opposite is true for the multiple-frequency reticle; there is essentially no signal when the target is on axis.

Reticles more complicated than these two reticles are sometimes used to degrade the effects of countermeasures and to reduce the effects of strong gradients in the background radiation from features such as cloud edges.

Scanning trackers. A scanning tracker consists of one or more relatively small detectors. Each detector has an instantaneous field of view that is a fraction of either the field of view or the field of regard of the seeker. A tracking logic circuit scans the field of detectors, one at a time. When a detector indicates that the incident radiation has exceeded a threshold value, the logic circuit notes the position of the instantaneous field of view of that detector. The signal processor accumulates the information from all of the instantaneous fields of view and determines the target polar and radial position within the seeker's field of view (or field of regard) during that scan. When the target lies within only one detector's instantaneous field of view, the target location is well defined, and multiple small targets can be resolved. For a large target seen by several detectors, the signal processor can track a particular location on the target, such as an edge or other identifiable point.

There are several types of scanning trackers, such as the rotating linear array, with its rotating line of detectors, the crossed array that uses conical scanning on four detectors arranged in a cross, and the rosette tracker.[57] The rosette tracker uses a single, fixed detector that is illuminated by the radiation incident on an optical device that has a relatively small instantaneous field of view. The optical device can consist of two counter-rotating optical elements (a prism and the secondary mirror) and scans the seeker field of view in a rosette pattern that consists of a number of loops or petals emanating from a common center, as illustrated in Fig. 3.74. When the optical device 'sees' the target, it directs the target's IR radiation on to the detector. The resultant signal from the detector tells the tracking circuit that a source of IR radiation is located at the particular instantaneous field

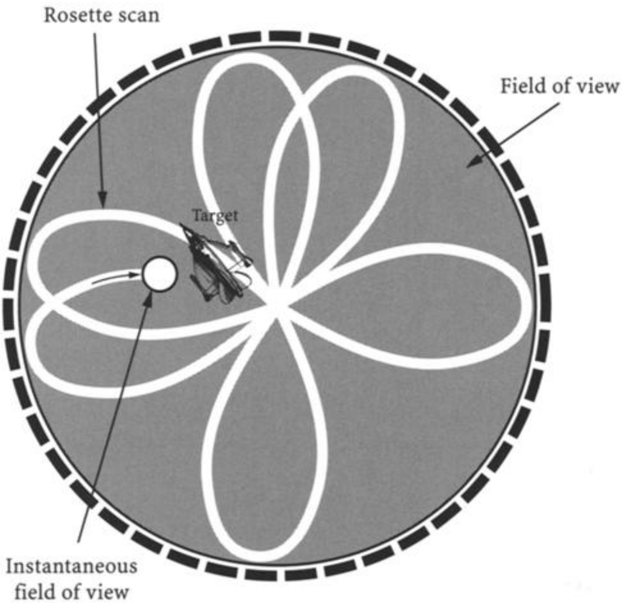

Fig. 3.74 Typical rosette pattern of a scanning tracker.

of view seen by the optical device (within the seeker field of view). No modulation of the incident radiation is required by this type of tracker.

Imaging trackers. An imaging tracker develops the total image within the seeker's field of view, and the target is tracked using techniques such as gated video or correlation. The two-dimensional image can be developed using a line of detectors and a linear raster scan or hundreds of detectors arranged in a two-dimensional array known as a focal plane array. The FPA is the most recent develoment in the evolution of IR seekers. The absence of a scanning mechanism in the FPA allows the tracker to be packaged in relatively small configurations. These trackers have the potential to detect and track specific locations on aircraft and to reject flares based upon the spatial distribution of the IR radiation.

Go to Problems 3.7.3 to 3.7.17.

3.7.2.8 Visually directed detection and tracking systems. A visually directed system is one that uses the human eye as the sensor for detecting and tracking aircraft. Many different threat systems use the visual signature of the aircraft for detection, and some use it for tracking, either as the primary signature or as a backup. The gun systems that use the visual signature are usually short to medium range and vary from hand-held and airborne guns to the larger AAA systems. Some short-range missile systems require visual detection prior to tracking using other signatures, and some medium-range missile systems have the capability to detect and accurately track the visual signature. The detection and tracking devices used by visually directed systems include iron sights, direct-view optical telescopes and periscopes with cross-hairs or range rings, and electro-optical imaging equipment, such as low-light-level television (LLTV).

The detection and tracking capabilities of these passive systems vary widely from very poor to highly accurate. Under good visibility conditions, direct-view optical and electro-optical trackers can provide angular tracking data accuracy equal to or better than radar, particularly for low-flying and maneuvering aircraft and when radar countermeasures are employed.

3.7.3 Firing and Launch Capabilities

Learning Objective 3.7.4 Describe the firing and launch capabilities of the threat terminal elements.

Some of the important firing and launch capabilities for a typical fire unit or device are discussed in detail in the following Subsections.

3.7.3.1 Firing and launch angles. Most surface-based mobile guns are capable of a full 360-deg range of azimuthal coverage. Guns emplaced in a fixed site are usually restricted in azimuth. All guns have upper and lower elevation limits. Typical elevation limits are −20 deg to +90 deg for small arms and −5 deg to +85 deg for AAA. Airborne guns are usually forward pointing and are carried internally or in a pod attached to the airframe, although helicopters and some large aircraft might have a gun turret.

Surface-based guided missiles are typically launched from rails or canisters that are fixed in elevation relative to the launching platform. Some rails can rotate through a limited range of azimuth. Man-portable missiles are launched from canisters typically pointed ahead and above the target aircraft by the gunner.

3.7.3.2 Rate of fire. Medium and heavy AAA are typically single-barrel weapons that fire single rounds continuously in slow succession. However, when several heavy AAA pieces are located at a central site, one gun might fire rapidly at the target for a short period of time, such as 1 or 2 s, while the other guns are silent. Each gun takes its turn firing at the target while the other guns cool down.

Light AAA and most small arms are automatic weapons that fire a number of rounds in rapid succession from one or more barrels, either continuously or in short bursts. The cyclic rate of fire is the theoretical maximum number of rounds fired per minute. The practical rate of fire is much lower because of ammunition restrictions, barrel heating, and firing doctrine. The number of rounds fired per burst can depend upon the range to the target. For targets at long range, short bursts of 2 to 10 rounds can be fired. For targets at medium to short range, longer bursts of 10 to 20 rounds can be fired. The cooling time between bursts usually depends upon the burst length, with 0.5 to 1 s between short bursts and 1 to 3 s between long bursts.

Table 3.16 Typical rates of fire of guns

Gun	Practical rate of fire, rounds per min per barrel
Small arms	≈100–400
Light AAA	≈100–600
Heavy AAA	≈10–70

A typical range of values for the rate of fire for various gun sizes is given in Table 3.16. The rates of fire given in Table 3.16 refer to a single barrel. Thus, if a gun system has four barrels the rate of for the system would be four times the rate of fire for the single barrel. For example, a four-barrel gun system with a practical rate of fire of 360 rounds per barrel per minute would fire 12 rounds in a 0.5 s burst.

3.7.3.3 Salvo and ripple fire. Salvo refers to the number of missiles launched at an aircraft in a relatively short period of time. For example, when two missiles are sequentially launched at a target in a shoot-shoot-look mode, the salvo is two. Ripple fire is the rapid firing of several missiles.

Go to Problems 3.7.18 to 3.7.19.

3.7.4 Fire Control Factors

Learning Objective **3.7.5 Describe the fire control factors.**

Fire control factors consist of the types of fire control, the types of coverage, and the types of errors.

3.7.4.1 Types of fire control. The usual types of fire control are an open sight, an on-mount direct-view optical or mechanical lead computing sight, radar, and electro-optical, possibly with nighttime capability. Small arms and light AAA typically use either the open or on-mount sight, whereas most medium and heavy AAA and guided missile systems use radar and/or a direct-view optical or electro-optical device, such as a FLIR.

3.7.4.2 Types of coverage. The types of coverage assigned to guns are aimed fire (at a specific target), sector intercept (fire directed to a sector of air space), barrage fire (general coverage of the air space at various altitudes), and curtain fire (weapons are aimed at a location in front of the target and bursts are fired until the target has passed through the aim point).

3.7.4.3 Types of errors. There are three major fire control errors: tracking error, aiming error, and lead-angle prediction error.

Tracking error. Tracking error is the error introduced into the firing or launch and guidance operations of a threat system by the inability of the tracking system to provide an exact record of the aircraft flight path. Tracking data are utilized by the air defense for many purposes, such as alerting appropriate fire units, establishing air defense tactics, establishing lead-angle information for weapon firing, and propagator guidance. Therefore, the source and magnitude of tracking errors are very significant factors in air defense effectiveness. The term tracking error is used to represent the net effect of all contributors or sources in specifying target position and rate data.

Aiming error. Aiming error is the error introduced into the firing or launching operations of threats caused by the inability to correctly position or aim the appropriate equipment in a desired direction. Aiming errors are used to represent those errors involved in pointing or positioning a device such as a weapon or weapon platform at the desired point predicted by the fire control system. These errors can stem from a human interface, from a machine, or from a combination of both. As an example, pilot aiming error results from an interaction between the pilot and the response of the aircraft.

Lead-angle prediction error. Lead-angle prediction is that fire control computational process used to establish the desired weapon positioning or aiming information. All weapons that fire ballistic projectiles must have some means of solving the fire control problem. From the measurement of current target position and velocity, the future target position must be estimated, weapon aim angles determined, and the weapon positioned and fired so that the projectile and the target will arrive at the same point in space (the intercept point) simultaneously. Many prediction methods use a linear extrapolation of the target's trajectory (assuming a constant velocity vector) to estimate the future target position. Lead-angle prediction error is the projectile miss distance resulting from errors in the prediction of the target flight path. Prediction errors can be the result of unexpected or evasive target maneuvers during the flight time of the projectile, known as jinking, or caused by limitations in the process used to predict future target position. The prediction error for any firing situation is usually defined as the distance from the predicted intercept point to the target's actual position at the time of intercept.

Jitter. Jitter is the combination of aiming and tracking errors produced by rough motion of the weapon system.

Go to Problems 3.7.20 to 3.7.23.

3.7.5 Trajectory Factors

Trajectory factors relate to or influence the missile or projectile path from the platform to the aircraft. These factors can be divided into two categories: those associated with ballistic propagators and those associated with guided missiles.

3.7.5.1 Ballistic projectiles.

Learning Objective	**3.7.6 Describe the trajectory factors associated with ballistic projectiles.**

There are several factors that affect the trajectory of ballistic projectiles.

Gravity drop. Gravity drop is a measure of the displacement of the flight path of a ballistic projectile attributable to gravitational force. The gravity drop is proportional to the time of flight and has been approximated by $gt^2/2$, where g is the gravitational force and t is the time of flight.

Ballistic dispersion. This is the scatter of impact points of projectiles about a mean point under fixed firing conditions and exclusive of aiming and installation factors. Ballistic dispersion refers to those variations in the impact point attributable only to gun and ammunition characteristics. Causes of ballistic dispersion are weight and surface variations between projectiles, variation in burning efficiencies, and variations in the aerodynamic forces on the projectile. Ballistic dispersion can increase the efffectiveness of a gun when the fire control errors and aircraft jinking cause large projectile miss distances.

Ballistic coefficient. The ballistic coefficient is a parameter or measure that is used to account for the attenuation of the velocity of a projectile or fragment in transit from the platform to the target as a result of atmospheric drag. The ballistic coefficient is equal to the weight of the body divided by the atmospheric drag on the body (the drag coefficient times the body's frontal area) and is normally used in approximate formulations to determine the average speed or time of flight for the projectile or fragment.

Go to Problems 3.7.24 to 3.7.25.

3.7.5.2 Guided missiles.

Learning Objectives	**3.7.7 Describe the types and phases of missile guidance.** **3.7.8 Describe the missile navigation laws and trajectories.**

The guided missile system contains a guidance package that attempts to navigate or steer the missile on a course that will eventually lead to an intercept with the target. Several methods of guidance are possible, and a given missile system can use a different method in each phase of the flyout. For most antiaircraft applications the types include inertial, command, beam-rider, homing (active, semiactive, and passive), and retransmission. The trajectory of the guided missile is determined by the type of navigation law used and may or may not be related to the method of guidance. The types of navigation laws used by most antiaircraft missiles in

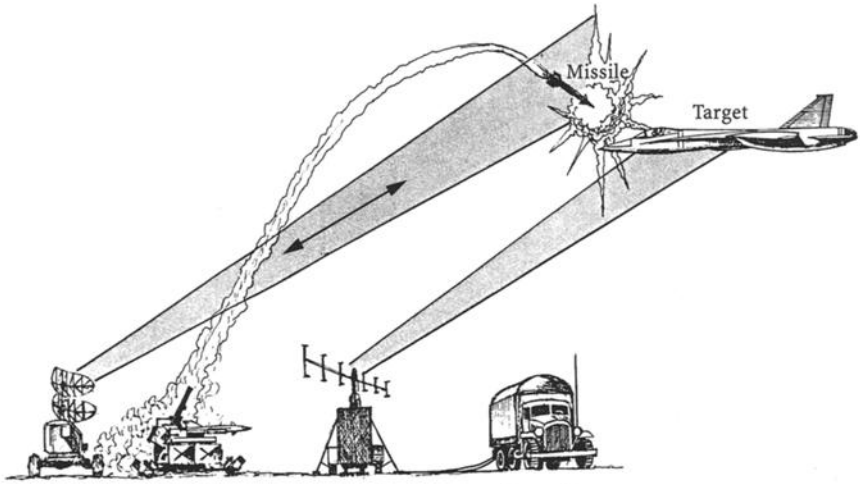

Fig. 3.75 Typical command guided missile system.

the midcourse and terminal phases of the flyout include pursuit, lead-angle, three-point, and proportional navigation. Inertial guidance can be used by long- and medium-range missiles in the launch and midcourse phases (Note 84).

Methods of guidance. Several of the current methods of missile guidance are described next.

Inertial guidance: Inertial guidance is a method of guidance that uses gyroscopes and accelerometers to 'fly' a missile over a predetermined path part way to the intercept with the target aircraft. The desired flight path is provided to the missile prior to launch, and updates to the path can be sent to the missile during the flyout.

Command guidance: Command guided missiles are missiles whose guidance instructions or commands come from sources outside the missile. Figure 3.75 illustrates one example of a command guidance system. In this method of guidance, a tracking system that is separated from the missile is used to track both the missile and the target. The tracking system might consist of two separate tracking units, one for the missile and one for the aircraft, or it might consist of one tracking unit that tracks both vehicles. The tracking can be accomplished using radar, optical, laser, or infrared systems. A radar beacon or infrared flare on the tail of the missile can be used to provide information to the tracking system on the location of the missile. The target and missile ranges, elevations, and bearings are fed to a computer. Using the position and position rate information, the computer determines the flight path the missile should take that will result in an intercept with the aircraft. It compares this computed flight path with the predicted flight path of the missile based on current tracking information and determines the correction signals required to move the missile control surfaces to change the current flight path to the new one.

These signals are the command guidance and are sent to the missile receiver via either the missile tracking system, or a separate command link, such as a radio, or it can be sent along a wire between the launching platform and the missile. Besides steering instructions, the command link can transfer other instructions to the missile, such as fuze arming, receiver gain setting, and warhead detonation. The specific path along which the missile is navigated is determined by the type of navigation law used by the system.

The particular combination of command guidance and three-point navigation, where the missile is commanded to always lie on the line-of-sight (LOS) between the aircraft tracking unit and the aircraft, is known as command-to-line-of-sight (CLOS). In automatic CLOS (ACLOS) both the target and the missile are tracked automatically. When an operator tracks the target and the missile is tracked automatically, the system is referred to as a semiautomatic CLOS (SACLOS). When the operator tracks both the target and the missile, the system is a manual CLOS (MCLOS). Command guidance all of the way to the target is used mostly with short-range missile systems because of the relatively large tracking errors that occur at long range.

Beam-rider guidance: In the beam-rider method of guidance, illustrated in Fig. 3.76, the aircraft is tracked by an electromagnetic beam, for example, radar or laser, transmitted by a tracking system offboard of the missile. The guidance equipment onboard the missile includes a rearward-facing antenna that senses the target-tracking beam. Steering signals that are based on the position of the missile with respect to the center (or the scanning axis) of the target tracking beam are computed onboard and sent to the control surfaces. These correction signals produce control surface movements intended to keep the missile as nearly as possible in the center of the target-tracking beam (or scanning axis). The missile can thus be said to ride the beam; it does not see the target. There is usually a wider, lower-power beam used to capture the missile shortly after it is launched. The beam-rider missile system uses the three-point navigation law.

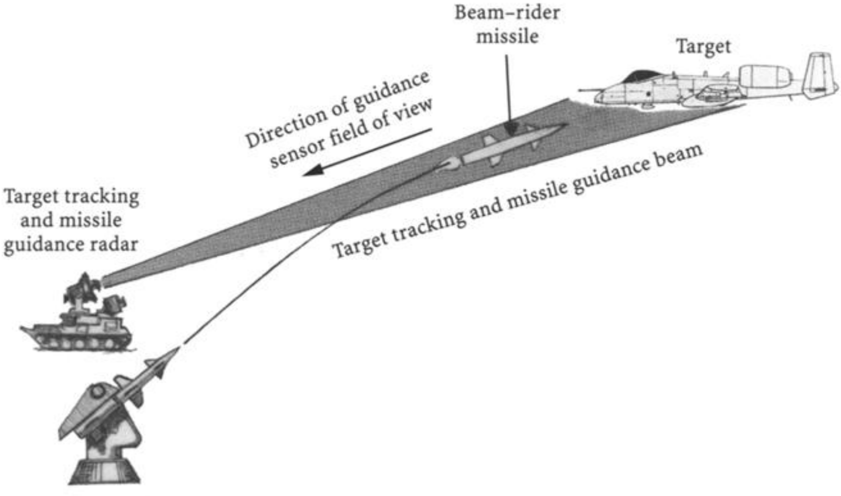

Fig. 3.76 Beam-rider missile system.

The beam-rider missile guidance method has both advantages and disadvantages. Because only the target tracking and missile guidance beam impinges on the target, aircraft without the appropriate threat warning equipment will be unable to react properly to the approaching missile. Also, this guidance system permits the launching of several missiles into the same beam because all of the guidance equipment is carried in the missile. This, however, makes each missile relatively large and expensive. Furthermore, the target-tracking beam must be reasonably narrow to ensure an intercept, and consequently the chance of loss of the missile through target maneuvering and evasion is increased. The problem of large tracking error for long-range targets usually restricts beam-rider missiles to short-range. Current short-range beam-rider missile systems typically use a laser beam because of its relatively narrow beamwidth.

Homing guidance—active, semiactive, and passive: The expression homing guidance is used to describe an onboard missile guidance package that can determine the position of the aircraft and formulate commands to guide itself to the aircraft. With homing guidance the tracking error is usually reduced as the missile approaches the aircraft. The three major methods of homing systems are illustrated in Fig. 3.77.

If the aircraft is tracked solely by electronic radiation equipment in the missile itself, the system is referred to as active. An example is a system that uses a radar

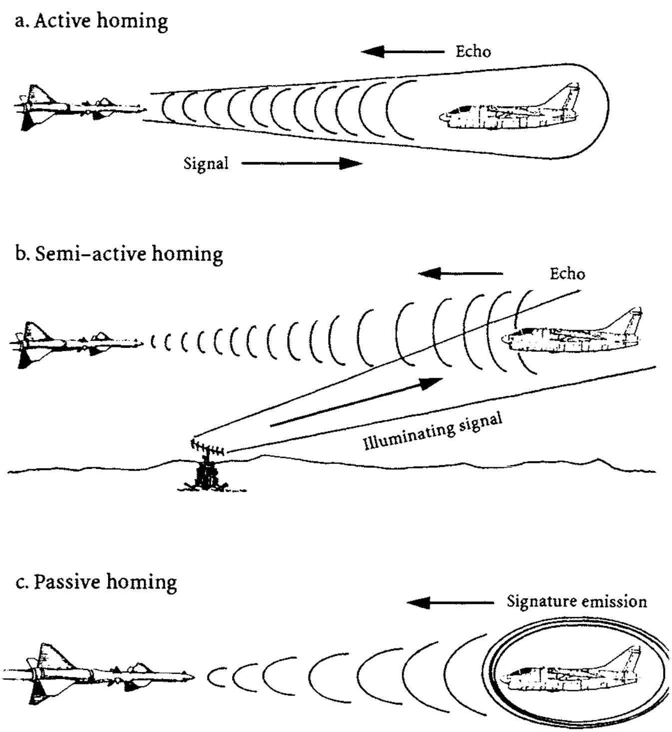

Fig. 3.77 Homing missiles.

transmitter located on the missile to illuminate the aircraft and then uses the radar reflections or echoes from the aircraft for navigation. A major advantage of active homing is the fact that the missile can be launched and forgotten by the shooter; no further tracking by the shooter is required. This is referred to as fire-and-forget, launch-and-leave, or shoot-and-scoot. Disadvantages of active homing are the additional weight and expense for each missile and the fact that the radiation from the missile can reveal its presence.

If the aircraft is illuminated by a tracking beam from some source not on the missile and if the beam echo from the aircraft in the direction of the missile is used by the missile for navigation, the system is referred to as a semiactive homing (SAH) system. The missile might also require direct illumination from the illuminator on to a rearward-facing receiver to use in the processing of the reflected signal from the target. With this method of guidance, the aircraft might know it is being tracked, but it does not know if a missile is on the way. An SAH missile may or may not require continual target illumination. This method of guidance has progressed from a requirement for one continuous illuminator per target to a system with a single illuminator that can track and illuminate several targets on a time-share basis. Thus, the missile receives the reflected illumination periodically. This is referred to as sample-data SAH.

Passive homing systems use electromagnetic emissions or natural reflections from the aircraft itself for target location. One example is an IR homing guidance system that homes in (closes) on the heat generated by the aircraft. Another is the antiradiation missile that homes in on radar navigation or fire control signals or on jamming signals from electronic countermeasure equipment in the aircraft.

Retransmission guidance: This method of guidance, also known as track-via-missile (TVM), is the latest technique to be used to direct missiles toward air targets. An illustration of TVM is given in Fig. 3.78. Typically, a radar tracking system tracks both the target and the missile, as in command guidance. However, in TVM the target-tracking beam also serves as a target illuminator, and a receiver on the missile detects the reflected illumination, as in semiactive homing guidance.

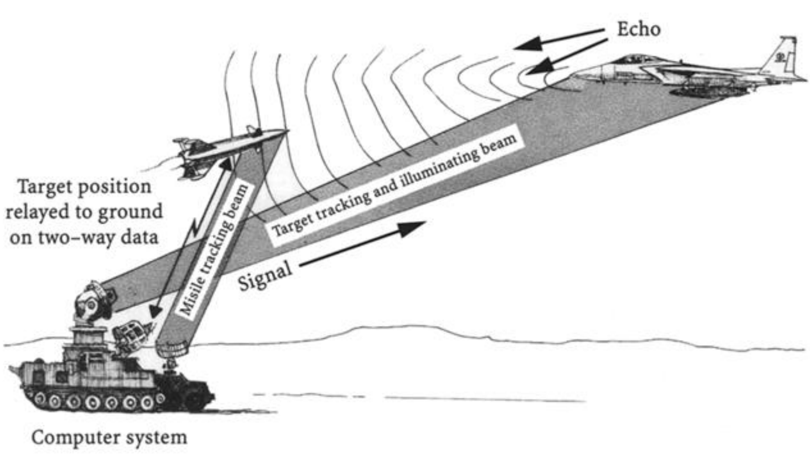

Fig. 3.78 Retransmission (TVM) guidance system.

The information on the relative target angular position gathered by the missile is relayed to a control unit. Guidance equipment at the control unit processes the echoes received directly from the target and missile and the information on relative target position received from the missile and determines the appropriate guidance commands, which are then sent to the missile on a data link. The tracking system usually has the capability to track several targets at one time, and the control system can direct several simultaneous engagements between missiles and aircraft.

Composite guidance systems: Generally, no one method of guidance is best suited for all three phases of the missile flyout. Consequently, many missile systems use more than one method, with each one operating during a certain phase of the flyout. A system can use inertial with command updates or semiactive homing from launch until the midcourse position, at which time the guidance switches to active or passive homing for more accurate tracking and navigation during the terminal phase. These systems are referred to as hybrid or composite guidance systems. Several methods of guidance can also be used simultaneously to degrade any countermeasures employed by the aircraft, such as the use of a decoy flare to draw an infrared homing system off of the radiation from the aircraft. If an active homing system is used in conjunction with a passive one, the missile might reject the flare and continue on toward the aircraft. Tables 3.17 and 3.18 present the methods of guidance *possibly* used by many of the current surface-to-air and air-to-air missile systems, respectively. Note that some of the systems, such as

Table 3.17 Missile guidance methods, surface-to-air

		Homing	
Command	Beam rider (laser)	Semiactive	Passive (IR)
PATRIOT (+TVM)	RBS 70/90	SEA SPARROW	STINGER
ROLAND (CLOS)	ADATS	STANDARD, MR	RAM (RF/IR)
CROTALE (CLOS)	—	STANDARD, ER	MISTRAL
BARAK (CLOS)	—	HAWK	TAN-SAM
BLOWPIPE (MCLOS)	—	SEADART	KEI-SAM
STARSTREAK (SACLOS)	—	BLOODHOUND	SA-7
RAPIER (CLOS)	—	ASPIDE	SA-9
SEAWOLF (CLOS)	—	SA-6	SA-13
SA-2	—	SA-11	SA-14
SA-3	—	SA-12	SA-16
SA-4	—	SA-17	SA-18
SA-5	—	—	—
SA-8	—	—	—
SA-10 (TVM)	—	—	—
SA-15	—	—	—
SA-19	—	—	—

Table 3.18 Missile guidance methods, air-to-air

Active homing	Semiactive homing	Passive homing
AMRAAM	PHOENIX (+ACTIVE)	SIDEWINDER
AA-12	SPARROW	ASRAAM
——	SKYFLASH	R550 MAGIC
——	SUPER 530	MICA
——	ASPIDE	SHAFRIR
——	AA-6	AA-1
——	AA-7	AA-2
——	AA-9	AA-8
——	AA-10	AA-10
——	——	AA-11

the AA-10, have several versions, and each version can use a different method of guidance.

Types of navigation laws and missile flight paths. Guidance systems can use any one of several types or laws to navigate a missile along a trajectory or flight path to an intercept with an aircraft. Four common laws are pursuit, lead angle, three-point, and proportional navigation. The flight paths for these four laws are illustrated in Fig. 3.79. The specific target flight-path information required by the navigation law depends upon which law is used. The most important pieces of information are the angle between the missile heading and the line-of-sight from the missile to the target, the distance between the missile and the target, and the rate of change of both the LOS angle and the distance.

Pursuit: In the pursuit trajectory, illustrated in the upper left corner of Fig. 3.79, the missile flies directly toward the target at all times. Thus, the line-of-sight between the missile and the aircraft is maintained essentially along the heading of the missile by the guidance system. Missiles flying a pursuit course usually end up in a tail chase situation, similar to a dog chasing a rabbit. There are two basic objections to the pursuit method. First, the maneuvers required of the missile become increasingly hard during the last, and critical, stages of flight. Second, the missile speed must be considerably greater than the aircraft speed. The sharpest curvature of the missile flight path usually occurs near the end of the flight. At this time the missile must overtake the aircraft. If the aircraft attempts to evade, the last-minute angular acceleration requirements placed on the missile could exceed its aerodynamic capability, thereby causing a large miss distance. Near the end of the flight, the missile is usually coasting because the booster (and sustainer) motor thrusts last for only a short part of the flight. Consequently, more energy is required to make short-radius, high-speed turns at a time when the missile is losing speed and has the least turning capability. The most favorable application of the pursuit course is against slow moving aircraft, or for missiles launched from a point directly to the rear of the aircraft, or head on toward an incoming aircraft.

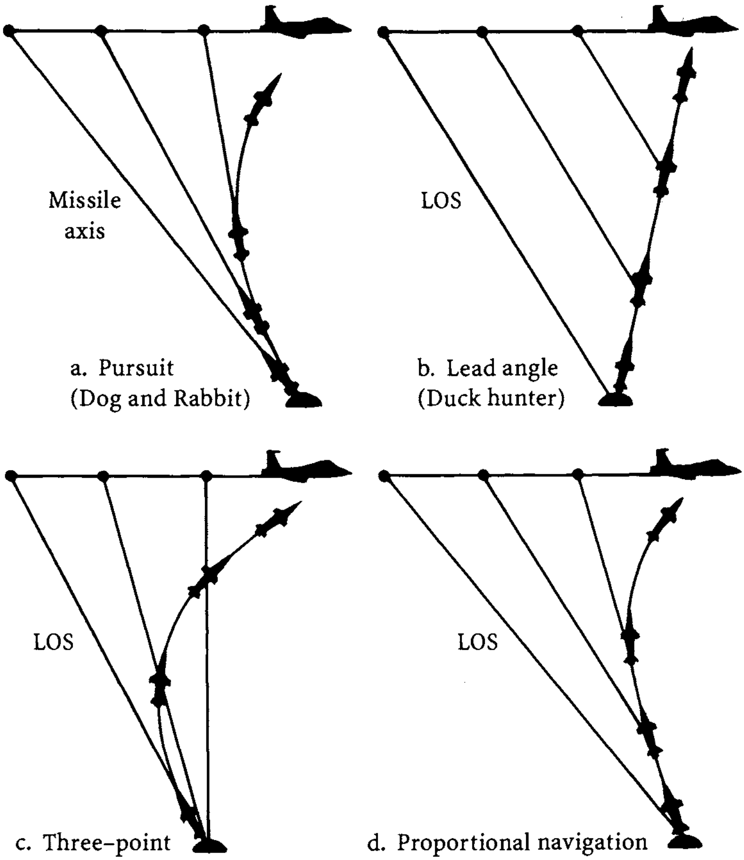

Fig. 3.79 Missile navigation laws and trajectories.

Lead angle: In the lead angle or constant bearing trajectory, shown in the upper right corner of Fig. 3.79, the guidance system flies the missile along a lead trajectory that results in an eventual intercept with the aircraft. For constant-speed, nonmaneuvering aircraft, the LOS between the missile and the aircraft remains at a constant angle, and the missile flies a straight-line trajectory. This is often referred to as a collision course. If the aircraft changes direction, the new lead angle required for a collision is determined, based on an assumed straight-line target flight path, and the missile is maneuvered to the new heading.

Three-point: In three-point navigation the missile is constantly being steered to lie on the line between the target tracker and the target, as shown in the lower left corner of Fig. 3.79, thus the name three-point guidance. This type of trajectory is typically used only in short-range missile systems employing CLOS or beam-rider guidance. An example of a CLOS system is one in which the target is tracked visually, using optics, and the missile is tracked by a sensor at the tracker that observes the off-axis position of a flare located on the tail of the missile. The amount of offset of the missile from the LOS (from the tracker to the target) and the range from the tracker to the missile are used by the guidance system to determine the appropriate steering commands to drive the missile back to the LOS. These commands are then relayed to the missile over a data link, such as a wire or radio.

Proportional navigation: The most common type of navigation in the final phase of the flyout is the proportional navigation law, or pro nav. To do proportional navigation, the guidance system must be able to determine the time rate of change of the LOS between the missile and the target, as illustrated in the lower right corner of Fig. 3.79. This can be accomplished by equipment located on the missile or on the ground. When ground-based equipment is used, the location of both the missile and the target must be determined. In proportional navigation the guidance system attempts to maintain an essentially constant LOS angle, and hence cause a collision, by making the rate of change of the missile heading directly proportional to the rate of change of the LOS. The constant of proportionality is referred to as the pro nav constant. The value of the constant can change as the missile flies the intercept. Typically, it has a low value when the missile is far from the target to minimize any energy lost as a result of minor target maneuvers and a high value as the missile approaches the midcourse position to ensure a sufficient reaction to any last ditch maneuver by the target.

Go to Problems 3.7.26 to 3.7.38.

3.8 Some Threat Air Defense Weapons

Learning Objectives	**3.8.1**	**Describe some of the current Russian Federation air defense weapons.**
	3.8.2	**Describe the characteristics and operations of the Trinity gun system and the SA-10 SAM.**

The number of air defense weapons produced around the world is large. For example, *Aviation Week & Space Technology's Aerospace Source Book 2002* lists 76 different surface-to-air missiles produced by 20 companies from 11 countries (Note 85). A large number of sites on the World Wide Web contain descriptions of one or more of the current antiaircraft weapons. Because of the availability of information on AD weapons on the World Wide Web and in printed form (Selected Bibliography), only a brief description of some of the land, sea, and air systems produced by the Russian Federation, as well as the Trinity naval gun system, is given in the following Subsections. These descriptions are general summaries of the descriptions available online and in the open literature and are not complete or entirely correct. They are provided here to give the reader a general understanding of the types and capabilities of the air defense weapons available today.

Here is a list of air defense weapon sites on the World Wide Web:

http://www.janes.com/defence/
http://jmr.janes.com/ (surface-to-air, air-to-air)
http://hometown.aol.com/threatmstr/airdef.htm
http://hometown.aol.com/jtfp01/siberian.html
http://www.hist.unt.edu/aaabib.htm
http://www.aeronautics.ru/aaavia.htm
http://www.galope.com/mike/frames.htm
http://www.milparade.com/catalog/part4/contents.shtml
http://www.armscontrol.ru/atmtc/Arms_systems/
http://www.army-technology.com/projects/index_main.html#Air Defence Missile Systems
http://www.army-technology.com/contractors/armoured/index.html
http://www.fas.org/nuke/guide/russia/airdef/index.html
http://www.fas.org/man/dod-101/sys/missile/row/index.html
http://www.aviation.ru/PVO/
http://www.wonderland.org.nz/
http://www.index.ne.jp/missile_e/index.html
http://www.tealgroup.com/products/missiles/
http://www.ocdefence.com/
http://www.designation-systems.net/non-us/
http://www.periscopeone.com/demo/weapons/missrock/antiair/
http://web.ukonline.co.uk/aj.cashmore/.weapons/index.html
http://www.cdiss.org/defences.htm
http://www.sci.fi/~fta/missiles.htm
http://www.hawk.dk/default.asp
http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/3-01.11/toc.htm

3.8.1 Some Russian Federation Land-Based AD Systems

3.8.1.1 Small arms and AAA.

Small arms. Standard weapon calibers defined as small arms and available in the former communist bloc countries are 7.62, 7.92, 12.7, and 14.5 mm. The types of small-arms weapons using the 7.62- and 7.92-mm projectiles include hand-held pistols, shoulder-fired rifles, carbines, assault rifles, submachine guns, and mounted light machine guns. These weapons are normally only effective against slow and low-flying aircraft within 600 m and are usually employed in the barrage fire mode. Mounted heavy antiaircraft machine guns use 12.7- and 14.5-mm projectiles. An example of one such system is the ZPU-4. This antiaircraft weapon has four 14.5-mm heavy machine guns with a combined cyclic rate of fire of 2200 to 2400 rounds per minute. It traverses 360 deg and, with its optical fire control, has a tactical range of 1400 m. It is currently being replaced by more modern equipment.

AAA. Antiaircraft artillery have sizes that range from 23 mm up to and including 130 mm. Weapons through 57 mm are usually mobile. The larger systems are located in fixed installations. Weapons larger than 85 mm are deployed in limited numbers, with the frequency of deployment decreasing with size. A typical 23-mm system is the ZU-23. This weapon consists of two 23-mm cannons and fires a maximum of 2000 rounds per minute. The ZU-23 traverses 360 deg and, with its optical fire control, has a tactical range of 2500 m. It also is currently being replaced by more modern equipment.

ZSU-23-4: One of the most important mobile air defense weapons is the Belarussian ZSU-23-4, sometimes referred to as the Shilka. This system is a self-contained package of mobile firepower with its own target acquisition and fire control equipment. It has a crew of four (commander, driver, radar observer, and gunner) in an NBC-sealed chassis mounted on a modified PT-76 armored vehicle. It can fire on the move at speeds up to 25 km/h. It has four 23-mm cannons and a maximum practical rate of fire of 2000 rounds per minute. It traverses 360 deg and, with the Gun Dish radar, has a tactical range of 3000 m. Using optical sights, the tactical antiaircraft range is 2500 m. First seen in the early 1960s, this vehicle was used throughout the former Warsaw Pact armies. It was found in the tank and motorized rifle regiments of tank and motorized rifle divisions and was integrated into the attack formations. The ability to move with the leading tank elements through underbrush and mud with sufficient armor to survive close enemy contact gives this system an advantage over the more fragile missile systems. Furthermore, pilots will find it difficult to distinguish this modern "flakpanzer" from the tanks it is accompanying. The latest version is the ZSU-23-4M5.[58]

2S6 Tunguska: The replacement to the ZSU-23-4 is the 2S6 Tunguska, which carries a twin-barrel 30-mm gun and eight SA-19 Grison (or Grisom) missiles. It is an all weather, day/night, shoot-on-the-move weapons system mounted on a tracked vehicle. Target detection and tracking are accomplished using the Hot Shot radar, with a maximum detection range of 18 km, and an optical sight. The firing rate per gun is approximately 5000 rpm, the projectile's muzzle velocity is 1000 m/s, and the tactical range is approximately 3 km. The method of guidance of the Grison missile is SACLOS, and the missile carries a 9-kg HE fragmentation warhead. The maximum range of the missile is approximately 12 km.

57-mm AAA: In the 57-mm category of AAA, the S-60 and the ZSU-57-2 are the most common systems. The S-60 has one 57-mm cannon with a cyclic rate of fire of 105 to 120 rounds per minute. It traverses 360 deg and, when directed by the off-carriage Flap Wheel radar, has a tactical range of 6000 m. The tactical range with on-carriage optical sights is 4000 m. Normally, six S-60 guns with associated fire control equipment constitute a battery. This system is usually found in antiaircraft regiments of maneuver divisions, but is being replaced by SAM (or a combination of gun and SAM) systems.

The ZSU-57-2 first appeared in the late 1950s and equipped all former Warsaw Pact forces and at least 11 other nations. This system has two 57-mm cannons with a combined rate of fire of 210 to 240 rounds per minute. It traverses 360 deg and has a tactical range of 4000 m. The ZSU-57-2 is mounted on a modified T-54 tank chassis and carries a five-man crew. Fire control is optically directed. The ZSU-57-2 is presently being replaced by more modern equipment. When found in maneuver units, it is normally located with tank regiments.

Tank guns: Tanks themselves pose a considerable threat to slow, low-flying or hovering variable-wing aircraft. Many tanks carry mounted small arms, and their main gun can fire proximity-fuzed HE shells using a laser range finder for targeting.

3.8.1.2 Surface-to-air missile systems. The current Russian Federation land-based surface-to-air missile systems in operation or production are the SA-2 through the SA-19.[59] An unofficial description of each of these systems is given next.

SA-2/SA-10. The SA-2, with the Guideline missile, is a high- to-medium-altitude air defense system. Several versions have appeared. The missile is command guided and has a slant range of approximately 40 km. It has two stages, a solid fuel booster and a liquid fuel rocket sustainer, that boost its 130-kg HE warhead to a maximum altitude of about 27,000 m. The typical SA-2 site consists of six launchers arranged in a star-like configuration around the Fan Song radar guidance equipment.

The SA-10, which is a replacement for the SA-2 and SA-3, is described in detail later in Sec. 3.8.5.

SA-3. The SA-3 system uses the Goa missile and the Flat Face and Low Blow radars. This air defense missile probably is command guided and may have some method of homing capability. The missile has an effective range of about 24 km. Powered by a two-stage solid fuel booster and solid fuel sustainer, the missile can carry its HE proximity-fuzed warhead to altitudes in excess of 13,000 m.

SA-4. The SA-4 system uses the Ganef missile and the Pat Hand and Long Track radars. This air defense missile has a range of approximately 70 km and is command guided to a maximum altitude of about 27,000 m. It is powered by four solid fuel boosters with canted nozzles and a ramjet sustainer and carries an HE proximity-fuzed warhead.

SA-5. The SA-5, with the Gammon missile, is not an element of the "troops of air defense of the Ground Forces" (voiska protivovozdushroi oborony Sudhoputniykh Voisk, abbreviated as PVO SV). It was developed for the defense of Soviet cities and is part of the Troops of National Air Defense (PVO). (http://www.fas.org/nuke/guide/russia/agency/pvo.htm.)

SA-6/SA-11/SA-17. The SA-6 system employs the Gainful missile. This air defense missile has a slant range of 30 km. It is powered by an integral solid rocket/ramjet system and is initially command guided by the Straight Flush fire control radar. Final intercept is by semiactive homing using continuous wave radar. The missile carries an 80-kg HE fragmentation warhead and can be employed against aircraft flying at altitudes from about 100 to 11,000 m. Mounted on a triple launcher on a modified PT-76 tank chassis called the TEL, a missile group consists of three triple launchers, one loading vehicle, and one Straight Flush radar, also PT-76 mounted. This system was used effectively during the 1973 Middle East War.

The SA-11, a replacement for the SA-6, uses the Mach 3.5, two-stage, Gadfly missile. The radars consist of the Snow Drift search radar and the Fire Dome target tracking radar. The system can engage targets at altitudes between 30 and 15,000 m at a maximum range of 30 km.

The SA-17 Grizzly is a replacement for the SA-11. It is mounted on the same tracked vehicle and can engage up to six targets simultaneously. The missile guidance is inertial with command updates up to the midcourse position, followed by SAH. The missile has a maximum range of approximately 50 km.

SA-8/SA-15. The SA-8, with the Gecko missile, is a short-range, low-altitude, all-weather air defense system. The missile operates by command guidance with proportional navigation and is effective at altitudes from 50 to 6500 m. It is fully self-contained, with acquisition, tracking, and two missile guidance radars mounted on a six-wheeled, amphibious vehicle. Four missiles are carried in an integrated mount. The two guidance radars make it possible to launch two missiles at the same target with each missile responding to a different frequency. The system also contains an electro-optical tracker, probably television. With a slant range of approximately 10 to 15 km and a 50-kg HE warhead, the highly mobile SA-8 can provide close support to armored and mechanized forces.

The SA-15, with the vertically launched Gauntlet missile, is the replacement for the SA-8. The search and target tracking radars are three dimensional, pulse-Doppler, electronically scanning array radars. The missile carries a 15-kg HE fragmentation warhead. The maximum range is estimated to be 12 km, the minimum engagement range is 1.5 km, and the altitude limits can be 10–6000 m.

SA-7/SA-14/SA-16/SA-18/SA-19. The SA-7 is a short-range, low-altitude MANPADS with a missile that uses passive infrared homing guidance. It is used mainly for defense against low and slow-flying aircraft. The 1.2-m-long Grail missile, which is fired from a shoulder launcher, has an HE warhead with a contact fuze. A solid fuel booster and sustainer propel the Grail missile to a maximum slant range of approximately 3.5 km. It can be fired from the ground or from a vehicle and can be used against aircraft flying at altitudes from approximately 50–3000 m.

The SA-14 with the Gremlin missile is a replacement for the earlier SA-7. The ordnance package on the missile consists of a 1–2-kg HE warhead and a contact fuze. The cooled lead sulfide IR detector contributes to the missile's all-aspect 4-km capability against aircraft pulling 8*g*.

The SA-16 with the Gimlet missile, also known as the Igla, is actually younger than the SA-18. (http://www.fas.org/man/dod-101/sys/missile/row/sa-16.htm.) It can have a two-color, cooled IR seeker, a 1–2-kg warhead, contact fuze, and a maximum range of 5 km and altitude of 3000 m.

The SA-18 with the Grouse missile, although similar in appearance to the SA-14, is a new design that provides longer range and higher speed.

The SA-19 with the Grison missile is part of the 2S6 Tunguska air defense system just described.

SA-9/SA-13. The SA-9 with the Gaskin missile is a short-range, low-altitude weapon that uses IR passive homing. It is used mainly for defense against low and slow-flying aircraft. The weapon system is transported on a modified BRDM-2 tracked, amphibious armored vehicle that carries a probable crew of four. The SA-9 has a slant range of approximately 5–6 km. The missile has an HE warhead. Four missile canisters, each with one missile, are normally carried on the launcher turret.

The SA-13 with the passive homing Gopher missile is the replacement for the SA-9. The IR detector is thought to be lead sulfide, probably cooled. The HE warhead weighs 5 kg. Maximum range for the SA-13 is estimated at 10 km, with an altitude capability between 50–5000 m.

SA-12. The SA-12, also known as the S-300V, uses the vertically launched Gladiator or Giant missile. (http://hometown.aol.com/threatmstr/airdef.htm.) The SA-12 radar system consists of the Bill Board surveillance radar and the Grill Pan guidance radar. The SA-12a/Gladiator is both an antiaircraft and an antitactical ballistic missile (ATBM) system, whereas the SA-12b/Giant is primarily for the ATBM role. The Bill Board surveillance radar can detect up to 200 targets and covers 0–55 deg in elevation and 10–250 km in range. The antenna rotates completely in 6–12 s, and the system accuracy is approximately 30 min of arc in azimuth and 250 m in range. The Grill Pan radar system can track up to 12 targets and control up to six missiles against these targets simultaneously. The radar can acquire a 2 m^2 target at a range of 150 km in manual mode and 140 km in automatic mode. The Grill Pan radar can search the horizon for new targets while tracking the targets assigned to it. The SA-12a missile has a maximum range between 75–90 km, and the SA-12b ATBM missile has a maximum range between 100–200 km.

Antitank weapons. Two antitank guided missiles, the Sagger and the Swatter, can be a threat to low-flying helicopters. Normally, they are mounted on the BMP personnel carrier or BRDM reconnaissance vehicle. The Swatter also can be mounted on the Hind A and D helicopter models.

3.8.2 Some Russian Federation Sea-Based Systems

The air defense systems onboard operational Russian Federation surface ships consist of AAA ranging in size from 23–76 mm and of seven surface-to-air missile systems, the SA-N-1 through SA-N-12.

The SA-N-1 system uses the Goa missile and the Peel Group radar system. The missile is assumed to be identical to that used in the SA-3 system with a roll-stabilized launcher. The Soviets consider this a dual-purpose antiship and antiaircraft weapon.

The SA-N-2 is the sea-based version of the SA-2 system. Apparently, it is installed on only one Soviet ship.

The SA-N-3 uses the Goblet missile and is deployed on Soviet helicopter carriers and several cruisers. Fire control is provided by the Head Light radar group.

The SA-N-4 is a short-range system that uses the SA-8 Gecko missile. The missile is concealed in a bin-type launcher with a pop-up launching mode. The fire control radar is the Pop Group.

The SA-N-5 with the SA-7 Grail missile is found on many small Soviet ships. It consists of four SA-7 launch tubes mounted on a platform that can be rotated.

The SA-N-6 is related to the SA-10 land-based missile system. The Grumble missiles are launched from vertical tubes located beneath the main decks of the Soviet Kirov and Frunze battle cruisers and the Slava class guided missile cruisers.

The SA-N-7 with the Gadfly is the naval equivalent of the land-based SA-11 system. Two single rail launchers are on the Sovremennyy class of guided missile destroyers.

3.8.3 Some Russian Federation Aircraft

The Russian Federation Air Forces known as Frontal Aviation or FA (Frontovaya aviatsiya) consists of manned interceptors armed with air-to-air missiles and/or guns. These include the MiG-21 (Fishbed), MiG-23/27 (Flogger), MiG-25 (Foxbat), MiG-29 (Fulcrum), MiG-31 (Foxhound), and the Su-27/33 (Flanker). All of these aircraft except the Foxbat, Foxhound, and Flanker carry 23- or 30-mm guns. Some of the air-to-air missiles carried by these aircraft are the AA-2 Atoll, AA-7 Apex, AA-9 Amos, AA-10 Alamo, AA-11 Archer, and AA-12 Adder. Most of these systems use passive (infrared) and/or semiactive (radar) homing versions, except perhaps the AA-10E and the Adder, which use active radar homing. These missiles have maximum ranges from 4–70 nautical miles.

There are other airborne threats to U. S. aircraft, such as the Hind D/E and Havoc attack helicopters and the defensive armament on the Russian Federation fixed-wing attack aircraft, bombers, and the antisubmarine warfare aircraft.

Go to Problems 3.8.1 to 3.8.5.

3.8.4 Trinity Naval Multirole Gun System

In the early 1990s Bofors designed, but did not produce, the TRINITY 40-mm naval multirole gun system,[60,61] which is similar to their 40 Mk 3 gun system shown in Fig. 3.80. (http://www.warships1.com/Weapons/WNSweden_4cm-70_m1948.htm, http://www.army-technology.com/contractors/artillery/bofors_ab/index.html, and http://www.defensys.ru/gallary/gallary_s300_eng.html.) The weapon system is comprised of the gun, the fire control system with sensors, and the ammunition. The TRINITY was designed for defense against low-flying, supersonic antiship missiles, maneuvering missiles at high subsonic speed, guided bombs, and conventional attacks by aircraft in a highly jammed environment. TRINITY was both a point defense weapon system and a close-in weapon system, with a secondary capability of combating surface targets. TRINITY had a modular design and was available in four different versions. TRINITY 01:1 was integrated with external fire control and sensors, but could also be locally controlled with a simple sight as a backup measure. TRINITY 01:2 was similar to the first but had the addition of a proximity-fuze programmer for the programmable 40-mm 3P round. TRINITY E1:1 had integrated fire control and sensors comprising TV, IR camera, and laser range finder. The weapon system could be controlled from the gun and/or from a CIC. It could program and fire the 3P round in all six fuze modes because of its range finding capability combined with the capability to compute times of flight. The weapon system was completely autonomous in the NORMAL COMBAT mode and required only target acquisition by external sensors, such as a surveillance radar or human observers. TRINITY E1:2 was similar to the preceding versions but with the addition of a tracking radar (Ku or

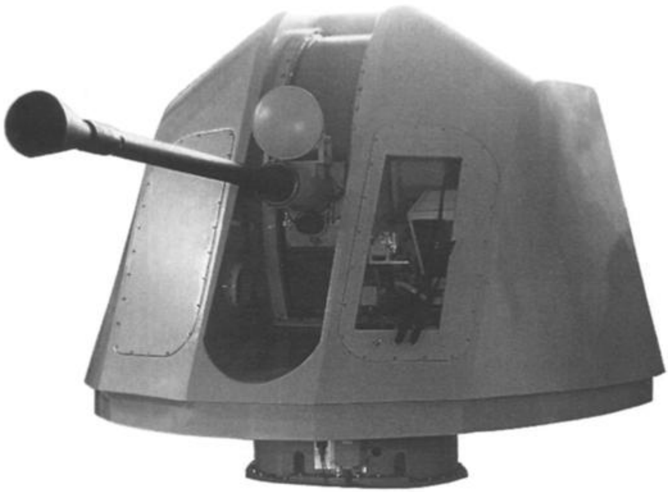

Fig. 3.80 Bofors 40 Mk 3 gun system (Reproduced with permission of Bofors Defence).

Ka bands), which provided the weapon system with all-weather capability and an exceptional resistance to jamming.

3.8.4.1 Gun. The TRINITY gun was 2800-mm long, and the magazine contained 101 rounds. The servo system for the aiming machinery was digital, which, in combination with gyro stabilization, ensured a high degree of aiming accuracy irrespective of sea conditions. The major parameters of the gun are given in Table 3.19.

3.8.4.2 Fire control system with sensors. The TRINITY E1:1 and E1:2 systems were equipped with integrated fire control and sensors for target tracking. Advanced filtering methods were used to compute lead angles for manueuvering targets. The split second a target was detected, the TRINITY fire control system selected the time to fire, the number of rounds to be fired, the type of target to be engaged, and the estimated target reaction. Each burst of fire consisted of 5 to 15 rounds. The firing or burst pattern around the target depended upon the type of

Table 3.19 TRINITY gun parameters[60]

Parameter	Numerical value
Rate of fire	330 rounds/min
Muzzle velocity (3P)	1012 m/s
Dispersion polar	0.7 mrad
Field of elevation	-20 to $+80$ deg

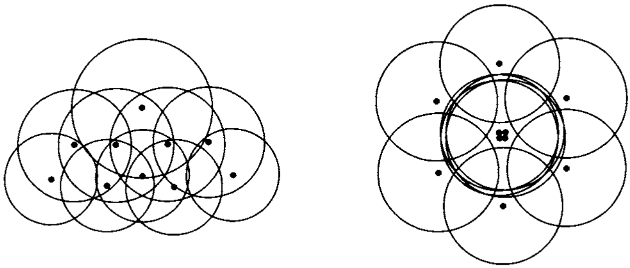

Fig. 3.81 Computer controlled burst patterns.[60]

target and its reaction. Figure 3.81 illustrates the computer controlled burst pattern for antiship missile targets and higher altitude targets, such as attacking aircraft. The dot at the center of each circle is the aim point, and the circle represents the dispersion polar of the ballistic projectile around the aim point. TRINITY E1:1 and E1:2 were resistant to jamming as a result of integrated jamming resistance circuits and the use of multisensor technology. The passive sensors included an IR camera and a TV camera, and the active sensors included a tracking radar and a laser range finder. Antiship missiles could be engaged at ranges in excess of 3000 m.

3.8.4.3 Ammunition. The TRINITY ammunition consisted of the Bofors 40 mm 3P round shown in Fig. 3.82. The high explosive is 120 g of PBX (or Octol in the TRINITY version), and the 975-g warhead case contains approximately 1100 tungsten pellets, each measuring 3 mm in diameter, covering both the cylindrical and the ogival front part of the shell for fragment distribution over a wide area. At burst more than 3000 pellets and secondary fragments have an initial velocity of 800–1500 m/s (Note 86).

The fuze consists of two major parts: one containing the safety and arming device and the pyrotechnics; and the other the containing the electronics for data storage, signal processing, control of the fuze functions, time setting, and circuits for electronic counter-countermeasures. The fuze is programmed by the proximity-fuze programmer in one of six modes in the last milliseconds before firing. The six modes are listed in Table 3.20.

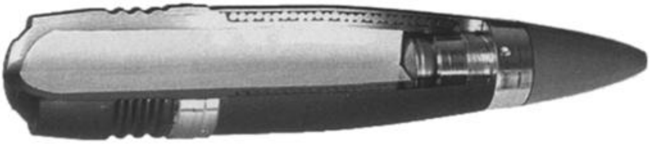

Fig. 3.82 3P round (Reproduced with permission of Bofors Defence).

Table 3.20 Fuze program modes[60]

Function/mode	Definition
Conventional proximity	When the fuze is fired unprogrammed, it will act as a conventional proximity fuze. If no target is detected, self-destruction will occur after 15 s.
Gated proximity	The fuze is provided data about the time of flight and the length of the range gate where the fuze is sensitive to target signals. The fuze ignores all incoming signals until reaching the gate. This results in total immunity to electronic countermeasures and natural disturbances in the trajectory. The sensitivity of the proximity fuze is 8–12 m against aircraft and helicopters and 5 m against missiles. If no target is detected, the fuze will self-destruct at the end of the gate. This fuze is used against attack aircraft, attack helicopters at extremely low altitudes, and ground support aircraft.
Gated proximity with impact priority	When the impact priority is selected, the proximity function of the fuze is delayed for a few milliseconds. Hits will result in a 0.3-ms delayed detonation, and close misses will result in a burst along the target, which is an advantage when combating armored helicopters or large transport aircraft.
Time	The predicted time of flight is fed into the fuze. This fuze mode is used against partly concealed, hovering helicopters, helicopters behind obstacles, antiarmour units, infantry, and targets behind slopes,
Impact	The impact function allows engagement of all types of light targets. The postimpact delay of 0.3 ms permits the shell to burst inside the target after penetration.
Armor piercing	The armor-piercing function is effective against lightly armored targets. The explosive charge is ignited by shock on hitting a hard target, resulting in a low-order detonation inside the target. The penetration capability is in excess of 15 mm of armor.

3.8.5 SA-10

The Russian Federation's Almaz Scientific Production Association builds a surface-to-air missile system known as the S-300 or NATO SA-10 and SA-N-6, the naval version.[59] (http://cns.miis.edu/research/cyprus/s300tdms.htm, http://www.hawk.dk/russian.asp, and http://www.cdiss.org/mos_as1.htm.) The system, which was originally intended to replace the SA-1 Guild SAM and later the SA-2 and SA-3, uses the Grumble missile. The system became operational in 1980, with many of the early sites located around Moscow. There currently are four versions: the SA-10a (S-300P) is towed on trailers, the 1982 SA-10b (S-300PM) is mobile on trucks, the improved 1985 SA-10c (S-300PMU), and the 1992 SA-10d (S-300PMU1/2/3). The system is an all-weather air defense system capable against low- to high-altitude high-speed low radar cross-section aircraft and cruise missiles. The latest evolution of the S-300 is the S-400/SA-20 Triumph SAM system. The S-400 is considered to be Russia's primary air defense weapon until 2020.[62] (http://www.fas.org/nuke/guide/russia/airdef/s-400.htm.)

3.8.5.1 SA-10 missile battery. The SA-10c/d battery is composed of a surveillance radar, an engagement radar, a command post/engagement control center, and up to 12 self-propelled transporter-erector-launchers (TEL) with four missile tubes on each TEL. The battery can deploy within 5 min after stopping. The trailer-mounted 360-deg surveillance radar is a large, three-dimensional, continuous wave/pulse-Doppler low-altitude radar known as Clam Shell. Clam Shell can detect targets flying at 500-m altitude at 90 km and can track up to 180 targets. The self-propelled engagement radar is an I/J-band, multifunction, electronically phased-array radar known as Flap Lid. Three detection scan modes are believed to be available: a 1-deg el $\times$ 90 deg az for low-altitude targets, a 13-deg el $\times$ 64 deg az for medium-altitude targets, and a 5-deg el $\times$ 64 deg az for high-altitude targets. Once the target is detected and acquired, the radar can be switched to either a 4-deg el $\times$ 4-deg az or 2-deg el $\times$ 2-deg az sectors for automatic tracking and missile guidance. The Flap Lid radar can engage up to six targets simultaneously, and two missiles are typically launched at a target in a shoot-shoot-look firing mode. The firing rate is one missile every 3 s from a TEL and three missiles per second from the battery. Thirty-two missiles are carried by the battery.

3.8.5.2 SA-10 battalion/regiment/brigade. The SA-10c/d battalion/regiment/brigade is composed of three to six missile firing batteries. The battalion can employ either the Big Bird or the 300-km capable, electronically phased array Tombstone three-dimensional surveillance radar. The battalion control system controls the Big Bird/Tombstone radar; the detection, acquisition, identification, and tracking of up to 100 targets; the IFF interrogation of the targets; the prioritization of the hostile targets; and the assignments of the targets to the individual batteries under its control. It also coordinates the battalions actions with other battallions and higher commands.

3.8.5.3 Grumble missile. The Grumble missile is a single-stage, solid rocket and is vertically launched. The warhead on the missile is an HE fragmentation warhead weighing 143 kg. The missile is guided by the Flap Lid radar using the TVM method of guidance. The missile is effective at altitudes somewhere between 50 ft and 100,000 ft and out to a maximum range of over 90 km.

Go to Problems 3.8.6 to 3.8.11.

3.9 Mission-Threat Analysis

3.9.1 System Threat Assessment Report

Learning Objective **3.9.1 Describe the System Threat Assessment Report.**

To develop properly a survivability design and the associated tactics for a specific aircraft that will enable it to effectively conduct its assigned missions, the specific threats to the aircraft must be determined, as well as the encounter conditions between the threats and the aircraft. The System Threat Assessment Report (STAR) documents the authoritative threat assessment for any aircraft acquisition program. The STAR is prepared by the appropriate service intelligence agency, and the Defense Intelligence Agency validates the STAR for the major acquisition programs.

The STAR is described online in Attachment 2 at http://www.deskbook.osd.mil/htmlfiles/rlframe/REFLIB_Frame.asp?TOC=/htmlfiles/TOC/411fbtoc.asp?sNode=L2-1&Exp=N&Doc=/reflib/maf/411fb/001/411fb001.doc.htm&BMK=C1021. According to that document the STAR contains a brief opening statement that includes a short description of the mission need for the system. This is followed by a summary that includes physical and technical characteristics, the initial operational capability (IOC), mission, operational concepts, and employment considerations that can reasonably be expected to impact on, or be impacted by, the threat. The next section is dedicated to the operational threat environment and includes a generalized overview of the operational, physical, and technological environment in which the system is expected to operate during its lifetime. Scenarios in this section are based on the Defense Planning Guidance scenarios. Areas covered include 1) threat force levels and enemy doctrine, 2) strategy, and 3) tactics affecting system mission and operations.

A section on the system targets is next, if applicable. An analysis of the capabilities and signatures of the full range of targets (such as vehicles, ships, aircraft, or silos) the U. S. system is designed to engage. Target employment, characteristics, command and control, and numbers are included. Types and density of targets can also be covered along with such common parameters as the thickness and types of armor the system must defeat.

The next section is the presentation of the system specific threat. This section includes an assessment of the threats that are directly relevant to the mission and performance of the U. S. system throughout its operational lifetime. It consists of two subsections: the threat at IOC of the U. S. system and the threat at IOC plus 10 years. Each subsection assesses the threat using three criteria: 1) description of the threat system; 2) magnitude of the threat (projected force level); and 3) threat integration a combined evaluation of the threat to the U. S. system when a potential adversary's employment doctrine, force levels, and systems are considered together. Any projected reactive threat is also presented, summarizing both the likely reactive threat and the technologically feasible threat. The likely reactive threat describes the system or capabilities that adversaries most typically develop and deploy during a specified period. The technologically feasible threat offers alternatives if the adversary's requirements differ from those that intelligence sources have generated. Although not constrained by intelligence projections, the technologically feasible threat is consistent with an adversary's technology, economic, and production capabilities.

Go to Problem 3.9.1.

3.9.2 Analysis Requirements

Learning Objective **3.9.2 Describe the three tasks in the mission-threat analysis.**

The mission-threat analysis was a required program task specified in MIL-STD-2069 (Note 87). According to that document, the missions and threat systems considered in a mission-threat analysis shall be those specified in the aircraft detail specification, operational requirements, and implementing documentation. Using this information, the contractor shall do the following:

1) Define each operational mode required by the specified missions. Aircraft configuration factors (weights, c. g. locations, fuel status, armament loading, etc.) and proposed operational concepts and tactics shall be included in the maximum detail possible.

2) List the threats and the threat characteristics applicable to the defined operational modes.

3) Analyze the aircraft operational modes and the threats and determine the encounter conditions.

The derived encounter conditions between the aircraft and the threats should then be used as a basis for the required survivability assessments and trade studies.

In general, the mission-threat analysis consists of three phases of study based upon the three tasks just listed. In the first phase the missions and mission or flight profiles or envelopes of the aircraft are defined. The output of this study would be the aircraft theaters of operation and types of missions, and the flight and operating conditions, including airspeeds, altitudes, configurations, and types of electromagnetic radiation, for the mission profile for each mission type. The second phase is the definition of the expected threat environment for each mission and theater. The strength, command structure, and disposition of the personnel, units, and equipment of any military force, known as the enemy order of battle (EOB), are identified. The identified weapon systems, including land, sea, and air units, are analyzed to determine their operating conditions and envelopes. The third phase combines the data gathered in the first two phases. The likelihood that the aircraft will be engaged by each threat system is estimated, and the conditions of both systems at the time of encounter are identified.

It is very important that all of the threats to an aircraft be correctly identified in the mission-threat analysis. Some situations are obvious. For example, aircraft conducting a close air support mission will most likely encounter small arms fire, small- and medium-caliber guns, and short- and medium-range guided missiles; whereas aircraft on an antisubmarine mission in the open ocean today most likely will not encounter these threats. However, new threats also must be forecasted. For example, a new, long-range enemy air interceptor with long-range air-to-air missiles and a submarine-launched antiaircraft missile are possible future threats to ASW aircraft in the open ocean.

Go to Problem 3.9.2.

3.9.3 Mission Plans

Learning Objective **3.9.3 Describe the mission plan and the computerized planning systems.**

Every mission begins with a plan. The main elements of the plan consist of the target or mission objectives; the mission geography and environmental setting, including time and weather data and the safe passage corridors; the threats that might be encountered and their locations; the friendly assets assigned to the mission, such as air-refueling tankers, standoff jamming aircraft, and fighter escorts; and the rules of engagement (ROE). Each plan has a timetable with major time-line events. The major time-line events of a typical strike mission are aircraft launch time, time of entry into the threat envelopes, time on target (TOT), and time of exit from the threat envelopes. According to Ref. 63,

> The (mission planning) process, in a nutshell, is as follows: Specific objectives are picked by headquarters. Those objectives are turned into tasking in the form of the Air Task Order. The tasking is split up into individual missions and assigned to squadrons with the appropriate mission-capable aircraft. Each mission is planned and deconflicted. The missions are flown. Results are analyzed and used to pick new objectives (Note 88).

Each mission is conducted by one or more assigned aircraft. The basic units of attacking tactical, fixed-wing aircraft often consist of two (section) or four aircraft (flight or division). In a section one aircraft is the leader, and the other is the wingman. A flight or division typically has a lead section and a trail section, possibly at an offset. A formation or group of aircraft consists of two or more flights or divisions. When several formations of aircraft attack a target, each formation of relatively closely spaced aircraft (in space and time) is known as a wave. Strategic aircraft can operate in flights of two or three aircraft or in large formations of perhaps 20 aircraft. These flights, formations, and waves can operate independently, or they can be combined into very large formations and waves of hundreds of aircraft.

The planning of a mission is accomplished either manually, using maps, charts, and simple calculations for route locations and times, weapons release points, and fuel remaining, based upon a selected mission profile; or automatically with the aid of a computerized planning system (CPS), such as the USN Tactical Mission Planning System (TAMPS), the Mission Planning System (MPS) module of the USAF Mission Support System (AFMSS), the Joint Mission Planning System (JMPS, the replacement for TAMPS and AFMSS) (http://www.tybrin.com/services/federal/missionplan/mpproduct_jmps.htm), the Strategic/Tactical Automated Mission Planning System (STAMPS), and the French Groupe SAGEM's CIRCE Mission Planning System.[63–66] Basic elements of a CPS are a digitized terrain or geographical database, such as that provided by the U. S. National Imagery and Mapping Agency (NIMA); a local environment database, including geographic navigation aids, refueling axes, and low-altitude obstacles; aircraft and own weapon flight performance data, and the characteristics, capabilities, and locations of potentially hostile air defense weapons. Functions provided by a CPS, such as MPS/AFMSS, consist of flight planning, route planning, threat penetration, weapons delivery, target area tactics, radar detection predictions mapping and imagery, and postflight analysis and debriefing.[67]

Go to Problem 3.9.3.

3.9.4 Mission Profiles

Learning Objective **3.9.4 Describe a typical mission profile.**

The mission profile consists of the flight path taken by an aircraft as it conducts its mission. Included in the profile is the route taken into the target area and the return route, with accompanying altitude, airspeed, and times. Also noted are any rendezvous points, CAP points, tanker points, SEAD points, geographic references, way points (locations to which an aircraft might be vectored), control points (CP, conspicuous terrain features or other identifiable objects used as an aid in navigation)[2], initial points (IP, a well-defined point used as a starting point for run into the target, or a point in the vicinity of a helicopter landing zone from which individual helicopters are directed to their prescribed landing sites)[2], the target or Bullseye location, and the threat locations.

The mission profiles used by bombers and attack aircraft as they approach the hostile target area, as they deliver their ordnance on the target, and as they depart the hostile territory, are typically high-low-high, low-low-low, low-low-high, and high-high-high, respectively, as shown by the multiple generic profiles illustrated in Fig. 3.83.

One set of altitude above ground level (AGL) definitions for the low, medium, and high altitudes, as well as very low and very high altitudes, is given in Table 3.21. The descriptors low, medium, and high used in the mission profiles, for example, high-low-high, include the very low and very high descriptors given in Table 3.21. For example, the descriptor low in the vicinity of the target could mean very low, and departure from the hostile territory at high altitude could mean very high.

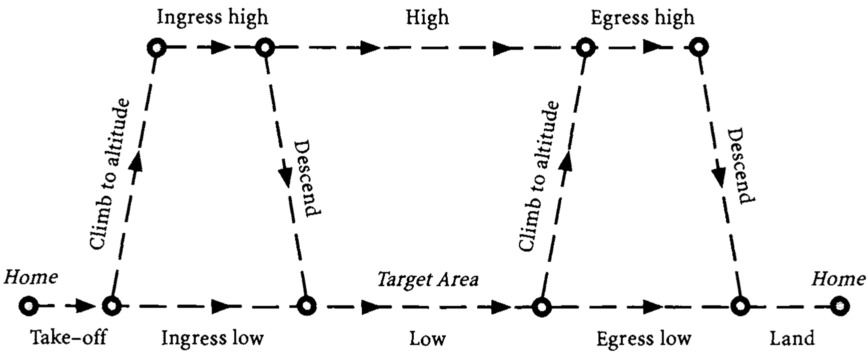

Fig. 3.83 Typical mission altitude profiles.

The attacking aircraft might approach the target area at very low altitude in order to increase their survivability against both the surface-based and the air-based AD. The very low-altitude approach to the target, using terrain following or terrain masking, can prevent the surface-based AD from detecting the attacker in time to engage it, and the air-based AD might not be able to detect the low-flying aircraft because of the difficulty in distinguishing it from the surface clutter (Note 89). On the other hand, the low-altitude approach puts the aircraft in the envelopes of the smaller, ground-based weapons. Consequently, when the friendly forces have air superiority the approach may be at the upper portion of the medium altitude, for example, above 16,000 ft, to stay out of the range of the surface-based guns and MANPADs.

Once near their target, tactical fixed-wing aircraft attacking surface targets from very low altitude with slick iron bombs or guns may use a pop-up or low-altitude ordnance delivery. Typical pop-up and ordnance delivery altitudes are 600–2300 m and 500–1500 m, respectively.[69] When high drag bombs or other ordnance such as napalm are used, a low-level lay-down delivery at approximately 150 m can be employed. This delivery allows the attacker to maintain a high-speed, low-altitude approach and delivery, making it more difficult for the defense to react in time. A speed of 350–500 kn is a compromise between a fast speed for survivability and a slow speed for accurate ordnance delivery.[69]

Each element in the flight can use a different weapon delivery profile in order to confuse and disrupt the AD. Using the high-altitude approach to the target, the aircraft is out of range of most of the surface-based AD weapons, and those AD weapons with a high-altitude capability might have difficulty overcoming the

Table 3.21 AGL altitude definitions[68]

Descriptor	Very low	Low	Medium	High	Very high
Altitude, m	0–150	150–600	600–7500	7500–15,000	>15,000
Altitude, ft	0–500	500–2000	2000–25,000	25,000–50,000	>50,000

electronic countermeasures employed by the attacking forces. On the other hand, locating the target might be very difficult from high altitude, and the delivery accuracy of unguided ordnance on the found target might be much less from high altitude. Consequently, when approaching the target from high altitude the aircraft might use a dive-bombing attack to improve delivery accuracy.

When precision guided air-to-surface weapons are used, the launching aircraft can release its weapon a relatively long distance away from the surface target and possibly outside of the range of the AD. Some air-to-surface missiles use a type of guidance that requires the aircraft to continue in towards the target. However, if the missile can operate autonomously after launch, such as a missile using GPS, the aircraft is free to turn away. This type of delivery is known as launch-and-leave, fire-and-forget, or shoot-and-scoot. The AD must then defend against the air-to-surface weapon itself. These missiles can approach the target in the same manner as a manned aircraft would approach, either from very low altitude or very high altitude. The low-altitude approach might require a pop-up some distance away from the target in order to locate the target, followed by a dive back to low altitude and a low-altitude approach for the remaining distance to the target. Some missiles can drop to low altitude after launch and remain there during their entire approach to the target (Note 90). For the missile that approaches the target at high altitude, the weapon will go into a dive at a steep angle toward its target, approaching it at very high speed.

Helicopters attacking surface targets, such as tanks, will approach their targets using nap-of-the-Earth (NOE) flight paths and terrain masking to delay their detection (Note 91). Once inside their weapon's maximum range to the target, they can pop-up to locate the target and fire their weapon. They might have to remain in sight of the target to guide their weapon, or they might be able to return to a hidden position if the weapon can guide itself or if another platform can perform the necessary guidance functions.

The computer program available from SURVIAC for determining an aircraft's flight path through a defended area is BLUEMAX. BLUEMAX is described in Chapter 1, Sec. 1.5.2.3.

Go to Problems 3.9.4 to 3.9.5.

Endnotes

1. The role of an aircraft refers to the broad and enduring purpose for which it was designed.
2. The distinction between tactical missions and strategic missions has become blurred in recent times.
3. The FLOT is "a line that indicates the most forward positions of friendly forces in any kind of military operation at a specific time. The FLOT normally identifies the forward location of covering and screening forces. The FLOT may be at, beyond, or short of the forward edge of the battle area. An enemy FLOT indicates the forward-most position of hostile forces."[2] The FEBA is "the foremost limits of a series of areas in which ground combat units are deployed, excluding the areas in which the covering or screening forces are operating, designated to coordinate fire support, the positioning of forces, or the maneuver of units."[2]

4. Official information on many U. S. military aircraft and their missions can be found online at http://www.chinfo.navy.mil/navpalib/factfile/ffiletop.html and http://www.af.mil/news/indexpages/fs_index.shtml. The interested reader will find additional information on military aircraft roles and missions in Refs. 3, 70–75. Literally hundreds of sites on the Web contain descriptions of the specific aircraft listed for each mission. Some of them are http://www.fas.org/man/dod-101/sys/ac/index.html, http://www.csd.uwo.ca/~pettypi/elevon/baugher_us/, http://www.btinternet.com/~military.aircraft/, and http://www.uksprite.com/search.htm?GetCat=/Recreation/Aviation/Military/.
5. Another categorization of tactical combat missions is the USAF Air Power Functions Counterair, Counterland, and Countersea.[75] "Counterair consists of operations to attain and maintain a desired degree of air superiority by the destruction or neutralization of enemy forces. Counterair's two elements, offensive counterair and defensive counterair, enable friendly use of otherwise contested airspace and disable the enemy's offensive air and missile capabilities to reduce the threat posed against friendly forces."[75] "Counterland involves those operations conducted to attain and maintain a desired degree of superiority over surface operations by the destruction or neutralization of enemy surface forces. The main objectives of counterland operations are to dominate the surface environment and prevent the opponent from doing the same."[75] Specific traditional functions associated with counterland operations are interdiction and close air support. "Countersea is a collateral function, defined in Ref. 2 as a mission other than those for which a force is primarily organized, trained, and equipped, that the force can accomplish by virtue of the inherent capabilities of that force."[75]

   "Countersea functions are an extension of Air Force functions into a maritime environment. The identified specialized collateral functions are sea surveillance, antiship warfare, protection of sea lines of communications through antisubmarine and antiair warfare, aerial minelaying, and air refueling in support of naval campaigns. Many of these collateral functions translate to primary functions of air and space forces such as interdiction, counterair, and strategic attack."[75]
6. A raid is "an operation, usually small scale, involving a swift penetration of hostile territory to secure information, confuse the enemy, or to destroy his installations. It ends with a planned withdrawal upon completion of the assigned mission."[2] A strike is "an attack that is intended to inflict damage on, seize, or destroy an objective."[2] Raids, also referred to as surgical strikes, are usually one-time 'surprise' operations designed to catch the enemy air defense off guard, whereas strikes are usually part of a campaign, for example, the U. S. raid on Libya in 1986 vs a B-52 strike on North Vietnam during Linebacker II operations in December 1972.
7. In the middle 1990s the decision was made to replace the U. S. Air Force's Raven with the Navy's Prowler on Air Force missions.
8. A transcript of a DoD news briefing 14 April, 1999, by Kenneth H. Bacon, ASD PA, with participation by Major General Chuck F. Wald, J-5 is available online at http://www.defenselink.mil/news/Apr1999/+04141999_+0414asd.html. A major part of that briefing concerned the FAC operations in Kosovo.
9. Because there are so many air defense forces in the world, describing the terminology and operations of each one is impractical. Consequently, the air defense terminology and operational concepts used by the U. S. Army air defense forces are described here to give the reader the necessary information to conduct a survivability

program. The interested DoD reader is referred to the U. S. Army FM 44-94 Air and Missile Defense Command Operations for the doctrinal guide to the AAMDC operations (http://www.adtdl.army.mil/cgi-bin/atdl.dllfm/44-94/toc.htm), U. S. Army FM 44-100 Air and Missile Defense Operations for the capstone doctrinal manual for the air defense combat function (http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/44-100/toc.htm), and U. S. Army FM 3-01.11 Air Defense Artillery Reference Handbook for the description of the Air Defense Artillery operations and weapons systems (http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/3-01.11/toc.htm)

10. The U. S. Army refers to both ground-based gun and surface-to-air missile systems as air defense artillery (ADA), which are "weapons and equipment for actively combating air targets from the ground."[2]
11. For missile systems both the system and the weapon can have a name, for example, the U. S. Navy's Aegis weapon system uses the Standard missile. The Standard missile is designated RIM-66 for the medium range (MR) version and RIM-67 for the extended-range (ER) version.
12. Although a particular weapon system might have been primarily designed for area defense, it can still be used for the point defense of a high-value asset.
13. AD aircraft at high altitude that can detect and fire missiles at incoming enemy aircraft traveling at low altitude are said to have a look-down, shoot-down capability.
14. If the air defense fighters are incapable of flying long distances and loitering on CAP, the FEZ can be inside of the MEZ.
15. A bogey is an air contact that is unidentified but assumed to be an enemy. It is not to be confused with an unknown contact.
16. When the aircraft is illuminated by a tracking beam from some source not on the missile and the beam echo from the aircraft in the direction of the missile is used by the missile for navigation, the system is referred to as a semiactive homing system. Descriptions of the specific types of missile guidance are given in Sec. 3.7.5.2.
17. The procedure for computing the probability of detection and the probability of false alarm is described in Chapter 4, Sec. 4.3.3.
18. Without track data correlation the sequence of target echoes from a single aircraft tracked by a track-while-scan (TWS) radar, or the tracks obtained by several sensors, could be interpreted as several aircraft. On the other hand, tracks from different sensors for many aircraft could be interpreted as tracks of a few aircraft. For automatic tracking systems computer software decision rules attempt to resolve tracking ambiguities, prevent the introduction of false targets, and provide accurate track data.[76]
19. The keep-out boundary is the radius from the AD site to that farthest location where an aircraft can launch a weapon and hit the defended target.
20. Some launching devices are vertical, allowing full 360-deg coverage and eliminating gaps in coverage caused by the presence of intervening objects, such as the superstructure of a ship.
21. Note that although the missile moves along the flight path relative to the stationary aircraft, the dashed line in Fig. 3.7, the missile body axis is not coincident with the relative flight path. This is primarily because the velocity vector of the missile with respect to the aircraft is the vector sum of the missile's velocity vector and the reverse of the aircraft's velocity vector. This is described in detail in Chapter 4, Sec. 4.3.6.

22. In some documents the miss distance refers to the distance between the target aircraft and the missile warhead detonation point. Here, that distance is defined as the detonation distance. The miss distance is shortest distance between the aircraft and the missile as the missile flies by the aircraft with no warhead detonation.
23. Other options for fuzing are presented in Chapter 4, Sec. 4.3.7.2
24. The missile signatures affect the missile's effectiveness because they can be seen by the target aircraft, giving the aircraft an opportunity to take evasive action, such as maneuvering away from the missile or turning on an electronic countermeasure device, or ejecting an expendable decoy. All of these actions will reduce the likelihood that the missile kills the aircraft.
25. A third method to estimate effectiveness is to use any actual combat data, if available.
26. The term reacting refers to aircraft that react to a propagator launch and flyout by performing an evasive maneuver and/or initiating one or more countermeasures, such as the ejection of decoys or the application of electronic countermeasures.
27. The Monte Carlo solution technique for scenarios with random outcomes is described in Appendix B, Sec. B.8.2, and the procedure for determining the numerical value for P_K (or $P_{K|SS}$) when a number of random shots are fired when the aircraft is at a particular location is described in Chapter 6, Sec. 6.2.2.
28. The three-dimensional, stochastic flight paths of the missile and the target and the very irregular shape of most aircraft cause considerable difficulty when attempting to define a representative spherical critical radius around the target center within which a warhead detonation is 'lethal.' Because of the difficulty in accounting for all of the three-dimensional effects in the endgame, the critical radius around the target center where an aircraft kill is declared has been defined elsewhere as one-half of the length of the target fuselage (or 50 ft, which ever is smaller) plus the warhead lethal radius.
29. The tracking rate can be relatively high when a missile using proportional navigation is launched from the forward hemisphere directly at the target aircraft compared with a rear hemisphere launch. This high tracking rate might prevent a cooled-seeker missile from being an all-aspect missile.
30. The definitions for the types of aircraft kills are given in Chapter 5, Sec. 5.2.2.1.
31. When the V/L Taxonomy was originally developed, the process started at level 1, where the target was about to be hit. Level 0, the beginning of the engagement, was added later for completeness. Hence the name vulnerability/lethality taxonomy.
32. Nonguided missiles, that is, rockets and rocket-powered grenades, also can be a threat to aircraft.
33. The size of a gun is denoted by its caliber. The word caliber is used in two different designations. It can denote the internal diameter of a gun and the external diameter of a projectile, for example, the caliber of the gun and its projectile is 12.7 mm or 0.50 in. or 0.50 cal. It also is used to denote the ratio of the length of a gun barrel to the diameter of its projectile, for example, a 5-in. 54-cal gun fires a 5-in.-diam projectile out of a 5 in $\cdot$ 54 $=$ 270 in. long barrel.
34. The definition of small arms has varied considerably over the years. Although the Joint Chief of Staff definition of small arms extends to 20 mm, the term small arms is often interpreted to refer to guns no larger than 14.5 mm. The original meaning of the term referred to guns that could be carried by hand. Today, the term has been expanded to include most crew-portable, direct-fire weapons.

35. The term threat propagator is also applicable to the radiation weapons described in Chapter 1, Sec. 1.1.14.1. For the DE weapons the threat propagator is the beam or pulse of electromagnetic radiation, or a stream of nuclear particles, that travels from the weapon to the target aircraft.
36. The various kinds of missile guidance are described in Sec. 3.7.5.2 of this chapter.
37. A third type of guided missile is one launched from a flying 'missile-containing' capsule released from a submerged submarine.[77] Missiles launched from submarines are referred to as SUBSAMs.
38. The term warhead is sometimes used to denote both the warhead and its associated fuze.
39. The weight of projectile cores and warhead fragments is usually given in grains, where 7000 grains = 1 lb at sea level. The U. S. quarter-dollar coin weighs approximately 150 grains, and an aspirin tablet is 5 grains.
40. The difference between a penetrator and a fragment in an HE warhead is the relative size, shape, and number carried by the warhead. For example, relatively large discrete rods can be referred to as penetrators, whereas small cubes and diamond-shaped chunks of metal are fragments. The difference between the two terms is not always distinct.
41. Comp B is composed of 60/40/1 (RDX/TNT/wax) by weight. Some HE warheads also contain aluminum. For example, Tritonal consists of 80% TNT and 20% aluminum, by weight.[78]
42. Specially shaped fragments can also be obtained from a continuous case by wrapping the case with wire, or by using roof-shaped or triangular inserts between the case and the HE charge.
43. The aimable fragmentation warhead also focuses the energy from the detonation, but is not referred to as a focused-energy warhead.
44. An exception is the Saab Bofors Dynamics RBS 70 missile warhead, which has both preformed fragments and a conical-shaped charge.
45. At sea level the velocity of the shock front U is approximately $330(1 + 6P_o/7P_a)^{1/2}$ m/s.
46. For a reference length the radius of a 1-lb sphere of TNT is 1.61 in.
47. For a warhead where the mass per unit length of the metallic case or the HE material changes along the axis of the warhead, V_0 is dependent upon the local value of the ratio C/M. For example, a concave (outward bowed) warhead will have more HE mass at the center than at the ends, and a case with varying fragment mass along the warhead longitudinal axis also will have a C/M that depends upon the location along the axis.
48. Weight densities at sea level are given in Tables 3.9a and 3.9b in addition to the mass densities because the parameter of interest is the nondimensional ratio of masses C/M, which has the same value as the ratio of weights.
49. In the published literature Shapiro's angle and Taylor's angle are measured from the normal to the warhead case to the fragment spray angle. They have been converted here to the angle from the missile axis to the spray angle.
50. This is to be expected because of the relatively short case length.
51. Two other phenomena associated with the ballistic impact of metallic penetrators and fragments on metallic targets are the generation of incendiary materials in the form of metallic sparks and a blast loading inside the target caused by the phenomenon

known as the vaporific effect. The bright glow that is observed when the metallic fragments from an HE warhead detonation hit the metallic surface of an aircraft is caused by the light radiated from the very hot metallic sparks generated by the impact. The vaporific effect is a similar effect in which fine aluminum particles or vapor from the back face of the impacted plate rapidly oxidize, emitting radiation in the form of light and heat. The heat generates a blast, and consequently the vaporific effect is considered with the blast damage mechanism.

52. Reference 29 contains a thorough description of the physics of the penetration of thin targets by metallic penetrators and fragments, and Ref. 30 considers penetration through armor materials.
53. In the following material on the damage processes and terminal effects associated with penetrators and fragments, only the penetrator will be referred to; the same statements also apply to fragments.
54. For an example of this type of response, find a plate glass window that has been hit by a BB from a BB gun. You will see a small hole in the front (hit) side of the window. Looking at the backside of the window, you will see that a 0.5-in. conical chunk of glass is missing. The author knows this from personal experience.
55. When tank armor is hit by a high-speed impactor or a detonation occurs on the outer surface of the tank armor, the spall ejected from the inner surface of the tank armor into the interior of the tank is often referred to as 'behind-armor debris' (BAD). BAD can be very lethal to the tank crew and components.
56. The angle of obliquity θ is the angle between the attack direction or shotline of the impacting penetrator and the outward normal to the plate surface. The yaw angle ϕ is the angle between the body of the penetrator and the shotline.
57. Reference 79 contains an excellent description of the experimental determination of the V_{50} PBL. This reference compares the V_{50} PBL determined by several laboratories from a given set of test panels. Among the findings were the following: "The intuition of the test engineer influences velocity selection and hence introduces bias into the outcome of the test."; "Another variability with this standard is the absence of specimen sizes and fixturing methodology."; and "To comply with cost and schedule requirements, existing standards permit the use of lower numbers of data points, typically four or six shots. This approach makes ballistic testing relatively straightforward but the calculated ballistic limits have statistically low confidence levels." The authors concluded that "Using a 95% confidence level, ballistic test results are *not* reproducible from one laboratory to the next for both steel and macrocomposite panels."; and that "Reducing the confidence level by increments of 5%, 10%, or 15% (to 90%, 85%, or 80%) does not alter the foregoing conclusion."
58. The residual velocity V_r is actually the residual velocity of the center of the total mass consisting of both the remaining mass of the original penetrator and the mass driven from the impacted skin.
59. Note that Eq. (3.12) for the residual velocity is not of the same form as that given in Eq. (3.10). Equations (3.11–3.13) are regression equations that fit the experimental data and are not derived using physical principles. Furthermore, note that the regression equations are not dimensionally consistent, which is true for regression equations in general. Thus, when calculating the desired variable, the numerical value of each variable in the regression equation must be in the defined unit for that variable.

60. The sonic velocity in air and in water is approximately 330 m/s and 1500 m/s, respectively, at sea level and low overpressure.
61. On 25 July, 2000, Air France Flight 4590, a supersonic Concorde, apparently rolled over a titanium strip as it took off from Paris–Charles de Gaulle airport on its way to New York City. Investigators have determined that the strip punctured a tire, and a large piece of rubber was thrown upward. The piece impacted the underwing skin just forward of the left main landing-gear strut. The impact generated a hydrodynamic ram pressure pulse in the fuel behind the impact area that caused a major rupture of the impacted tank skin, and an estimated 100 liters per second of fuel flowed through the hole. The leaking fuel was ignited by an unknown source. The crew shut down the no. 2 engine in response to a fire alert, and the performance of engine no. 1 was degraded because of the fire. The aircraft eventually crashed. To protect the Concorde against future impact events, Kevlar/rubber liners have been installed in the lower, inboard portions of the wing tanks to reduce the amount of fuel leakage by physically blocking the hole and somewhat attenuating the hydrodynamic ram pressure.[80]
62. The continuous limit shown in Fig. 3.50 is sometimes referred to as the flammability limits, where the left side of the limit is the lower flammability limit, and the right side is the upper flammability limit.
63. The flash point is defined as the lowest temperature, corrected to 101.3 kPa of pressure, at which the application of an ignition source causes a vapor of a liquid sample to ignite momentarily under specified conditions of testing. The flash point is close to, but slightly higher than, the lower flammability limit because of the particulars of the test apparatus. There are several accepted flash-point test methods. They involve a container of fuel that is slowly heated and periodically subjected to a spark until a flash is observed.[81]
64. Knowledge of the temperature/fuel/oxygen conditions in fuel tank ullages of flying aircraft became very important after the loss of TWA 800 (a Boeing 747 airplane) on 18 July 1996 was ascribed to a fuel-air explosion within the center wing tank.[82]
65. Harmonically oscillating refers to the fact that the equation for the electric and magnetic fields in the wave can be expressed in the form $\sin(\omega t)\sin(2\pi z/\lambda)$, where $\omega = 2\pi f$, and the term transverse denotes the fact that both fields are normal to the z axis, the direction of wave propagation.
66. The speed of light in a vacuum is $2.99792458 \cdot 10^8$ m/s. (http://physics.nist.gov/cgi-bin/cuu/Value?c/search_for=universal_in!.) The speed of light in the Earth's atmosphere is 99.97% of the speed of light in a vacuum. (http://www.fnal.gov/pub/ferminews/santa/index.html.)
67. Two media are dissimilar when the velocity of EM wave propagation is different.
68. The GCI radar is used to direct interceptors to hostile aircraft.
69. The angle tracking techniques that are used to determine a more accurate estimate of the target's angular position are described in Sec. 3.7.2.6 of this chapter.
70. The radar community often uses dB to denote both a reference power of 1 W and a nondimensional number, such as antenna gain, and it uses dBm to denote a reference value of 1×10^{-3} W. This notation is not used here. Here, dBm refers to a decibel with a reference value of 1 m, so that dBsm has a reference value of 1 m^2.
71. An impulse or spread spectrum radar is one in which the pulse width is very short, the frequency bandwidth is very high, and the peak power is very high.

72. A wave is circularly polarized when the direction of the electric field at a particular location in space rotates around the propagation axis, and the field strength remains constant, as the wave passes.
73. The SWIR, MWIR, and LWIR bandwidths have no 'official' standard. Different documents use somewhat different bandwidths. Another IR-band division scheme used with the IR detectors on guided missiles is the band I, II, III, and IV designation, for example, a particular missile is a band IV missile. The approximate bandwidth for each of the four bands is 1.7–2.8 μm, 2.7–3.5 μm, 2.8–3.8 μm, and 3.8–4.7 μm, respectively. Also, note that the optical band includes the IR band, the visible band, and the upper part of the ultraviolet band. Systems that sense radiation in the infrared band of the EM spectrum are sometimes referred to as electro-optics systems, where electro-optics systems have been defined as the field of systems that convert photons to electrons.[83] Many lasers have wavelengths in the IR band, such as Neodymium-YAG, which lases at 1.064 mm, and CO_2, which lases at 10.6 μm.
74. When the reflection of sunlight from the target aircraft is the primary source of IR radiation sensed by an IR seeker on a passive homing missile, theoretically, the method of guidance is not passive homing, but instead is semiactive homing because the original source for the target signature is the sun, not the target.
75. Suppose your head was the seeker head and your eyes were the detectors. Stand still and stare straight ahead. Next, stretch your arms out in front of your body, and then move them horizontally in a circular manner around your head toward your ears. Keep staring straight ahead. The FOV of your sight is defined by the angular limits of your eye's ability to see your hands. Mine is about ±80 deg. An IR seeker's FOV might be a few degrees or less. Next, stop staring straight ahead, look to the right as far as you can, holding your head still, and then look to the left. The field of regard of your seeker is defined by the angular limit of your eye movement. Mine is about ±45 deg. An IR seeker's field of regard might be ±30 deg or more. A wide field of regard means a target can be tracked at a wide angle from the missile axis. To illustrate the instantaneous field of view, stare straight ahead. Now bring your hands together in front of your face, and form a hole with your fingers. Look out through the hole. That is the instantaneous field of view within the FOV.
76. The following Web site contains a list of the emissivities of many metals and nonmetals with several different surface conditions and temperatures: http://www.omega.com/literature/transactions/volume1/emissivity.html.
77. The upper bound of the visible region is between 0.7 and 0.8 μm. The 0.7 limit is used here for convenience.
78. The calculator can be obtained by contacting this Web site: http://www.judtech.com.
79. The unit solid angle is the steradian. The steradian is defined in Ref. 84 as "the unit of measure equal to the solid angle subtended at the center of a sphere by the area equal to the radius squared on the surface of the sphere." Recall that the unit plane angle is the radian, and there are 2π radians in the 360 deg of a circle. Furthermore, the length of a circular arc of radius R and angle α is equal to α (in radians) $\cdot$ R. Thus, the circumference of the complete circle is $2\pi R$ because there are 2π radians in the circle. Similarly, there are 4π steradians in a sphere, and the total surface area of a sphere of radius R is $4\pi R^2$. The partial surface area of a sphere that is enclosed by a solid angle Ω is equal to Ω (in steradians) $\cdot$ R^2. For a view of a solid angle, look inside an ice cream cone (without the ice cream)—not the flat bottomed cone,

but the sugar cone with a point on the bottom. The exterior of the ice cream cone subtends a solid angle.

80. Every molecule is made up of atoms, and the atoms are arranged in the molecule in a specific way. For example, the arrangement of the atoms in CO_2 is O-C-O, with the oxygen atoms equidistant from the carbon atom. Motion of one of the atoms in the molecule creates a force on the adjacent atoms, and the atoms within the molecule vibrate as a multiple degree of freedom spring-mass system. There are four vibrational modes associated with the CO_2 molecule. When the vibration mode shape is such that there is an electric dipole moment created, that is, there is a net difference in the distance between the positive and negative charges, radiation is emitted at a specific frequency. For example, one of the vibration modes of CO_2 occurs when one oxygen atom and the carbon atom move toward each other and the other oxygen atom moves away, maintaining a fixed center of gravity. This creates an electric moment, and the wavelength associated with the natural frequency of this mode is 4.3 μm.
81. "The 'greenhouse effect' is the warming of climate that results when the atmosphere traps heat radiating from Earth toward space. Certain gases in the atmosphere resemble glass in a greenhouse, allowing sunlight to pass into the greenhouse, but blocking Earth's heat from escaping into space. The gases that contribute to the greenhouse effect include water vapor, carbon dioxide (CO_2), methane, nitrous oxides, and chlorofluorocarbons (CFCs). Life on Earth depends on energy coming from the sun. About half the light reaching Earth's atmosphere passes through the air and clouds to the surface, where it is absorbed and then radiated upward in the form of infrared heat. About 90% of this heat is then absorbed by the greenhouse gases and radiated back toward the surface, which is warmed to a life-supporting average of 59° F (15°C)" (http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/earthsci/green.htm). The analogy to the glass in a greenhouse comes from the fact that window glass is transparent to the wavelength band between 0.3 and 3 μm. (http://www.nrc.ca/irc/bsi/88-2_E.html.) Thus, much of the radiant incidence on the glass from the sun, which peaks at 0.5 μm, will pass through the glass and shine on the plants. The plants, because they are at room temperature, will radiate at 10 μm. The glass is opaque to this wavelength, and, consequently, the heat from the plants is trapped inside the greenhouse.
82. The valence band of an atom is the outer most full band of electrons. The conduction band is the outermost band that is not full of electrons. The forbidden gap, band, or energy gap is the 'energy' separation between the valence band and the conduction band.
83. Note that InSb has a significant response to radiation in the 5–6 μm range, whereas the general detector bandwidth used here extends from 3–5 μm, not 6 μm. The reason 5 μm is used as the upper limit is because most of the radiation above 5 μm is absorbed by the atmosphere.
84. References 85 and 86 contain tutorial information on precision guided munitions and the types of guidance employed.
85. Air defense weapons of the United States or friendly countries are referred to as blue threats; air defense weapons built by the Russian Federation, communist, or Soviet counties are usually known as red threats; those built by countries other than the U. S. or Soviet Union are gray threats; and rainbow threats are threats that span technologies and platforms from many different countries and design philosophies. (http://www.sew-lexicon.com/gloss_gr.htm.)

86. Reference 87 contains information on the function and performance of the Bofors 40-mm PFHE Mk 2 round.
87. MIL-STD-2069 is described in Chap. 1, Sec. 1.3.4.
88. To deconflict a mission is to ensure that all mission aircraft flight paths are sufficiently separated in space and time to avoid midair collisions and the blast and fragments from any exploding air-to-surface ordnance.
89. Terrain following is flight that maintains, as closely as possible, a constant altitude above the ground contour. Terrain masking is flight behind terrain features, such as hills and trees, in order to avoid detection and tracking by the AD.
90. Antiship missiles that come in at low altitude are called sea skimmers.
91. Nap-of-the-Earth flight is flight that follows, as closely as possible, the contour of the Earth at very low altitude.

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Problems

3.1.1 What is the role of an aircraft?

3.1.2 What is an aircraft mission?

3.1.3 Military missions are of two general types. What are these types?

3.1.4 Tactical combat missions typically involve the bombing of the enemy's territory and its war-making facilities: True or False.

3.1.5 Describe air superiority and its importance to aircraft combat survivability.

3.1.6 The interception mission consists of the destruction of incoming enemy bombers or cruise missile carriers, typically from long range and in any weather, day or night: True or False.

3.1.7 The defensive counterair mission is to achieve a desired degree of air superiority by the destruction or neutralization of enemy forces using offensive counterair operations: True or False.

3.1.8 What is the primary difference between the OCA and the DCA mission?

3.1.9 The close air support mission involves air action against ground-based hostile targets: True or False.

3.1.10 What is the primary purpose of the CAP mission?

3.1.11 What is the difference between a strike and a raid?

3.1.12 List the five primary missions associated with tactical air-to-surface operations.

3.1.13 SEAD stands for what mission?

3.1.14 What is the difference between the SEAD and DEAD missions?

3.1.15 Describe three combat support missions.

3.1.16 In the first strike on the Dragon's Jaw bridge in North Vietnam during the SEA conflict, more aircraft were used to enhance the survivability portion of the mission (the SR) than were used to enhance the offensive capability portion of the mission (the MAM): True or False.

3.1.17 List one example of the use of each of the six susceptibility reduction concepts in Operation Desert Storm.

3.2.1 According to the JCS Dictionary, air defense consists of those defensive measures designed to destroy attacking enemy aircraft or missiles in the Earth's envelope of atmosphere: True or False.

3.2.2 List the three primary types of air defense weapons considered here.

3.2.3 A machine gun is not, by definition, an air defense weapon: True or False.

3.2.4 The AD of an assigned area is accomplished using only ground- or sea-based AD forces or only airborne forces: True or False.

3.2.5 Describe the two types of air defense territories.

3.2.6 Area defense weapons can also be point defense weapons, but point defense weapons can not be area defense weapons: True or False.

3.2.7 What is layered AD and why is it used?

3.2.8 Describe the FEZ, MEZ, and inner defense zone of a layered sea-based AD.

3.2.9 List the five major components of an IADS.

3.2.10 Consider the operational functions of an air defense listed in the following table. Relate these functions to the probabilities associated with the kill chain described in Chapter 1 (P_A, $P_{D|A}$, $P_{L|D}$, $P_{I|L}$, $P_{H|I}$, $P_{F|I}$, $P_{K|H}$, $P_{K|F}$, and P_K).

Probability	Operational function
	Move to the assigned location and set up, if necessary.
	Communicate with other units in the AD.
	Search for aircraft.
	Detect and acquire contacts.
	Track one or more contacts.
	Identify the contacts as hostiles, unknowns, or friendlies.
	Prioritize the hostile contacts as targets (and assign a fire unit).
	Compute a fire control solution for each target.
	Fire a ballistic projectile or launch a guided missile.
	Fly the projectile or guide the missile to an intercept.
	Hit the target with the propagator warhead,
	or
	Detonate (fuze) the HE warhead.
	Kill the target with the propagator hit,
	or
	Kill the target with the warhead detonation (fuzing).
	Evaluate the outcome of the shot.
	Fire again, if necessary, or slew to another target.

3.2.11 Sketch the big picture for the one-on-one encounter up to intercept. Include the weapon envelope, the detection envelope, the propagator flight path with phases, and the time-line events.

3.2.12 The detection envelope represents the location in space where the aircraft is detected with certainty: True or False.

3.2.13 What is the criterion for successful target acquisition?

3.2.14 What is the criterion for a successful intercept?

3.2.15 Describe the CPA.

3.2.16 Describe the endgame and the endgame events.

3.2.17 What is the detonation distance and how does it differ from the miss distance?

3.2.18 What two probabilities are known as the warhead lethality functions?

3.2.19 Sketch the area around the aircraft where a proximity-fuzed warhead detonation has a significant probability of killing the aircraft.

3.2.20 What is the warhead lethal radius?

3.2.21 When an aircraft's radar signature is reduced, the effectiveness of a radar directed AD weapon is decreased: True or False.

3.2.22 Consider an antiaircraft gun. List three of the factors associated with the gun projectile and the fire control that affect the effectiveness of the gun.

3.2.23 Consider a SAM. List three of the factors associated with the missile and the fire control that affect the effectiveness of the SAM.

3.2.24 Describe the generic weapon envelope.

3.2.25 Describe the distinguishing features of the lethal (launch) and lethal (intercept) envelopes, the intercept or engagement envelope, the lethal missile footprint, and the LAR.

3.2.26 Estimate the maximum extent of the lethal (launch) envelope of a 170-mm missile and the effective slant range of a 30-mm gun.

3.2.27 What is the difference between weapon system effectiveness and air defense effectiveness?

3.3.1 Ballistics is the scientific study of the firing of weapons: True or False.

3.3.2 The scientific study of the destructive effects of a weapon on a target is known as terminal ballistics: True or False.

3.3.3 Fill in the Threat Topical Field shown in the following table:

Threat characteristics	Threat operations
1) Threat types	1)
2)	2) Launch or fire
3) Damage mechanisms	3)

3.3.4 Fill in the Aircraft Response Topical Field shown in the following table:

Damage processes	Aircraft vulnerability	Response measures
1) Impact	1)	1)
2)	2)	2) Kill levels
3)	3) Kill criteria	
4)		
5) Blast loading		

3.3.5 What is a damage mechanism, and give an example of one?

3.3.6 Give an example of the damage processes associated with the damage mechanism you listed in Problem 3.3.5.

3.3.7 Describe the term kill mode.

3.3.8 Describe the term terminal effects.

3.3.9 Give an example of a kill criterion.

3.3.10 Give an example of a response measure.

3.3.11 Give an example of the sequence of events that occur when an aircraft gets hit, using the terms damage mechanism, damage process, kill mode, terminal effect, and aircraft response.

3.3.12 List the five levels in the V/L Taxonomy, including their title.

3.3.13 A metric for level 1 is the ballistic projectile hits the port side of the aircraft at 2000 fps at a 30-deg angle of incidence: True or False.

3.3.14 A metric for level 2 is the aircraft is out of control 30 s after the hit: True or False.

3.3.15 A metric for level 4 is the left engine was killed by the hit: True or False.

3.4.1 Describe the two general types of threat elements, and give an example of each.

3.4.2 What are the two types of firing platforms?

3.4.3 Guns and missile launchers are examples of______?

(a) firing platforms
(b) surface-based platforms
(c) nonterminal threat elements
(d) propagators
(e) terminal threat elements and firing devices

3.4.4 What is the term used to describe the terminal threat element that carries the warhead from the firing platform to the target aircraft? Give two examples.

3.4.5 What threat just sits and waits for an unsuspecting helicopter to fly by?

3.4.6 Match the following gun terms on the left with the descriptions on the right:

a) AAA	_______Fires 14.5-mm AP projectiles
b) SA	_______Fires 21- to 40-mm HE rounds
c) Light AAA	_______Fires HE rounds greater than 40-mm
d) Cannon	_______Fires 20-mm projectiles
e) Heavy AAA	_______Fires 20-mm HE projectiles
f) AA	_______Fires 7.62-mm rounds

3.4.7 What is the ordnance package?

3.4.8 What is the purpose of the warhead?

3.4.9 What does the core of a warhead consist of?

3.4.10 What is a "hittile"?

3.4.11 Define the term damage mechanism.

3.4.12 What are the three primary types of damage mechanisms associated with penetrator and HE warheads?

3.4.13 What are the damage mechanisms associated with penetrator warheads?

3.4.14 List the three major types of penetrator warheads.

3.4.15 What are the penetrator warhead parameters that influence the lethality of penetrator warhead?

3.4.16 The muzzle velocity of small-arms projectiles typically is between what values? The velocity at intercept at 1500 m is typically between what values?

3.4.17 What is the approximate weight in grains of a U. S. quarter and a 7.62 AP projectile?

3.4.18 High-explosive warheads are always circular cylindrical: True or False.

3.4.19 The type of explosive most often used in HE warheads is TNT: True or False.

3.4.20 What are the five major types of HE warheads used against aircraft?

3.4.21 What are the primary damage mechanisms carried or generated by HE warheads?

3.4.22 What is the primary disadvantage of a blast warhead?

3.4.23 What are the three general types of fragmentation warhead cases?

(a) continuous rod, discrete rod, and smooth.
(b) preformed, continuous, and noncontrolled.
(c) natural, perforated, and scored.
(d) natural, controlled, and preformed.
(e) none of the above.

3.4.24 Why is the size of the fragments in a warhead controlled?

3.4.25 Warhead fragments are usually steel, titanium, or magnesium: True or False.

3.4.26 What two capabilities are required for a warhead to be aimable?

3.4.27 Name at least three factors associated with the metallic case fragments that influence a fragmentation warhead's lethality.

3.4.28 What is the difference between a discrete rod case and a continuous rod case?

3.4.29 The ROLAND warhead is a conical-shaped charge warhead: True or False.

3.4.30 During a sea-level test of 1 lb of TNT, an overpressure probe at sea-level senses 30 psi shortly after the TNT is detonated. How far was the probe from the detonation, and what is the blast wave positive phase duration at this distance?

3.4.31 If 100 lb of TNT were detonated at sea level, what is the distance from the detonation point where $P_o = 30$ psi?

3.4.32 A blast warhead with 15 lbs of TNT detonates 15 ft from a helicopter flying at an altitude of 10,000 ft. Calculate the peak overpressure and impulse per unit area on the helicopter.

3.4.33 What controls the extent of the fragment spray zone in a fragmentation warhead?

3.4.34 If you expect relatively large miss distances from a long range SAM with a fragmentation warhead, then the missile probably has a relatively narrow, converging fragment spray zone: True or False.

3.4.35 Intelligence information on a new fragmentation warhead estimates that the length and outer diameter of the warhead are 12 in. and 8 in., respectively. The warhead designer is known to use HMX for the high explosive and preformed 50-grain cubic steel fragments arranged in two layers for the warhead case.

(a) Determine the size of each fragment.
(b) Determine the weight of the HE and the steel case.
(c) Calculate the Gurney velocity for the case fragments.
(d) Determine the number of fragments in the case.
(e) Calculate the Taylor spray angle. Assume a single detonator at the base end.

3.4.36 A comparison of the velocity computed using the Gurney formula with the velocity obtained from tests results for a single detonator located at one end reveals that the Gurney velocity is generally lower than the experimental velocity: True or False.

3.4.37 The fragment spray from a circular cylindrical warhead with a detonator at both ends converges: True or False.

3.4.38 A new circular cylindrical HE warhead is detonated in a field test. The number of fragments recovered are grouped within the following categories: 500 between 90 and 100 grains and 200 between 100 and 110 grains, within the spray-angle band 75 to 80 deg; and 150 between 90 and 100 grains and 100 between 100 and 110 grains, within the spray-angle band 80 to 85 deg. Sketch the fragment distribution by polar angle.

3.4.39 List the primary types of fuzes.

3.4.40 What is the TDD on a fuze?

3.4.41 What is the advantage of a delayed contact fuze?

3.4.42 Describe the operation of an active optical fuze.

3.4.43 Why does an aimable fuze increase the lethality of a proximity-fuzed HE warhead?

3.4.44 If you were told that the diameter of a new antiaircraft missile was estimated to be 150 mm, what is your estimate of the weight of the warhead on that missile?

3.5.1 The impact on, and possible penetration through, a target by a penetrator is referred to as penetrator impact: True or False.

3.5.2 Describe spall.

3.5.3 List at least four parameters that influence the penetration of a plate by a penetrator.

3.5.4 In most penetrations damage to the plate caused by sharp penetrators is confined to an area no more than two or three penetrator diameters: True or False.

3.5.5 Soft, blunt penetrators cause metallic plates to petal as a result of penetration: True or False.

3.5.6 What is plugging?

3.5.7 Complete penetration defined by the protection ballistic limit is that condition where light can be seen through one or more holes in the witness plate: True or False.

3.5.8 Define the V_{50} PBL.

3.5.9 Suppose a 200-grain rectangular steel fragment is fired eight times at a plate of 2024 aluminum alloy at an angle of obliquity of 0 deg off of the normal to the plate. The impact velocity and the penetration outcome for each shot is given here. Use four shots to define the ballistic limit.

Velocity (fps): 1900, 1840, 1780, 1720, 1660, 1600, 1540, 1480

Penetration: yes, yes, no, yes, yes, no, no, yes

3.5.10 An aircraft is hit by a 12.7-mm AP-I at 1000 fps. The V_{50} PBL of the aircraft skin at the impact point is 80 fps. What is the residual velocity of the projectile? Assume the projectile weighs 300 grains and no plugging occurs.

3.5.11 Penetration is assumed to occur when the impact velocity is equal to or greater than the V_{50} PBL: True or False.

3.5.12 A penetrator that impacts a flat plate at a relatively low angle of obliquity and at a velocity much above the V_{50} travels in essentially the same direction after penetration: True or False.

3.5.13 A penetrator that impacts a flat plate at a relatively high angle of obliquity and at a velocity somewhat above the V_{50} travels in essentially the same direction after penetration: True or Fulse.

3.5.14 Penetrators and fragments that hit a target can shatter or break up as they penetrate through the target components: True or False.

3.5.15 Assume you are the pilot of an F/A-24 Bomb Cat flying at 20,000 ft enroute to strike an enemy power plant 20 miles north of your present position. Your aircraft has one operational flight control computer located below the cockpit floor. This computer is a nonredundant critical component. Suddenly, much to your surprise, the enemy launches a long-range SAM at you. Although you perform an evasive maneuver as the SAM approaches, an intercept occurs, and the warhead detonates approximately 100 ft below your aircraft. You are lucky, or unlucky depending upon your point of view, that you are hit by only one single 250-grain cubic fragment from the steel case. Unfortunately, the initial fragment shotline intersects your flight control computer.

The impact velocity of the fragment is 4000 fps, and the angle of obliquity is 30 deg with the skin and 10 deg with the computer box. The skin of your aircraft at the impact point is 0.05-in. thick, and the box enclosing the flight computer box is 0.10-in. thick. Both skin and box are made of aluminum alloy 2024 T-3. From previous vulnerability studies of the computer, it was determined that the computer will be killed and the aircraft lost if a 250-grain fragment penetrates the box with a residual velocity greater than 500 fps. Use the THOR penetration equations with the coefficients given in Table 3.11 even though the fragment weight is slightly above the maximum velocity used to determine the coefficients. Assume the fragment impacts the target face-on.

(a) Will your aircraft survive the single hit?
(b) What should the thickness of the box be to stop the fragment from killing the computer?

3.5.16 How can six simultaneous fragment hits relatively close together cause more damage than six widely spread simultaneous hits?

3.5.17 Six simultaneous fragment hits relatively close together can be considered to have six independent outcomes: True or False.

3.5.18 Give three examples of the terminal effects associated with impact and penetration.

3.5.19 Hydrodynamic ram is only a vulnerability problem when the fluid-containing vessel is full: True or False.

3.5.20 Hydrodynamic ram has three phases: True or False.

3.5.21 The damage caused by hydrodynamic ram is primarily at the entry hole: True or False.

3.5.22 Explain why hydrodynamic ram is a vulnerability problem in wing fuel tanks made of composite materials.

3.5.23 Explain why hydrodynamic ram is a vulnerability problem in fuselage fuel tanks located next to engine air inlets.

3.5.24 List the three primary gases/vapors in a fuel tank ullage and their percent by volume.

3.5.25 What conditions are required for combustion to occur?

3.5.26 The combination of ullage pressure and temperature where combustion can occur is indicated in the ______.

3.5.27 What is the maximum combustion overpressure in aviation fuels?

3.5.28 The magnitude of the ignition source influences the occurrence of combustion and the magnitude of the overpressure: True or False.

3.5.29 Describe the terminal effects of the combustion damage process inside a wing fuel tank.

3.5.30 The vaporific phenomenon occurs when a metallic penetrator impacts a high-explosive material: True or False.

3.5.31 Describe the damage process associated with an air blast.

3.5.32 Describe the terminal effects associated with the blast damage process.

3.6.1 List the EM signatures of an aircraft that are used by the enemy air defense for detection and tracking.

3.6.2 Describe electromagnetic radiation as a continuous wave.

3.6.3 The velocity of EM radiation in a vacuum is approximately ______.

3.6.4 The velocity of EM radiation in the Earth's atmosphere is essentially the same as the velocity in a vacuum: True or False.

3.6.5 The velocity of EM radiation in water is essentially the same as in a vacuum: True or False.

3.6.6 A linearly polarized wave in which the magnetic field is horizontal with respect to the Earth is said to be vertically polarized: True or False.

3.6.7 Match the following phenomena with the correct description:

_______Transmission	1. Waves add vectorially.
_______Reflection	2. Waves bend around edges.
_______Absorption	3. Waves shift phase.
_______Interference	4. Waves bend when they pass from one material to another.
_______Diffraction	5. Wave energy is converted to heat.
_______Refraction	6. Waves striking a conducting body are scattered.
	7. Waves pass through the material.

3.6.8 Describe electromagnetic radiation in the IR band.

3.6.9 The energy of a photon depends upon the intensity of the radiation: True or False.

3.6.10 EM radiation is emitted by what?

3.6.11 What happens when an EM wave from a radio station strikes the radio antenna on your automobile?

3.6.12 What does the acronym RADAR stand for?

3.6.13 What are the three major parts of a typical radar system?

3.6.14 Radar signals are either CW or pulsed: True or False.

3.6.15 How does a bistatic radar system differ from a monostatic radar system?

3.6.16 What are the two broad categories of air defense radars?

3.6.17 Radars used to detect the presence of aircraft at long ranges generally operate as CW radars at relatively low frequencies, long pulse widths, and wide beamwidths: True or False.

3.6.18 Radars that provide the accurate targeting information necessary to allow the weapon to be brought to bear on a target typically operate at high signal frequencies, long pulse widths, and narrow beamwidths: True or False.

3.6.19 PPI stands for ___________.

3.6.20 Describe track-while-scan.

3.6.21 A radar pulse is transmitted, and an echo is received 0.1 ms later. How far away is the target from the radar?

3.6.22 A target's angular location is accurately determined by noting the direction the antenna is pointing when the echo from a single pulse is received: True or False.

3.6.23 Write the decibel power ratio expression.

3.6.24 Write the decibel equivalent to the decimal expression given in the following:

Decimal	Decibel
0.001	
0.01	
0.1	
1.0	
10	
100	
1,000	
$1 \cdot 10^6$	
$1 \cdot 10^9$	
2	
$2 \cdot 2$ or 4	
$2 \cdot 2 \cdot 2$ or $2 \cdot 4$ or 8	
$2 \cdot 8$ or 16	
$2 \cdot 16$ or 32	
$8 \cdot 8$ or 64	
8/2 or 4	
1,000/4 or 250	
1,000/2 or 500	
$10 \cdot 64$ or 640	
$(1{,}000)^2$	
$(1{,}000)^{0.5}$	
$(10{,}000)^{0.25}$	
1 W	
(10)(1 W)	
(100 W)/(10)	
(100 W)/(1W)	
1,000 W − 100 W	

3.6.25 At what speed do radar signals propagate in the Earth's atmosphere?

3.6.26 Define wavelength (in words), then write the expression that relates wavelength to frequency.

3.6.27 An I-band radar is also an X-band radar and vice versa: True or False.

3.6.28 High PRF radars have a long maximum unambiguous range R_u: True or False.

3.6.29 What is R_u for a radar with a PRF of 5000 PPS?

3.6.30 The pulse width of a pulse radar is 2 μs, and two aircraft 20-m long are flying in line and 200 m apart. How many echoes will be received by the radar?

3.6.31 What effects do approaching and receding targets have on the Doppler shift?

3.6.32 The radar transmits a signal at 1 GHz. The Doppler shift from the echo is 1000 Hz. What is the relative radial velocity of the target?

3.6.33 An aircraft flying a level circle around a radar cannot be detected by a pulse-Doppler radar: True or False.

3.6.34 One form of MTI is the use of the Doppler shift to distinguish moving targets from stationary objects: True or False.

3.6.35 What is pulse compression, and why is it used in radar systems?

3.6.36 What are the two primary functions of a radar antenna?

3.6.37 Described antenna gain (in words).

3.6.38 The gain of an antenna increases with increasing antenna size and increasing wavelength: True or False.

3.6.39 Why are side lobes a problem to the radar designer?

3.6.40 Define beamwidth (in words).

3.6.41 What is the gain and beamwidth of a dish antenna with an area of 6.25 m^2, an efficiency of 0.8, a uniform feed horn, and a wavelength of 10 cm?

3.6.42 What are the advantages with respect to beam shape and scan rate of an electrically phased array radar over a traditional scanning radar antenna?

3.6.43 What is the atmospheric attenuation of a 3-GHz radar signal and a 30-GHz radar signal over a distance of 50 km?

3.6.44 Long-wave radar signals are attenuated by rain and fog more than short-wave radar signals: True or False.

3.6.45 Infrared radiation has a longer wavelength than visible radiation: True or False.

3.6.46 List the four bands within the IR band.

3.6.47 List the four major parts of an IR missile seeker.

3.6.48 What is the difference between the field of view and the field of regard of a seeker?

3.6.49 The IR radiation from a body is a function of what two parameters?

3.6.50 The emissivity of a blackbody is ________.

3.6.51 A body is at 300 K temperature. What is the wavelength associated with the peak spectral radiant emittance?

3.6.52 The radiant exitance from a body sensed by a detector in the MWIR band is proportional to T^4: True or False.

3.6.53 Mathematically relate the amount of incident radiation absorbed to the amount reflected for opaque bodies.

3.6.54 Efficient emitters at a given temperature are also efficient absorbers at the same temperature: True or False.

3.6.55 What is a physical distinction between a line radiator or emitter and a continuum radiator or emitter?

3.6.56 What happens to infrared radiation that propagates through the atmosphere?

3.6.57 Why is 4.3-μm radiation of significant interest to military aviators?

3.6.58 How does the absorption of IR caused by CO_2 vary with altitude?

3.6.59 List the two major categories of infrared detectors.

3.6.60 Why are the photon detectors more sensitive and faster to respond than thermal detectors?

3.6.61 List two materials commonly used in photon detectors.

3.6.62 Why are photon detectors cooled?

3.6.63 An uncooled PbS detector can detect radiation from the CO_2 in an engine exhaust plume: True or False.

3.7.1 Describe some aspect of an encounter between an aircraft and an air defense weapon that is not included in the threat operations subfield.

3.7.2 List the three categories of environmental factors, and give an example of how each category can affect the threat operations.

3.7.3 List the target data collected by air defense sensors.

3.7.4 List four different types of air defense sensors.

3.7.5 Maximum slew rate is the maximum rate a radar antenna can move as it tracks an aircraft: True or False.

3.7.6 An air defense command center receives word that a hostile aircraft is approaching the defended territory. A weapon is assigned, and orders are sent from the center to the assigned weapon to search for the aircraft and to fire at the earliest opportunity. The weapon system is ready to search and fire 45 s after receiving the assignment. What is the name of this time interval? The aircraft is acquired 75 s after receiving the assignment. What is the name of this time interval?

3.7.7 What are the two general techniques used by weapon-control radars to track an aircraft in angle?

3.7.8 A conical scan tracker requires multiple pulses to determine the target direction relative to the antenna boresight: True or False.

3.7.9 A LORO tracker requires multiple pulses to determine the target direction relative to the antenna boresight: True or False.

3.7.10 A monopulse tracker requires multiple pulses to determine the target direction relative to the antenna boresight: True or False.

3.7.11 Both conical scan and monopulse trackers are very susceptible to angular position errors caused by target scintillation: True or False.

3.7.12 List the three major types of IR trackers.

3.7.13 Why is the spinning reticle shown in Fig. 3.72a 50% opaque in both halves?

3.7.14 Suppose location A on the reticle shown in Fig. 3.73a appeared in front of the target $\frac{1}{3}$ of a rotation after A was up and four modulations occurred during one rotation. What are the polar and radial locations of the target?

3.7.15 Why is the stationary wagon-wheel reticle a more accurate tracker than the spinning reticle?

3.7.16 Why is the scanning rosette IR tracker analogous to radar monopulse tracking?

3.7.17 What is the latest evolution in IR tracking, and why is it a better tracker?

3.7.18 The official practical rate of fire of a particular gun is listed as 3000 rounds per minute. Therefore, when the gun fires at an aircraft for an elapsed time of one minute, 3000 rounds will be fired: True or False.

3.7.19 What is a missile salvo?

3.7.20 Give an example of an electro-optic fire control device.

3.7.21 What type of coverage is usually used when an air defense consisting of guns is unable to accurately track the attacking aircraft?

3.7.22 Provide the term for the given definition concerning the fire control factor errors.

(a) ______The inability to correctly position or aim the appropriate equipment in a desired direction.
(b) ______The inability of the system to provide an exact record of aircraft flight path, position, and rate data.
(c) ______Projectile miss distance resulting from errors in the prediction of the target flight path.
(d) ______Error caused by rough motion of the weapon system.

3.7.23 What tactic can pilots employ to increase the lead-angle prediction error?

3.7.24 A ballistic projectile is fired at a 45-deg elevation angle with a muzzle velocity of 3000 fps. Neglecting the decrease in velocity caused by atmospheric drag, what is the projectile altitude 3 s after firing? Assume $g = 32.2$ fps.

3.7.25 Explain how ballistic dispersion can increase the effectiveness of a gun.

3.7.26 In command guidance the target tracker and the missile tracker are always collocated: True or False.

3.7.27 In command guidance how are the commands sent to the missile?

3.7.28 List the advantages and the disadvantages of beam-rider guidance.

3.7.29 Describe the essential difference between the three types of homing guidance.

3.7.30 Explain the similarities and the differences between retransmission guidance and semiactive homing guidance.

3.7.31 Give examples of missiles that use command, beam-rider, active homing, semiactive homing, passive homing, or retransmission guidance.

3.7.32 List the three phases of guidance.

3.7.33 Give an example of a composite guidance system.

3.7.34 Sketch the trajectory of a missile that uses the three-point navigation law.

3.7.35 The most common navigation law used by missiles is the lead-angle navigation law: True or False.

3.7.36 A missile system that is based upon CLOS uses the three-point navigation law: True or False.

3.7.37 Missiles that use beam-rider guidance use the three-point navigation law: True or False.

3.7.38 Proportional navigation uses the LOS between the missile and the target to determine the correction to the missile heading: True or False.

3.8.1 The replacement to the ZSU-23-4 is the ______.

3.8.2 Match the following missile names with the RF SAM systems:

______SA-2	1. Goa
______SA-3	2. Gainful
______SA-4	3. Gopher
______SA-6	4. Grateful
______SA-7	5. Gaskin
______SA-8	6. Guideline
______SA-9	7. Grison
______SA-11	8. Ganef
______SA-12	9. Gadfly
______SA-13	10. Gremlin
______SA-14	11. Gecko
	12. Gaunlet
	13. Grail
	14. Gladiator
	15. Giant

3.8.3 List the RF-IR missiles.

3.8.4 Which sea-based SAM system is related to the SA-10 land-based SAM?

3.8.5 The maximum range of Russian Federation air-to-air missiles is from ______ n miles to ______ n miles.

3.8.6 What is the weight in grains of the 3-mm-diam tungsten pellets in the TRINITY round?

3.8.7 What is the sensitivity of TRINITY's gated proximity fuze against aircraft?

3.8.8 The SA-10 SAM system uses the ______ missile.

3.8.9 The SA-10 is also known as the S-______ .

3.8.10 The engagement radar used in the SA-10 system is the ______.

3.8.11 The maximum range of the SA-10 missile is estimated to be ______.

3.9.1 The STAR assessment includes the threats to the system at IOC and at IOC plus 25 years: True or False.

3.9.2 Describe the three tasks in the mission-threat analysis.

3.9.3 The primary mission planning system used by the U.S. Air Force is TAMPS: True or False.

3.9.4 Low altitude is below 4000 ft: True or False.

3.9.5 List the advantages and the disadvantages of bombing from high altitude.

Chapter 4
Susceptibility (P_H and P_F)

4.1 Susceptibility and the Susceptibility Program

Learning Objective	**4.1.1**	**Describe susceptibility and the three major tasks in a susceptibility program.**

Susceptibility refers to the inability of an aircraft to avoid being hit by one or more damage mechanisms in the pursuit of its mission. The level or degree of susceptibility of an aircraft in an encounter with a threat is dependent upon three major factors: the threat, the aircraft, and the scenario. The important features of the threat are its characteristics, its operations, and its effectiveness. The aircraft observables or detectable signatures, any countermeasures used, and the aircraft performance capabilities and self-protection armament are some of the important factors associated with the aircraft itself. The scenario includes the physical environment in which the encounter occurs, the threat deployment and activity, and the aircraft flight path and tactics, including any supporting forces.

To illustrate the many and varied features of an encounter between one aircraft and one threat, a one-on-one encounter, consider a utility helicopter attempting to deliver troops on a bright, sunny day to a location near the forward edge of the battle area. As the helicopter crosses the FEBA, it drops down into a valley to take advantage of terrain masking. However, a hostile self-propelled, radar-directed AAA system is in the valley and detects the helicopter with its search radar. The observer inside the AAA vehicle looks at the approaching helicopter through an optical tracker and identifies it as an enemy aircraft. The AAA radar is then switched to the single target tracking mode. Meanwhile, the radar warning receiver in the helicopter has detected the scanning signal from the AAA radar and alerted the pilot about the type, location, and status of the threat. The pilot immediately ejects chaff, attempts to break the lock of the tracking radar by maneuvering the helicopter, and searches for some terrain or vegetation to hide behind. The AAA radar receiver sees the chaff and starts to track it instead of the helicopter. However, the observer on the AAA platform has been watching the helicopter through an optical tracker and redirects the tracking radar back to the helicopter. A short time later, after a fire control solution has been obtained, a burst of contact-fuzed HE and AP-I projectiles are fired at the maneuvering helicopter. One or more of the projectiles might hit the helicopter. The more likely the helicopter is hit in this scenario the more susceptible is the helicopter.

An examination of the susceptibility of the helicopter in the scenario just described consists of three major program tasks. First, determine those factors in the scenario that affect the helicopter's susceptibility; second, determine how susceptible is the helicopter; and third, reduce the susceptibility of the helicopter.

Consider the first task in the program: the determination of what makes the helicopter susceptible. Obviously, there are many diverse factors in this scenario that influence the helicopter's susceptibility, many of which are difficult to model and to quantify. To determine which of the factors are essential and which ones can be neglected, an essential events and elements analysis (E^3A) should be conducted. In the E^3A the essential events, such as the detection of the helicopter and its subsequent engagement, and the important elements, such as the helicopter's radar signature, the effectiveness of the chaff in defeating the radar tracker, and the number of rounds fired in the burst.

The second task in a susceptibility program is the modeling, quantification, and simulation of the scenario events and elements identified in the E^3A to determine the likelihood the helicopter is hit by each round from the gun. This task is referred to as a susceptibility assessment. The output of the assessment can consist of the miss distance of the projectile fired at the aircraft, the probability the aircraft is hit by the projectile, the probability the proximity-fuzed HE warhead on the projectile fuzes, the location of the detonation of the HE warhead, and the number of warhead fragments that hit the aircraft and their locations.

Finally, the third task in the program is the use of susceptibility reduction technology to design for the lowest possible susceptibility of the aircraft within the design and operational constraints of cost, performance, weight, maintainability, supporting forces, and the other aspects of aircraft and force effectiveness.

Table 4.1 contains a list of the major subtasks in each of the three susceptibility program tasks. The remainder of this chapter will describe these subtasks in some detail.

Table 4.1 Tasks in a susceptibility program

Susceptibility program task	Subtasks
Task I: Identify the essential events and elements (What makes the aircraft susceptible?)	Identify the scenarios of interest. Conduct an essential events and elements analysis for those scenarios to determine the events and elements that affect the aircraft's susceptibility.
Task II: Perform a susceptibility assessment (How susceptible is the aircraft?)	Model, quantify, and simulate the scenario events and elements identified in the E^3A to determine the probability the aircraft is hit by one or more damage mechanisms.
Task III: Design for low susceptibility using susceptibility reduction technology (What can be done about it?)	Propose SR features that prevent or minimize the probability the aircraft is hit using the six SR concepts. Conduct trade studies to determine the benefits and impacts of each of the SR features proposed.

Go to Problems 4.1.1 to 4.1.3.

4.2 Task I: Identify the Essential Events and Elements

Learning Objective 4.2.1 Describe and conduct the essential events and elements analysis for any scenario.

In Appendix B a process in survivability is described as any combat operation, action, or incident that consists of a timewise sequence or combination of interrelated actions involving one or more parameters and variables associated with a system. An example of a process is the encounter between an aircraft and a threat weapon. A process typically has two or more outcomes of interest, and an event is the occurrence of one or more of the process outcomes. For example, one event in an encounter is the detection of a hostile aircraft (an outcome). Another event is the detonation of the proximity-fuzed HE warhead on the missile in the vicinity of the aircraft (another outcome). The elements associated with the events are the physical or measurable factors that affect the outcomes of the event. Important elements of the detection event include the height and area of the radar antenna and the flight path of the aircraft with respect to the antenna.

In the essential events and elements analysis the timewise sequence or chain of events in the encounter to be assessed is examined in detail, starting with the final undesired event and proceeding to the initial event (Note 1). To illustrate the E^3A, consider the scenario consisting of an encounter between a friendly strike aircraft and an enemy interceptor carrying an air-to-air, infrared homing missile. The enemy aircraft would like to launch the IR missile from a position behind the target aircraft because that is where the IR signature is usually the most intense. The launched missile will home in on the IR radiation emitted and reflected by the target. When the missile gets close enough to the target, the proximity fuze will detonate the HE warhead. The final (and undesired) event in the susceptibility portion of the encounter is when the blast wave and fragments from the detonated warhead strike the aircraft. In the E^3A this encounter is examined by starting with the final event and working backwards in time.

For the blast wave and fragments to strike the aircraft, the HE warhead must detonate within a certain distance from the aircraft. That distance depends upon the fragment velocities and spray angles and the relative velocity vectors and attitudes of the aircraft and the missile, as illustrated in Figs. 3.7–3.10. To detonate the warhead, the fuze must first detect the target and then initiate the detonation chain at the right time. For fuzing to occur, the missile must first intercept the target, which requires proper functioning of both the propulsion system and the guidance system. For the guidance system to function properly, the IR seeker must be locked on to the proper IR source, such as the target's engine hot parts or exhaust gas, and not some other spurious IR source or decoy, such as a flare. To achieve a lock-on, the IR source must be within the tracking system's field of regard. To place the target within the tracking system's field of regard and inside the missile's maximum range, the enemy fighter must be maneuvered to come within a certain launch acceptability region with respect to the target. This requires certain

Table 4.2 E^3A summary

Essential events	Questions
1) Blast and fragments strike the aircraft (A/C).	How many fragments hit the A/C, and where do they hit?
2) Missile warhead detonates within lethal range.	Can the onboard ECM suite inhibit the functioning of the proximity fuze?
3) Radar proximity fuze detects A/C.	Will chaff decoy the fuze?
4) Missile propelled and guided to vicinity of A/C	Can the target A/C outmaneuver the missile? Are IR flares effective decoys?
5) Missile guidance system functions in flight.	Are IR flares effective decoys?
6) Missile motor ignites.	
7) Missile's seeker locks on to target's engine IR radiation	Are IR flares effective decoys? Is the engine's IR suppressor effective in preventing lock-on?
8) Target's engines within missile's field of view	Are the engine hot parts shielded?
9) Enemy fighter maneuvers to put target into field of view and within maximum range.	Does the enemy fighter have a performance edge? Does the target A/C have an offensive capability against the enemy fighter?
10) Target acquired by enemy fighter's onboard sensors	Does the onboard ECM suite inhibit acquisition by the fighter's radar? Do the tactics place the target outside sensor limits? Is the camouflage paint scheme effective against visual acquisition?
11) Enemy fighter given steering by ground control intercept net to acquire target	Does the onboard or standoff ECM suite have a communications-jamming capability? Is a fighter escort available?
12) Target A/C designated to enemy fighter and fighter launched	Does the onboard or standoff ECM suite have a communications-jamming capability?
13) Fighter available to launch against target	Are there any supporting forces to destroy the enemy fighter on the ground?
14) Enemy C^3 net functions properly.	Does the onboard or standoff ECM suite have a communications-jamming capability?
15) GCI picks up track on target A/C.	Is the target A/C easily detected and tracked by radar? Is the standoff ECM suite effective against search radars?

(Continued)

Table 4.2 E^{3}A summary (Continued)

Essential events	Questions
16) Target designated hostile by enemy commander	Does the standoff ECM suite have IFFN countermeasures?
17) Early warning net detects and establishes track (course and speed) of target A/C.	Is the target A/C easily detected and tracked by radar? Is the standoff ECM suite effective against search radars? How much do the tactics expose the target A/C to the detection sensors?

performance capabilities of the enemy fighter aircraft, such as speed, turn radius and rate, and acquisition of the target aircraft by the fighter crew with their onboard sensors (radar, visual, etc.). To detect the target, the fighter must be within the limits of the onboard sensors, which are influenced by the signatures of the target aircraft.

The chain does not end here, but this example is enough to illustrate the process that should be continued back to the point where the friendly aircraft first enters the hostile airspace. A summary of the essential events for this encounter is given in Table 4.2, and some questions associated with each event are listed. There are, of course, practical limits to the degree to which the chain should be broken down. The E^{3}A should, however, be sufficiently precise to allow the identification of each important event and element. In particular, it is important to note those elements that the friendly forces have control over, for those are the ones that should be examined for the possibility of reducing the susceptibility. Table 4.3 contains many of the essential elements and events that are applicable to most encounters.

Table 4.3 Some essential events (Ev) and elements (El) for a susceptibility assessment

Threat	Scenario	Aircraft
C^3 capabilities (El)	Weapons locations (El)	Countermeasures (El)
Detection capabilities (El)	Terrain (El)	Threat warning (El)
Tracking capabilities (El)	A/C flight path and tactics (Ev)	Signatures (El)
Fire control procedures and ballistic projectile characteristics (El)	A/C detection and tracking (Ev)	Performance (El)
Missile performance and guidance capabilities (El)	Propagator launch/firing and flyout (Ev)	Armament (El)
Warhead and fuzing characteristics (El)	Warhead detonation (Ev)	
	Supporting forces (El)	

Go to Problems 4.2.1 to 4.2.2.

4.3 Task II: Perform a Susceptibility Assessment

4.3.1 Susceptibility Modeling and Measures

Learning Objectives	**4.3.1**	**Describe susceptibility assessment.**
	4.3.2	**List the major susceptibility measures.**

A susceptibility assessment is a modeling and quantification of the sequence of events and elements in the encounter between the aircraft and the threat until one or more hits on the aircraft occur. Those events and elements that were identified in the E^3A as important should be included in the model. In general, the events can be divided into two categories. The first category consists of those events that are associated with target detection, tracking, fire control, launch of a missile or firing of a gun projectile, and the guidance of the missile or the ballistic trajectory of projectile out to an intercept with the target aircraft. Large-scale modeling of the events and elements in this category is usually done on a computer, and the model is referred to as a flyout model. Small-scale modeling usually consists of relatively simple equations that provide estimates or evaluations of each of the phases of the encounter.

The output from the flyout model consists of one or more susceptibility measure predictions. One of the most important susceptibility measures is the closest point of approach or miss distance of a missile or projectile to a particular location on the aircraft. Generally, the smaller the miss distance, the more likely the aircraft will be hit. The probability that the aircraft is hit depends upon the miss distance and upon the size and extent of the aircraft presented to the propagator. Other important susceptibility measures are the probability the aircraft is detected and the errors associated with the tracking system. Because the probability of detection, the tracking errors, and the effectiveness of countermeasures are so strongly dependent upon the size of the signatures of the aircraft, the determination of the aircraft signatures is an essential part of any susceptibility assessment, and the sizes of the signatures are important susceptibility measures. This section examines the signatures of aircraft and the other important events and elements that are part of the flyout phase of the scenario. The major susceptibility measures quantified here are 1) the radar and IR signatures of aircraft, 2) the probability the aircraft is detected P_D, 3) the measures of tracking accuracy, 4) the miss distance, and 5) the probability the aircraft is hit P_H or an HE warhead fuzes P_F.

The second susceptibility assessment category consists of those events and elements that are associated with the fuzing of a proximity-fuzed HE warhead in the vicinity of the aircraft and includes the geometry between the missile and the aircraft at the time of detonation, the fuzing capabilities and logic, and the damage mechanism generation and propagation toward the aircraft. When the vulnerability of the aircraft to the impacting damage mechanisms is included in the second category, this part of the assessment is referred to as the endgame analysis. The output of the endgame analysis is the joint probability $P_{F|I} P_{K|F}$. The endgame analysis is presented in two parts. In Sec. 4.3.7.2 the number of fragments from a warhead detonation that hit the aircraft is determined, and the probability warhead fuzing occurs given the intercept is developed. The second part of the endgame, the vulnerability of the aircraft to these hits, is described in Chapter 5, Sec. 5.3. Assessments that include the events in both categories (flyout and endgame) are called survivability assessments. These assessments are described in Chapter 6.

The computational methodology used in the susceptibility assessment should have the capability to account for the six susceptibility reduction concepts presented in Chapter 1, Sec. 1.1.8.1 in order to properly reflect the benefits associated with the application of susceptibility reduction techniques. These six concepts are threat warning, noise jamming and deceiving, signature reduction, expendables, threat suppression, and the final concept of weapons and tactics, flight performance, and crew training and proficiency. These six concepts will be examined in detail in the susceptibility reduction presentation given in Sec. 4.4 of this chapter.

Go to Problems 4.3.1 to 4.3.4.

4.3.2 Aircraft Signatures

The characteristics of the aircraft that are used by the threat nonterminal elements for detection and tracking are called the observables ("the characteristics of an object or phenomenon by which it can be detected," http://www.sew-lexicon.com/gloss_o.htm) or signatures ("an observable that permits identification of the generating object," http://www.sew-lexicon.com/gloss_s.htm#SIGNATURE). Aircraft have several different signatures, such as the radar signature, the infrared signature, and the aural signature, but all of the signatures, except for the aural signature, are electromagnetic in origin. Figure 4.1 shows the location of the three major electromagnetic signature bands within the electromagnetic spectrum: the radar (radio/microwave/millimeter), the infrared, and the visible. In addition to these three signatures, any intentional or inadvertent electromagnetic emissions from the aircraft, such as the aircraft's navigation radar, altimeter, and radio communications, can be used by the threat detection, tracking, and guidance elements.

4.3.2.1 Radar signature (Note 2).

Learning	**4.3.3**	**Describe the RCS of simple shapes and the types of scattering.**
Objectives	**4.3.4**	**Describe the RCS of an aircraft, target scintillation, and target glint.**
	4.3.5	**Describe how to compute RCS.**

Radar cross section. When a radar antenna radiates an electromagnetic pulse or continuous wave in the direction of an airborne aircraft or target, the power in the signal wave front or beam is spread out in space as the signal travels toward the aircraft (similar to the beam of light from a flashlight). The intensity of the signal at any location in the wave front can be expressed as the power density, which is the signal power per unit surface area of the beam (W/m^2) (Note 3). As

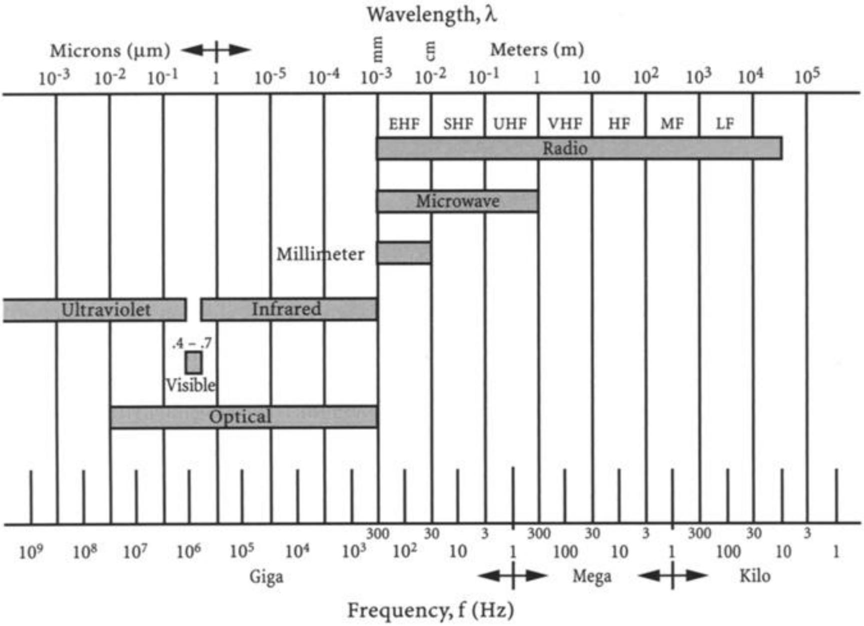


Fig. 4.1 Location of the electromagnetic signature bands within the electromagnetic spectrum.

the signal passes over the aircraft, a portion of the incident power can be absorbed as heat, another portion can pass completely through parts of the aircraft, and the remainder is reradiated or scattered in many different directions by the various electrically conducting surfaces on the aircraft. The reradiated signal is caused by the harmonic oscillation of charged particles on the aircraft's surfaces induced by the oscillating electric and magnetic fields of the radar signal and is usually referred to as the scattered or reflected signal. A very simple, but effective, way of looking at this phenomenon is as follows: the incident radar signal causes oscillating electric currents on the conducting surfaces of the aircraft, and the aircraft glows like a light bulb.

The total portion of the impinging signal eventually scattered in the direction of the radar's receiving antenna is the portion of interest. This portion is known as the aircraft's echo. The size, magnitude, or amplitude of the echo (the brightness of the light bulb) depends upon the power density of the impinging radar signal and the amount of incident signal that is 'captured' and reflected in the direction of the receiver. This amount depends upon the 'radar size,' capture area, or scattering cross section of the aircraft, denoted by σ (Note 4). When the radar transmitter and receiver are collocated, as is the case for monostatic radars, the scattering cross section is referred to as the backscattering cross section or radar cross section. When the two are not collocated, σ is called the bistatic scattering cross section. One unit of measurement of σ is the square meter, and another is the decibel or dBsm, where the reference level is 1 m^2 (0 dBsm).

There is not just one value of σ for an aircraft. The scattering cross section of an aircraft depends strongly upon the direction from which the signal arrives and the direction of the receiving antenna. The shape of the aircraft, the materials on the various surfaces of the aircraft, and the size of the aircraft affect σ, as do the signal wavelength and polarization. For most aircraft the scattering cross section does not bear a simple relationship to the physical area. In fact, σ is a very complex parameter.

RCS of simple shapes: In theory, the reradiated or scattered field, and thus the radar cross section, can be determined by solving Maxwell's equations with the appropriate boundary conditions for the given target shape, which is called the scatterer. However, when using classical mathematical analysis techniques, such as an infinite series, this can be accomplished only for the most simple of shapes, such as a perfectly conducting sphere, and even the simple shapes exhibit several complex phenomena. For example, Fig. 4.2a shows the variation of the normalized far field, RCS of a perfectly conducting sphere of radius a with respect to the radius to radar wavelength ratio a/λ. The term far field implies that the receiver is located a relatively long distance from the scatterer and hence the impinging signal is a plane wave (or a spherical wave with a very large radius) (Note 5). Note that there are essentially three RCS regions in Fig. 4.2: the low frequency or Rayleigh region, where $\lambda >> a$ and the RCS monotonically increases with decreasing λ; the resonance region, where $\lambda \approx a$ and the change in RCS is relatively large as λ changes; and the high frequency or optical region, where $\lambda << a$ and the RCS is essentially independent of λ. All three regions can be pertinent to the RCS of an aircraft, where the various scattering surfaces can vary from much larger to much smaller than the radar wavelength.

Consider the sphere/wavelength geometry in Fig. 4.2b for the three RCS regions shown in Fig. 4.2a. The sphere has a radius of 1 m. In the Rayleigh region, where the sphere is small with respect to the radar wavelength, σ is approximately equal to $9(2\pi a/\lambda)^4(\pi a^2)$, and the RCS increases as λ decreases. The scattering body is a relatively small obstruction in the path of the wave front, and the shape of the body has relatively little effect on the magnitude of the RCS.

In the resonance region, where the sphere and wavelength are of the same order of magnitude, there is no simple relationship between σ and λ. The decaying oscillation of the solution as the wavelength decreases is caused by interference effects between the wave reflected from the front of the sphere and waves from the back known as creeping waves (described next). Here, the body shape is important. When the waves from the front and back are in phase, the interference is constructive, and the RCS is relatively large; when they are out of phase, the interference is destructive, and the RCS is relatively small. The decaying oscillation with respect to λ is because the sphere is becoming much larger than the wavelength. As a consequence, the creeping waves from the back face are decaying more as they travel toward the front surface, and the RCS increasingly is caused by the front surface of the sphere. In the optical region the sphere is very much larger than the wavelength, and the RCS is caused only by the local surface in the vicinity of the nose of the sphere; the creeping waves are insignificant. In this region the shape of the body where the wave impinges has a major effect on the RCS.

The optical region is often the region of interest for aircraft-radar encounters for two reasons: 1) many of the scattering surfaces on an aircraft are relatively large

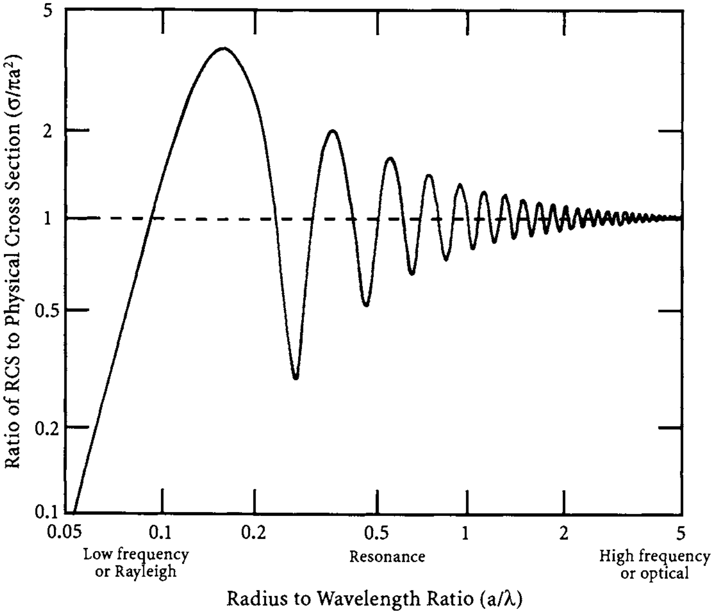


Fig. 4.2a RCS of a sphere of radius a vs radar wavelength λ[Ref. 1].

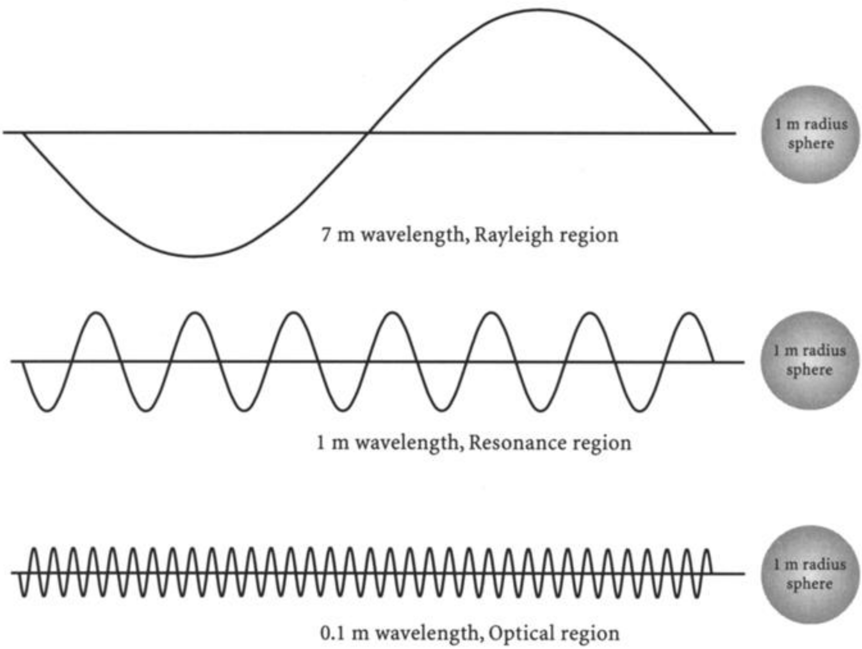


Fig. 4.2b Rayleigh, resonance, and optical regions.

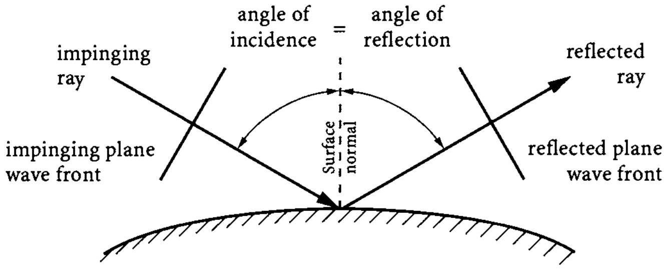


Fig. 4.3a Reflection from a perfectly smooth, perfectly conducting surface.

with respect to the radar wavelength, and 2) the optical theory is the simplest theory to solve. In this region the scattering from surfaces is usually approximated by the theory of ray or geometrical optics (GO) or the theory of wave or physical optics (PO). In the theory of geometrical optics, an incident plane wave is assumed to be composed of an infinite number of parallel rays. Each ray in the wave is reflected from a smooth surface such that the angle between the incident ray and the reflected ray is bisected by the normal to the surface at the point of contact, as shown in Fig. 4.3a, that is, the angle of reflection is equal to the angle of incidence. This type of reflection from a smooth surface is referred to as specular reflection. When the impinging ray is coincident with the normal to the surface, the reflected ray is coincident with the incident ray. When the surface is perfectly conducting and second order (doubly curved), the backscatter RCS in the direction of the normal is $\pi \rho_1 \rho_2$, where ρ_1 and ρ_2 are the principal radii of curvature of the surface at the reflection point.

How is the incident radar signal scattered from a sphere? Consider the situation where a plane wave strikes a perfectly conducting, perfectly smooth sphere, as illustrated in Fig. 4.3b. Five rays are identified in the figure. Ray 1 is coincident with the normal to the sphere and is reflected back in the direction of the receiver of a monostatic radar. Ray 2 impinges at a location where the angle of incidence is 30 deg, and consequently it is reflected at an angle of 60 deg. Ray 3 is at 45 deg and reflects at 90 deg. Ray 4 is at 60 deg and reflects at 120 deg, and ray 5 skims the surface. No ray from the wave impinges on the back surface of the sphere, and hence it is in the shadow zone. Note that all of the rays except ray 1 are reflected away from the monostatic radar receiver. Because $\rho_1 = \rho_2 = a$ for the sphere, the backscatter RCS according to the GO theory is equal to πa^2, which is the same as the physical cross-sectional area of the sphere. Hence, the normalized backscatter RCS of the sphere is unity, as shown in Fig. 4.2a. The nonbackscatter or bistatic RCS for the sphere is also equal to πa^2 for a large range of aspect angle. Note that the backscatter RCS is independent of the direction of the impinging ray and that the polarization of the impinging signal has no effect on the RCS.

Now consider the situation where a plane wave strikes a finite, perfectly conducting flat plate of area A, as illustrated in Fig. 4.4a. When the wave front is parallel to the plate surface (the diagram on the left side of Fig. 4.4a), all of the rays that strike the plate are coincident with the normal to the plate, and hence all

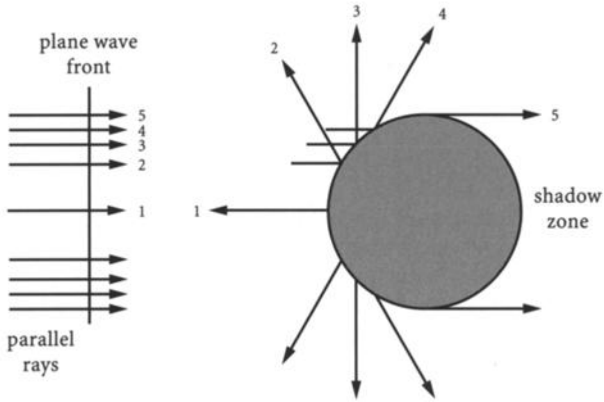


Fig. 4.3b Scattering from a sphere in the optical region.

of the impinging signal is reflected directly backwards. Because $\rho_1 = \rho_2 = \infty$ for the flat plate, the theory of geometrical optics results in an infinitely large RCS, which is, of course, unreasonable (Note 6). Consequently, the geometrical optics theory is not valid in this limiting case, and the theory of physical optics can be used to determine the RCS of the flat plate. In the PO theory the assumptions are made that the radii of curvature of the surface are large with respect to the wavelength and that the surface current is distributed in the same manner as the impinging signal. Thus, because the incident signal is uniform across the plate, as illustrated in the left side of Fig. 4.4a, the current is assumed to be uniformly distributed as well, which is not quite correct because of the presence of the plate edges (Note 7). According to the theory of physical optics, the flat-plate backscatter RCS is equal to $4\pi A^2/\lambda^2$, which is dependent upon λ^{-2}. Consequently, the RCS of a flat plate can be an extremely large value compared to the RCS of a sphere of the same cross-sectional area for small wavelengths, as demonstrated in Example 4.1.

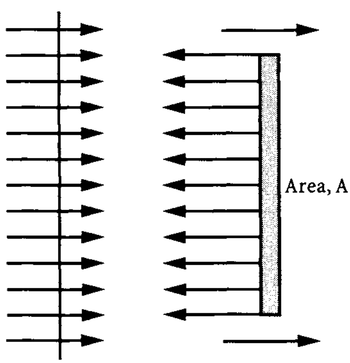


Fig. 4.4a Normal reflection from a flat plate.

Example 4.1 Comparison of the RCS of a Sphere and a Flat Plate

Assume that the cross-sectional area of both the sphere and the flat plate is 1 m^2 and the radar wavelength is 3 cm. Thus,

$$\text{sphere radius } a = (1\ \text{m}^2/\pi)^{1/2} = 0.56\ \text{m}$$
$$a/\lambda = (0.56\ \text{m})/(0.03\ \text{m}) = 18.8$$

which is well within the optical region of the RCS. Thus, the RCS of the sphere is closely approximated using

$$\sigma = \pi a^2 = 1\ \text{m}^2 \quad \text{or} \quad 0\ \text{dBsm}$$

which is the same as the physical cross section.

According to the PO theory, the flat plate RCS is

$$\sigma = (4\pi A^2)/\lambda^2 = [4\pi(1\ \text{m}^2)^2]/(0.03\ \text{m})^2 = 13{,}963\ \text{m}^2 \quad \text{or} \quad 41.4\ \text{dBsm}$$

which is four orders of magnitude larger than the sphere. In general, the ratio of the RCS of the flat plate to the sphere with equal areas is

$$(\text{flat plate RCS})/(\text{sphere RCS}) = 4\pi A/\lambda^2$$

What happens when the direction of propagation of the impinging wave is not normal to the flat plate, as illustrated in Fig. 4.4b? According to the GO theory, all rays that strike an interior point on the surface of the plate are reflected away from the approach direction, as illustrated by ray 1 in the middle of the plate. Consequently, none of the rays that strike the interior of the plate contribute to the plate's RCS. However, note that rays 2 and 3 strike a sharp edge. Rays that strike

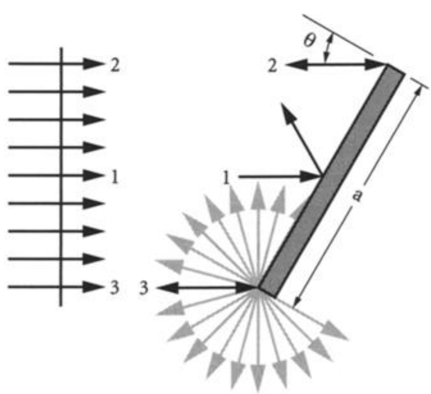


Fig. 4.4b Scattering of an incident plane wave from a flat plate.

a sharp edge are diffracted from the edge in many directions, as illustrated by the idealized diffraction of ray 3 in Fig. 4.4b. (In general, the diffracted rays from the edge will not be uniform.) A similar diffraction of ray 2 occurs at the top edge of the plate.

One ray diffracted by the top edge and one ray diffracted by the bottom edge will be in the backscatter direction, as indicated by the black arrows 2 and 3, respectively. These rays are singly diffracted rays (first-order diffraction[2]) and are the main contributors to the flat plate's RCS. However, the gray ray from the bottom edge that is parallel to the plate will travel up the surface and strike the top edge. This diffracted ray will be diffracted by that edge, resulting in a doubly diffracted ray from the top edge (second-order diffraction[2]), which is in the backscatter direction and makes a second-order contribution to the plate's RCS. The magnitude of the contribution of the second-order diffraction is larger for a vertically polarized wave than for a horizontally polarized wave because the vertical polarization causes a travelling wave described next. Similar smaller contributions to the backscatter RCS are made by the doubly diffracted rays from the top edge to the bottom edge and from the front bottom edge to the back bottom edge.

Note that the diffracted rays 2 and 3 from the top and bottom edges, respectively, will travel different distances to the radar receiver and consequently will interfere at the receiving antenna. The degree of interference depends upon the angle of incidence and the wavelength. The PO equation for the normalized RCS of the square flat plate with edge length a for arbitrary θ and λ is

$$\frac{\sigma}{\sigma_0} = \left[\frac{\sin(ka\,\sin\theta)}{ka\,\sin\theta}\right]^2 (\cos\theta)^2$$

where $\sigma_0 = 4\pi A^2/\lambda^2$ (the RCS of the flat plate with $\theta = 0$) and $k = 2\pi/\lambda$. Figure 4.4c shows the normalized RCS of a flat plate as a function of the angle of incidence with $a = 1$ m and $\lambda = 3$ cm ($a/\lambda = 33.3$ and $ka = 209$) (Note 8). Example 4.2 examines the decay of the RCS of the flat plate.

Example 4.2 Effect of the Angle of Incidence upon the Decay of the RCS

Note in Fig. 4.4c that the RCS is down by approximately 25 dB for a 4.75-deg angle of incidence. Nevertheless, the RCS caused by edge diffraction can be large because σ_0 is very large. In Example 4.1, $\sigma_0 = 41.4$ dBsm for a 1-m^2 flat plate. Consequently, the RCS of the plate for θ between 5 and 6 deg is

$$(41.4 - 25)\ \text{dBsm} = 16.4\ \text{dBsm} \quad \text{or} \quad 43.6\ \text{m}^2$$

which is a relatively large value for the RCS of an aircraft. As a/λ decreases, the decay in RCS with θ is less. For example, when $a = 15$ cm and $\lambda = 3$ cm the RCS is down 25 dB from σ_0 at $\theta \approx 30$ deg (Ref. 3). Thus, smaller plates (with respect to the wavelength) will have a significant RCS over a larger angle of incidence.

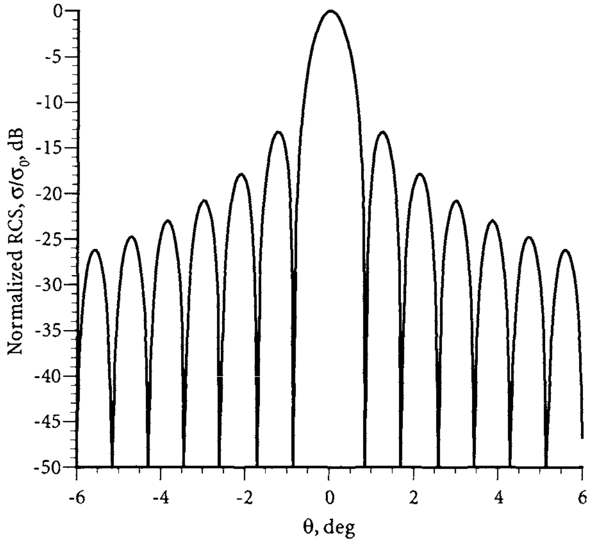


Fig. 4.4c Backscattering from a square flat plate of length a vs the angle of incidence θ ($a/\lambda = 100/3$).

Now consider the situation shown in Fig. 4.4d, where a vertically polarized wave strikes a sharp, vertical edge. Diffraction occurs at the edge as illustrated in the figure. If the ray of the vertically polarized wave in Fig. 4.4c was not normal to the vertical edge, rays would be diffracted away from the edge and lie on the surface of the Keller cone.[4] If the wave was horizontally polarized, very little scattering would occur from the vertical edge (Note 9). When an edge is curved, for example, the intersection of a curved surface with a flat surface or the intersection of two curved surfaces, the diffracted rays will emanate from an impinging ray over a very wide angle; and the magnitude of these diffracted rays can be significant.

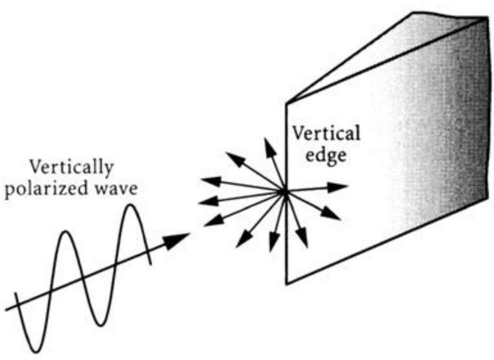


Fig. 4.4d Diffraction from an edge.

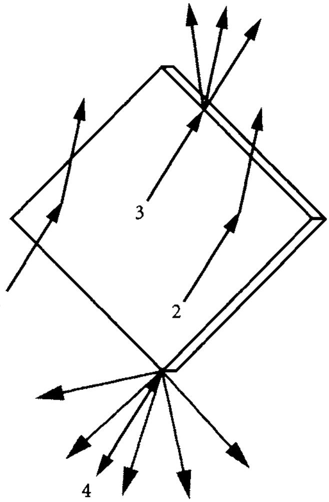


Fig. 4.4e Diffraction from a tip.

A third possibility for the reflection of a wave from a flat plate is illustrated in Fig. 4.4e. The plate has been rotated 90 deg about the normal from its position in Figs. 4.4a and 4.4b. The black rays pointing up and to the right (rays 1, 2, 3, and 4) are in the impinging wave. Note that the impinging rays in the wave are reflected from the plate surface (rays 1 and 2) and diffracted from the plate edges (ray 3) in directions other than the backscatter direction. However, diffraction at each of the four corners of the plate will occur, as illustrated by the gray arrows from the bottom corner of the plate, and a ray from each corner will be diffracted in the backscatter direction, as illustrated by the black arrow at the bottom corner (ray 4). This is called corner or tip diffraction. The diffracted rays from the four corners of the plate in the backscatter direction will interfere, and hence the RCS caused by tip diffraction will have a distribution with respect to the angle of incidence similar to that for edge diffraction shown in Fig. 4.4c. Generally, the RCS caused by tip diffraction is on the order of λ^2 and consequently is much smaller than that caused by edge diffraction for high frequencies.[5]

If two flat plates are joined together along one edge, forming a dihedral, they can have a very large backscatter RCS not only for the aspects normal to each plate, but also for a region of aspect angle between the two plates where the reflection of a ray from one plate is subsequently reflected from the other plate back in the direction of the monostatic receiver, as illustrated by the two dihedrals shown in Fig. 4.4f. This is known as retroreflection, and the two plates form a dihedral retroreflector. For the 90-deg dihedral on the left side of the figure, a ray at any angle of incidence in the plane normal to the edge of the dihedral will be retroreflected as illustrated by the two bounces of the ray in the figure. When the angle subtended by the two plates is less than 90 deg, such as the 45-deg dihedral shown in the center of Fig. 4.4f, rays at certain angles of incidence will be retroreflected after more than two bounces. When three orthogonal plates are joined together, they form a corner reflector, as illustrated on the right side of Fig. 4.4f. The retroreflection from the

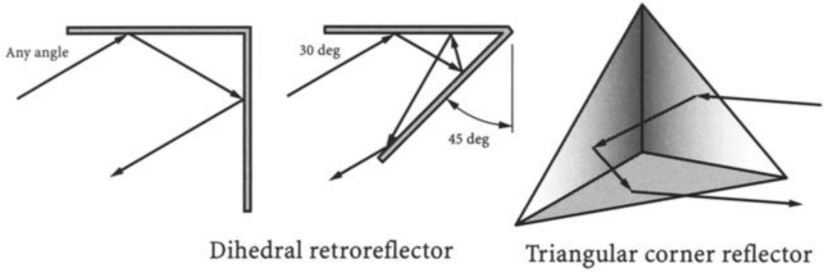


Fig. 4.4f Retroreflection from a dihedral and a corner reflector.

corner reflector can be very large over a relatively large region of aspect angle as a result of the multiple reflections of rays from any aspect.

Other contributions to the RCS of a body in the optical and upper resonance region can come from creeping and traveling waves on the surfaces. Creeping waves are caused by the currents that exist on those surfaces which are not directly impinged by the incident wave. These surfaces are referred to as shadow surfaces. The creeping wave starts at the shadow boundary, propagates over the shadow surface, and emerges at another shadow boundary, thus contributing to the scattered wave. Discontinuities in the shadow surface can cause defraction of the creeping wave. The creeping waves are important in the resonance region. The traveling wave occurs along a surface that is illuminated by a wave whose rays are in a low (long surfaces) to moderate (short surfaces) grazing angle of incidence. As the incident wave travels over the surface, the traveling wave is driven forward. If there is a change in the surface condition, such as a gap, edge, or change in curvature, the traveling wave can be backscattered. The contribution of the traveling wave to the RCS can be significant, provided there is a component of the incident electric field in the plane containing the surface normal and the ray. For example, when a vertically polarized wave strikes a horizontal aircraft wing there is very little diffraction of the incident wave by the wing's leading edge, but a traveling wave is developed on the wing skin. This surface wave can be backscattered by any abrupt change in the surface condition, such as a gap or step in the skin, or by the wing's trailing edge.[6] For example, in Fig. 4.4b, if the polarization of the wave is vertical, a traveling wave will be developed that will be scattered when it reaches the top edge, resulting in a second-order backscatter ray (ray 2).

Theoretical values of the peak RCS as a result of specular reflection are given in Table 4.4 for several 'simple' scatterers. The scatterers with the largest RCS are usually those whose RCS is inversely proportional to the wavelength.

Effects of materials on RCS: The RCS values given in Table 4.4 are for bodies composed of materials that are perfect electrical conductors. Aircraft metals, such as steel, aluminum, and titanium, fall into this category.

When the material of the scatterer is not a perfect conductor, the RCS will be reduced from that of the perfect conductor because of the reduced reradiated electromagnetic field. In this situation some of the incident signal will pass into and possibly through the body. In general, the amount of reduction in RCS is strongly dependent upon the wavelength and the type and thickness of the material. Just because a scatterer is made of a nonmetallic material does not necessarily mean that

Table 4.4 Maximum RCS values for several scatterers

Body	Maximum backscatter RCS	Comments
Sphere	πa^2	Radius a
Curved surface	$\pi \rho_1 \rho_2$	Normal to a surface with principal radii of curvature ρ_1 and ρ_2
Flat plate	$4\pi A^2/\lambda^2$	Normal to the surface of plate of area A
Triangular corner reflector	$4\pi L^4/(3\lambda^2)$	Side length L
Large cylinder	$2\pi L^2 a/\lambda$	Normal to the axis, radius a, length L

there is a significant reduction in RCS. For example, the return from a relatively thick fiberglass laminate might be down from that of a perfect conductor by only 6 dB over a wide range of wavelengths. [The relative amount of radar signal reflected from a particular material is given in Eq. (4.59) in terms of the material's permeability and permittivity.]

Aircraft RCS. An aircraft is composed of many individual conducting surfaces or scatterers, each with different scattering properties that vary as the viewing or striking angle changes. For example, consider the generic scatterer shown in Fig. 4.5. As the signal passes over the scatterer, some of the rays will strike smooth surfaces and will be reradiated away from the body toward the radar receiver (rays 1 and 3 are the specular return for the monostatic radar). Some rays will impinge on other conducting surfaces on the body, resulting in multiple reflections that are eventually backscattered (rays 2 and 4). Some rays will be diffracted by edges (ray 5), and some will be diffracted after traveling along the surface (ray 6). And then there are the creeping waves that can occur when the wavelength is relatively long. The individual locations on the surface that are the source of the backscatter rays are known as glitter points. The resultant RCS of the scatterer is the vectorial combination of all of the individual returns from the glitter points.

Now consider the scattering from the airplane and helicopter shown in Figs. 4.6a and 4.6b, respectively. Because flat plates, dihedrals, edges, and corners exhibit such a relatively large RCS, those surfaces on the aircraft that are either somewhat flat or whose intersections form edges, dihedrals, or corners can be sources of a strong echo. Relatively flat surfaces usually occur on the sides of some fuselages, on the vertical tail, and on the upper and lower surfaces of the wing and horizontal tail. Consequently, the RCS of many aircraft are largest when the aircraft is viewed from the sides and from directly above and below. Edges occur on the wings, tail, inlets, canopy frames, and at any electrically discontinuous gap, such as access panels, skin gaps, and bomb bay doors. Dihedrals and corners typically occur in or around jet engine inlets and exhaust nozzles, the fuselage-wing intersection, and weapon pylon-wing intersections. The cockpit can be a major contributor to the echo from the forward aspect because of the passage of the radar signal through

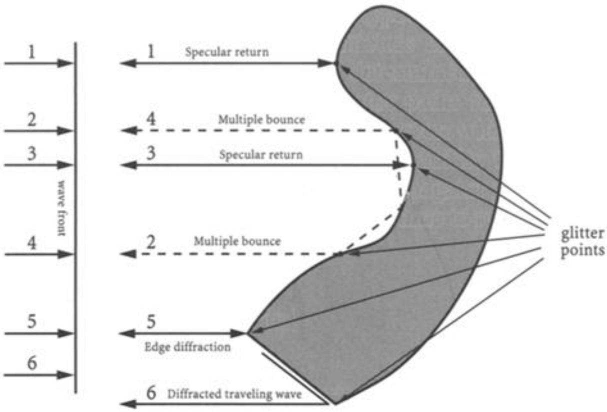


Fig. 4.5 Reflection from a general scatterer.

a radar transparent canopy and the subsequent impingement on the bulkheads and other flat surfaces in the cockpit itself. Antenna compartments in the aircraft and in any external stores can also be sources of a strong return as a result of the possible signal gain caused by the antenna itself and to the flat bulkheads in these locations (Note 10).

A typical polar plot of an aircraft backscatter RCS in one plane with respect to aspect is shown in Fig. 4.7a. The aircraft is the A-7 Corsair II, the radar frequency is 9.2 GHz, and the signal and echo polarizations are vertical.[7] Note the drastic change in the amplitude of the RCS with respect to very small changes in aspect

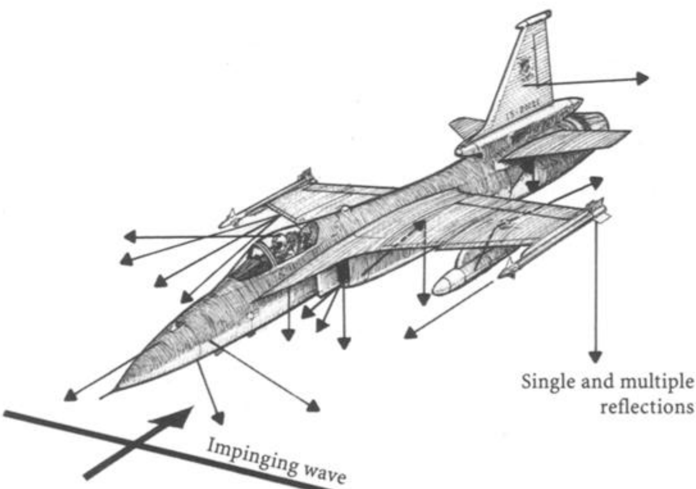


Fig. 4.6a Various scattering surfaces on an airplane.

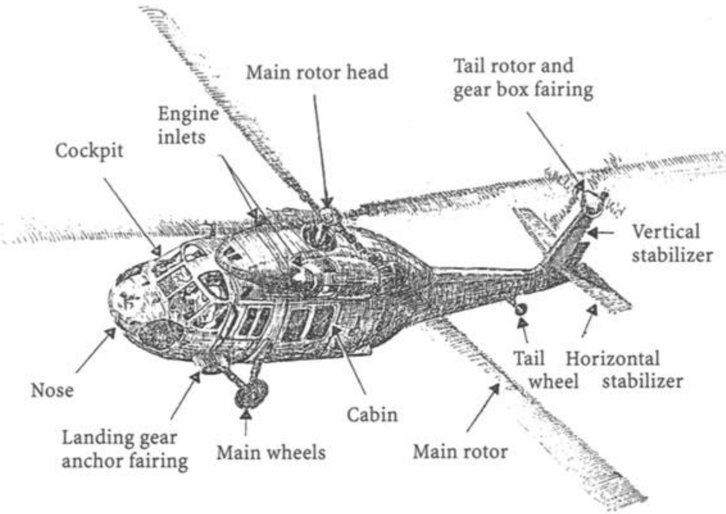


Fig. 4.6b Typical radar glitter points on a helicopter.

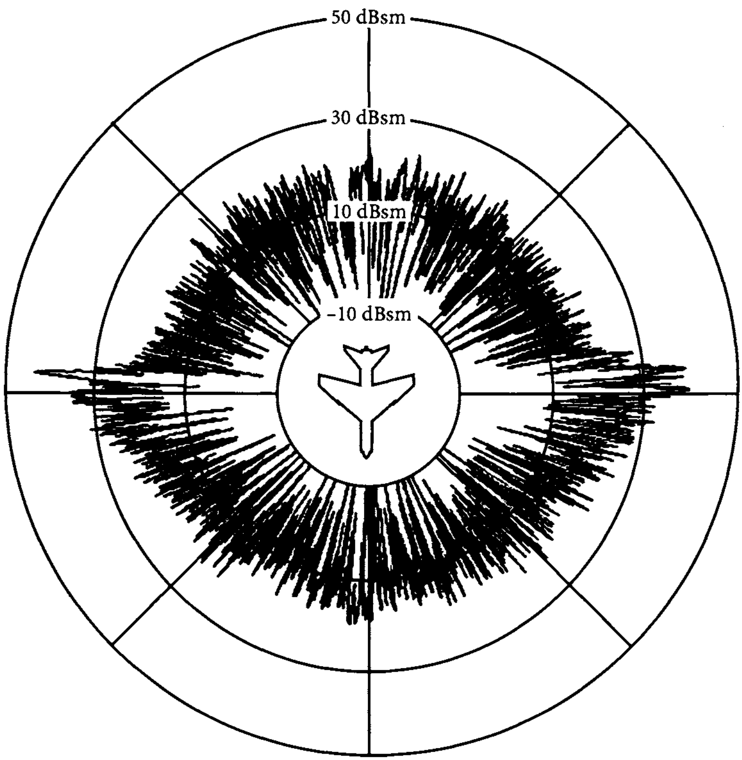


Fig. 4.7a Polar plot of the A-7 Corsair II RCS.[7]

angle. This phenomenon is known as RCS scintillation. Because of the different path lengths of the individual glitter point echoes, the phases of the individual singly and multiply scattered echoes will differ. For example, in Fig. 4.5 the ray 1 echo path length is twice the length of the solid line, whereas the ray 4 (and ray 2) echo path length is equal to the sum of the lengths of the dotted line. Because of the different path lengths, the amplitudes of the individual surface echoes may add (in phase) to give a relatively large σ, or they may subtract (out of phase), resulting in a relatively small σ. Consequently, the interference of the individual echoes, in conjunction with the highly specular return from the various surfaces and the possible depolarization of the scattered field, is the cause of the RCS scintillation. In general, the amount of scintillation decreases as the wavelength increases. This interference of the individual surface echoes can also cause the apparent 'centroid' of the aircraft RCS as seen by the radar tracker to wander in angle as a result of very small changes in aspect angle, a phenomenon known as target glint or bright spot wander. For example, on one pulse the return from the nose of the aircraft might be the dominant part of the echo, whereas on the next pulse the return from the tail might be dominant because the returns from the scatterers in the nose are out of phase and cancel each other out. Trackers that use the wave front of the composite echo wave to determine the target's angular location can erroneously locate the target outside of the actual target surface when the major glitter points are out of phase. Target glint becomes increasingly important as a radar receiver, such as the receiver on the nose of a homing missile, comes close to the target.

Sometimes the many different RCS values over a small interval of viewing angle in Fig. 4.7a, such as 10 deg, are grouped together, and either the resultant average or median σ is plotted at the midpoint of the interval, as illustrated in Fig. 4.7b. The average or median values for σ for each interval midpoint are then connected by straight or curved lines. This procedure is known as aspect smoothing, and it eliminates the appearance of the scintillation in the RCS. For most contemporary aircraft the RCS can vary from less than 1 to more than 1000 m^2 at microwave frequencies over all aspects. Figure 4.7c presents some typical values.

The presentation on aircraft RCS up to this point has focused on the magnitude of the RCS, and hence the magnitude of the echo, and has not considered the radar frequency of the echo. In most combat scenarios usually the aircraft, or the radar, or both are moving; and consequently, the radar frequency of the aircraft echo is modified by the Doppler effect. The primary source of the echo from an aircraft is usually the return from the aircraft's surface, typically known as the skin return. The Doppler frequency shift of the skin return can be determined using Eq. (3.21b), which is a function of the radial motion of the aircraft with respect to the radar V_r. In addition to the skin return, reflecting surfaces that are moving relative to the aircraft skin, such as helicopter blades, engine propellers, and jet engine fan blades, are also echo sources; and they have the additional feature of providing a Doppler shift that is different than the shift associated with the skin return. The Doppler frequencies associated with the both the skin return and the moving surfaces can be exploited by some threat radar systems to enhance detection and tracking capabilities.

Figure 4.7d illustrates the Doppler signature of a fixed wing, turboprop aircraft as it flies a complete 360-deg circle around a center located some distance from the radar, thus presenting all aspects of the aircraft to the radar. The abscissa in the

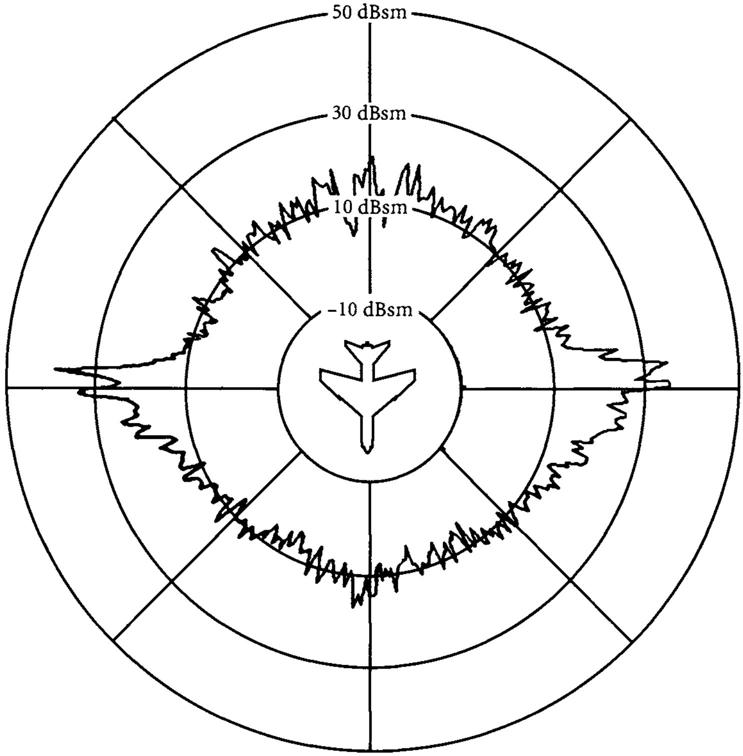


Fig. 4.7b Polar plot of A-7 Corsair II median RCS.[7]

figure is the aircraft aspect, and the ordinate is the Doppler shift. The horizontal white dashed line is the zero Doppler shift axis. The magnitude of the RCS from each of the echo sources on the aircraft is indicated by the intensity of the solid white lines; the thicker and whiter the line, the larger the RCS. The thick, solid white line varying in smooth sinusoidal manner about the Doppler shift axis is the Doppler shift of the skin return over the 360-deg circle from tail-on to nose-on

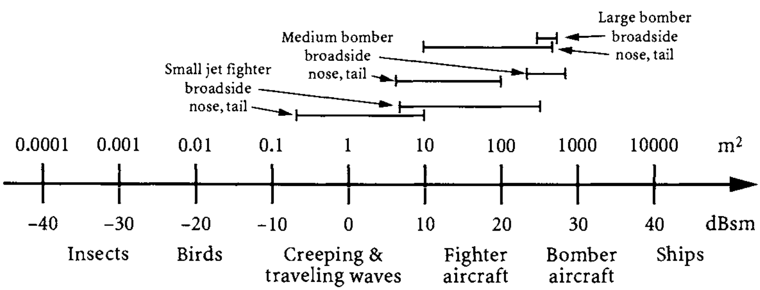


Fig. 4.7c Typical values of RCS (below the axis,[8] above the axis[9]).

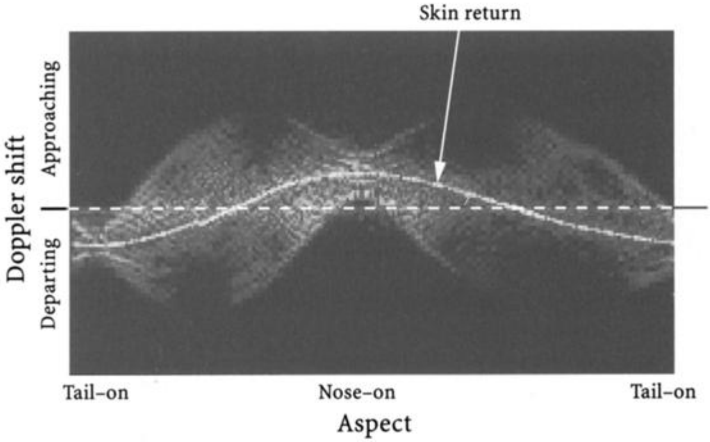


Fig. 4.7d Doppler shift from a moving turboprop aircraft (Courtesy of the Atlantic Test Range, Naval Air Warfare Center, Aircraft Division, Patuxent River, MD).

to tail-on. Note that the Doppler shift of the skin return is maximum positive when the radar wave front is nose-on as the aircraft approaches the radar, that is, V_r is maximum positive, and is a maximum negative when the front is tail-on to the outbound aircraft, that is, V_r is maximum negative. The Doppler shifts from the rotating propeller blades are indicated by the varying shades of light white lines above and below the shift from the skin return. There are several Doppler shifts in both directions at any given aspect because there are several blades moving toward the radar and several blades moving away from the radar, at that aspect. Note that the relative Doppler shift of the blades from the skin return is minimum when the wave front is nose-on and tail-on, where the radial motion of the blades with respect to the radar is approximately the same as the radial motion of the airframe. However, the magnitude of the echo from the blades is maximum at these same two aspects because the wave front is parallel to the face of the blade. Also note that the maximum positive and negative Doppler shifts occur when the radar signal front is broadside. At this aspect the Doppler shift from the skin return is zero (the Doppler notch in Fig. 3.14a), but the shift from the blades is maximum because V_r of the blades is maximum. Because the radar wave front is parallel to the curved edge of the blades at this aspect, the magnitude of the echos from the blades is relatively small.

RCS prediction and measurement. The accurate prediction and measurement of the RCS of a specific aircraft as a function of viewing angle or aspect for a given radar are very difficult tasks for many reasons. Looking at the RCS plot shown in Fig. 4.7a, it is very difficult to tell what the RCS value is at any one aspect angle, and is that specific value important anyway? Because the aircraft is in motion, its aspect with respect to the radar is bound to vary by some small amount on every scan of the target, and this variation can cause a significant fluctuation in the magnitude of σ seen by the radar (the scintillation phenomenon). In actual fact, radar echoes from aircraft do fluctuate, and this fluctuation has an important effect upon the probability the aircraft is detected and the accuracy with which it is tracked. The 'Swerling' distribution models define several possible cases of RCS fluctuation.[10]

RCS prediction: The backscatter RCS value at a given aspect can be assessed by considering the aircraft to be made up of a collection S of the most important glitter points, such as the flat plates, dihedrals, corners, antennas, edges, etc. For example, the generic scatterer shown in Fig. 4.5 has six glitter points. Each of these S scatterers has a backscatter RCS in the aspect and polarization of interest σ_s, and each has a relative path length 1_s. The relative path length is the distance from a reference plane parallel to the radar wave front to the sth scatter. For example, in Fig. 4.5 the relative path length of ray 1 is twice the length of the ray 1 solid line, and the relative path length of rays 2 and 4 is the sum of the lengths of the four dotted lines. The composite echo is the vectorial sum of the individual echoes, and the RCS is proportional to the square of the electric field strength of the composite wave. Thus, σ is given by

$$\sigma = \left| \sum_{s=1}^{S} \sqrt{\sigma_s} \exp\left(i4\pi 1_s/\lambda\right) \right|^2 \tag{4.1}$$

where $i = \sqrt{-1}$. This procedure is sometimes referred to as ray tracing. A simpler approach is to assume that the individual scattered waves are randomly distributed in phase, that is, the waves are noncoherent. In this random phase method the approximate RCS of the aircraft at the aspect of interest is just the sum of the backscatter echo from each of the scatterers

$$\sigma = \sum_{s=1}^{S} \sigma_s \tag{4.2}$$

The upper bound on the backscatter RCS occurs when the echoes from all of the scatterers are in phase and is given by

$$\sigma = \left(\sum_{s=1}^{S} \sqrt{\sigma_s} \right)^2 \tag{4.3}$$

A number of digital computer programs have been developed to predict aircraft RCS values. These programs have the capability to predict RCS values for a variety of target geometries, including the external surfaces of aircraft (fuselage, wings, nacelles, empennage, etc.) and certain types of engine cavities. The codes fall into one of five categories: the physical optics and physical theory of diffraction (PTD) based codes that use geometric components to model complex targets, the geometrical theory of diffraction (GTD) codes that use geometrical components to model complex targets, the method of moments (MM) for rotationally symmetric targets, the MM using triangular surface patches to model complex targets, and the finite difference time-domain codes for the analysis of transient responses.[11] The Electromagnetic Code Consortium (EMCC) was established to develop and transition basic computational electromagnetics research activities to support the applications users effectively. (http://www.arl.hpc.mil/PET/cta/cea/emcc/.) Those readers who are interested in learning more about the computational aspects of electromagnetic scattering should also visit the Web site of the Applied Computational Electromagnetics Society at http://aces.ee.olemiss.edu.

Experimental techniques for determining RCS: Values for aircraft RCS can also be obtained experimentally, either dynamically or statically.[12–15] (More data are available online at http://www.acq.osd.mil/te/pubfac/holloman.html#RadarTarget Scatter, http://www.nawcwpns.navy.mil/~rrl, and http://www.nawcwpns.navy.mil/~pacrange/r1/Etcheron.htm.) The dynamic experimentation method is a flight test in which an aircraft flies a set flight path, and the RCS for that specific aircraft configuration is measured. This method has the disadvantages of requiring precise aspect control and range calibration, of the inability to identify the contributions of the individual scatterers, and of the difficulty of incorporating proposed RCS reduction designs. The elevation angles are also usually limited to a narrow elevation band below the plane of the wings.

Static testing consists of illuminating a stationary, rotatable target from various aspects. It can be done on models ranging in size from small to full size. Small- or medium-size models can be tested in anechoic chambers, such as the one shown in Fig. 1.22, whereas full-scale testing of very large scatterers might have to be accomplished on outdoor ranges (Note 11). Both the backscatter cross section for monostatic radars and the bistatic cross section for bistatic radars can be determined. Basically, an aircraft model is mounted on a spindle at varying degrees of roll angle. The spindle is then rotated through 360 deg of azimuth, and the RCS data are recorded for specific aspect angles while the aircraft is illuminated by a stationary test radar. This gives a great circle roll or orange slice of the RCS. The advantages of static testing with small-scale models are the reduced measurement range, ease of handling and storage, reduced material costs, reduced target size and weight, the simplified target support system, and the reduced variability in wind conditions. The disadvantages are the high-frequency radar equipment required (because of the requirement to have the same target dimension-to-radar wavelength ratio in the scale model test as that in the actual situation), special antennas must be used to form a plane wave at the target, the tolerances are difficult to maintain, the model materials must have the same radar reflective properties as those on the actual target, and the target echo-to-background clutter ratio is decreased.

Another static experimental technique that has some utility for identifying the glitter points on an aircraft for very short wavelength radars is flare-spot photography. In this technique a small, shiny aircraft model is illuminated by a light source. The experiment is conducted in an enclosed chamber, and the walls are covered with a nonreflecting material. A photograph is taken of the illuminated model. The illuminating light is analogous to the radar signal, and the bright spots on the illuminated model indicate the locations of the glitter points on the actual target where the specular return can be expected to be large.

Go to Problems 4.3.5 to 4.3.24.

4.3.2.2 Infrared signature (Note 12).

Learning Objective **4.3.6 Describe the IR signature of an aircraft.**

An aircraft's IR signature is composed of radiation emitted by and reflected from the aircraft in the 0.77- to 1000-μm band of the electromagnetic wave spectrum shown in Fig. 4.1. However, most of IR signature of interest lies within the 1- to 3-μm (SWIR) band, the 3- to 5-μm (MWIR) band, and the 8- to 12-μm (LWIR) band. The three general sources of this signature are 1) the radiation emitted by the airframe and the propulsion system; 2) the radiation emitted by the exhaust gas or plume from the engine(s) and other power equipment, such as an auxiliary power unit; and 3) the reflected radiation incident on the aircraft. Figure 4.8a illustrates some examples of these IR sources, and Fig. 4.8b presents a chart showing the general radiation phenomena. The relative contribution of each of the sources to the total IR signature within the bandwidth of an IR seeker depends upon the aircraft materials, surface conditions and coatings, components and configuration, the exhaust gases, the aircraft operating condition, and the viewing angle. In general, the solid surfaces emit and reflect IR radiation with an intensity that varies as a function of the radiation wavelength λ, surface temperature T, surface emissivity ε, and the viewing angle relative to the surface. The wavelength associated with the peak spectral radiant emittance can be estimated using Wein's displacement law given by Eq. (3.29), $\lambda(\mu\text{m}) \approx 3000/\text{T(K)}$. Thus, the surfaces between 375 and 250 K (room temperature is 300 K) emit most of their radiation in the 8–12 mm (LWIR) band. Similarly, the hot solid surfaces between 1500 and 500 K emit radiation in the 2–6 μm (SWIR and MWIR) band. Radiation from the engine exhaust plume occurs at several discrete wavelengths or lines in the MWIR band, such as 2.7 and 4.3 μm, that depend on the plume gas species. Reflected solar IR radiation is normally in the 0.77- to 3-μm (SWIR) band. All of the radiation from the aircraft must pass through the attenuating and scattering atmosphere as it propagates toward an IR missile seeker.

Airframe. The airframe is a continuum radiator and emits radiation from aerodynamically heated surfaces and from hot parts, such as the heat exchanger, oil cooler, auxiliary power unit, and any airframe surfaces heated by the hot engine exhaust, such as the tail boom on a helicopter. At subsonic speeds and medium to high altitude the skin radiation in the SWIR and MWIR bands caused by aerodynamic heating is usually negligible compared to the radiation from the hot parts and hot exhausts. However, the radiation in the LWIR band can be significant, particularly if the hot parts and exhaust emissions are surpressed. Furthermore, as shown in Fig. 4.8b, for aircraft flying at high Mach numbers at low altitude, the skin IR emission can be a significant contributor to the IR signature in the MWIR band, depending upon the the emissivity of the skin and the intensity of the radiation from the other sources. Additional sources of IR radiation associated with the airframe are the formation and cockpit lights.

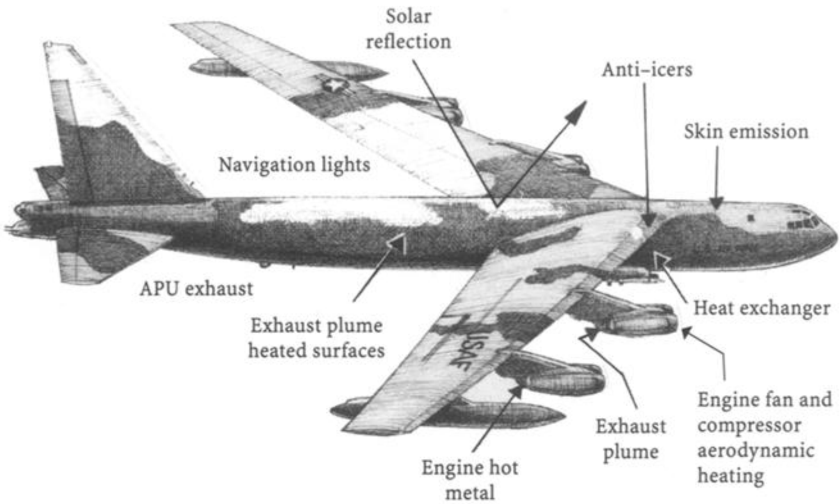


Fig. 4.8a Typical major IR sources.

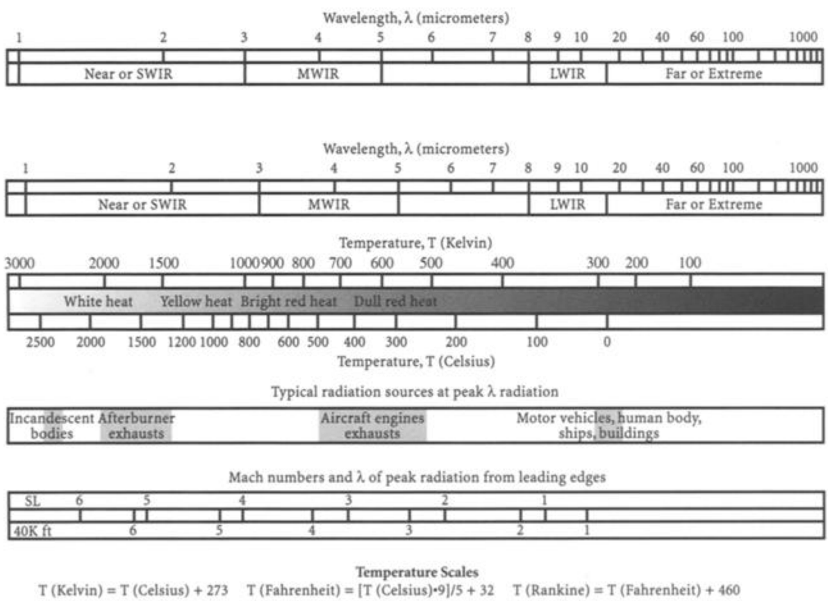


Fig. 4.8b Infrared data chart.[16]

Propulsion system. The propulsion system contributes IR radiation from the engine hot parts and the exhaust nozzle or tail-pipe hot parts. This radiation is a major contributor to the aircraft's IR signature, particularly when the engine is operating in the afterburner (A/B) mode, as shown in Fig. 4.8b. Typical temperature bandwidths for modern engines is 500 to 700 K for turboshaft engines, 700 to 900 K for high-bypass turbofans, and 900 to 1200 K for low-bypass turbofans. The maximum intensity of radiation from the engine and the tail-pipe hot parts usually occurs tail-on, where the hot parts are easily seen. The radiant intensity from the propulsion system hot parts is significantly less when viewed from the sides and front of the aircraft where most of the hot parts are usually hidden from view. However, hot engine front fan and compressor blades will contribute to the IR radiation toward the forward aspect.

Engine exhaust plume contribution. The plume IR signature is composed mainly of radiation from the hot carbon dioxide (CO_2) and water vapor (H_2O) in the exhaust gas. Additional factors that influence the strength of the plume IR signature are the static temperature and pressure and the physical extent of the plume. Most of the plume IR radiation is caused by the hot CO_2 and occurs at 4.3 μm, in the MWIR band, with a typical bandwidth of approximately 0.4 μm. The plume radiation can be seen from all directions around the aircraft, particularly when an afterburner is used. However, the attenuation of the plume radiation as it propagates through the atmosphere toward an IR detector can be significant (as described next); consequently, the plume emissions are more important at the shorter ranges, where the attenuation is less. Note that the peak radiation wavelength from the plume, because it is a line radiator, does not change with an increase in temperature, whereas the peak radiation wavelength from a continuum radiator does change. Consequently, when an engine goes into the afterburning mode and the exhaust temperature increases from around 700 K to over 1500 K, the peak radiation wavelength from the plume is still at 4.3 μm. However, the intensity is significantly higher.

Reflected radiation. Reflected solar radiation off of the airframe, including the canopy, is known as sun glint and can also be a significant source of IR radiation, particularly for the 1- to 3-μm detectors. The spectral distribution of the reflected radiation resembles that of the solar radiation at 6000 K, and the magnitude depends upon the incident illumination; the angles between the sun, the aircraft, and the observer; and the shape, condition, and reflectivity of the surface.

Atmospheric absorption of the IR signature. The IR radiation propagating away from the aircraft through the atmosphere is absorbed by the various gases in the atmosphere at several discrete wavelengths, as shown in Fig. 3.67. Those wavelength bands where the atmospheric absorption is small are called windows. The absorption is typically concentrated at 1.4 and 1.9 μm (H_2O), 2.7 μm (CO_2), 4.3 μm (CO_2), 5 to 8 μm (H_2O), and 14 to 16 μm (CO_2).

Those CO_2 and H_2O bands where the greatest atmospheric absorption occurs are also the bands that have high emissivity. Thus, because these two gases are also present in the exhaust plume from an aircraft engine, a large amount of energy will be radiated from the plume in these bands. As this radiation propagates away from

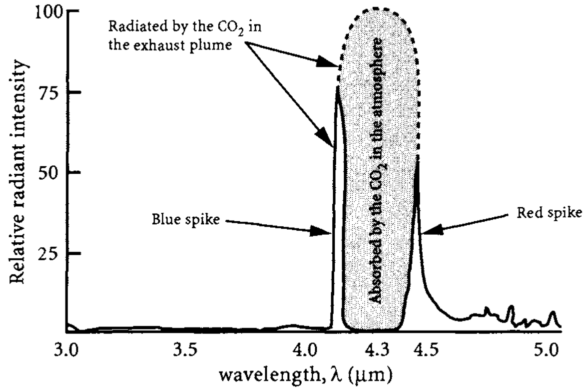


Fig. 4.9 Exhaust plume IR radiation at 4.3 μm and the absorption by the atmosphere.[17]

the plume and through the surrounding atmosphere, the CO_2 and H_2O molecules in the atmosphere will absorb it. However, the radiation from the hot CO_2 and H_2O molecules in the exhaust plume will not be totally absorbed by the carbon dioxide and water molecules in the surrounding atmosphere because the plume and atmosphere are at significantly different temperatures and pressures. Thus, their emission and absorption values are somewhat different. This feature is illustrated in Fig. 4.9, which shows both the radiation from the plume (the dashed line) and the atmospheric absorbtion (the gray area) in the vicinity of the 4.3-μm carbon dioxide band. Note, however, that spikes of radiation from the plume on both sides of the 4.3-μm wavelength, known as the blue spike and the red spike, are not absorbed as a result of the differences between the plume and atmosphere.

Infrared image of a helicopter. Figure 4.10 shows a 320 × 256 pixel image of the IR radiation in the 3- to 5-μm band (InSb in Fig. 3.69) from a taxiing Dauphin helicopter. The white areas represent areas with a relatively high radiation intensity level in the 3- to 5-μm band, and the black areas have a relatively low intensity level. Note the significant amount of radiation from the engine exhaust plume and the exhaust heated tailboom in the band of the detector. The emissions from the tailboom, and other aircraft surfaces near the plume, consist of the radiation emitted by the hot surfaces themselves and the radiation from the plume that is reflected by the surfaces in the direction of the IR detector.

Aircraft IR signature pattern. A typical infrared radiation signature at several locations around a jet-engined aircraft at some arbitrary distance away might have the appearance shown in Fig. 4.11a. The magnitude of the signature is usually expressed as the spectral radiant intensity, that is, the power per unit solid angle per unit wavelength (watts/steradian/micrometer) or as the radiant intensity, that is, the power per unit solid angle (watts/steradian). Note the change in the scale of intensity in Fig. 4.11a for the different aspects. When the aircraft is viewed from the front and the sides, the plume radiation might be the primary source of the IR

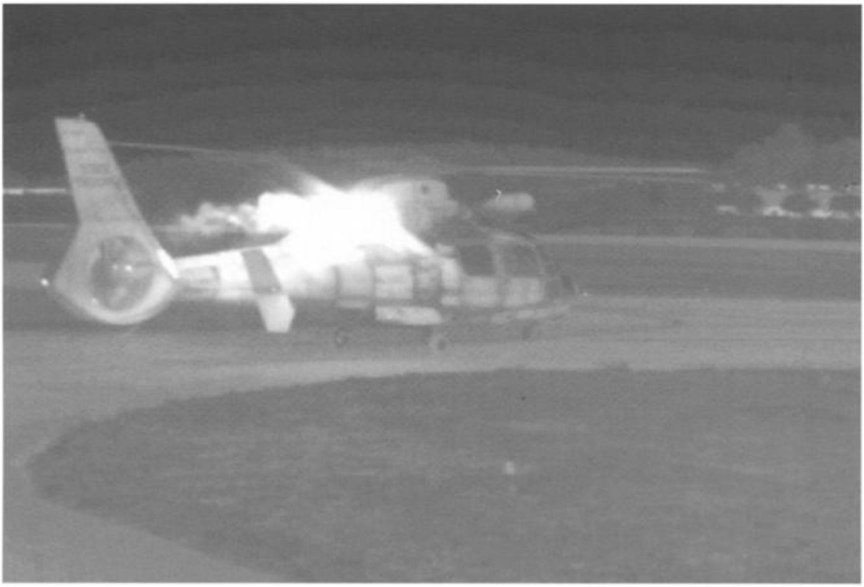


Fig. 4.10 IR image of a Dauphin helicopter (Courtesy of the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD).

signature in the MWIR band, unless the front face of the engine is hot. Note that the radiation is most intense at the two spikes of the CO_2 radiation line centered at 4.3 μm. When viewed from the tail, the engine hot parts become the major IR source in the SWIR and MWIR bands, and the red and blue spikes of radiation from the plume are dwarfed by the hot parts emissions, as shown in the 180 deg view in Fig. 4.11a. A helicopter typically exhibits the same type of IR radiation as a fixed-wing aircraft. However, the pattern might differ from that shown in Fig. 4.11a if the engine does not exhaust to the rear. A polar plot of the radiant intensity from a rear-exhaust helicopter within a limited wavelength band is given in Fig. 4.11b.

Typical values of the radiant intensity of jet-engined aircraft in the MWIR band can range from 100 W/steradian to over 1000 W/steradian. In general, at constant thrust turbojets have a larger IR signature than turbofans, and turbofans have a larger signature than turboprops. Helicopters with their turboshaft engines typically have much lower values.

Infrared signature prediction and measurement. "Infrared signature prediction models fall into two categories: empirically based and physics based. In the empirical models IR measurements are acquired for an operating aircraft at multiple angles and flight conditions. The data are assembled using algorithms to fill in the gaps between the data. These models are useful, but only after the aircraft is designed and built. The physics-based models are no more accurate than the data going into the model. The aircraft geometry is usually the easiest to obtain. Emissivity is also relatively easy if samples of the surface can be obtained and optically measured. Temperature, particularly for engine signature prediction, is

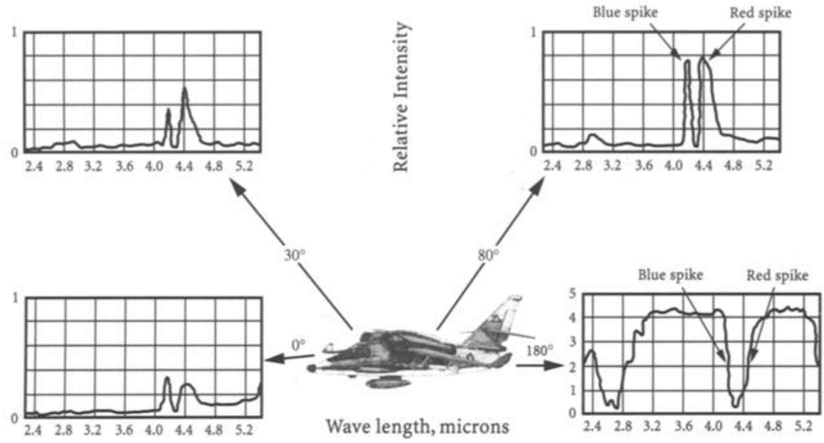


Fig. 4.11a IR signature around an aircraft.

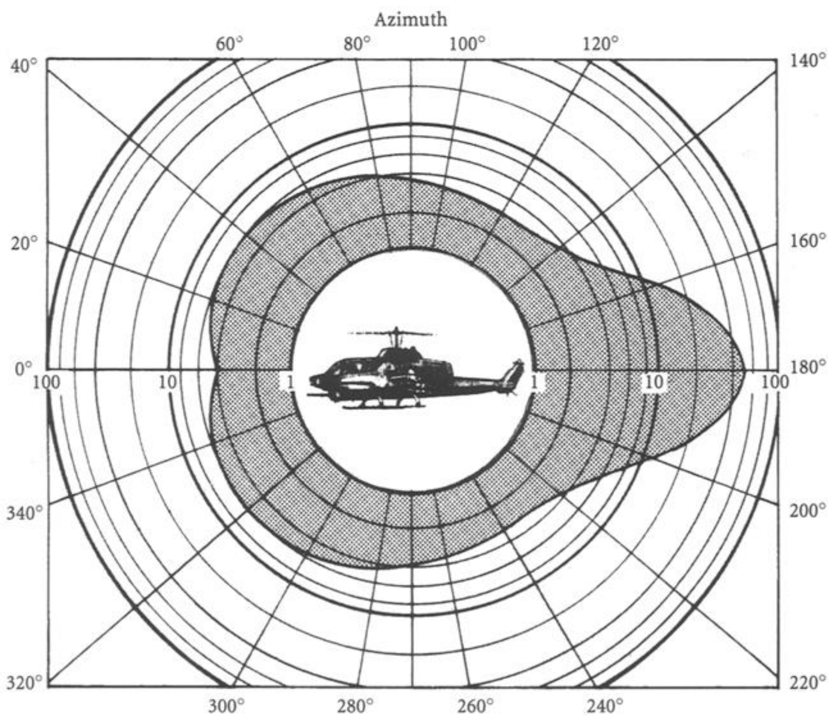


Fig. 4.11b Polar plot of the radiant intensity (watts/steradian) from a helicopter in a given wavelength band.

more difficult to obtain because of engine throttle setting, engine deterioration, cooling system performance, radial and axial temperature profiles, and gas hot streaks. Particularly important for accuracy is the resolution of the model. Sufficient elements must be included to model surface curvature, surface emissivity distribution, and temperature gradients. The model must also accommodate reflections of one hot surface by another. The atmospheric attenuation must be handled on a wavelength-by-wavelength basis rather than by wavelength bands to get an accurate answer at long ranges."*

Several IR physics-based signature prediction computer models are currently available. These models are founded upon the underlying physics of thermal radiation, reflection, and transmission. In one of the programs, the IR prediction method is broken down into groups of computational steps or modules. One module models the airframe surface areas, emissivity, and temperature as viewed from specified aspect angles. A second module is used to model the engine exhaust system areas, temperatures, and radiant interchange between these areas and the ambient environment. A third module models the spatial distribution of engine exhaust products, such as H_2O and CO_2, as they mix to lower temperature and concentrations with the ambient air. A fourth module models the IR emission and attenuation of the exhaust and atmospheric gases in the path between the aircraft hot components and exhaust gases and the observer location in space. Other modules are available to calculate an IR missile's utilization of this incident radiant energy. The input data for the program are obtained from the aircraft design. Typical input quantities are the airframe geometry, the engine interior geometry, the engine exhaust temperature profile, and the H_2O and CO_2 concentrations.

Experimental measurement of the IR signature of aircraft is conducted at several facilities in the U. S. Infrared radiometers and digital focal-plane-array cameras are used to determine the radiant intensity and the spatial distribution of the radiation over a band of wavelengths, and spectrometers are used to measure the spectral distribution of the radiation from the target. A guidebook, "The Aircraft Infrared Measurements Guide," JTCG/AS-81-C-002,[18] has been prepared by the JTCG/AS as a reference source for the infrared measurement community.

Go to Problems 4.3.25 to 4.3.33.

4.3.2.3 Visual signature.

Learning Objective	**4.3.7**	**Describe the visual signature of an aircraft.**

A large number of the combat aircraft killed in past conflicts were hit by projectiles from visually directed weapons. In many cases the enemy simply aimed a barrage in

*Wollenweber, G. C., personal communication,General Electric Aircraft Engines, Cincinnati, OH, 24 Jan. 2002.

the direction of the visual observables of the aircraft, such as a smoke trail, before the aircraft itself could be observed. In addition to smoke, visual observables from sources on or near the aircraft include contrails and, at night, the engine exhaust glow, formation lights, and the cockpit lighting. Certain expendables and other features designed to reduce an aircraft's susceptibility to nonvisually directed weapons, such as the IR flare, also can attract the attention of the air defense in the visible band.

In general, the visual detectability of an aircraft is dependent upon the difference between the background and the aircraft. There are four parameters that influence the detectability of the visual signature. These are luminance, chromaticity, clutter, and movement. Of these four, the most important is the aircraft luminance contrast with the background luminance. Luminance is the radiance (the power/unit solid angle/unit area) of an object weighted by the luminosity function of a standard observer. Aircraft luminance is the sum of the luminance of any onboard luminance sources, such as exterior and cockpit lighting and the glowing exhaust nozzle, and the luminous reflection from the aircraft exterior surfaces. Aircraft detection can occur when the aircraft luminance is too low compared with its background (the aircraft appears as a dark spot in a bright background) or when the aircraft luminance is too high with respect to the background. (A bright aircraft is easily observed against a dark background.)

For aircraft that have a low luminance contrast with the background, the chromatic contrast between the aircraft and the background can become the dominant detection feature. An aircraft painted with a brown and green camouflage scheme for protection from attacks from the air while parked will be quite visible from above when it is flying over sand or water. Because color sources can differ in hue (a chromatic characteristic), as well as their luminance, the term color encompasses both luminance and chromatic contrast.

Clutter contrast also affects visual detectability. Examples where clutter contrast is important are helicopter nap-of-the-Earth flight profiles and low-altitude flight paths of fixed-wing aircraft. In these situations the observer attempts to discriminate between the moving aircraft and a changing background of confusing forms. For many observers detection is immediately achieved, once fixation in the general direction is achieved, when the target luminance contrasts with the background clutter.

Movement is the fourth parameter that influences the visual detectability of an aircraft. Movement is more easily observed when there is a strong luminance, chromatic, or clutter contrast between the aircraft and the background. In the case of rotary-wing aircraft, one movement that can be detected is the rotation of the rotor blades. Against a background of relatively high luminance, such as the sky, the rotating blades might present a negative contrast or a flickering stimulus. Under some illumination conditions, the rotating blades exhibit a glint-flicker signature that is a highly detectable cue as a result of the high luminance associated with the glint combined with the temporal enhancement caused by flicker.

Go to Problem 4.3.34.

4.3.2.4 Aural signature.

Learning Objective **4.3.8 Describe the aural signature of an aircraft.**

Aircraft are often heard before being seen by ground observers, primarily as a result of engine and/or rotor blade noise. For example, low-flying helicopters can sometimes be heard as early as 30 s before they become visible because of rotor blade noise. (Under battlefield conditions, however, background noise from tanks, guns, and other aircraft can prevent or delay aural detection.)

The factors that determine aural detectability include the intensity and the spatial pattern of the noise generated by the aircraft, the frequency spectrum and real-time character of the noise, the distance between the noise source and the receiver, the atmospheric attenuation of the noise, the scattering effects caused by atmospheric winds, the atmospheric temperature gradient and turbulence, the noise attenuation (absorption and scattering) caused by terrain, the level and frequency of the background noise in the vicinity of the receiver, and the sensitivity of the receiver to the noise. Although these factors have been identified as significant contributors to aural detection by enemy ground observers, they also influence undersea detection of aircraft. In this situation the aircraft-generated noise passes through the atmosphere, across the atmosphere-to-water interface, and along ocean bottom-reflected paths. The aural signature, if detected, could be used by a submarine to launch an air defense missile, if available, or to take evasive maneuvers.

The noise from an aircraft comes from many sources, which can include propeller/rotor blade rotational and vortex noises, engine inlet, combustion, exhaust, and rotary noises, and airframe aerodynamic noise. For rotary-wing aircraft the three main components of noise are the sounds produced by the main rotor, the antitorque system, and the engine(s). In the case of propeller-driven aircraft, aerodynamic boundary-layer noise might exceed the noise from the propellers. Engine cycle type is a significant factor that determines the percentage of engine noise to the total aircraft noise. Aircraft utilizing high-bypass turbofan engines have a reduced noise level from that of turbojet engines of equivalent thrust and aircraft type. The noise from all of these sources is usually highly spectral in content, with much of the intensity concentrated within specific narrow frequency bands.

Go to Problem 4.3.35.

4.3.3 Aircraft Detection and Acquisition (P_D)

The operational functions of an air defense weapon system and the big picture for the one-on-one encounter are described in Chapter 3, Secs. 3.2 and 3.3. Once the weapon is set up and searching for aircraft, the first requirement is the detection of the aircraft. Figure 3.5 is an illustration of the general extent of a detection envelope for a radar system. Of interest here is the quantification of the limits of the ability of major types of detection and tracking systems to detect aircraft and the probability associated with that limit $P_{D|A}$, the probability the aircraft is detected given an active threat. Here, the assumption is made that the weapon system is active, and the probability of detection will be denoted by P_D. The two major types of detection and acquisition systems considered here are the radar and the infrared.

4.3.3.1 Radar

Learning Objectives	**4.3.9**	**Compute the radar horizon and the maximum range a radar can detect an aircraft.**
	4.3.10	**Describe the process for the detection of echoes in noise, determine the relationship between (S/N), P_D, P_{fa}, and R, and determine the false-alarm time.**
	4.3.11	**Compute the probability a radar detects and acquires an aircraft after S pulses or scans.**

A radar can detect an aircraft only if the aircraft is above the radar horizon and if it is within the maximum range of the radar. The equations for the radar horizon and the maximum radar range are presented in the following subsections.

Radar horizon. In Fig. 4.12a two aircraft on the right, one at high altitude and one at low altitude, are approaching a radar site on the left. The high-altitude aircraft is far above the radar horizon in free space, whereas the nose of the low-altitude aircraft is just at the radar horizon.

The maximum distance a radar antenna at a height h_{ant} can see an aircraft flying at an altitude h_{ac} is defined by the radar horizon R_h, which is given by

$$R_h = 1.23\left(\sqrt{h_{\text{ant}}} + \sqrt{h_{\text{ac}}}\right) \quad \text{(n miles)} \tag{4.4}$$

where h_{ant} and h_{ac} are given in feet. This equation assumes a standard refraction of the radar wave of 4/3 because of the Earth's atmosphere. When horizontal ducting

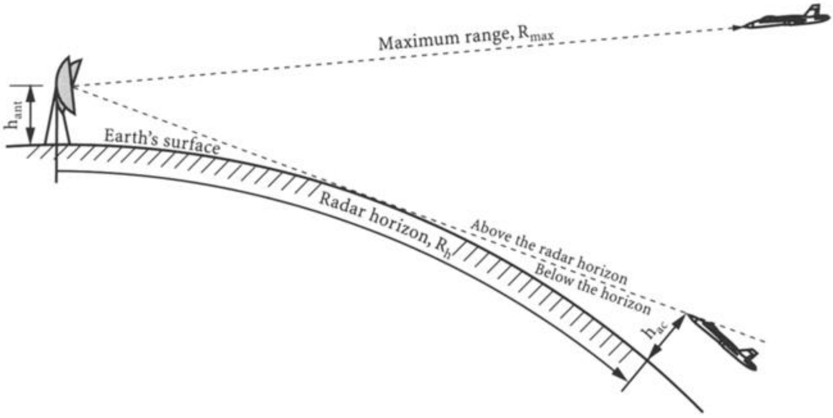
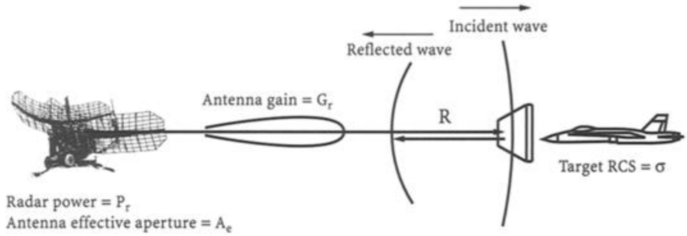


Fig. 4.12a Radar horizon and the maximum range.



$$\text{Target echo power at antenna (W)} = S = \left(\left(\frac{P_r}{4\pi R^2}\right)\cdot G_r\right)\cdot(\sigma)\cdot\left(\frac{1}{4\pi R^2}\right)\cdot(A_e)$$

Incident omnidirectional power density (W/m²)

Incident power density with antenna gain (W/m²)

Echo power at target (W)

Echo power density at antenna (W/m²)

Echo power captured by antenna (W)

Fig. 4.12b Radar range equation.

of the radar signal occurs as a result of atmospheric conditions, the actual radar horizon can be much further.[19]

Maximum range. The relationship that determines the effectiveness of a monostatic radar is known as the radar range equation. This equation defines the maximum range at which a given radar can detect a given target in free space, as illustrated by the aircraft above the radar horizon in Fig. 4.12a. Figure 4.12b shows the sequential development of the radar-range equation.

The aircraft in Fig. 4.12b is located a distance R from the radar. The hostile radar has a peak power output of P_r. If the power of the radar is radiated into space omnidirectionally, the power would be distributed evenly over the surface of a sphere whose center is located concentrically with the source of the power. At the distance R from the radar, the surface area of the sphere is $4\pi R^2$. Thus, the incident power density on the target for the omnidirectional antenna is

$$\text{Omnidirectional power density at distance } R = \frac{P_r}{4\pi R^2} \quad (\text{W/m}^2) \tag{4.5a}$$

However, most air defense radar antennas have a gain factor G_r. Thus, the power density of the signal at the target, which is at the distance R from the radar, is given by

$$\text{Incident power density with antenna gain} = \frac{P_r G_r}{4\pi R^2} \quad (\text{W/m}^2) \tag{4.5b}$$

The product of P_r and G_r in Eq. (4.5b) is known as the radar's effective radiated power (ERP), and the reduction in the power density in the beam caused by the propagation of the signal from the antenna to the target $1(4\pi R^2)$ is called the spreading or space loss.

The radar signal illuminates the target presented area A_t, creating a power at the target. The portion of the signal that is scattered in the direction of the radar receiver will either amplify or degrade this power by the gain factor G_t. The product $A_t G_t$ is the aircraft's radar cross section σ. Thus, multiplying the signal power density at the target by $A_t G_t$, or σ, gives the echo power reflected at the target in the direction of the receiver, as if the target itself was a source of power:

$$\text{Echo power at the target} = \frac{P_r G_r}{4\pi R^2}(A_t G_t) = \frac{P_r G_r \sigma}{4\pi R^2} \quad \text{(W)} \qquad (4.5\text{c})$$

As the echo propagates away from the target and toward the radar receiving antenna, the density of the echo power decays inversely with the radius from the target squared, just as the original signal decayed as it propagated away from the transmitter. The power density of the echo of interest is that at the radar receiver, which is assumed to be located at the transmitter, and so the radius of the echo sphere is given by R, and the surface area of the echo is given by $4\pi R^2$. The echo power density impinges on the receiving antenna, which has an effective aperture A_e, and the echo power density is converted to the echo power S. Thus,

$$\text{Echo power at the antenna} = S = \frac{P_r G_r \sigma A_e}{(4\pi R^2)^2} \quad \text{(W)} \qquad (4.5\text{d})$$

This is the basic radar equation, and it can be rewritten in several different ways. By combining terms and using the relationship between the antenna gain, the wavelength, and the effective area of the antenna given by Eq. (3.23), the following equation can be derived:

$$S = \frac{P_r G_r^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \qquad (4.5\text{e})$$

Up to now, the effects of signal and echo power losses and extraneous noise have not been considered. The various signal and echo power losses that occur as a result of atmospheric attenuation and polarization losses as the signal travels out to the aircraft and the echo returns to the radar antenna can be accounted for by dividing the echo power at the receiver by a factor L_a, where L_a is equal to unity when there are no losses and is greater than unity when losses occur. Similarly, power losses that occur inside the radar receiver can be accounted for by the factor L_s (Note 13).

$$S = \frac{P_r G_r^2 \lambda^2 \sigma}{(4\pi)^3 L_a L_s R^4} \qquad (4.5\text{f})$$

The extraneous noise that must be dealt with by the radar receiver can be accounted for by N, where N is the noise power that lies within the signal bandwidth of the radar receiver. The noise consists of the internal receiver noise $N_0 B$, where N_0 is the noise factor per unit bandwidth and B is the receiver bandwidth in hertz, and any external noise, such as background clutter from rain or surface features in the range resolution cell, the return from reflected paths off of a glistening surface, and any electronic countermeasure noise (Note 14). The ability of a radar receiver to detect the echo from an aircraft in the presence of noise is dependent upon the ratio of the echo power to the noise power, known as the signal-to-noise ratio S/N. Thus, dividing both sides of Eq. (4.5f) by N results in

$$\frac{S}{N} = \frac{P_r G_r^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_a L_s N} \tag{4.5g}$$

The signal-to-noise ratio plays a major role in the detection and tracking capabilities of a radar system. During the operation of any radar system, the goal of the radar operator or signal processor is to be able to distinguish aircraft echoes from the noise. There are many signal processing techniques to assist him/her/it in this endeavor, such as setting echo thresholds so high that most of the noise is below the threshold and is rejected, which eliminates the detection of low RCS targets, and integrating more than one echo to determine whether a target is present. Ultimately, it is up to the operator or the built-in detection logic to decide when a target echo has been received.

The maximum range at which the radar can detect an aircraft can be estimated using the S/N form of the radar equation given in Eq. (4.5g). A plot of S/N as a function of R is given in Fig. 4.12c. Let $(S/N)_{\min}$ be defined as the minimum detectable signal-to-noise ratio, and define $R_{\max}$ as the range at which $(S/N)_{\min}$ occurs.

Replacing S/N with $(S/N)_{\min}$ and R with $R_{\max}$ in Eq. (4.5g) and solving for $R_{\max}$ results in the radar range equation

$$\text{Maximum range} = R_{\max} = \left[\frac{P_r G_r^2 \lambda^2 \sigma}{(4\pi)^3 L_s L_a N (S/N)_{\min}}\right]^{\frac{1}{4}} \tag{4.5h}$$

The final modification to the radar range equation applies to low-flying aircraft and is caused by signal reflections from the surface of the Earth as the signal travels

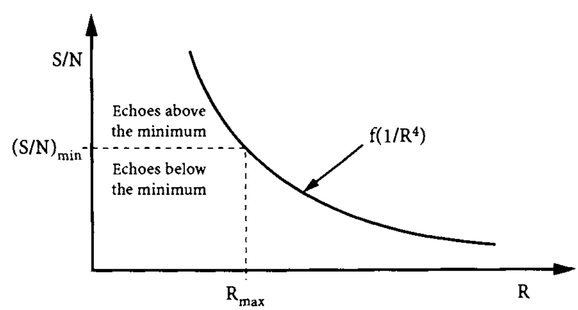


Fig. 4.12c S/N as a function of R.

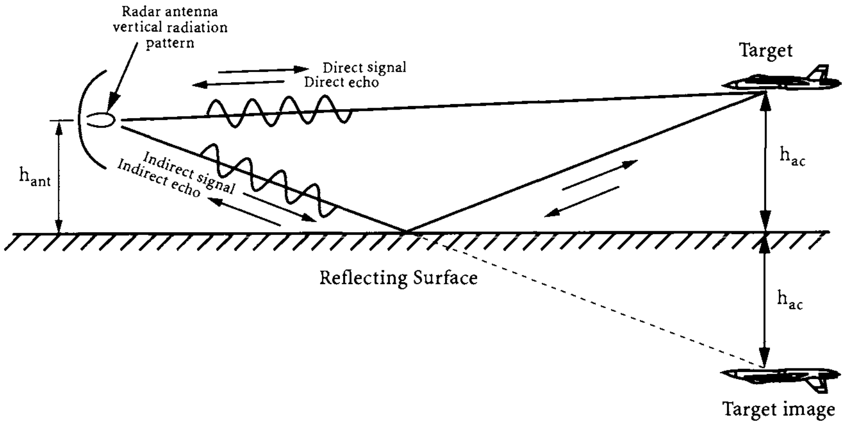


Fig. 4.12d Multipath phenomenon.

from the transmitting antenna to the aircraft and back. Some of the outbound signal that is not propagating directly toward the aircraft might actually reach the aircraft and return to the antenna by an indirect path that includes a reflection from the Earth's surface, as shown in Fig. 4.12d. This is known as the multipath phenomenon or low E problem. The multipath phenomenon creates two problems for the radar as it attempts to detect the target and to determine its elevation. First, determination of the target's elevation is complicated because the direct-path echo and the multipath echo approach the antenna from two different elevation angles, one for the real target and one for the target image, as illustrated in Fig. 4.12d. Consequently, the radar might not be able to determine which is the real target.

Second, detection of the target in the presence of multipath echos is complicated by the fact that the surface reflected signal in Fig. 4.12d travels a longer distance than the direct signal and interferes with the direct signal, first at the aircraft and then again at the antenna. The interference will strengthen or reinforce the echo when the two signals are in phase and weaken or destructively interfere with the echo when they are out of phase. As the aircraft travels along a path of constant altitude toward the radar, the echo will fluctuate in strength, growing stronger and then weaker, as the two signals differentially change in path length, and hence phase. Figure 4.12e illustrates the peaks and nulls in the combined echo power. The detection lobes indicate areas where the aircraft can be detected because of the strength of combined echo power, and the elevation angle to the first detection lobe is given in the figure. The change in the electric field strength of the combined signals at the target will vary from a minimum of zero, when the two signals are exactly out of phase (indicated by the nulls in Fig. 4.12e), to a maximum factor of two, when they are exactly in phase (indicated by the peak of the detection lobes), assuming the reflected signal and the direct signal are of equal strength and polarization. The composite field strength is called the pattern propagation factor and is denoted by F. Because the echo power is proportional to the field strength squared and because the path from the target to the radar is assumed to be the

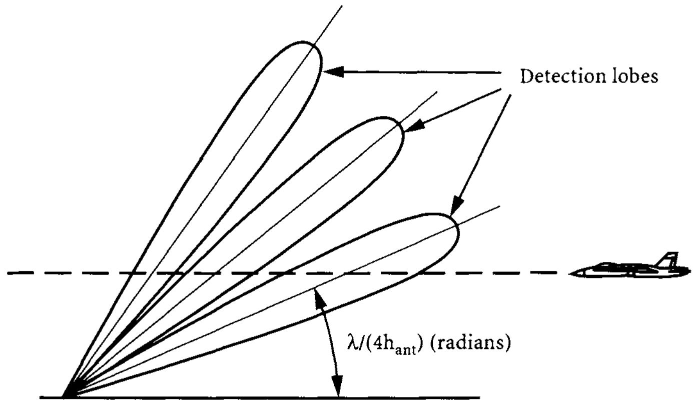


Fig. 4.12e Echo power vs target range with multipath.

same as that from the radar to the target, the power of the combined echoes at the receiving antenna is given by F^4, where $0 \leq F \leq 2$. When no multipath signals are present, which is the free-space condition, $F = 1$. Including the multipath factor F in the radar range equation gives

$$R_{\max} = \left[\frac{P_r G_r^2 \lambda^2 \sigma F^4}{(4\pi)^3 L_a L_s N (S/N)_{\min}}\right]^{\frac{1}{4}} \tag{4.5i}$$

Thus, when $F = 2$, $R_{\max}$ is twice the free-space detection range and when $F = 0$, $R_{\max}$ is zero. The drastic changes in the echo strength and the wandering of the apparent target elevation angle that occur because of the multipaths can make accurate tracking very difficult at beam angles less than one-half of a beamwidth above the surface.

Maximum unambiguous range. A final consideration for pulse radars is the maximum unambiguous range R_u given by Eq. (3.18b). If R_u is less than $R_{\max}$, then a return from a detectable target beyond R_u could be erroneously interpreted as a return from a closer target caused by the multiple pulses. Thus, the detection capability of a radar system is governed by the three ranges R_h, $R_{\max}$, and R_u.

Example 4.3 Radar Horizon and Maximum Range

Given the following parameters of a radar system and target aircraft

$$f = 15\ \text{GHz} \quad P_r = 100\ \text{kW} \quad G_r = 40\ \text{dB} \quad \tau = 1\ \mu\text{s}$$

$$\text{PRF} = 1500\ \text{PPS} \quad L_a = 3\ \text{dB} \quad L_s = 10\ \text{dB} \quad (S/N)_{\min} = 16\ \text{dB}$$

$$h_{\text{ant}} = 16\ \text{ft} \quad h_{\text{ac}} = 2500\ \text{ft} \quad N = 2.5 \times 10^{-16}\ \text{W} \quad \sigma = 1\ \text{m}^2$$

compute the radar horizon, the free-space maximum range, the maximum range with multipath effects, the elevation angle of the first multipath lobe, and the maximum unambiguous range. Use both the decimal and the decibel approach for the maximum range.

Radar horizon: The radar horizon is given by Eq. (4.4). Thus,

$$R_h = 1.23\left(\sqrt{16\text{ ft}} + \sqrt{2500\text{ ft}}\right) = 66.4\text{ n miles or } 66.4\text{ n miles}$$
$$\times 1.85\text{ km per n mile} = 123\text{ km}$$

Maximum range: The maximum range is given by Eq. (4.5i). Using the decimal approach results in

$$P_r = 100{,}000\text{ W} \quad G_r = 10{,}000 \quad \lambda = c/f = (300 \times 10^6\text{ m/s})/(15 \times 10^9\text{ Hz}) = 0.02\text{ m}$$

$$\sigma = 1\ m^2\ L_a = 2 \quad L_s = 10 \quad N = 2.5 \times 10^{-16}\text{ W} \quad (S/N)_{\min} = 40 \quad F = 1$$

$$(4\pi)^3 = 1984.4$$

$$R_{\max} = \left[\frac{(10^5\text{ W})(10^4)^2(0.02\text{ m})^2(1\text{ m}^2)1^4}{(4\pi)^3(2)(10)(2.5 \times 10^{-16}\text{ W})(40)}\right]^{\frac{1}{4}} = 56.3\text{ km}$$

Using the decibel approach results in

$$P_r = 50\text{ dBW} \quad G_r = 40\text{ dB} \quad \lambda = -17\text{ dBm}$$
$$\sigma = 0\text{ dBsm} \quad L_a = 3\text{ dB} \quad L_s = 10\text{ dB} \quad N = -156\text{ dBW}$$
$$(S/N)_{\min} = 16\text{ dB} \quad F = 1$$
$$(4\pi)^3 = 32.976\text{ dB} \approx 33\text{ dB}$$
$$R_{\max} = 0.25 \times [(50 + 40 \times 2 - 17 \times 2 + 0 + 0 \times 4) - (33 + 3 + 10 - 156 + 16)] = 47.5\text{ dBm}$$

which is equal to 56.2 km, essentially the same answer obtained using the decimal approach. Note that several of the decibel numbers were rounded off, resulting in the small difference.

The maximum range considering multipath effects, which is twice the free-space detection range, is 112.6 km or 50.5 dBm

Elevation angle of the first multipath lobe: From Fig. 4.12e,

$$\text{Angle to the first multipath lobe} = \lambda/(4h_{\text{ant}}) = (0.02\text{ m})/(4 \times 16\text{ ft} \times 0.305\text{ m/ft}) = 0.00102\text{ radian} = 0.059\text{ deg}$$

Maximum unambiguous range: The maximum unambiguous range R_u is given by Eq. (3.18b). Hence,

$$R_u = (300 \times 10^6\text{ m/s})(1/1500\text{ PPS})/2 = 100\text{ km}$$

Summary:

$R_h = 123$ km $\quad R_{max} = 56.3$ km or 112.6 km with multipath $\quad R_u = 100$ km

---

Radar detection envelope. The radar detection envelope or coverage can be depicted by the diagram shown in Fig. 4.12f. The horizontal axis is the slant range from the radar to the aircraft, and the vertical axis is the altitude of the aircraft above the Earth's surface. The radar antenna is assumed to be located on the Earth's surface at the lower left corner of the diagram. The elevation angle of the radar is denoted by the straight dotted lines. Note that both the slant range contours and the altitude contours are curved. The slant range is curved because it is a function of both the horizontal range and the altitude. This is illustrated by the 5-n mile slant range contour, which is 5 n miles from the radar at 0-deg elevation and is 30 Kft directly overhead the radar. The altitude contours are curved because the Earth's surface is curved. Because the radar is assumed to be located on the surface, the 0-deg elevation angle is the radar horizon. Consequently, Fig. 4.12f can be used to estimate R_h for different aircraft altitudes. For example, an aircraft located at the 60-n mile slant range from the radar is below the radar horizon. If it approaches the radar at a constant altitude of 1000 ft above the Earth's surface, it will reach the radar horizon at a slant range of between 40 n miles and 35 n miles, according to Fig. 4.12f. Using Eq. (4.4) to determine the radar horizon results in $R_h = 38.9$ n miles. If the antenna is above the Earth's surface, its contribution to R_h must be included in Eq. (4.4).

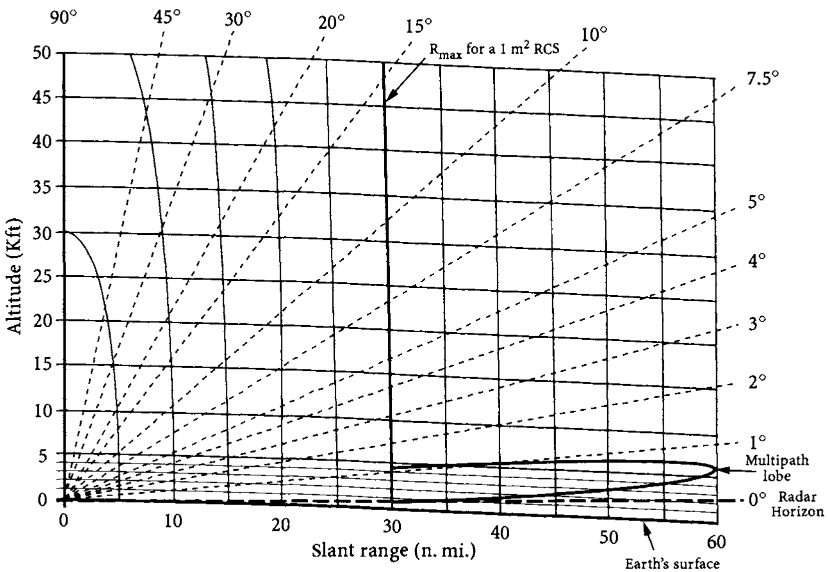


Fig. 4.12f Idealized radar detection envelope.

Suppose R_{max} for a given radar is 30 n miles for an aircraft with a RCS of 1 m^2, the usual RCS for radar detection envelopes. The corresponding idealized detection envelope is shown in Fig. 4.12f by the solid line along the 30-n mile slant range. Also shown is the first detection lobe caused by the multipath effect (Note 15).

Go to Problems 4.3.36 to 4.3.37.

$(S/N)_{min}$ *and the probability of detection and probability of false alarm.* The equation for R_{max} requires a value for the minimum detectable signal-to-noise ratio $(S/N)_{min}$. Because both the echo power S and the noise power N are random variables, detection is a stochastic process, and the phrase minimum detectable signal-to-noise ratio must be replaced with minimum detectable signal-to-noise ratio with a probability of detection P_D and an associated probability of false alarm of P_{fa}. The procedure to determine $(S/N)_{min}$ based upon selected numerical values for P_D and P_{fa} is briefly described next.

Consider the power processed by a radar receiver in Fig. 4.13a as a function of time. The noise is a continuous, random variable, and three echoes (1, 2, and 3) are received during the time interval shown. A detection is said to occur when the total power level $(S + N)$ is above a selected power level called the threshold. The S/N ratio when $S + N$ is equal to the threshold is defined as $(S/N)_{min}$. Three thresholds (A, B, and C) are shown in Fig. 4.13a. If the threshold for detection is set high at level A, the power does not exceed that level during the interval. Consequently, no detections occur, and the aircraft is undetected. Lowering the threshold to level B results in the detection of echo 3, but echoes 1 and 2 are missed. Consequently, only one out of the three echoes is detected at this threshold. Lowering the threshold to level C to increase the likelihood of detecting more echoes results in the detection of all three echoes; however, three noise pulses (a, b, and c) are also detected. These noise pulses are false alarms. Furthermore, note that as the magnitude of the echoes S decreases with respect to the noise N, the probability of detecting the echoes for a given threshold decreases. In summary, lowering the power threshold for detection

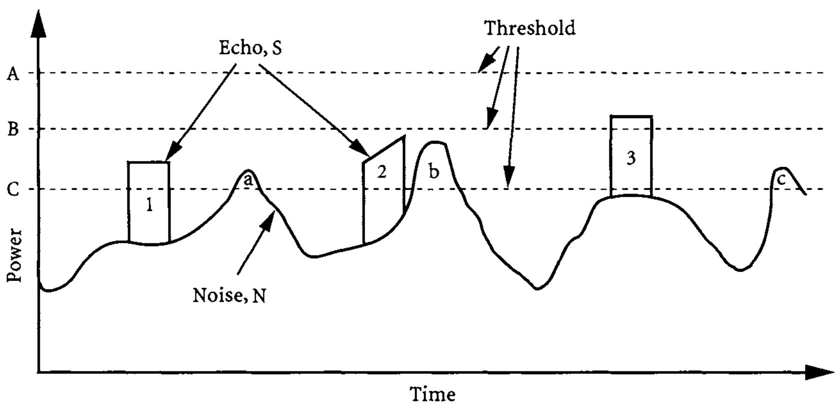


Fig. 4.13a Receiver power as a function of time.

increases the probability of detecting the aircraft and increases the probability that a detection is a false alarm, and a decrease in S relative to N decreases P_D for a given threshold level.

The detection of echo 3 shown in Fig. 4.13a occurred at the threshold level B because the combination of the noise power at the time echo 3 was received and the power of echo 3 crossed the threshold. The noise power was smaller when echoes 1 and 2 were received, and consequently detection of those echoes did not occur with threshold B. A different noise power curve would lead to different detection and false alarm results. Consequently, the detection process must be treated as a stochastic process. The questions to be answered are what is the probability an echo S will be detected when noise N is present and what is the associated probability of false alarm for a given threshold. The relationship between $(S/N)_{\min}$, P_D, and P_{fa} can be determined by assuming a statistical distribution of the processed noise, such as the Rayleigh probability density function, and possibly a statistical distribution of the echo power, typically the Swerling cases (Note 16). Plots relating these three parameters have been developed for many different situations.[20] For example, Fig. 4.13b shows the relationship for the situation where the echo power plus noise power $(S + N)$ is represented by a sine wave (the echo) immersed in Gaussian distributed noise with zero mean.

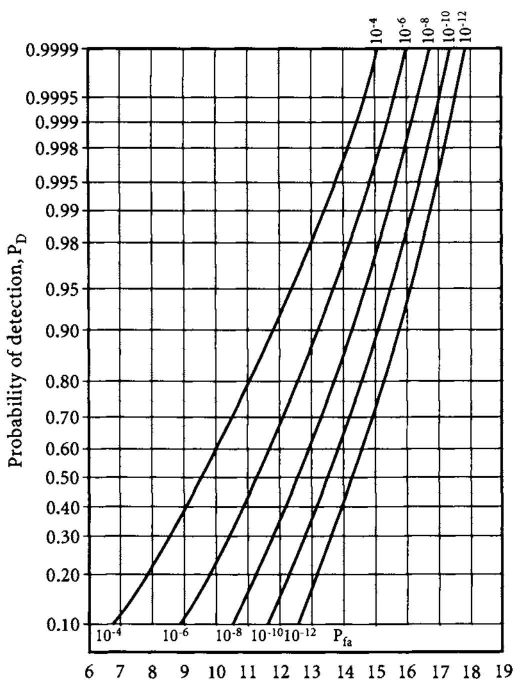


Fig. 4.13b Probability of detection of a sine wave in noise.[23] (Skolnik, M. I., "Introduction to Radar Systems," McGraw-Hill Book Company, 1962. Reprinted with permission of The McGraw-Hill Companies.)

Example 4.4 Relationship Between $(S/N)_{min}$, P_D, and P_{fa}

Suppose the desired P_D is 0.90 and P_{fa} is 1×10^{-10}.

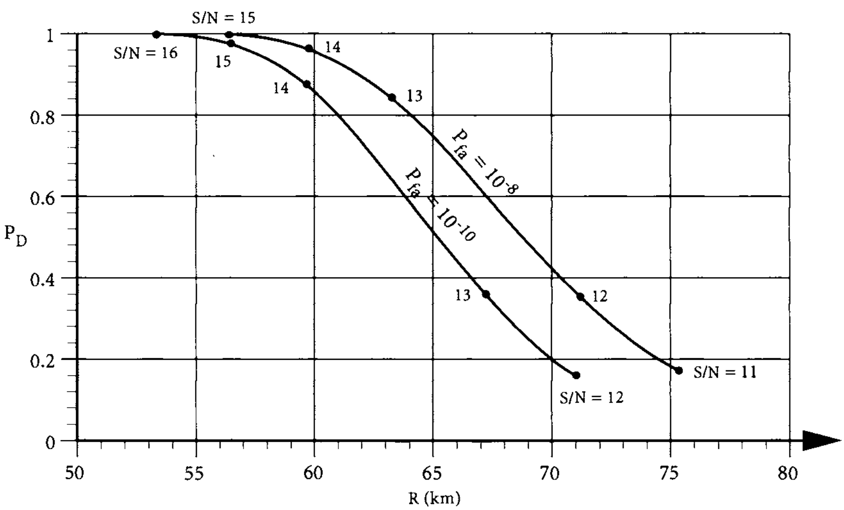
According to Fig. 4.13b, $(S/N)_{min}$ is slightly more than 15 dB.

Increasing P_D to 0.95 and keeping the same P_{fa} results in a $(S/N)_{min}$ of approximately 15.5 dB.

Retaining the same P_{fa} means retaining the threshold level, and increasing P_D increases the required signal-to-noise ratio; the echo strength must increase to ensure that more echoes are detected at the same threshold.

The $(S/N)_{min} = 16$ dB in Ex. 4.3 has a P_D of 0.94 for a P_{fa} of 1×10^{-12} or a P_D of 0.985 for a P_{fa} of 1×10^{-10} according to Fig. 4.13b. The threshold for the second pair is lower than the threshold for the first pair to increase the likelihood that an echo is detected, but lowering the threshold also results in more false alarms.

The results given in Fig. 4.13b can be used in conjunction with S/N given by Eq. (4.5g) to determine P_D as a function of R for a given P_{fa}. The results for the radar described in Ex. 4.3 are shown here for two different P_{fa} and a 1-m^2 RCS aircraft. According to the figure, the P_D at 70 km is 0.44 and increases to 0.94 at 60 km for $P_{fa} = 10^{-8}$.



According to Ref. 22, the average time interval between crossings of the threshold by noise alone, the false-alarm time T_{fa}, is given by

$$T_{fa} = 1/(P_{fa} B) \tag{4.6}$$

Table 4.5 False-alarm time

T_{fa}	P_{fa}
0.1 s	1×10^{-5}
1 s	1×10^{-6}
10 s	1×10^{-7}
100 s	1×10^{-8}
16.7 min	1×10^{-9}
2.8 h	1×10^{-10}
28 h	1×10^{-11}

where B is the bandwidth of the envelope detector. Table 4.5 lists values for T_{fa} for several values of P_{fa} for a bandwidth of 1 MHz.

Go to Problems 4.3.38 to 4.3.41.

Probability of detection and acquisition after S *pulses or scans.* During each scan of the target by the radar beam, a large number of pulses will be transmitted and echoes received. The receiver either will process these echoes individually, or several of the echoes will be summed or integrated to improve detection performance. The performance improvement is in the form of a larger probability of detection and/or a smaller probability of false alarm for the same peak power. The signal-to-noise ratio for a specified probability of detection and of false alarm $(S/N)_{min}$ is based upon the number of integrated pulses. For the sth pulse or scan of the target, there will be a certain probability of detection $P_D(s)$ based upon the actual signal-to-noise ratio, which can be determined from the radar equation and is a function of target range and radar cross section, both of which can vary with each pulse or scan. Thus, $P_D(s)$ is generally a function of time. The probability of detecting a target at least once after S pulses or scans $P_D^{(S)}$ is the complement of the probability the target has not been detected, NOT $P_D^{(S)}$. Thus, the probability that the target has been detected after S pulses or scans is given by

$$P_D^{(S)} = 1 - \text{NOT } P_D^{(S)} = 1 - [1 - P_D(1)][1 - P_D(2)][1 - P_D(3)]\dots$$
$$\times [1 - P_D(S)] = 1 - \prod_{s=1}^{S}[1 - P_D(s)] \tag{4.7a}$$

If $P_D(s)$ is a constant value for each scan P_D, then Eq. (4.7a) simplifies to

$$P_D^{(S)} = 1 - (1 - P_D)^S \tag{4.7b}$$

Once an aircraft has been detected, it must be acquired. Acquisition might require a sequence of detections to reduce the likelihood of a false acquisition because a sequence of random false alarms is very unlikely. For example, acquisition can be

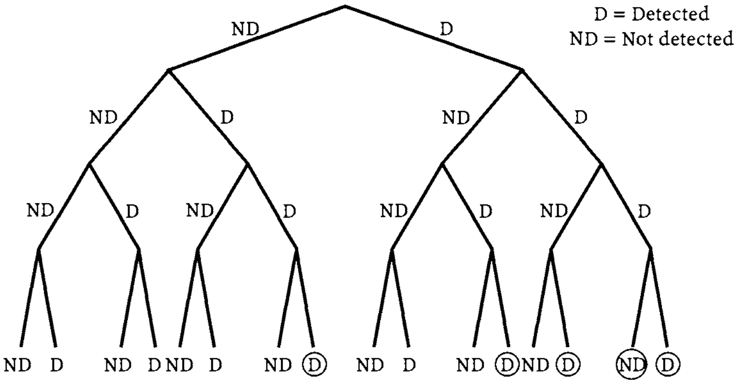


Fig. 4.14 Probability at least three out of four echoes are detected.

defined to occur when at least three out of four consecutive echoes (or integrated echoes) are detected. The probability that acquisition will occur when at least three out of four echoes are detected can be determined using the tree diagram shown in Fig. 4.14. The probability that at least three out of four echoes are detected is the sum of the probabilities associated with the five unique paths down the tree diagram shown in Fig. 4.14 that have at least three detections (indicated by a circle). Thus,

$$
\begin{aligned}
P_D(3 \text{ or } 4 \text{ out of } 4) &= P_D^4 + P_D^3 P_{\text{ND}} + P_D^2 P_{\text{ND}} P_D + P_D P_{\text{ND}} P_D^2 + P_{\text{ND}} P_D^3 \\
&= P_D^4 + 4 P_D^3 P_{\text{ND}} \qquad (4.7\text{c})
\end{aligned}
$$

where $P_{\text{ND}} = 1 - P_D$.

Example 4.5 Probability of Detection After Multiple Pulses or Scans

Assume $P_D = 0.1$ for all pulses. What is the probability that the aircraft is detected at least once after 40 pulses?

According to Eq. (4.7b),

$$P_D^{(S)} = 1 - (1 - 0.1)^{40} = 0.985$$

What is the probability that the aircraft will be detected on at least three out of four pulses?

According to Eq. (4.7c),

$$P_D(3 \text{ or } 4 \text{ out of } 4) = (0.1)^4 + 4(0.1)^3(1 - 0.1) = 0.0037$$

The probability that the aircraft is acquired at least once in 10 sets of 4 echoes can be determined using Eq. (4.7b) with P_D replaced with P_D (3 or 4 out of 4) and assuming that the acquisition process considers each echo once. Thus,

$$P(\text{accquired at least once}) = 1 - (1 - 0.0037)^{10} = 0.036$$

Go to Problem 4.3.42.

Computer programs for radar detection. The SURVIAC program for evaluating the radar performance of airborne radars is AIRADE, and ALARM determines the detection performance of ground-based radar systems against aircraft targets. Both programs are available from SURIVAC and are briefly described in Chapter 1, Sec. 1.5.2.

4.3.3.2 Infrared.

Learning Objective 4.3.12 Compute the lock-on range of an IR seeker.

The detection of an aircraft by an IR seeker occurs when the infrared radiation from the aircraft (within the operating wavelength band of the detector) collected by the seeker reaches the minimum power level for detection in the presence of noise. When detection occurs, the tracking process is initiated, provided the tracking platform is uncaged. When the tracker is continuously and automatically tracking the target, the seeker is said to be locked-on. The range at which lock-on occurs is called the lock-on range R_{LO}. The equation for the IR lock-on range can be derived in a manner similar to the derivation of the maximum range of a radar.

The aircraft is at a distance R from the seeker. The radiant intensity at the aircraft in the direction of the sensor and in the band of the sensor is denoted by I and has units *W/sr*. As the radiation propagates over the distance R to the seeker, it spreads spherically and is attenuated by the atmosphere by a factor $1/L$, where $L \geq 1$. Thus, the irradiance on the seeker, which is the signal S, is given by (Note 17).

$$\text{Irradiance on the seeker} = S = \frac{I}{R^2 L} \quad (\text{W/m}^2) \tag{4.8a}$$

The signal processor must contend with the internal noise N when attempting to detect the radiation from the target. The noise can be defined as the noise equivalent flux density (NEFD) or noise equivalent irradiance (NEI) on the seeker that produces an irradiance equal to the internal noise and is denoted by NEFD (or NEI) with the units W/cm^2. Thus, dividing the irradiance on the seeker given by

Eq. (4.8a) by NEFD results in

$$\frac{\text{Irradiance on the seeker}}{\text{Noise equivalent flux density}} = \frac{S}{N} = \frac{I}{R^2 L(\text{NEFD})} \tag{4.8b}$$

The minimum detectable signal-to-noise ratio ($S/N_{\min}$) occurs at the lock-on range R_{LO}. Hence, solving Eq. (4.8b) for R_{LO} results in (Note 18).

$$R_{\text{LO}} = \left[\frac{I}{L(S/N)_{\min}(\text{NEFD})}\right]^{1/2} \tag{4.8c}$$

Because the IR detection problem is similar to the radar detection problem (both attempt to detect a stochastic signal in the presence of internal and external noise), associated with $(S/N)_{\min}$ in Eq. (4.8c) is a probability of detection and a probability of false alarm.[23,24]

The lock-on range varies with aspect because the aircraft's signature varies with aspect. The locus of points around the aircraft or the missile that defines the lock-on range is called the lock-on envelope or boundary. Typically, the lock-on range is long when the seeker is looking at the aft end of the aircraft and short when looking at the forward end, as illustrated in Fig. 3.14b.

Go to Problems 4.3.43 to 4.3.46.

4.3.4 Aircraft Tracking

Learning Objectives	**4.3.13**	**Describe some of the contributors to tracking errors.**
	4.3.14	**Compute the normal mean, variance, standard deviation, error probable, and CEP of one- and two-dimensional tracking systems for a given set of tracking errors.**
	4.3.15	**Describe the total error model.**

Air defense systems utilize several methods to track aircraft, such as the conical scan, monopulse, and rosette methods described in Chapter 3, Sec. 3.7.2. These methods usually result in a timewise progression of accuracy of aircraft location starting from a warning that an aircraft is approaching from a general direction and ending with a relatively accurate determination of the aircraft's location in azimuth and elevation (or line-of-sight), range, and velocity. Each threat system, whether it be a radar directed gun, an air-to-air IR homing missile, or an infantryman with a rifle, usually follows this sequence in one form or another. However, the specific techniques used to accomplish the tracking and the accuracy of these techniques are dependent upon the specific threat system. Nevertheless, the location of the target determined by every threat tracking system will contain tracking errors. Because these errors can have a major effect on the susceptibility of an aircraft, the contributors to the errors and the assessment of the magnitude of these tracking errors are described in the following section.

4.3.4.1 Contributors to the tracking errors. The determination of the tracking accuracy of any tracking system is a complex problem caused by the many influential variables that can continuously change with time.

Radar. The tracking accuracy of a radar system is influenced by such factors as the mechanical properties of the radar antenna and pedestal, the method by which the angular position of the antenna is measured, the quality of the servo system that moves the antenna, the stability of the electronic circuits, the noise level of the receiver, and the antenna beamwidth and side lobes. These factors are associated with the radar system itself and consequently are usually not affected by the aircraft or its tactics. Other factors that also influence tracking accuracy, and that can be affected by the aircraft and its tactics, are atmospheric conditions, the presence of clutter and any radar countermeasures, and the radar reflection characteristics and altitude of the aircraft. Atmospheric conditions can affect the signal strength, and clutter and any countermeasures can contribute external noise and false targets, making the echo more difficult to detect.

The reflection characteristics of the aircraft determine both the RCS level and the amount of RCS scintillation and target glint, all of which affect tracking accuracy. The aircraft altitude can have a major effect on the elevation accuracy of ground-based radars when the aircraft flies low enough to cause the multipath phenomenon to become significant. Many pulse radars are unable to track aircraft that fly at elevation angles less than some fraction (typically 0.5 to 0.7) of the radar beamwidth caused by the multipath phenomenon. Low-flying aircraft are also difficult to track from above because of Earth clutter.

Infrared. Contributors to the errors of an IR tracker include refraction of the radiation from the target by the radome and radome heating; the quality of the sensor stabilization mechanism, actuators, and inertial sensing components; irregularities in the optical elements; irregularities in the detector elements in focal plane arrays, the type of tracking (reticle, scanning, or imaging); the noise and nonlinearity in the processing electronics; and the fluctuations in the target signal.

Visual. The detection and tracking capabilities of visually directed systems vary widely from very poor to highly accurate. Under good visibility conditions direct-view optical and electro-optical trackers can provide angular tracking data accuracy equal to or better than radar, particularly for close, low-flying, and maneuvering aircraft, and when radar countermeasures are employed. Studies of the actual detection and tracking performance of human operators using visual tracking devices have been conducted by the Air Force Research Laboratory Human Effectiveness Directorate (http://www.he.afrl.af.mil/), Wright-Patterson Air Force Base, Ohio, as part of the Air Force Manned Threat Quantification Program.

Go to Problem 4.3.47.

4.3.4.2 Tracking accuracy.

Tracking error measures. When a weapon system tracks an aircraft, the target coordinates measured by the tracking sensors, such as range, angles, and velocity,

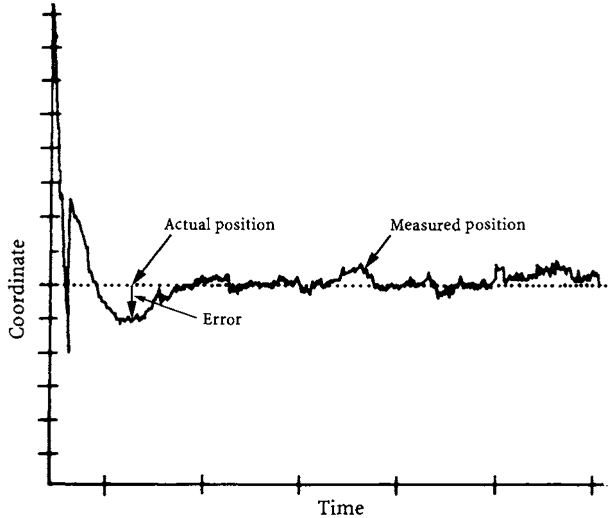


Fig. 4.15 Measured target coordinate vs time.

will typically fluctuate about the true value with time, as illustrated in Fig. 4.15. The tracking error ε is the difference between the true coordinate data and the measured data. Two important measures of the error shown in Fig. 4.15 are its average value, or bias, or mean μ, over a period of time and its variance σ^2 and standard deviation σ about the mean (Note 19).

If ε is sampled at N locations along the time axis, the sample mean M is given in terms of ε_i, the error of the ith sample, by

$$M = \frac{1}{N}\sum_{i=1}^{N}\varepsilon_i \tag{4.9}$$

The sample variance of the error S^2 (based on the N values of ε_i) is given by

$$\begin{aligned}\text{Sample Var}(\varepsilon) = S^2 &= \frac{1}{N}\sum_{i=1}^{N}(\varepsilon_i - M)^2\\ &= \frac{1}{N}\left(\sum_{i=1}^{N}\varepsilon_i^2 - \sum_{i=1}^{N}2\varepsilon_i M + \sum_{i=1}^{N}M^2\right) = \frac{1}{N}\sum_{i=1}^{N}\varepsilon_i^2 - M^2\end{aligned} \tag{4.10}$$

where $(\varepsilon_i - M)$ is the deviation tracking error. The square root of the variance S is referred to as the root mean square (rms) of the deviation error.

If each of the N numerical values of ε_i is put into one of several classes or finite intervals of error values according to the value of the error, a histogram of the error data is obtained. The histogram can be used to determine the corresponding discrete probability mass function (PMF). For a variety of reasons, the discrete PMF is usually replaced or approximated by a continuous probability density function (PDF) for the error ε. The continuous distribution most often used in this type of analysis is the normal or Gaussian PDF. The normal PDF $f(\varepsilon)$ can be given in the general form (Note 20).

$$\text{Normal pdf} = f(\varepsilon) = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5\left(\frac{\varepsilon-\mu}{\sigma}\right)^2} \tag{4.11a}$$

where μ is the mean and σ is the standard deviation. The PDF does not give the probability that the error has any specific value, but instead is used to compute the probability that the error falls within an error interval. For example, the probability that the error falls between the interval from ε_a to ε_b is given by the integral

$$\text{Probability}\,(\varepsilon_a \leq \varepsilon \leq \varepsilon_b) = \int_{\varepsilon_a}^{\varepsilon_b} f(\varepsilon)\,\mathrm{d}\varepsilon \tag{4.11b}$$

The particular limit on both sides of the mean that corresponds to a 0.5 probability that the error is within the interval is known as the error probable (e. p.) or probable error (p. e.) and is equal to

$$\text{e. p.}\,(\varepsilon) = \pm 0.6745\sigma$$

The relationship between the sample mean M and the normal mean μ and the sample variance S^2 and the normal variance σ^2 are usually given in the form

$$\mu = M \tag{4.12a}$$

and

$$\sigma^2 = \left(\frac{N}{N-1}\right) S^2 \tag{4.12b}$$

although σ^2 is sometimes set equal to S^2, particularly when N is large compared to unity. The procedure for estimating the μ and σ of the normal PDF for a particular set of tracking error data is described in Example 4.6.

Example 4.6 Estimating the Numerical Values for the Normal Mean and Standard Deviation.

The measured target coordinate trace shown in Fig. 4.15 was sampled at 57 equally spaced locations along the time axis. The minimum error was larger than −0.2 mrad, and the maximum error was smaller than 0.9 mrad. Consequently,

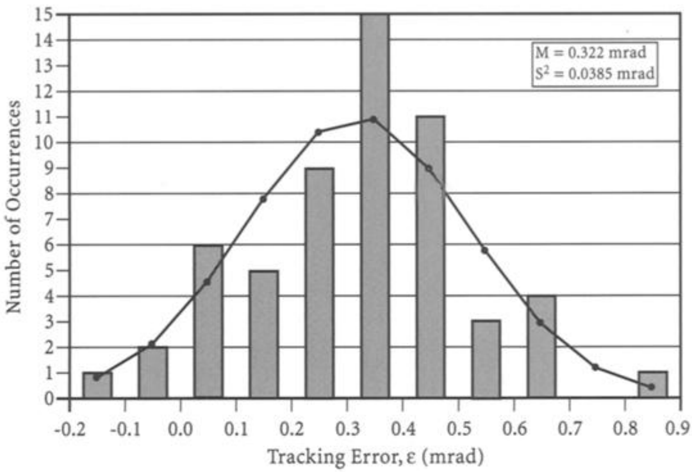


Fig. 4.16a Histogram of tracking error.

11 error intervals of width 0.1 mrad were created, starting with the interval −0.2 to −0.1 mrad and ending with the interval 0.8 to 0.9 mrad. The 57 error values were then put into the appropriate interval. The columns in Fig. 4.16a indicate the number of occurrences for each of the 11 intervals. For example, 1 of the 57 error values was between −0.2 and −0.1 mrad, and 2 values were between −0.1 and 0.0 mrad. The sample mean and sample variance computed using the 57 error values and Eqs. (4.9) and (4.10), respectively, are $M = 0.322$ and $S^2 = 0.0385$.

According to Eq. (4.12a) and (4.12b), the corresponding values for μ and σ for the normal distribution are

$$\mu = 0.322 \text{ mrad} \quad \text{and} \quad \sigma^2 = (57/56) \cdot (0.0385) = 0.03919 \text{ mrad}^2$$

Hence,

$$\sigma = 0.198 \text{ mrad} \quad \text{and} \quad \text{e. p.} = \pm 0.6745 \cdot 0.198 = \pm 0.134 \text{ about the mean}$$

The normal PDF given by Eq. (4.11) with these values for μ and σ is shown in Figs. 4.16a and 4.16b. Also shown in Fig. 4.16b is the histogram of Fig. 4.16a. In Fig. 4.16a the ordinate of the normal PDF has been converted from a PDF value to the number of occurrences, and the abscissa is a continuous variable. The conversion from the normal PDF value to the number of occurrences is accomplished by determining the probability the error lies in each of the error intervals using the normal cumulative distribution shown in Fig. B.25b and multiplying that probability by 57, the total number of error values. This value is indicated by the small black dot in the center of each error interval. Note that the normal distribution results in noninteger occurrences. For example, in the error interval 0.1 to 0.2 mrad there would be nearly eight occurrences according to the normal distribution.

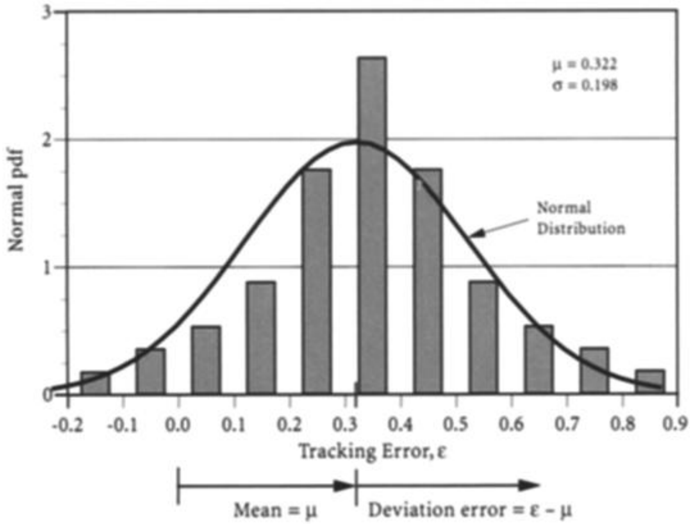


Fig. 4.16b Normal distribution of the error.

In Fig. 4.16b the number of occurrences in each error interval has been changed to a PDF value by applying Eq. (B.9) to determine the probability associated with each interval and Eq. (B.47) to determine the value of PDF, which results in the area within each interval being equal to that probability. For example, the interval with 15 occurrences has a probability of 15/57 with an interval size of 0.1. Thus,

$$\text{PDF}\,(0.3\text{ mrad to }0.4\text{ mrad}) = (15/57)/0.1 = 2.63$$

Coordinate tracking errors. The tracking error in any one coordinate is the net result of the combination of the errors in that coordinate associated with the different tracking factors. For example, the error shown in Fig. 4.15 could be the net azimuth error caused by the azimuth error due to noise $\varepsilon_{\text{noise}}$ and the azimuth error due to target glint $\varepsilon_{\text{glint}}$. Thus,

$$\varepsilon = \varepsilon_{\text{noise}} + \varepsilon_{\text{glint}} \tag{4.13}$$

Each of the individual errors can also be represented by the normal distribution, with a specific mean and variance associated with each error. The individual error distributions can be combined mathematically into one error distribution such that the mean and the variance of the total error are numerically equal to the mean and variance of the sum of the individual errors. For example, the mean of the azimuth error is given by

$$M = \frac{1}{N}\sum_{i=1}^{N}\varepsilon_i = \frac{1}{N}\sum_{i=1}(\varepsilon_{\text{noise}_i} + \varepsilon_{\text{glint}_i}),$$

$$= \frac{1}{N}\sum_{i=1}^{N}\varepsilon_{\text{noise}_i} + \frac{1}{N}\sum_{i=1}^{N}\varepsilon_{\text{glint}_i} = M_{\text{noise}} + M_{\text{glint}} \tag{4.14}$$

Thus, the mean of the sum of errors is equal to the sum of the individual mean errors. For the variance of the error

$$S^2 = \frac{1}{N}\sum_{i=1}^{N}(\varepsilon_i - M)^2 = \frac{1}{N}\sum_{i=1}^{N}(\varepsilon_{\text{noise}_i} + \varepsilon_{\text{glint}_i} - M_{\text{noise}} - M_{\text{glint}})^2$$

$$= \frac{1}{N}\sum_{i=1}^{N}(\varepsilon_{\text{noise}} - M_{\text{noise}})^2 + \frac{1}{N}\sum_{i=1}^{N}(\varepsilon_{\text{glint}_i} - M_{\text{glint}})^2$$

$$+ \frac{2}{N}\sum_{i=1}^{N}[(\varepsilon_{\text{noise}_i} - M_{\text{noise}})(\varepsilon_{\text{glint}_i} - M_{\text{glint}})]$$

The term

$$\frac{1}{N}\sum_{i=1}^{N}[(\varepsilon_{\text{noise}_i} - M_{\text{noise}})(\varepsilon_{\text{glint}_i} - M_{\text{glint}})]$$

is called the covariance between the $\varepsilon_{\text{noise}}$ and $\varepsilon_{\text{glint}}$ errors. If the two errors are independent (neither is influenced by the other), the covariance is zero, and the variance is given by

$$S^2 = S^2_{\text{noise}} + S^2_{\text{glint}} \tag{4.15a}$$

and hence,

$$\sigma = \sqrt{\sigma^2_{\text{noise}} + \sigma^2_{\text{glint}}} \tag{4.15b}$$

Thus, the standard deviation of the sum of errors is the square root of the sum of the squares (rss) of the individual standard deviations.

In general, the individual tracking errors can be categorized either as random errors that may or may not fluctuate about a zero mean or as systematic errors that may or may not fluctuate about a nonzero mean. For radar tracking systems the zero mean random errors are associated with such factors as receiver noise, tracking jitter, scintillation, and target glint. The systematic errors are caused by factors such as antenna misalignment, servo lags, and multipath. Radar countermeasures can cause both kinds of errors. In general, the standard deviation for all coordinates as a result of noise can be given in the form

$$\sigma_{\text{noise}} = \frac{K_n}{\sqrt{S/N}} \tag{4.16}$$

where S/N is the single-look signal-to-noise ratio and K_n is a constant that depends upon the type of radar system and the specific target coordinate. The signal must be large compared with the noise for this estimate to be valid. For angular measurements K_n is directly proportional to the antenna beam width.

Another important radar tracking error is that caused by target glint. The standard deviation of a target at a range R caused by glint for all coordinates has been estimated to be

$$\sigma_{\text{glint}} = L_x K_g \tag{4.17}$$

where L_x is the target projected width to the radar and the coefficient K_g is a constant that depends on the type of radar system and the specific target coordinate. For angular measurements K_g is inversely proportional to R. The combined tracking error in any coordinate can be obtained using these and other estimates for the individual error measures and the relationships given by Eqs. (4.14) and (4.15b).

Two-dimensional errors. The one-dimensional normal PDF for the tracking error given by Eq. (4.11a) can also be used to determine the normal PDF in a two-dimensional or bivariate (two variable) space, $f(\varepsilon_1, \varepsilon_2)$. For example, if the two orthogonal angular tracking errors ε_1 and ε_2 are independent, the two-dimensional normal PDF of the angular errors is given by the product of the two one-dimensional normal PDFs. Hence,

$$\begin{aligned} f(\varepsilon_1, \varepsilon_2) = f(\varepsilon_1) f(\varepsilon_2) &= \left[\frac{1}{\sigma_1\sqrt{2\pi}} e^{-0.5\left(\frac{\varepsilon_1-\mu_1}{\sigma_1}\right)^2}\right]\left[\frac{1}{\sigma_2\sqrt{2\pi}} e^{-0.5\left(\frac{\varepsilon_2-\mu_2}{\sigma_2}\right)^2}\right] \\ &= \frac{1}{2\pi\sigma_1\sigma_2} e^{\left[-0.5\left(\frac{\varepsilon_1-\mu_1}{\sigma_1}\right)^2 - 0.5\left(\frac{\varepsilon_2-\mu_2}{\sigma_2}\right)^2\right]} \end{aligned} \tag{4.18}$$

where μ_1 and μ_2 are the two angular means and σ_1 and σ_2 are the two angular standard deviations. The mean and standard deviation for each coordinate are evaluated using Eqs. (4.9) and (4.10) to determine the sample means and sample variances for each coordinate and Eqs. (4.12a) and (4.12b) to relate μ to M and σ to S.

Circular normal PDF: When a circularly symmetric or axisymmetric tracking sensor, such as the dish antenna of a radar system, is used, σ_1 and σ_2 are often found to be, or are assumed to be, equal, and the two means are found to be, or are assumed to be, zero. For this situation the bivariate normal distribution given by Eq. (4.18) simplifies to the one-dimensional circular normal PDF for the radial angular error ε_r, given by (Note 21)

$$f(\varepsilon_r) = \frac{1}{2\pi\sigma_r^2} \exp\left(\frac{-\varepsilon_r^2}{2\sigma_r^2}\right) \tag{4.19}$$

where $\mu_1 = \mu_2 = 0$, $\sigma_1 = \sigma_2 = \sigma_r$, and $\varepsilon_1^2 + \varepsilon_2^2 = \varepsilon_r^2$. The probability that the error lies somewhere within a radial error interval from ε_a to ε_b is given by

$$\begin{aligned} \text{Probability}\,(\varepsilon_a \le \varepsilon_r \le \varepsilon_b) &= \frac{1}{2\pi\sigma_r^2} \int_0^{2\pi} \int_{\varepsilon_a}^{\varepsilon_b} \exp\left(\frac{-\varepsilon_r^2}{2\sigma_r^2}\right) \varepsilon_r \, d\theta \, d\varepsilon_r \\ &= \frac{1}{\sigma_r^2} \int_{\varepsilon_a}^{\varepsilon_b} \varepsilon_r \exp\left(\frac{-\varepsilon_r^2}{2\sigma_r^2}\right) d\varepsilon_r \end{aligned} \tag{4.20}$$

The integrand in Eq. (4.20) is known as the Rayleigh PDF and is shown in Fig. B.28a. The probability that the error lies within the radial interval from 0 to ε_b is shown in Fig. B.28b. A special case of Eq. (4.20) is when $\varepsilon_a = 0$ and ε_b is that particular value, called the circular error probable (CEP) or circular probable error (CPE), which results in a 0.5 probability that the error lies within the interval from 0 to the CEP. Solving Eq. (4.20) for the CEP gives

$$\text{CEP} = 1.177\sigma_r \tag{4.21}$$

The CEP for the circularly symmetric error distribution is analogous to the error probable for the one-dimensional distribution, and the relationship between them is shown in Fig. B.29.

Radial error data only: When the error data for the circularly symmetric situation are available only for the radial error ε_r, Eq. (4.10) for the sample variance S^2 is not applicable. Instead, S^2 can be determined using the following analysis. If the error data for the circularly symmetric situation were available in the two coordinates ε_1 and ε_2, then

$$S_1^2 = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_{1_i}^2, \quad S_2^2 = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_{2_i}^2, \quad \text{and} \quad S_1^2 = S_2^2 \tag{4.22a}$$

according to Eq. (4.10). Furthermore, ε_r is related to ε_1 and ε_2 by

$$\varepsilon_{r_i}^2 = \varepsilon_{1_i}^2 + \varepsilon_{2_i}^2 \tag{4.22b}$$

as shown in Fig. B.29. Therefore

$$S_1^2 + S_2^2 = 2S_r^2 = \frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_{1_i}^2 + \varepsilon_{2_i}^2\right) = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_{r_i}^2 \tag{4.22c}$$

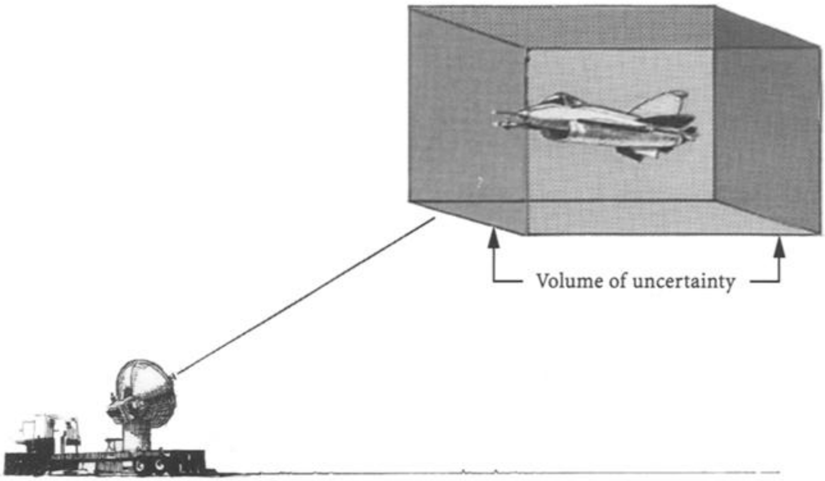


Fig. 4.17 Volume of uncertainty around the aircraft.

Solving Eq. (4.22c) for the sample variance S_r^2 leads to

$$S_r^2 = \frac{1}{2N} \sum_{i=1}^{N} \varepsilon_{r_i}^2 \tag{4.22d}$$

Hence, the standard deviation for the circular normal σ_r can be determined from the data for the radial error using Eqs. (4.22d) and (4.12b). The corresponding CEP is given by Eq. (4.21).

Another approach to computing σ_r when only radial data are available is to first determine the CEP based upon the N values of ε_i, that is, one-half of the values of ε_i are smaller than the CEP and one-half are larger. Equation (4.21) can then be used to determine σ_r based upon the CEP.

Total tracking error model. The preceding discussion described the distribution and measures of the individual range and angular tracking errors. These coordinate tracking errors can be combined in such a manner as to give a total tracking error model that permits a simple estimate of the overall tracking accuracy. However, this model does not allow the consideration of the component of the total error in a specific direction or coordinate. This total error represents a volume of uncertainty that surrounds the aircraft as illustrated in Fig. 4.17. The aircraft is actually located at the center of this volume (zero mean), but the tracking system, as a result of the tracking errors, will place its location somewhere else on each scan. The total tracking error of a target ε_t at a slant range R is given by

$$\varepsilon_t = \left[\varepsilon_R^2 + R^2\left(\varepsilon_{a1}^2 + \varepsilon_{a2}^2\right)\right]^{1/2} \tag{4.23}$$

where the range error ε_R and R are in meters and the orthogonal angular errors ε_{a1} and ε_{a2} are in radians.

Go to Problems 4.3.48 to 4.3.52.

4.3.5 Engagement and Flyout to Intercept ($P_{L|D}$ and $P_{I|L}$)

Learning Objective	**4.3.16**	**Describe the trajectory for ballistic projectiles and the flight path of a guided missile.**

Once an aircraft is detected and accurately tracked, a decision is made (with the probability $P_{L|D}$) to engage the aircraft by firing a gun or launching a missile. Figure 3.6 is an illustration of the launch of a guided missile and the flyout of the missile through the boost and midcourse phases to an intercept in the terminal phase. Of interest here are the flight path of a missile, the trajectory of a ballistic projectile, and the subsequent geometry of a successful intercept (with the probability $P_{I|L}$).

4.3.5.1 Ballistic trajectories. Projectile trajectories for a specific encounter scenario are predicted by computer models for air defense guns, such as RADGUNS which is described in Chapter 1, Sec. 1.5.2. The errors and factors that influence the trajectory of a ballistic projectile are presented in Chapter 3, Secs. 3.7.4 and 3.7.5.

In general, a round fired from a gun will follow the parabolic trajectory given by

$$\text{height} = (V_0 \sin\theta)t - 0.5gt^2 \tag{4.24a}$$

$$\text{horizontal range} = (V_0 \cos\theta)t \tag{4.24b}$$

where V_0 is the muzzle velocity, θ is the elevation angle of the gun, g is the gravitational constant, t is time, and the deceleration caused by drag has been neglected (Note 22). Within the effective range of most guns, the drop in altitude caused by gravity is relatively small compared to the altitude. Consequently, the trajectory is a slightly curved line from the gun to the aircraft. Example 4.7 presents a typical situation.

Example 4.7 Trajectory of a Ballistic Projectile

Consider a 30-mm gun with an tactical (slant) range of 3 km or 10,000 ft. The muzzle velocity is 3000 ft/s. The gun elevation angle is 30 deg. Neglecting the effects of projectile drag, the projectile reaches the tactical range in (10,000 ft)/(3000 ft/s) = 3.3 s. At that time the projectile is at an altitude of (3.3 s)

(3000 ft/s)[sin(30 deg)] = 4950 ft minus the decrease in altitude as a result of gravity of $0.5 \cdot (32.2 \text{ ft/s}^2)(3.3 \text{ s})^2 = 145$ ft according to Eq. (4.24a). Accounting for projectile drag will increase the time required to reach 10,000 ft, and hence the decrease in altitude caused by gravity will increase.

4.3.5.2 Missile flight paths. Missile flight paths for a specific encounter scenario are predicted by computer models for air defense missile systems, such as ESAMS, which is described in Chapter 1, Section 1.5.2.

The errors and factors that influence the flight path of a missile are presented in Chapter 3, Secs. 3.7.4 and 3.7.5. In general, there are two types of flight paths illustrated in Fig. 4.18: the direct-line flight path from the missile launch site to the intercept point, used by short- and some medium-range missiles, and the up and over flight path used by the longer-range missiles.

Go to Problems 4.3.53 to 4.3.54.

4.3.6 Miss Distance

Learning Objectives	**4.3.17**	**Determine the propagator miss distance given the intercept conditions.**
	4.3.18	**Describe the factors that influence the miss distance.**

The aircraft was detected and tracked for nearly a minute. The enemy then decided to engage the aircraft with a missile (or a projectile). The propagator has flown out to an intercept with the aircraft as illustrated in Fig. 3.7 and reflected in Fig. 4.19. The measure of the threat system's ability to position a warhead within the vicinity of the aircraft is the closest point of approach or miss distance of the propagator with respect to the aircraft. The miss distance is essentially an error. In general, the

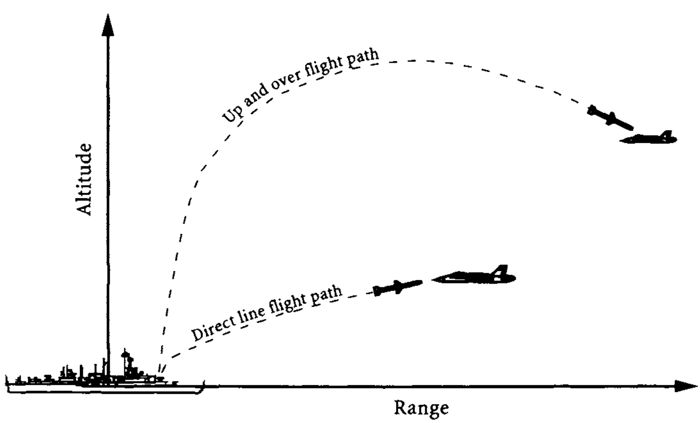


Fig. 4.18 Missile flight paths.

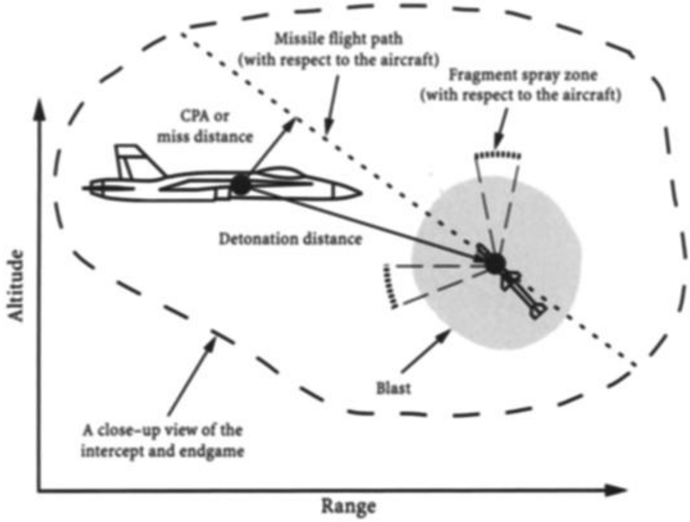


Fig. 4.19 Intercept and endgame.

miss distance is a function of the three spatial coordinates (x, y, z) whose origin is centered at the aim point on the target. However, in many evaluations the problem is simplified to two spatial dimensions (x, y), and sometimes only one dimension (r) is used in simple estimates.

4.3.6.1 Determining the miss distance. The miss distance for both missiles and projectiles can be determined using some relatively simple equations when neither the propagator (missile or projectile) velocity vector $\boldsymbol{V}_P$ nor the aircraft velocity vector $\boldsymbol{V}_T$ changes during closure. Figure 4.20a shows the initial intercept conditions $(t = 0)$ in the terminal phase of the flyout. The aircraft is located in the global, stationary (X, Y, Z) coordinate system at $(T_X, 0, T_Z)$, and the propagator is located at (P_X, P_Y, P_z). The aircraft velocity vector $\boldsymbol{V}_T$ is in the (X, Z) plane and is parallel to the X axis. The elevation angle of the propagator velocity vector $\boldsymbol{V}_P$ is Ψ_P measured from the (X, Y) plane, and the azimuthal counterclockwise angle from the X axis to the projection of $\boldsymbol{V}_P$ on to the (X, Y) plane is Ω_P, as shown in Fig. 4.20a.

In the global coordinate system both the aircraft and the propagator move along the (dashed line) flight paths. If a local (x, y, z) coordinate system is attached to the center of the moving aircraft and if the x and z axes are parallel to the global X and Z axes, respectively, the flight path of the propagator with respect to the aircraft in the local coordinates is obtained by subtracting the aircraft's velocity vector $\boldsymbol{V}_T$ from the propagator's velocity vector $\boldsymbol{V}_P$, resulting in the velocity vector of the propagator with respect to the (stationary) target $\boldsymbol{v}_p$, as shown in Fig. 4.20b for a two-dimensional intercept in the (X, Z) plane. (Upper-case variables and subscripts denote global variables, and lower-case variables and subscripts denote local variables.) The two-dimensional situation exists when the aircraft, the propagator, and the aircraft and propagator velocity vectors are in the (X, Z) plane.

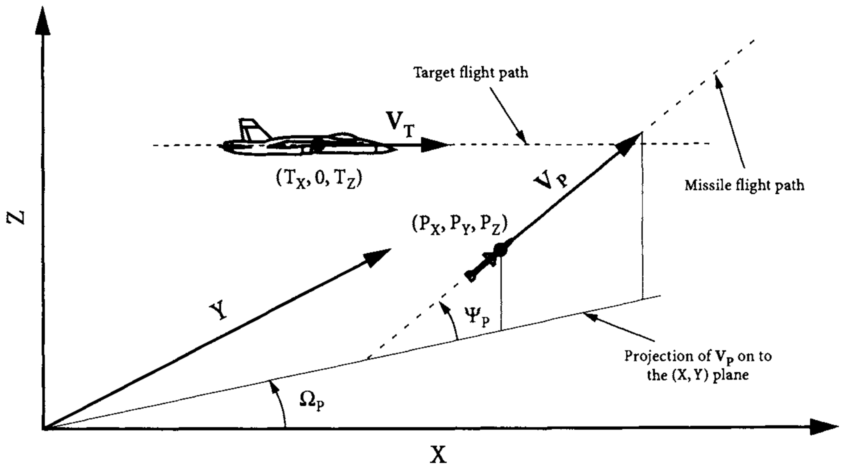


Fig. 4.20a Three-dimensional intercept conditions at $t = 0$, global (X, Y, Z).

Here, $\Omega_P = 0$, and $0\,\text{deg} \leq \Psi_P \leq 360$ deg. Four different intercept values for Ψ_P are shown in Fig. 4.20b (Note 23).

The propagator's flight path with respect to the target is coincident with v_p as shown by the black dashed line in Fig. 4.20b. Note that the propagator's elevation angle Ψ_P in the global system is not the same as the propagator's flight-path angle with respect to the target ψ_p. Because this missile passes in front of the target, it is an early bird. The missile shown in the lower left corner of the figure passes behind the aircraft. Consequently, that missile is a late bird.

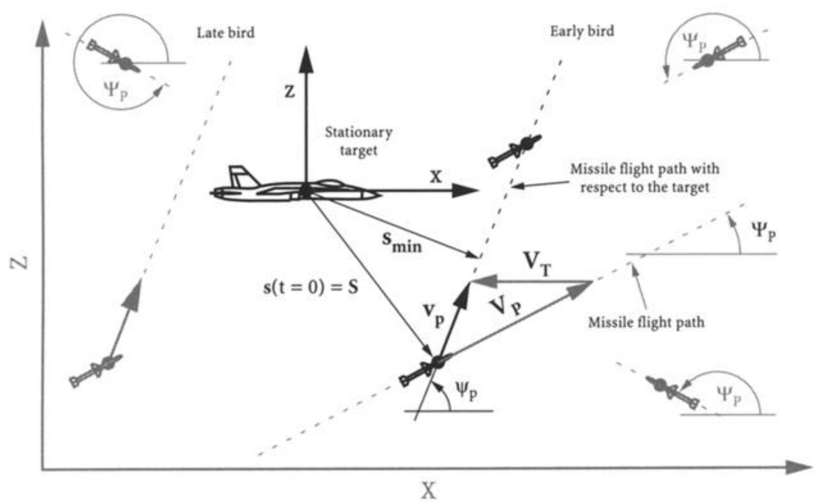


Fig. 4.20b Two-dimensional intercept conditions, local (x, z).

In the general three-dimensional intercept the components of $\boldsymbol{v}_p$ in the local coordinates (x, y, z) are given by

$$\begin{aligned}(v_p)_x &= V_P \cos(\Psi_P)\cos(\Omega_P) - V_T\\ (v_p)_y &= V_P \cos(\Psi_P)\sin(\Omega_P)\\ (v_p)_z &= V_P \sin(\Psi_P)\end{aligned} \tag{4.25a}$$

The velocity of the propagator relative to the target aircraft v_p is given by

$$v_p = \sqrt{(v_p)_x^2 + (v_p)_y^2 + (v_p)_z^2} \tag{4.25b}$$

The elevation angle and the azimuthal angle of $\boldsymbol{v}_p$, ψ_p, and ω_p, respectively, are related to the components of $\boldsymbol{v}_p$ by

$$\begin{aligned}\psi_p &= \arctan\left[\frac{(v_p)_z}{\sqrt{(v_p)_x^2 + (v_p)_y^2}}\right]\\ \omega_p &= \arctan\left[\frac{(v_p)_y}{(v_p)_x}\right]\end{aligned} \tag{4.25c}$$

where $-90\,\text{deg} \le \psi_p \le 90\,\text{deg}$ and $0\,\text{deg} \le \omega_p \le 360\,\text{deg}$. In the two-dimensional analysis

$$\begin{aligned}\psi_p &= \arctan\left[\frac{(v_p)_z}{(v_p)_x}\right]\\ \omega_p &= 0\,\text{deg}\end{aligned} \tag{4.25d}$$

The separation distance from the aircraft to the missile is indicated by the vector $\boldsymbol{s}$ in the local coordinate system shown in Fig. 4.20b. At time $t = 0$ the separation distance $\boldsymbol{S}$ is defined by the components S_X, S_Y, and S_Z, where

$$S_X = P_X - T_X, \quad S_Y = P_Y - T_Y, \quad \text{and} \quad S_Z = P_Z - T_Z \tag{4.26a}$$

For $t > 0$ the missile moves along the flight path with respect to the aircraft, and the separation distance s and its components s_x, s_y, and s_z are given by

$$s_x = S_X + (v_p)_x t, \quad s_y = S_Y + (v_p)_y t, \quad \text{and} \quad s_z = S_Z + (v_p)_z t \tag{4.26b}$$

where $(v_p)_x$, $(v_p)_y$, and $(v_p)_z$ are given by Eq. (4.25a). The separation distance s is given by

$$s = \sqrt{s_x^2 + s_y^2 + s_z^2} \tag{4.26c}$$

The miss distance is the minimum value of the separation distance s as shown in Fig. 4.20b. Thus, taking the derivative of s given by Eq. (4.26c) with respect to time, equating that expression to zero, and solving for the time τ when $s = s_{\min}$ results in

$$\tau(s = s_{\min}) = \frac{-[S_X(v_p)_x + S_Y(v_p)_y + S_Z(v_p)_z]}{v_p^2} \tag{4.27}$$

The miss distance and its components are given by Eqs. (4.26c) and (4.26b), respectively, with $t = \tau$.

Example 4.8 Miss Distance in Two Dimensions

An aircraft is flying straight and level, from left to right, and a missile is approaching from in front and below. The two-dimensional intercept conditions are

$$T_X = 1000 \text{ ft} \quad T_Z = 1000 \text{ ft} \quad P_X = 1200 \text{ ft} \quad P_Z = 900 \text{ ft}$$
$$V_T = 800 \text{ ft/s} \quad V_P = 1600 \text{ ft/s}$$
$$\Psi_P = 120 \text{ deg} \quad \Omega_P = 0 \text{ deg}$$

(In the three-dimensional notation, $\Psi_P = 60$ deg $\Omega_P = 180$ deg.)

According to Eqs. (4.26a), (4.25a), (4.25b), and (4.25d),

$$S_X = 1200 \text{ ft} - 1000 \text{ ft} = 200 \text{ ft} \quad S_Z = 900 \text{ ft} - 1000 \text{ ft} = -100 \text{ ft}$$
$$(v_p)_x = (1600 \text{ ft/s}) \cdot \cos(120 \text{ deg}) - 800 \text{ ft/s} = -1600 \text{ ft/s}$$
$$(v_p)_z = (1600 \text{ ft/s}) \cdot \sin(120 \text{ deg}) = 1386 \text{ ft/s}$$
$$v_p = [(-1600 \text{ ft/s})^2 + (1386 \text{ ft/s})^2]^{0.5} = 2117 \text{ ft/s}$$
$$\psi_p = \arctan[(1386 \text{ ft/s})/(-1600 \text{ ft/s})] = -40.9 \text{ deg} \quad \text{or} \quad 139.1 \text{ deg}$$

(Note 24).

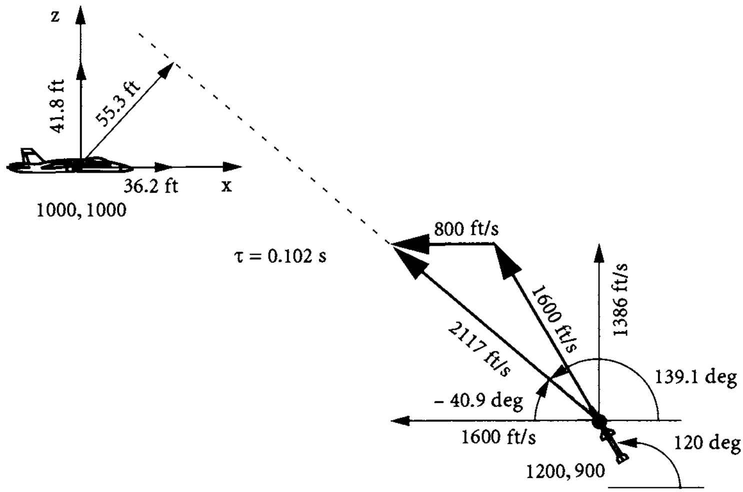
The time when the miss distance occurs is

$$\tau = -[(200 \text{ ft})(-1600 \text{ ft/s}) + (-100 \text{ ft})(1386 \text{ ft/s})]/(2117 \text{ ft/s})^2 = 0.102 \text{ s}$$

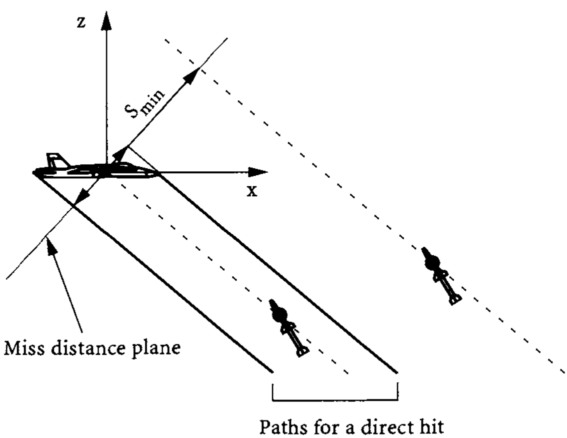
according to Eq. (4.27). The miss distance and its components are given by Eqs. (4.26c) and (4.26b) with $t = \tau$. Thus,

$$s_x = 36.2 \text{ ft} \quad s_z = 41.8 \text{ ft} \quad s = 55.3 \text{ ft}$$

The intercept geometry is shown next. The missile is an early bird.



Every intercept with the same velocity vectors but different starting locations P_X and P_Z will have a miss distance vector that lies in the same miss distance plane, as indicated in the following diagram. Also shown in the diagram is the location of any propagator whose path relative to the target will intersect the target. Thus, any miss distance less than the presented extent of the target will result in a direct hit.



4.3.6.2 Factors that influence the miss distance. The miss distance for ballistic projectiles is affected by the accuracy of the tracking system, the logic and operation of the fire control system, the forces acting on the propagator as it approaches the target, and the flight path of the aircraft. For guided missiles there are several important factors relating to the aerodynamic design of the missile that influence the miss distance. One of these factors is the missile response time. The response time defines the relative ability of the missile to rapidly change direction. Missiles that have a relatively short response time are highly maneuverable, whereas missiles that have a relatively long response time are slow to respond and can continually oscillate about the desired flight path. The missile energy in the terminal phase of the encounter is also an important factor. Generally, short-range missiles have a significant speed advantage over the target aircraft. However, medium- and long-range missiles might have only a small speed advantage at the beginning of the terminal phase of the encounter, and any last-second aircraft maneuvers will reduce the speed advantage as a result of maneuver-induced drag on the missile. The missile's maximum turning rate also affects the miss distance. This rate is directly proportional to the maximum load factor of the missile and inversely proportional to the velocity. For example, a missile traveling at Mach 3 (three times the speed of sound) requires a 27-g maneuver capability to have the same turning rate as a target aircraft pulling 9 g at Mach 1.

The guidance and control laws that navigate many of today's missiles are usually approximations to the proportional navigation law, and these approximations can have a significant effect on the miss distance, particularly for maneuvering targets. The measurement of all of the target coordinates, such as position and velocity, allows the use of more sophisticated navigation laws. However, a loss of one or more of the coordinate data, or a sudden target maneuver, can have a significant effect on the missile's ability to intercept the target when a more sophisticated law is used.

When radar target tracking is used, internal thermal noise and external noise, target glint, and scintillation will cause errors in the measured target coordinates that will contribute to the miss distance. At the beginning of an engagement, the thermal and external noise can seriously degrade missile performance by causing erroneous maneuvers that unnecessarily add to the drag on the missile, slowing it down. When the signal-to-noise ratio is low, the missile can literally chase the noise. Target glint can also be a serious problem, particularly when the missile gets close to the target because it is inversely proportional to the relative range. As the missile approaches the target, the target ceases to be essentially a point target and becomes an area target, possibly with widely separated scatters. Target scintillation is another contributor to the tracking error, and hence the miss distance. This error is independent of range and might be smaller than the larger of the noise and glint errors. Passive IR homing missiles also have angular tracking errors. When the seeker tracks the engine exhaust plume, it is tracking a source behind the aircraft that can cause a bias error toward the aft end of the aircraft.

Go to Problems 4.3.55 to 4.3.57.

4.3.7 Hits on the Aircraft ($P_{H|I}$ and $P_{F|I}$)

The propagator (projectile or missile) is approaching the miss distance. Will it hit the aircraft? If the warhead is a proximity-fuzed HE warhead, will it detonate; and if it detonates, how many fragments will hit the aircraft? The equations required to answer these questions depend upon the type of assessment and the type of warhead. In Example 4.8, where the parameters and equations were assumed to be deterministic, the miss distance was determined for a given set of initial conditions, and the locations of the propagator paths relative to the target that would result in a direct hit were identified. However, when the stochastic nature of the intercept and end game is considered, probability theory must be used to determine the probability an aircraft is hit by a propagator given the intercept $P_{H|I}$ and the probability the warhead fuzes at the right time to result in fragments on the target $P_{F|I}$.

4.3.7.1 *Contact warheads* ($P_{H|I}$).

Learning	**4.3.19**	**Describe the total miss distance model.**
Objectives	**4.3.20**	**Compute the probability that a propagator hits an aircraft given the bivariate normal or circular normal miss distance distribution.**

Miss distance probability density function. The miss distance is essentially an error. Therefore, it can be expressed by a probability density function of the same form as the tracking error, and Eqs. (4.9–4.12b) and (4.18–4.22d) apply. To illustrate the physical and mathematical features of the miss distance, consider the aircraft with the propagator miss distances indicated by the black dots in Fig. 4.21. Assume that N propagators are launched or fired toward the side of the aircraft and that they all travel parallel paths normal to the page and relative to a stationary aircraft. The miss distance plane, with the coordinates (ξ, ζ), is the plane that contains the miss distance vector from the target aim point to the CPA and is normal to the relative propagator path. In this explanation it is the (x, z) local (target) coordinate system. The N shots intersect the miss distance plane at N locations of (ξ_i, ζ_i)

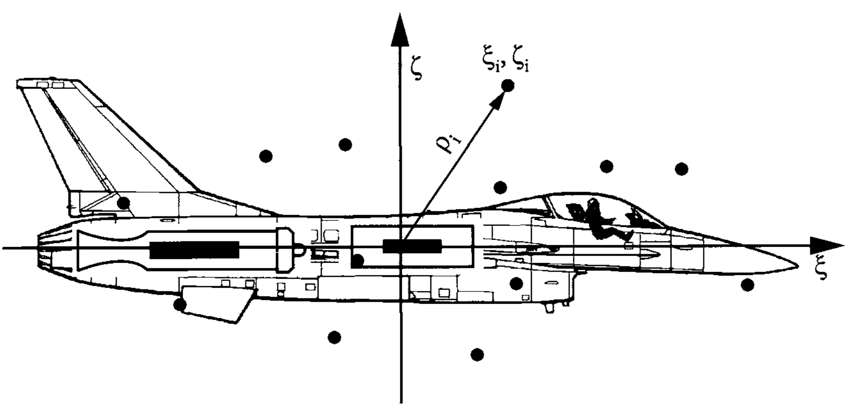


Fig. 4.21 Miss distance plane, a target, and N propagator miss distances.

pairs. The distance ρ_i from the aircraft aim point (the origin of the coordinate system and normally the aircraft centroid) to any (ξ_i, ζ_i) pair is the miss distance $s_{\min}$ for that shot, and the distances ξ_i and ζ_i are the coordinate errors.

The N shots will have a miss distance mean and variance in both the ξ and ζ directions in the miss distance plane. The sample means M_ξ and M_ζ are given by

$$M_\xi = \frac{1}{N}\sum_{i=1}^{N}\xi_i, \quad M_\zeta = \frac{1}{N}\sum_{i=1}^{N}\zeta_i \tag{4.28a}$$

where ξ_i and ζ_i denote the ξ and ζ location of the miss distance for the ith shot, and the sample variances S_ξ^2 and S_ζ^2 are computed using

$$S_\xi^2 = \frac{1}{N}\sum_{i=1}^{N}(\xi_i - M_\xi)^2 \quad \text{and} \quad S_\zeta^2 = \frac{1}{N}\sum_{i=1}^{N}(\zeta_i - M_\zeta)^2 \tag{4.28b}$$

If the N miss distances are independent from one another and there is no correlation between the ξ and ζ components of the miss distance, the assumption is made that the probability density function of the miss distance $\eta(\xi, \zeta)$ can be represented by the bivariate normal distribution given by Eq. 4.18 (Note 25). Thus,

$$\eta(\xi, \zeta) = \frac{1}{2\pi\sigma_\xi\sigma_\zeta}\exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2} - \frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2}\right] \tag{4.29a}$$

where the means μ_ξ and μ_ζ and the standard deviations σ_ξ and σ_ζ are related to the sample means M_ξ and M_ζ and variances S_ξ^2 and S_ζ^2 by

$$\mu = M \tag{4.29b}$$

$$\sigma^2 = \left(\frac{N}{N-1}\right)S^2 \tag{4.29c}$$

If the two means are found, or assumed, to be equal to zero, and if the two standard deviations are found, or assumed, to be equal, the bivariate distribution simplifies to the circular normal distribution given by

$$\eta(\rho) = \frac{1}{2\pi\sigma_\rho^2}\exp\left(-\frac{\rho^2}{2\sigma_\rho^2}\right) \tag{4.30a}$$

where ρ is the radial miss distance from the target aim point and σ is the circular standard deviation, which is equal to both σ_ξ and σ_ζ. The circular miss distance within which one-half of the shots fall, the CEP, is given by

$$\text{CEP} = 1.177\sigma_\rho \tag{4.30b}$$

Total miss distance model. The miss distance is dependent upon the threat system's ability to track the aircraft accurately and to guide or point the propagator toward an intercept. The system predicts the aircraft will be at a certain location at a certain time and fires or launches and guides accordingly. If its measurement of the current target location is greatly in error, the predicted future target position will most likely be greatly in error. Furthermore, if the propagator cannot reach a correctly predicted target position the miss distance will probably be large. Thus, the miss distance is dependent upon both the tracking accuracy and the fire control/trajectory/guidance accuracy of the system. From a total error point of view, the total miss distance standard deviation σ_{miss} (in meters) is related to the tracking error standard deviation σ_{tracking} (in meters) and the fire control/trajectory/guidance miss distance standard σ_{guidnace} (in meters) by the relationship

$$\sigma_{\text{miss}} = \sqrt{\sigma_{\text{tracking}}^2 + \sigma_{\text{guidance}}^2} \tag{4.31}$$

when the two errors are independent. The σ_{guidance} relates to the ability of the threat system to get the propagator to where the system thinks the aircraft will be at intercept (based upon the current aircraft tracking data), and the σ_{tracking} relates to the ability of the tracking system to determine the current aircraft flight-path parameters accurately, such as position and velocity.

The expression for σ_{miss} given by Eq. (4.31) can be used to estimate the total miss distance standard deviation based upon the contributions of all of the individual errors. The variance of the errors caused by the tracking, fire control, guidance, and propagator flight path can also be estimated or measured. Guns have jitter, ballistic rounds have dispersion, and missiles have electronic boxes for receiving and/or transmitting target position data and for controlling the flight path of the missile. The error associated with each one of these features can be represented by a normal distribution with a standard deviation. The aircraft flight path also affects the miss distance. However, its contribution to the miss distance is more difficult to estimate because of its variability, and consequently most simple assessments assume a nonmaneuvering aircraft.

If both the angular tracking errors and the fire control/guidance errors are circular symmetric and if the range tracking error is neglected, the total radial miss distance standard deviation σ_r is given by

$$\sigma_{\text{miss}} = \sigma_r = \sqrt{R^2\sigma_{\text{angle tracking}}^2 + \sigma_{\text{guidance}}^2} \tag{4.32}$$

where $\sigma_{\text{angle tracking}}$ is the circular standard deviation of the angular tracking error in radians and R is the slant range to the aircraft in meters (Note 26).

Probability a propagator hits the aircraft. Propagators with either non-HE warheads or contact-fuzed HE warheads must actually hit an aircraft in order to cause damage. In general, the probability an aircraft is hit by a propagator P_H depends upon the shape or extent of the aircraft projected in the miss distance plane and the miss distance distribution. For example, consider the aircraft and the miss distance PDF shown in Fig. 4.22a. The presented area of the aircraft in the

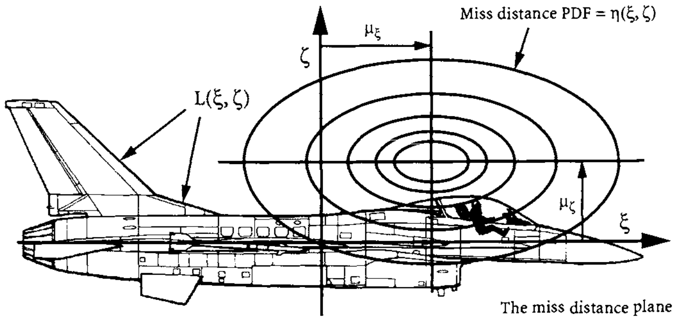


Fig. 4.22a Target and the bivariate normal miss distance distribution.

miss distance plane is given by

$$A_p = \int_L \int L(\xi, \zeta)\, \mathrm{d}\xi\, \mathrm{d}\zeta \tag{4.33}$$

The aircraft shown in Fig. 4.22a is hit only when ξ and ζ define a location within the physical extent of the aircraft; locations of (ξ, ζ) pairs outside the aircraft boundary are misses. Consequently, the probability of a propagator hit on the presented area of the aircraft is given by the integral of $\eta(\xi, \zeta)$ over the extent of the aircraft

$$P_H = \int_L \int \eta(\xi, \zeta)\, \mathrm{d}\xi\, \mathrm{d}\zeta \tag{4.34}$$

If the bivariate normal is used for the miss distance PDF and if the aim point of the target is taken to be the center of the aircraft, then P_H is given by

$$P_H = \int_L \int \left(\frac{1}{2\pi\sigma_\xi\sigma_\zeta}\right) \exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2} - \frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2}\right] \mathrm{d}\xi\, \mathrm{d}\zeta \tag{4.35}$$

according to Eq. (4.29a).

Cookie-cutter and Carlton hit functions: Because of the difficulty in evaluating Eq. (4.35) for a general aircraft shape, such as that shown in Fig. 4.22a, the real shape can be approximated by a rectangle or shoe box with side lengths ξ_0 and ζ_0, as shown in Fig. 4.22b. Thus, a hit on the shoe box can occur only when $|\xi| \geq \xi_0/2$ and $|\zeta| \geq \zeta_0/2$. Under these conditions Eq. (4.35) takes the form

$$P_H = \int_{-\zeta_0/2}^{\zeta_0/2} \left(\frac{1}{\sqrt{2\pi}\,\sigma_\zeta}\right) \exp\left[-\frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2}\right] \mathrm{d}\zeta$$

$$\times \int_{-\xi_0/2}^{\xi_0/2} \left(\frac{1}{\sqrt{2\pi}\,\sigma_\xi}\right) \exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2}\right] \mathrm{d}\xi \tag{4.36a}$$

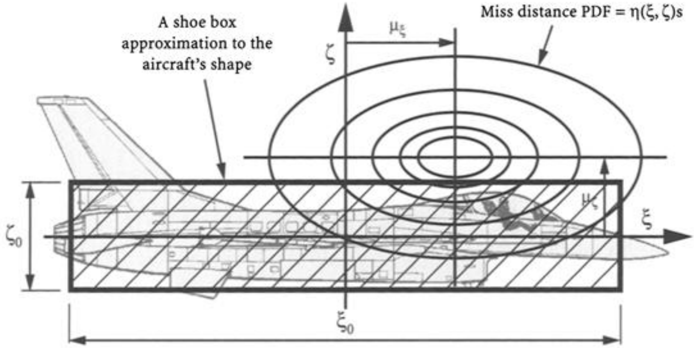


Fig. 4.22b Shoe-box target and the bivariate normal miss distance distribution.

where

$$\xi_0 \zeta_0 = A_P \tag{4.36b}$$

and A_P is given by Eq. (4.33). There is no analytical solution to Eq. (4.36a). However, the numerical value for P_H for any shoe-box aircraft and bivariate normal miss distance PDF can be determined using Eq. (4.36a) and the normal cumulative probability shown in Fig. B.25b, as shown by Example 4.9.

Example 4.9 P_H for a Shoe-Box Aircraft

The shoe-box aircraft shown in Fig. 4.22b has the dimensions

$$\xi_0 = 30 \text{ ft} \quad \zeta_0 = 10 \text{ ft}$$

The bivariate normal PDF for the miss distance for a particular gun in a particular firing situation is given by

$$\mu_\xi = 10 \text{ ft} \quad \mu_\zeta = 8 \text{ ft} \quad \sigma_\xi = 20 \text{ ft} \quad \sigma_\zeta = 10 \text{ ft}$$

which is representative of the PDF shown in Fig. 4.22b.

The cumulative probability for the normal distribution shown in Fig. B.25b is given in terms of the nondimensional coordinate χ, where

$$\chi = (\xi - \mu)/\sigma$$

Thus, the nondimensional random variables in the ξ and ζ coordinates are given by

$$\chi_\xi = (\xi - 10\text{ ft})/(20\text{ ft}) \quad \chi_\zeta = (\zeta - 8\text{ ft})/(10\text{ ft})$$

and the shoe-box limits of -15 ft and $+15$ ft in ξ and -5 ft and $+5$ ft in ζ become

$$(-15\text{ ft} - 10\text{ ft})/(20\text{ ft}) = -1.25 \quad \text{and} \quad (15\text{ ft} - 10\text{ ft})/(20\text{ ft}) = 0.25$$

in χ_ξ and

$$(-5\text{ ft} - 8\text{ ft})/(10\text{ ft}) = -1.3 \quad \text{and} \quad (5\text{ ft} - 8\text{ ft})/(10\text{ ft}) = -0.3$$

in χ_ζ.

According to Fig. B.25b, the cumulative probabilities for the limits on χ_ξ are

$$-\infty \text{ to } -1.25 = 0.11 \quad \text{and} \quad -\infty \text{ to } 0.25 = 0.61$$

Thus, the probability that the ξ component of the miss distance will be within the interval $\xi = -15$ ft and $\xi = +15$ ft is $= 0.61 - 0.11 = 0.50$.

Similarly, the cumulative probabilities for the limits on χ_ζ are

$$-\infty \text{ to } -1.3 = 0.10 \quad \text{and} \quad -\infty \text{ to } -0.3 = 0.38$$

and the probability that the ζ component of the miss distance will be within the interval $\zeta = -5$ ft and $\zeta = +5$ ft is $= 0.38 - 0.10 = 0.28$.

The probability the miss distance will be within the shoe-box limits for both ξ and ζ is given by the product of the two coordinate probabilities. Thus,

$$P_H = 0.50 \cdot 0.28 = 0.14$$

As a result of the nonavailability of an analytical, closed-form solution for the P_H, the diffused Gaussian or Carlton hit function is sometimes used to define the extent of the aircraft. By introducing a hit function $H(\xi, \zeta)$, which defines the probability that the target is hit given a propagator location (ξ, ζ), Eq. (4.34) can be rewritten as

$$P_H = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \eta(\xi, \zeta) H(\xi, \zeta)\, d\xi\, d\zeta \tag{4.37a}$$

where

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \zeta)\, d\xi\, d\zeta = A_P \tag{4.37b}$$

For Eq. (4.37a) to correspond to Eq. (4.34), $H(\xi, \zeta) = 1$ when ξ and ζ lie inside the aircraft perimeter, and $H(\xi, \zeta) = 0$ when ξ and ζ lie outside the aircraft perimeter. This particular form of $H(\xi, \zeta)$ is sometimes referred to as the cookie-cutter hit function because of its demarcation property. The P_H given by Eq. (4.36a), for the shoe-box approximation to the aircraft shape, is an example of the cookie-cutter hit function applied to a rectangle.

In the Carlton approach $H(\xi, \zeta)$ is taken in the form

$$H(\xi, \zeta) = \exp\left(\frac{-\pi\xi^2}{\xi_0^2}\right)\exp\left(\frac{-\pi\zeta^2}{\zeta_0^2}\right) \tag{4.38a}$$

where the parameters ξ_0 and ζ_0 are scaling parameters related to the aircraft presented area by the expression

$$A_P = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp\left(\frac{-\pi\xi^2}{\xi_0^2}\right)\exp\left(\frac{-\pi\zeta^2}{\zeta_0^2}\right) \mathrm{d}\xi\,\mathrm{d}\zeta = \xi_0\zeta_0 \tag{4.38b}$$

Both the cookie-cutter and the Carlton hit functions are plotted as a function of ξ (with $\zeta = 0$) in Fig. 4.23.

Note that the Carlton hit function gives a nonzero probability of a hit occurring for miss distances larger than the extent of the aircraft and a less than unity probability of a hit for miss distances smaller that the aircraft size. Also note that the use of the Carlton function eliminates the mutually exclusive feature of the cookie cutter function. With the cookie-cutter function the aircraft is either hit, or is not hit, by a propagator, whereas with the Carlton function there is always a nonzero probability the aircraft is hit for all finite miss distances. Substituting Eq. (4.38a) into Eq. (4.37a) with $\eta(\xi, \zeta)$ expressed by the bivariate normal given in Eq. (4.29a)

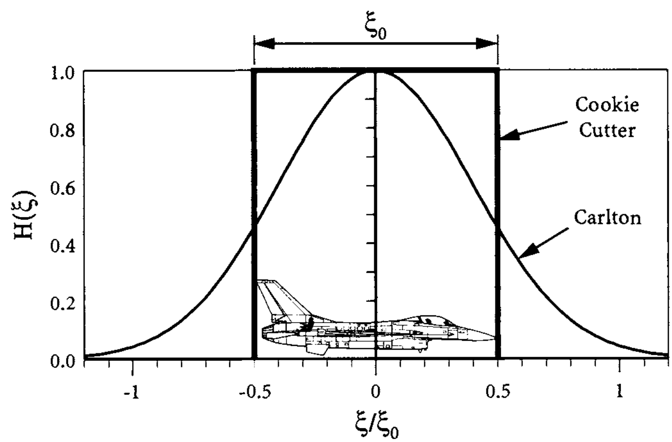


Fig. 4.23 Cookie-cutter and Carlton hit functions.

leads to

$$P_H = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_\xi\sigma_\zeta} \exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2} - \frac{\pi\xi^2}{\xi_0^2}\right]$$

$$\times \exp\left[-\frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2} - \frac{\pi\zeta^2}{\zeta_0^2}\right] \mathrm{d}\xi\, \mathrm{d}\zeta \tag{4.39a}$$

This expression for P_H can be integrated, and carrying out the integration gives

$$P_H = \frac{A_P}{\sqrt{2\pi\sigma_\xi^2 + \xi_0^2}\sqrt{2\pi\sigma_\zeta^2 + \zeta_0^2}}$$

$$[3pt] \qquad \times \exp\left(-\frac{\pi\mu_\xi^2}{2\pi\sigma_\xi^2 + \xi_0^2} - \frac{\pi\mu_\zeta^2}{2\pi\sigma_\zeta^2 + \zeta_0^2}\right) \tag{4.39b}$$

when Eq. (4.38b) is used.

If the assumption is made that the shoe box is square, $\xi_0 = \zeta_0$, and, Eq. (4.39b) becomes

$$P_H = \frac{A_P}{\sqrt{2\pi\sigma_\xi^2 + A_P}\sqrt{2\pi\sigma_\zeta^2 + A_P}}$$

$$[3pt] \qquad \times \exp\left(-\frac{\pi\mu_\xi^2}{2\pi\sigma_\xi^2 + A_P} - \frac{\pi\mu_\zeta^2}{2\pi\sigma_\zeta^2 + A_P}\right) \tag{4.40a}$$

If the argument in the exponential in Eq. (4.40a) is very small because of relatively small means, or large standard deviations, or aircraft presented area, the exponential function is approximately equal to unity. Hence,

$$P_H \approx \frac{A_P}{\sqrt{2\pi\sigma_\xi^2 + A_P}\sqrt{2\pi\sigma_\zeta^2 + A_P}} \tag{4.40b}$$

provided

$$\xi_0 = \zeta_0$$

$$[2pt] - \frac{\pi\mu_\xi^2}{2\pi\sigma_\xi^2 + A_P} - \frac{\pi\mu_\zeta^2}{2\pi\sigma_\zeta^2 + A_P} \ll 1 \tag{4.40c}$$

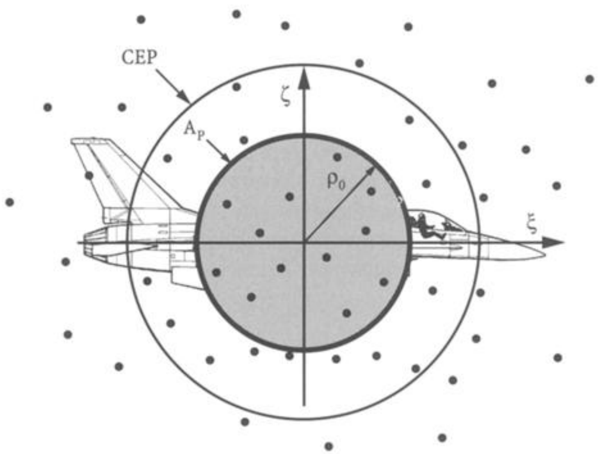


Fig. 4.24 Circular symmetric miss distance.

Further, if $\sigma_\xi = \sigma_\zeta = \sigma$

$$P_H \approx \frac{A_P}{2\pi\sigma^2 + A_P} \tag{4.40d}$$

Circular symmetry: If circular symmetry about the aim point is assumed for the miss distance distribution, the two means are zero, and the two standard deviations are $\sigma_\xi = \sigma_\zeta = \sigma_\rho$. The circular symmetric miss distance situation is illustrated in Fig. 4.24.

First, consider the cookie-cutter hit function. If the aircraft presented area is taken as a circle of radius ρ_0,

$$A_P = \pi\rho_0^2 \tag{4.41a}$$

then P_H becomes

$$P_H = \int_0^{2\pi}\int_0^{\rho_0} \frac{\rho}{2\pi\sigma_\rho^2}\exp\left(\frac{-\rho^2}{2\sigma_\rho^2}\right) \mathrm{d}\rho\,\mathrm{d}\theta = 1 - \exp\left(\frac{-A_P}{2\pi\sigma_\rho^2}\right) \tag{4.41b}$$

according to Eqs. (4.30a) and (4.37a).

For the circular Carlton hit function

$$H(\rho) = \exp\left(\frac{-\rho^2}{\rho_0^2}\right) \tag{4.42a}$$

and

$$A_P = \int_0^{2\pi} \int_0^{\infty} \rho \exp\left(-\frac{\rho^2}{\rho_0^2} \right) \mathrm{d}\rho \, \mathrm{d}\theta = \pi \rho_0^2 \tag{4.42b}$$

Thus,

$$P_H = \int_0^{2\pi} \int_0^{\infty} \frac{\rho}{2\pi\sigma_\rho^2} \exp\left(-\frac{\rho^2}{2\sigma_\rho^2} - \frac{\rho^2}{\rho_0^2} \right) \mathrm{d}\rho \, \mathrm{d}\theta = \frac{A_P}{2\pi\sigma_\rho^2 + A_P} \tag{4.42c}$$

according to Eqs. (4.42a) and (4.30a).

When ρ_0 is small compared with σ_ρ, both the cookie-cutter and the Carlton expressions for P_H simplify to

$$P_H \approx \frac{A_P}{2\pi\sigma_\rho^2} \qquad \text{provided} \quad 2\pi\sigma_\rho^2 \gg A_P \tag{4.43}$$

Component hits: The probability of hitting any individual component in the aircraft with a presented area A_p also can be computed using the equations just presented, provided the component shape is approximated with a rectangle, with $\xi_0\zeta_0 = A_p$, and the miss distance means μ_ξ and μ_ζ are measured with respect to the location of the component center rather than the target center.

Go to Problems 4.3.58 to 4.3.61.

4.3.7.2 Proximity warheads ($P_{F|I}$).

Learning Objectives	**4.3.21**	**Determine the fragment velocity decay.**
	4.3.22	**Determine the detonation zones for fuzing.**
	4.3.23	**Determine the number of fragments from a given warhead detonation that hit the aircraft.**
	4.3.24	**Describe the options for $P_{F|I}$.**

The propagator with a proximity warhead does not have to hit the aircraft to kill it. Instead, the aircraft is killed when the proximity warhead fuzes in a location that causes one or more warhead fragments or penetrators to hit the aircraft and these hits are sufficient to kill the aircraft. (Because the discussion that follows holds for both warhead penetrators and fragments, except for the continuous rods which are a special case, only the fragments will be referred to.) Consequently, of interest here is the miss distance of each of the fragments from a given warhead detonation and the number of fragments that hit the target. The fragment spray from an idealized high-explosive warhead detonation is shown in Fig. 3.33. The primary parameters are the number of fragments in the warhead N, the shape and mass m_f of each fragment, the initial fragment velocity from a static warhead detonation V_0, and the spray angle α for each fragment in the warhead.

Fragment velocity from a warhead detonation. Consider the propagator high explosive warhead detonation shown in the global (X, Z) coordinate system shown in Fig. 4.25a. Both the aircraft velocity vector $\boldsymbol{V}_T$ and the propagator velocity vector $\boldsymbol{V}_P$ are in the (X, Z) plane. The aircraft is located at (T_X, T_Z), and the propagator is located at (P_X, P_Z) at the time of detonation $t = 0$. The fragment has the velocity vector $\boldsymbol{V}_0$ from the warhead at the spray angle α measured counterclockwise from the nose of the propagator. Because the warhead is on a propagator moving with the velocity V_P, the global velocity vector of the fragment as it moves through the surrounding air $\boldsymbol{V}_F$ is the vector sum of the propagator velocity vector $\boldsymbol{V}_P$ and the fragment static detonation velocity vector $\boldsymbol{V}_0$ as shown in Fig. 4.25a. Thus, the magnitude of the global velocity of the fragment at the detonation point $V_F(t = 0)$ is

$$V_F(t = 0) = \sqrt{(V_P + V_0 \cos\alpha)^2 + (V_0 \sin\alpha)^2} \tag{4.44}$$

As the fragment moves through the surrounding air, its velocity will decay as a result of viscous drag. The magnitude of the decay depends upon the mass density of the ambient air ρ_a, the presented or frontal area of the fragment A_F, the coefficient of drag of the fragment C_D, and the mass of the fragment m_F. The equation for the global fragment velocity at any distance s from the detonation $V_F(s)$ is

$$V_F(s) = V_F(0)\exp(-Ks) \tag{4.45a}$$

where K is given by

$$K = (\rho_a A_F C_D)/(2m_F) \tag{4.45b}$$

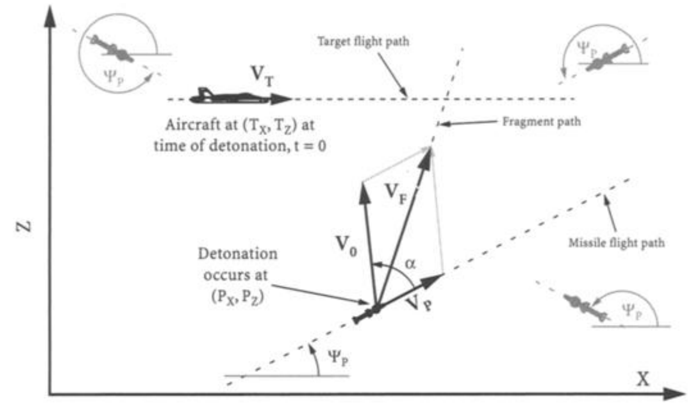
Equation (4.45a) is derived using the assumption that all parameters in K remain constant as the fragment travels outward from the detonation. The value for C_D depends upon the shape of the fragment and the fragment's velocity. Typical values of C_D for supersonic fragments are

$$\begin{aligned} C_D &\approx 1.0 && \text{for a sphere} \\ C_D &\approx 1.25 && \text{for a cube corner-on} \\ C_D &\approx 1.75 && \text{for a cube face-on} \end{aligned} \tag{4.45c}$$

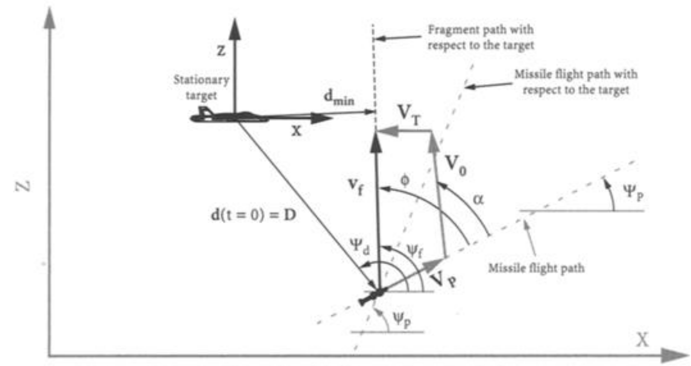
The procedure for computing the velocity decay of a warhead fragment is described in Example 4.10.

Example 4.10 Velocity Decay of the Fragments from a Warhead Detonation

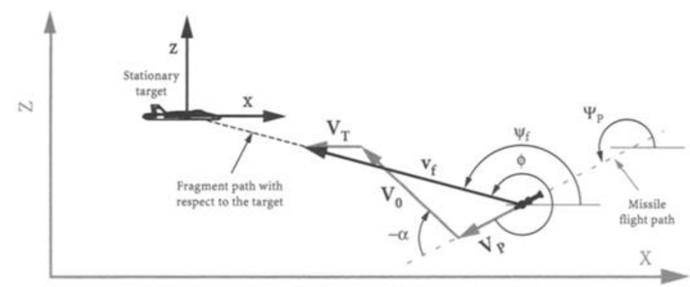
Of interest is the velocity of the fragments from the warhead detonation described in Example 3.3 at a distance s from the detonation. The detonation occurs at 20,000 ft. The missile is moving with a velocity of 2000 fps at the time of detonation. From Example 3.3 the fragments are 200 grain, $0.5 \times 0.5 \times 0.4$ in.^{3} steel cubes, $V_0 = 5577$ fps, and $\alpha = 82.7$ deg. Thus, the initial global velocity of



(a) Two-dimensional detonation conditions, global (X, Z)



(b) The two-dimensional detonation conditions, local (x, z)



(c) A missile flight path from a different direction, local (x, y)

Fig. 4.25 Warhead detonation and the fragment miss distance.

the fragments is

$$V_F(0) = \{[2000 \text{ ft/s} + (5577 \text{ ft/s}) \cdot \cos(82.7 \text{ deg})]^2 + [(5577 \text{ ft/s}) \cdot \sin(82.7 \text{ deg})]^2\}^{1/2} = 6159 \text{ fps}$$

according to Eq. (4.44).

The decay in the velocity of the fragments at distance s from the detonation is

$$V_F(s) = V_F(0) \cdot \exp(-Ks) = (6159 \text{ ft/s}) \cdot \exp(-Ks)$$

where K is given by Eq. (4.45b).

At 20,000 ft the weight density of air is 0.0408 lb/ft^3 according to Table 3.8. The weight of the 200-grain fragment is 0.0286 lb. Assuming the fragments travel face-on

$$A_F = (0.5 \text{ in.}) \cdot (0.5 \text{ in.}) = 0.25 \text{ in.}^2 = 0.00174 \text{ ft}^2 \quad \text{and} \quad C_D = 1.75$$

according to Eq. (4.45c).

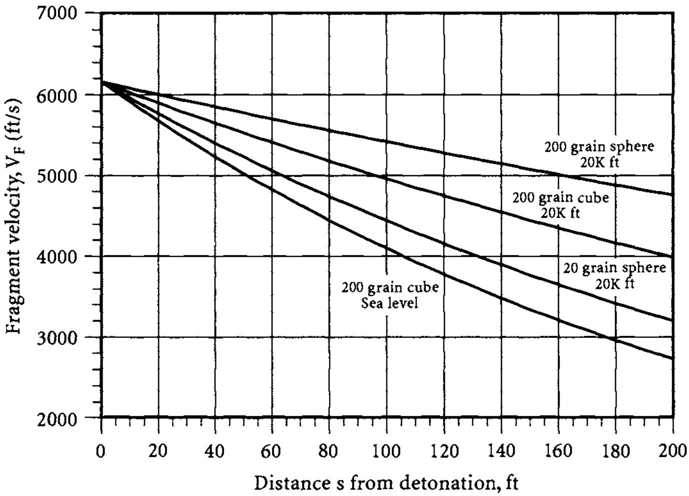
Thus, according to Eq. (4.45b) and (4.45a)

$$K = (0.0408 \text{ lb/ft}^3) \cdot (0.00174 \text{ ft}^2) \cdot (1.75)/(2 \cdot 0.0286 \text{ lb}) = 0.00217/\text{ft}$$

and

$$V_F(s) = (6159 \text{ ft/s}) \cdot \exp(-0.00217s)$$

The following figure shows the velocity of the 200-grain cubic fragment traveling face-on for the detonation at 20,000 ft and at sea level, where the weight density of air is 0.0765 lb/ft^3 according to Table 3.8. Also shown in the figure are the velocities for a 200-grain and a 20-grain steel sphere at 20,000 ft with the same $V_F(0)$.



Go to Problem 4.3.62.

Fragment miss distance. Figure 4.25a illustrates the velocity V_F and path of a single fragment with spray angle α and velocity V_0 from a detonation located at (P_X, P_Z) and a target located at (T_X, T_Z) at $t = 0$. In the two-dimensional (X, Z) global coordinate system shown in Fig. 4.25a, both the aircraft and the fragment move along the (dashed line) paths. The assumption is made here that both the target velocity vector and fragment velocity vector are constant for $t > 0$. Consequently, if a local (x, z) coordinate system is attached to the center of the moving aircraft in a manner similar to the propagator miss distance geometry shown in Fig. 4.20b, the path of the fragment with respect to the aircraft in the local coordinates is obtained by subtracting the aircraft's velocity vector $\boldsymbol{V_T}$ from the fragment's velocity vector $\boldsymbol{V_F}$, resulting in the velocity vector of the fragment with respect to the (stationary) target $\boldsymbol{v_f}$, as shown in Fig. 4.25b (Note 27). The (x, z) components of the relative velocity vector $\boldsymbol{v_f}$ are given by

$$\begin{aligned}(v_f)_x &= V_P \cos\Psi_P + V_0 \cos(\Psi_P + \alpha) - V_T \\ (v_f)_z &= V_P \sin\Psi_P + V_0 \sin(\Psi_P + \alpha)\end{aligned} \tag{4.46a}$$

and the relative velocity of the fragment v_f is

$$v_f = \sqrt{(v_f)_x^2 + (v_f)_z^2} \tag{4.46b}$$

The path of the fragment in the local coordinate system has the elevation angle ψ_f, measured counterclockwise from the x axis, which is given by

$$\psi_f = \arctan\left[\frac{(v_f)_z}{(v_f)_x}\right] \tag{4.46c}$$

The fragment spray angle in the local coordinate system ϕ, measured counterclockwise from the nose of the propagator, is shown in Figs. 4.25b and 4.25c and is determined using

$$\phi = \psi_f - \Psi_P \tag{4.46d}$$

where ψ_f is given by Eq. (4.46c). (This ϕ is not to be confused with the ϕ that refers to the yaw of a penetrator.)

The equations for the separation vector $\boldsymbol{d}(t)$ from the target to the fragment at time t are the same as Eqs. (4.26a), (4.26b), and (4.26c) for the separation distance between the target and the propagator, with the components of the propagator relative velocity $\boldsymbol{v_p}$ replaced by the components of the fragment relative velocity $\boldsymbol{v_f}$ and the initial separation distance coordinates S_X and S_Z replaced by the coordinates at detonation D_X and D_Z. Thus,

$$\begin{gathered}D_X = P_X - T_X, \quad D_Z = P_Z - T_Z, \quad \text{and} \quad D = \sqrt{D_X^2 + D_Z^2} \\ d_x = D_X + (v_f)_x t \quad \text{and} \quad d_z = D_Z + (v_f)_z t \\ d = \sqrt{d_x^2 + d_y^2}\end{gathered} \tag{4.47a}$$

The separation distance between the aircraft and the warhead at the time of detonation, $d(t = 0)$ is given by D in Eq. (4.47a) and is known as the detonation distance. The time when the separation distance d is a minimum τ is given by Eq. (4.27) for the propagator miss distance, with the appropriate velocity and component substitution. Thus,

$$\tau(d = d_{\min}) = \frac{-[D_X(v_f)_x + D_Z(v_f)_z]}{v_f^2} \tag{4.47b}$$

Note in Fig. 4.25b that the fragment passes in front of the aircraft.

A different intercept geometry is shown in Fig. 4.25c, where the propagator elevation angle is greater than 180 deg. Note in Fig. 4.25b that the fragment comes from the left side of the warhead; however, in Fig. 4.25c the fragment comes from the right side. Hence, the fragment spray angle for this geometry is $-\alpha$, not α. The vector $\boldsymbol{v}_f$ is defined by Eqs. (4.46a) and (4.46b), and ϕ is defined by Eqs. (4.46c) and (4.46d). Note in this figure that the fragment from the detonated warhead hits the aircraft (Note 28).

Detonation zones. When a warhead bursts in the vicinity of an aircraft, the warhead fragments or penetrators are usually ejected uniformly around the propagator axis and begin to propagate outward in a divergent spherical-like spray pattern at a velocity that is the vector sum of the initial fragment ejection velocity from a static warhead detonation V_0 and the propagator velocity V_P. The fragment at the front of the warhead is assumed to propagate outward at the leading spray angle α_1, and the fragment at the tail end of the warhead is assumed to propagate along the trajectory at the trailing spray angle α_2, as shown in Fig. 3.33. All of the other fragment trajectories lie between these two spray angles and make up the fragment spray.

Now consider the four detonation points in the local (x, z) coordinate system shown in Fig. 4.26. The fragment spray at each detonation point in the local coordinate system is between the leading and trailing fragment angles ψ_{f1} and ψ_{f2} (and ϕ_1 and ϕ_2) respectively. The detonation at the lower left side of the figure on line 1 corresponds to the situation where the leading fragment hits the tail of the target. The detonation on line 2 corresponds to the situation where the leading fragment hits the nose of the target. The detonation on line 3 corresponds to the situation where the trailing fragment hits the tail of the target; and the detonation on line 4 corresponds to the trailing fragment hit on the nose of the target. Thus, any detonation along the relative flight path between lines 1 through 4 will result in at least one fragment hit on the target. The four lines divide the area beneath the aircraft into the four zones: I, II, III, and IV. The length of the two sides of the triangle that forms zone II can be determined using the Law of Sines with the length of the aircraft L and the two angles ψ_{f1} and ψ_{f2}.

Any detonation within zones I and III will result in hits on part of the target by part of the fragment spray. Any detonation within zone II will result in the entire fragment spray hitting part of the target, and detonations within zone IV result in part of the fragement spray hitting the entire target. In general, for any given relative flight path the largest number of hits occurs in zones II and IV. Thus, the fuze lean angle and time delay shown in Figs. 3.38a and 3.38b would normally be designed to create detonations within these two zones. Note that although the

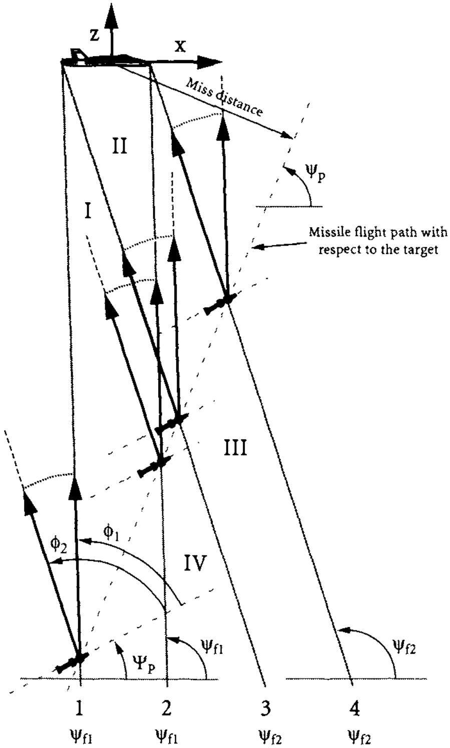


Fig. 4.26 Detonation zones.

lines 1 through 4 will change directions if any of the parameters, such as Ψ_P, V_T, and V_0, change, and hence the required fuze lean angle shown in Figs. 3.38a and 3.38b changes, the four zones still exist in any intercept (Note 4.29).

Note in Fig. 4.26 that the warhead must detonate before it reaches the closest point of approach to the target. This is true in general. Thus, the miss distance is not the same as the detonation distance. The relationship between the two is given by

$$CPA/D = \sin(\Psi_d - \psi_p) \tag{4.48a}$$

where Ψ_d is the angle from the horizontal to the detonation distance shown in Fig. 4.25b and is equal to

$$\Psi_d = \arctan(D_Z/D_X) \tag{4.48b}$$

where D_X and D_Z are given by Eq. (4.47a).

Example 4.11 Detonation Zones Around an Aircraft

Given a 30-ft-long aircraft flying straight and level with a velocity of 800 ft/s with a missile velocity of 1600 ft/s and warhead parameters of $V_0 = 5000$ ft/s,

$\alpha_1 = 80$ deg, and $\alpha_2 = 95$ deg, determine the detonation zones around the aircraft for a missile with an elevation angle of 40 deg and 220 deg. Also determine the extent of zone II for the 40-deg early bird missile.

For the 40-deg early bird missile (as shown in Fig. 4.25b) and the leading fragment ($\alpha_1 = 80$ deg)

$$(v_{f1})_x = (1600 \text{ ft/s}) \cdot \cos(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(40 \text{ deg} + 80 \text{ deg})$$
$$-800 \text{ ft/s} = -2074 \text{ ft/s}$$

$$(v_{f1})_z = (1600 \text{ ft/s}) \cdot \sin(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(40 \text{ deg} + 80 \text{ deg})$$
$$= 5359 \text{ ft/s}$$

according to Eq. (4.46a). Thus,

$$\psi_{f1} = \arctan(5359/-2074) = -68.8 \text{ deg or } 111.2 \text{ deg}$$

according to Eq. (4.46c). Similarly, for the trailing fragment ($\alpha_2 = 95$ deg)

$$(v_{f2})_x = (1600 \text{ ft/s}) \cdot \cos(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(40 \text{ deg} + 95 \text{ deg})$$
$$-800 \text{ ft/s} = -3110 \text{ ft/s}$$

$$(v_{f2})_z = (1600 \text{ ft/s}) \cdot \sin(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(40 \text{ deg} + 95 \text{ deg})$$
$$= 4564 \text{ ft/s}$$

Thus,

$$\psi_{f2} = \arctan(4564/-3110) = -55.7 \text{ deg or } 124.3 \text{ deg}$$

For the 220-deg early bird missile (as shown in Fig. 4.25c) and the leading fragment ($\alpha_1 = -80$ deg)

$$(v_{f1})_x = (1600 \text{ ft/s}) \cdot \cos(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(220 \text{ deg} - 80 \text{ deg})$$
$$-800 \text{ ft/s} = -5856 \text{ ft/s}$$

$$(v_{f1})_z = (1600 \text{ ft/s}) \cdot \sin(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(220 \text{ deg} - 80 \text{ deg})$$
$$= 2185 \text{ ft/s}$$

Thus,

$$\psi_{f1} = \arctan(2185/-5856) = -20.5 \text{ deg or } 159.5 \text{ deg}$$

For the trailing fragment ($\alpha_2 = -95$ deg)

$$(v_{f2})_x = (1600 \text{ ft/s}) \cdot \cos(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(220 \text{ deg} - 95 \text{ deg})$$
$$-800 \text{ ft/s} = -4894 \text{ ft/s}$$

$$(v_{f2})_z = (1600 \text{ ft/s}) \cdot \sin(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(220 \text{ deg} - 95 \text{ deg})$$
$$= 3067 \text{ ft/s}$$

Thus,

$$\psi_{f2} = \arctan(3067/{-4894}) = -32.1 \text{ deg or } 147.9 \text{ deg}$$

For the 40-deg late bird missile (as shown in Fig. 4.20b) and the leading fragment ($\alpha_1 = -80$ deg)

$$(v_{f1})_x = (1600 \text{ ft/s}) \cdot \cos(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(40 \text{ deg} - 80 \text{ deg})$$
$$-800 \text{ ft/s} = 4256 \text{ ft/s}$$

$$(v_{f1})_z = (1600 \text{ ft/s}) \cdot \sin(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(40 \text{ deg} - 80 \text{ deg})$$
$$= -2185 \text{ ft/s}$$

Thus,

$$\psi_{f1} = \arctan(-2185/4256) = -27.2 \text{ deg or } 332.8 \text{ deg}$$

For the trailing fragment ($\alpha_2 = -95$ deg)

$$(v_{f2})_x = (1600 \text{ ft/s}) \cdot \cos(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(40 \text{ deg} - 95 \text{ deg})$$
$$-800 \text{ ft/s} = 3294 \text{ ft/s}$$

$$(v_{f2})_z = (1600 \text{ ft/s}) \cdot \sin(40 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(40 \text{ deg} - 95 \text{ deg})$$
$$= -3067 \text{ ft/s}$$

Thus,

$$\psi_{f2} = \arctan(-3067/3294) = -43.0 \text{ deg or } 317.0 \text{ deg}$$

Finally, for the 220-deg late bird and the leading fragment ($\alpha_1 = 80$ deg)

$$(v_{f1})_x = (1600 \text{ ft/s}) \cdot \cos(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(220 \text{ deg} + 80 \text{ deg})$$
$$-800 \text{ ft/s} = 474 \text{ ft/s}$$

$$(v_{f1})_z = (1600 \text{ ft/s}) \cdot \sin(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(220 \text{ deg} + 80 \text{ deg})$$
$$= -5359 \text{ ft/s}$$

Thus,

$$\psi_{f1} = \arctan(2185/{-5856}) = -84.9 \text{ deg or } 275.1 \text{ deg}$$

For the trailing fragment ($\alpha_2 = 95$ deg)

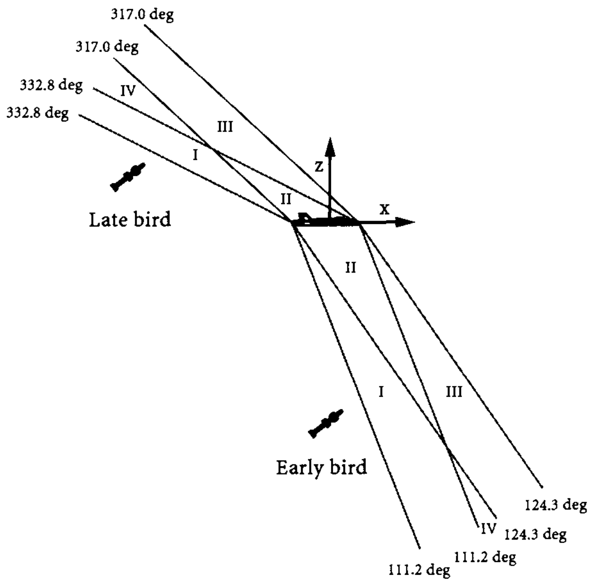
$$(v_{f2})_x = (1600 \text{ ft/s}) \cdot \cos(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \cos(220 \text{ deg} + 95 \text{ deg})$$
$$-800 \text{ ft/s} = 1510 \text{ ft/s}$$

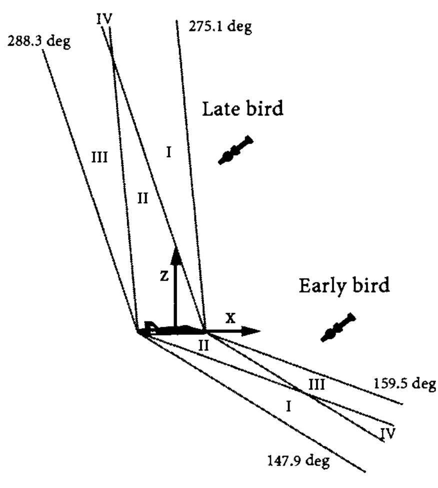
$$(v_{f2})_z = (1600 \text{ ft/s}) \cdot \sin(220 \text{ deg}) + (5000 \text{ ft/s}) \cdot \sin(220 \text{ deg} + 95 \text{ deg})$$
$$= -4564 \text{ ft/s}$$

Thus,

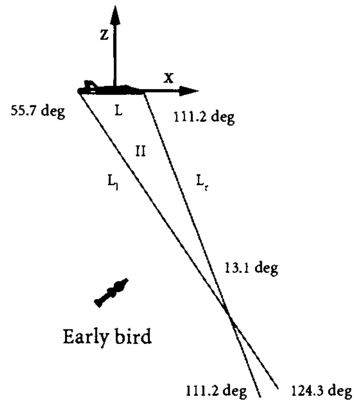
$$\psi_{f2} = \arctan(-4564/1510) = -71.7 \text{ deg or } 288.3 \text{ deg}$$

The detonation zones for the four intercepts are shown next.





The length of each of the two sides of zone II for the 40-deg early bird is determined using the law of sines and the diagram shown here:



The three interior angles of the triangle that defines zone II are, clockwise from tail of the aircraft, 180 deg − 124.3 deg = 55.7 deg, 111.2 deg, and 180 deg − 55.7 deg − 111.2 deg = 13.1 deg. The length of the target is 30 ft. Thus, according to the Law of Sines

$$(30\text{ ft})/\sin(13.1\text{ deg}) = L_l/\sin(111.2\text{ deg}) = L_r/\sin(55.7\text{ deg})$$

Hence,

$$L_l = (30\text{ ft})\sin(111.2\text{ deg})/\sin(13.1\text{ deg}) = 124\text{ ft}$$
$$L_r = (30\text{ ft})\sin(55.7\text{ deg})/\sin(13.1\text{ deg}) = 109\text{ ft}$$

Go to Problem 4.3.63.

Number of fragment hits. The damage inflicted on the aircraft by an external HE warhead detonation depends on the number and the location of the fragment impacts and on the terminal effects parameters, such as the fragment mass and impact velocity. The probability of an aircraft kill as a result of the fuzing and subsequent detonation of a specific warhead for a particular set of encounter conditions $P_{K|F}$ is dependent upon how many fragments hit the aircraft and the aircraft's vulnerability to the hits. In general, the fragments will be randomly distributed throughout the fragment spray zone. The expected number of hits on a horizontally moving aircraft can be estimated by assuming a presented area of the aircraft is hit with a uniform density spray of fragments. In this situation the expected number of hits E on the aircraft presented area at the aspect under consideration A_P is given by

$$E = \rho A_P \tag{4.49}$$

where ρ is the average number of fragments per unit area of fragment spray, known as the fragment spray density.

If the fragments are assumed to have a uniform velocity and to be uniformly spread over a spherical segment between the leading and trailing fragment dynamic trajectories ϕ_1 and ϕ_2 with respect to a stationary target in the local (x, y) coordinate system, as shown in Fig. 4.26, the fragment spray density (relative to the target) at the distance D from the detonation point shown in Fig. 4.25b can be approximated by

$$\rho = \frac{M}{2\pi D^2(\cos\phi_1 - \cos\phi_2)} \tag{4.50}$$

where M is the total number of fragments in the warhead, ϕ_1 and ϕ_2 are given by Eq. (4.46d), and D is given by Eq. (4.47a).

The number of hits depends upon the area presented to the fragment spray. Consider the intercept situation shown in Fig. 4.26. When the detonation is within zone II, the entire spray arc hits a portion of the bottom surface of the aircraft. The length of the arc of the spray between ϕ_1 and ϕ_2 at the aircraft, l, is given by

$$l = D|\phi_2 - \phi_1| \tag{4.51a}$$

Assume the impacted target surface has an average width [normal to the (x, z) plane] W. Thus, the area of the fragment spray that impacts the target A_P is

$$A_P = l \times W \tag{4.51b}$$

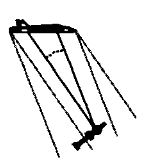
When the detonation occurs in zone IV in Fig. 4.26, the entire bottom surface of the target A_T gets hit by the fragment spray. In general, the fragment spray will impact the bottom of the aircraft at an average angle $\psi_{f1} < \psi_f < \psi_{f2}$. Thus, the area of the fragment spray that impacts the target is

$$A_P = A_T|\sin\psi_f| = W \times L|\sin\psi_f| \tag{4.51c}$$

where $L|\sin\psi_f|$ is the target length presented to the spray arc.

Example 4.12 Number of Fragment Hits

The early bird missile elevation angle of 40 deg in Example 4.11 detonates in zone II at $D = 60$ ft as shown here:



There are 1000 fragments in the warhead. How many fragments hit the aircraft if the aircraft's bottom area is approximated by $L = 30$ ft and $W = 10$ ft?

The fragment spray angles ψ_{f1} and ψ_{f2} for the 40-deg early bird are

$$\psi_{f1} = 111.2 \text{ deg} \quad \psi_{f2} = 124.3 \text{ deg}$$

Therefore,

$$\phi_1 = 111.2 \text{ deg} - 40 \text{ deg} = 71.2 \text{ deg} = 1.24 \text{ rad}$$
$$\phi_2 = 124.3 \text{ deg} - 40 \text{ deg} = 84.3 \text{ deg} = 1.47 \text{ rad}$$

according to Eq. (4.46d).

The fragment spray density is

$$\rho = \frac{1000 \text{ fragments}}{2\pi(60 \text{ ft}^2)[\cos(71.2 \text{ deg}) - \cos(84.3 \text{ deg})]} = 0.198 \text{ fragments/ft}^2$$

according to Eq. (4.50).

The length of the spray arc for $D = 60$ ft is

$$l = (60 \text{ ft}) \cdot |1.47 \text{ rad} - 1.24 \text{ rad}| = 13.8 \text{ ft}$$

according to Eq. (4.51a). The area of the fragment spray that impacts the target is

$$A_P = (13.8 \text{ ft}) \cdot (10 \text{ ft}) = 138 \text{ ft}^2$$

according to Eq. (4.51b). Hence,

$$E = (0.198 \text{ fragments/ft}^2) \cdot (138 \text{ ft}^2) = 27.3 \text{ fragments}$$

Suppose the detonation distance was in zone IV at 175 ft. The fragment spray density at that detonation distance is

$$\rho = \frac{1000 \text{ fragments}}{2\pi(175 \text{ ft}^2)[\cos(71.2 \text{ deg}) - \cos(84.3 \text{ deg})]} = 0.0233 \text{ fragments/ft}^2$$

Because the detonation is in zone IV, the entire bottom area of the target is impacted at an average $\psi_f = 118$ deg. Hence,

$$A_P = (10 \text{ ft})(30 \text{ ft})|\sin(118 \text{ deg})| = 265 \text{ ft}^2$$

according to Eq. (4.51c). Thus,

$$E = (0.0233 \text{ fragments/ft}^2) \cdot (265 \text{ ft}^2) = 6.2 \text{ fragments}$$

All of the equations presented here to determine the expected number of fragments that hit an aircraft are based upon the assumption that the neither the velocity vector of the aircraft nor that of the fragments changes as the fragments travel away from the detonation point. However, according to Example 4.10, the velocity of a 200-grain fragment decays from slightly more than 6000 ft/s to approximately 4200 ft/s in 175 ft. This means that the straight lines that define the four zones shown in Fig. 4.26 should be curved lines.

Go to Problem 4.3.64.

Probability of fuzing ($P_{F|I}$). As the propagator moves along the path relative to the aircraft shown in Fig. 4.26, the target detection device on the propagator looks for the target. In the most lethal situation the target would be detected prior to the propagator reaching the first detonation zone, and, after some delay the fuze would detonate the high-explosive charge when the propagator reached zone II or zone IV. In general, the preferred detonation location would be along the line from the target centroid through the center of zones II and IV, as illustrated in Fig. 4.27. Note that the angle of the optimum fuze line is approximately halfway between the leading fragment angle ψ_{f1} and the trailing fragment angle ψ_{f2}.

Considering the stochastic nature of the intercept and subsequent fuzing, three different possibilities for $P_{F|I}$ are postulated in Fig. 4.27. For example, fuzing

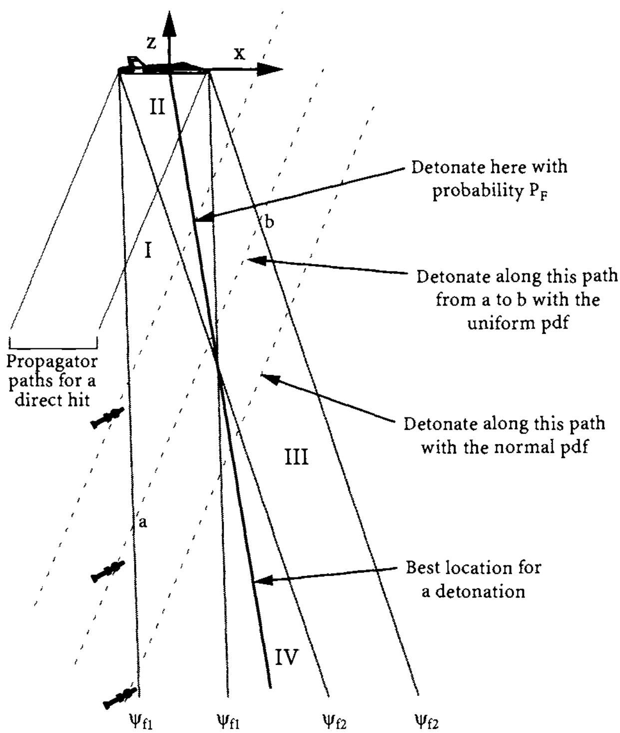


Fig. 4.27 Probability of fuzing.

could occur at one specific location with the probability P_F as illustrated by the top-most propagator. That point could be the centerline, as shown in Fig. 4.27, or it could be the location along the flight path predicted by a fuze test or a computer model. A second possibility illustrated by the middle propagator is the assumption that fuzing occurs with equal likelihood at any location along the path length p from a to b. This assumption is satisfied by the uniform probability density function P_F/p. The probability that fuzing occurs within an interval Δp is $P_F(\Delta p/p)$. A third possibility is the assumption that the fuzing is normally distributed about the 'best detonation location.' Note that many TDDs have a range cutoff; they do not function when the separation distance between the propagator and the target is greater than the cutoff value.

Go to Problem 4.3.65.

4.3.7.3 Impact conditions.

Learning Objective	**4.3.25**	**Determine the penetrator impact conditions, including the impact velocity and the shotline direction.**

When the miss distance of a missile, projectile, fragment, or penetrator is less than the extent of the aircraft, a hit occurs. (Because the impact conditions described next are applicable to all bodies, only the penetrator is referred to in the presentation, and the subscript p can be interpreted as a penetrator, propagator, or fragment.) The direction of approach of the penetrator toward the aircraft, relative to the aircraft, is known as the attack direction or shotline. Figure 4.28 shows two parallel shotlines, one at A on the port (left) wing and one at B on the starboard (right) wing. Both shotlines start from above the aircraft and pass through the aircraft's wing, emerging from the lower surface. Consequently, a penetrator traveling along either one of these shotlines impacts the upper surface of a wing. Whether or not it penetrates the wing skin and proceeds along the shotline through the wing depends upon the penetrability of the skin and the components along the shotline.

Shotline direction and the impact velocity. The global (X, Y, Z) and local (x, y, z) coordinate systems in Fig. 4.28 are the same as those shown in Figs. 4.20 for the propagator miss distance and in Fig. 4.25 for the fragment miss distance. The velocity vector of the penetrator relative to the target $\boldsymbol{v}_p$ and the separation vector $\boldsymbol{s}$ between the center of the target and the center of the propagator were determined in the preceding subsections. The relative velocity vector $\boldsymbol{v}_p$, as shown in Figs. 4.20b and 4.25b, defines the shotline, as shown in Fig. 4.28, and the relative velocity v_p, defined by Eq. (4.25b), is the impact velocity V_i. The (x, y, z) coordinates of $\boldsymbol{v}_p$ are given by Eq. (4.25a) in terms of the global velocities V_T and V_P and the propagator global elevation angle Ψ_P and azimuthal angle Ω_P. However, the shotline angles ψ_s and ω_s in the local (x, y, z) system shown in Fig. 4.28 are not the same as ψ_p and ω_p defined by Eq. (4.25c). Instead, the shotline

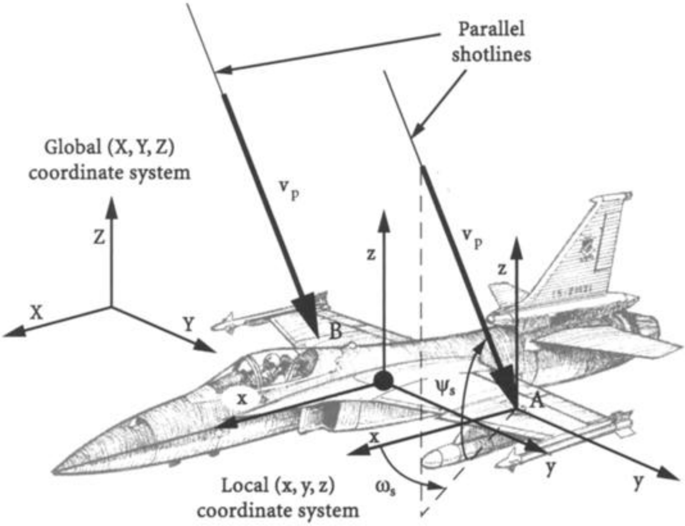


Fig. 4.28 Two parallel shotlines.

angles are in the reverse direction, and hence are given by

$$\psi_s = -\psi_p \quad \text{and} \quad \omega_s = \omega_p - 180 \text{ deg} \tag{4.52}$$

When Eq. (4.25c) is solved for ω_p, the value provided by a calculator will not distinguish between impacts from behind and on the starboard side and those from in front and on the port side since the argument is positive in both cases. Nor will it distinguish those from the front on the right side from those from the back on the left side when the argument is negative. Consequently, the decision as to the correct direction of the shotline can be made by examining the sign of the three velocity vector components. If $(v_p)_z$ is negative, the shotline is descending from above; and if it is positive, it is coming from below the aircraft. If $(v_p)_x$ is negative, the direction of the propagator velocity vector is in the opposite direction of the aircraft velocity vector, and the impact is from the front; and if it is positive, the propagator is traveling in the same direction as the aircraft, and the impact is from behind the aircraft. If $(v_p)_y$ is negative, the impact is on the port side of the aircraft, and if it is positive, the starboard side gets hit.

Generally, the shotline will not be normal to the target surface at the impact point. The angle between the approaching shotline and the outward normal to the target plate at the impact point is known as the angle of obliquity, θ. Every impact point on the aircraft that is not an edge or corner has a unique outward normal whose direction can be defined in terms of the surface azimuthal and elevation angles ω_n and ψ_n, as illustrated in Fig. 4.29. The value of θ can be determined for any attack direction and surface orientation using the geometric relationship

$$\begin{aligned}\theta = \arccos[&(\cos\psi_s \cos\omega_s)(\cos\psi_n \cos\omega_n) + (\cos\psi_s \sin\omega_s)(\cos\psi_n \sin\omega_n)\\ &+ (\sin\psi_s)(\sin\psi_n)] \qquad 0 \le \theta \le 90 \text{ deg}\end{aligned} \tag{4.53}$$

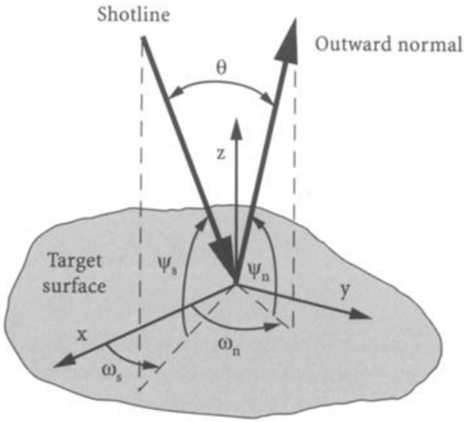


Fig. 4.29 Impact angle of obliquity.

Another parameter that can influence penetration by ballistic projectiles and elongated fragments is the yaw of the projectile from the shotline ϕ (not the fragment spray angle), which impacts the plate. Assuming the projectile longitudinal axis is in the direction of penetrator travel in the global coordinate system, there will be a penetrator yaw relative to the shotline when $V_T > 0$. The magnitude of yaw is given by

$$\phi = \arccos\{(\cos\psi_s \cos\omega_s)[-(v_p)_x/v_p] + (\cos\psi_s \sin\omega_s)[-(v_p)_y/v_p] + (\sin\psi_s)[-(v_p)_z/v_p]\} \quad (4.54)$$

Example 4.13 presents the calculations for the impact velocity, shotline direction, and the obliquity angle for an aircraft passing by a gun.

Example 4.13 Impact Velocity, Shotline Direction, and Angle of Obliquity

An aircraft is flying straight and level at an altitude of 300 m. It is traveling from left (south) to right (north) at a speed of 200 m/s. A 12.7-mm machine gun at 0-m elevation is northwest of the aircraft. The gun is pointing in the southwest direction and is aimed ahead of the aircraft at the aircraft's predicted straight and level flight path. A burst of rounds is fired at the approaching aircraft. One round hits the aircraft. The following equations define the conditions at the point of impact. The relative velocity components are

$$(v_p)_x = -700 \text{ m/s} \quad (v_p)_y = -500 \text{ m/s} \quad (v_p)_z = 280 \text{ m/s}$$

The impact velocity is

$$v_p = \sqrt{(-700 \text{ m/s})^2 + (-500 \text{ m/s})^2 + (280 \text{ m/s})^2} = 904.7 \text{ m/s}$$

Previous Page

according to Eq. (4.25b), and

$$\psi_p = \arctan\left[\frac{280 \text{ m/s}}{\sqrt{(-700 \text{ m/s})^2 + (-500 \text{ m/s})^2}}\right] = 18.0 \text{ deg}$$

$$\omega_p = \arctan\left(\frac{-500 \text{ m/s}}{-700 \text{ m/s}}\right) = 35.5 \text{ deg or } 215.5 \text{ deg}$$

according to Eq. (4.25c). Because $(v_p)_z$ is positive, the shotline is from below the aircraft, and hence

$$\psi_s = -18.0 \text{ deg}$$

according to Eq. (4.52). Because $(v_p)_x$ is negative and $(v_p)_y$ is negative, the shotline impacts the port side from the front, and hence

$$\begin{aligned} &\omega_p = 215.5 \text{ deg} \\ &\therefore \omega_s = 215.5 \text{ deg} - 180 \text{ deg} = 35.5 \text{ deg} \end{aligned}$$

according to Eq. (4.52).

The round hits the aircraft in the lower portion of the port side of the forward fuselage below the cockpit. The normal to the surface at the impact point is

$$\psi_n = -45 \text{ deg} \quad \omega_n = 45 \text{ deg}$$

Consequently, the impact angle of obliquity is

$$\begin{aligned} \theta = \arccos \{ &[\cos(-18.0 \text{ deg}) \cos(35.5 \text{ deg})] \cdot [\cos(-45 \text{ deg}) \cos(45 \text{ deg})] \\ &+ [\cos(-18.0 \text{ deg}) \sin(35.5 \text{ deg})] \cdot [\cos(-45 \text{ deg}) \sin(45 \text{ deg})] \\ &+ \sin(-18.0 \text{ deg}) \sin(-45 \text{ deg}) \} = 28.1 \text{ deg} \end{aligned}$$

according to Eq. (4.53).

Go to Problems 4.3.66 to 4.3.67.

4.4 Task III: Design for Low Susceptibility Using Susceptibility Reduction Technology

4.4.1 Some Terms, Definitions, and Susceptibility Reduction Concepts

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Learning Objectives	4.4.1	**Describe the terms countermeasures, passive and active countermeasures, electronic warfare, electronic attack, electronic countermeasures, electronic protection, electronic counter-countermeasures, and electronic warfare support.**

4.4.2 Give examples of how each of the six susceptibility reduction concepts affects P_H and P_F.

4.4.3 Use the Joint Electronics Type Designation System to decode the designation of U. S. electronic equipment.

Designing for low susceptibility means designing to reduce P_H and P_F, and using the susceptibility reduction technology means using the six susceptibility reduction concepts listed in Table 1.3 and shown in Fig. 4.30 with some typical techniques. The history of reducing an aircraft's susceptibility to hostile air defense systems is mainly a story of reactions to a changed or unanticipated threat situation, most of them conducted on a short-term crash basis in order to keep aircraft losses to an 'acceptable' level. As a consequence, this approach to survivability enhancement through the use of susceptibility reduction technology is often referred to as countermeasures because its purpose is to counter or degrade the actions of the threat elements. The development and production of passive and active countermeasures systems and techniques (Note 30), and their application to the enhancement of aircraft survivability, have in the past followed the ebb and flow of immediate military needs and have tended, therefore, to lag the development of air defense weapons. However, the hard lessons learned in the last half-century have given countermeasures the proper credentials to make them a major consideration for survivability enhancement; and susceptibility reduction is now given serious attention over the entire life span of aircraft, from the earliest conceptual design phase until retirement from the inventory.

The increasing use of electromagnetic radiating and receiving devices for target acquisition and tracking and for the guidance and fire control of propagators has led to a major emphasis on countermeasures to the electronic threat elements, and the

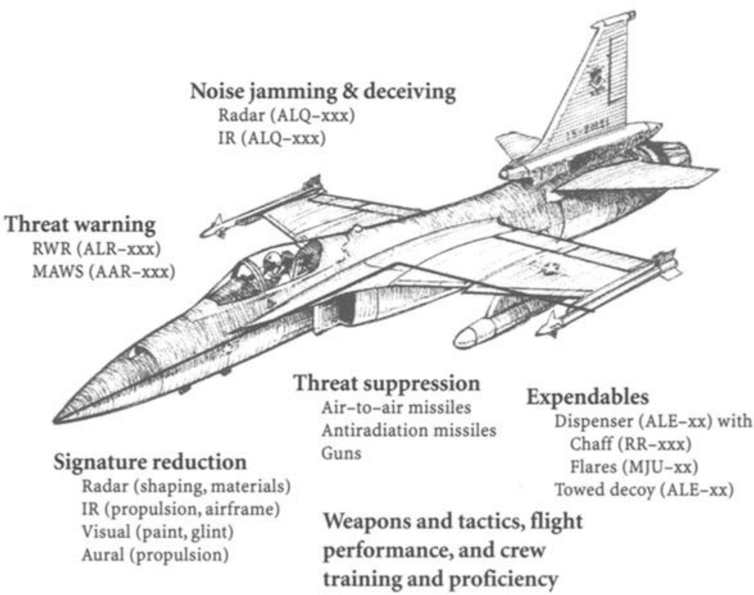


Fig. 4.30 Six susceptibility reduction concepts with some typical techniques.

terms electronic warfare (EW), electronic attack (EA), electronic countermeasures (ECM), electronic protection (EP), electronic counter-countermeasures (ECCM), and electronic warfare support (ES) have become familiar to anyone associated with aircraft survivability. For those not familiar with these terms, their definitions are given in Table 4.6.

Almost all of the threat systems use a particular region of the electromagnetic frequency spectrum shown in Fig. 4.1. The earliest electronic systems used the radio portion for target detection and tracking. These were called radar systems. The many new detection, tracking, and homing devices, such as the electro-optical and laser devices, rely on the entire spectrum, from the lowest radio frequencies through microwaves, infrared, visible light, and out to ultraviolet. Aircraft survivability is now dependent upon countermeasures that must cover this ever-expanding frequency spectrum.

Many different types of countermeasures or SR techniques have been developed to degrade the effectiveness of the various elements of the hostile air defense systems. For example, it was shown in Chapter 1, Eqs. (1.5a) and (1.5b), that the probability of an aircraft hit or HE proximity warhead fuzing could be expressed as the product of a series of individual probabilities in the form

$$P_H = P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I} \tag{1.5a}$$

$$P_F = P_A P_{D|A} P_{L|D} P_{I|L} P_{F|I} \tag{1.5b}$$

All of these probabilities can be affected in some manner by SR techniques, as illustrated in Fig. 1.6. The probability the threat is active P_A can be reduced by the use of antiradiation missiles and iron bombs to destroy active radar units and other threat platforms and by the use of tactics that catch the enemy off guard or overwhelm him. The probability of successful detection by an active weapon system $P_{D|A}$ can be reduced by tactics that employ terrain masking to reduce the probability that the threat will have a clear line of sight to the aircraft. The probability of detection can also be affected by passive measures that reduce or disguise the signatures of the aircraft. Countermeasures in the form of self-protection or support electronic jamming of the enemy's electronic tracking devices can be actively employed to reduce the probability of accurate target tracking and subsequent missile launch or gun firing. Similarly, the probability of a successful missile guidance to an intercept $P_{I|L}$ can be decreased by jamming missile command guidance signals or missile downlinks, and proximity-fuze jamming techniques can cause a premature detonation or disabling of the weapon arming system, thus reducing the probability of a successful HE warhead proximity detonation $P_{F|I}$ (Note 31). In general, the combined effects of all of these techniques are usually synergistic and can significantly enhance the probability of aircraft survival in the hostile environment.

All six of the susceptibility reduction concepts shown in Fig. 4.30, except some aspects of signature reduction and tactics, involve some piece of equipment, device, or armament that is carried either by the aircraft for self-protection or by another special purpose aircraft in a support role. Specific applications of each of these concepts have been developed for the important portions of the electromagnetic spectrum (radar, IR, and visual), and in most combat situations combinations of these concepts are used to degrade more than one aspect of the total air defense system. Because most of this equipment is referred to by its type designation, Fig. 4.31

Table 4.6 Electronic warfare terminology

Term	Definition
Electronic warfare (EW)[a]	"Any military action involving the use of electromagnetic and directed energy to control the electromagnetic spectrum or to attack the enemy. The three major subdivisions within electronic warfare are electronic attack, electronic protection, and electronic warfare support."[a]
Electronic attack (EA)[a]	"That division of electronic warfare involving the use of electromagnetic, directed energy, or antiradiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability. EA includes 1) actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum, such as jamming and electromagnetic deception and 2) employment of weapons that use either electromagnetic or directed energy as their primary destructive mechanism (lasers, radio frequency weapons, particle beams)."[a]
Electronic countermeasures (ECM)[b]	"That division of electronic warfare involving actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum. (Note that ECM is the first part of EA.)"[b]
Electronic protection (EP)[a]	"That division of electronic warfare involving actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy employment of electronic warfare that degrade, neutralize, or destroy friendly combat capability."[a]
Electronic counter-countermeasures (ECCM)[b]	"That division of electronic warfare involving actions taken to ensure friendly effective use of the electromagnetic spectrum despite the enemy's use of EW."[a]
Electronic warfare support (ES)[a]	"That division of electronic warfare involving actions tasked by, or under direct control of, an operational commander to search for, intercept, identify, and locate sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition. Thus, electronic warfare support provides information required for immediate decisions involving electronic warfare operations and other tactical actions such as threat avoidance, targeting, and homing."[a]

[a] http://www.dtic.mil/doctrine/jel/doddict/index.html and http://www.dtic.mil/doctrine/jel/new_pubs/jp1_02.pdf.
[b] http://www.jedefense.com/updir/shelf/ewdef.html under the link Resource Guide/EWReference-Shelf/Definitions of EW terms.

AN / A L Q - 99 A

Set (AN)

- A — First Modification
- 99 — Model = 99
- Q — Purpose = Special or Combination
- L — Type = Countermeasures
- A — Installation = Airborne

Installation	Type	Purpose
A Piloted aircraft B Underwater mobile submarine D Pilotless carrier F Fixed ground G General ground use K Amphibious M Mobile (ground) P Portable S Water T Transportable (ground) U General utility V Vehicular (ground) W Water surface and underwater combination Z Piloted—pilotless airborne vehicle combination	A Invisible light, heat radiation C Carrier D Radiac G Telegraph or teletype I Interphone and public address J Electromechanical or inertial wire covered K Telemetering L Countermeasures M Meteorological N Sound in air P radar Q Sonar and underwater sound R Radio S Special or combinations of types T Telephone (wire) V Visual and visible light W Armament X Facsimile or television Y Data processing	B Bombing C Communications D Direction finder, reconnaissance and/or surveillance E Ejection and/or release G Fire control or searchlight directing H recording and/or reproducing K Computing M Maintenance and/or test assemblies N Navigational aids Q Special or combination of purposes R Receiving, passive detecting S Detecting and/or range and bearing search T Transmitting W Automatic flight or remote control X Identification and recognition Y Surveillance (search, detect, and multiple tracking) and control (both fire and air)

Fig. 4.31 Joint Electronics Type Designation System.

presents the Joint Electronics Type Designation System (JETDS) used for U. S. military electronic equipment.

The remainder of this section presents descriptions and examples of each of the six susceptibility reduction concepts. For additional information there are several periodicals devoted to one or more aspects of susceptibility reduction, such as the biennial *International Electronic Countermeasures Handbook* and the monthly *Journal of Electronic Defense* (the Association of Old Crows Electronic Warfare and Information Operations publication located at http://www.jedonline.com). The JED Web site has an archival section that goes back more than 10 years. *Aviation Week and Space Technology* occasionally publishes a special issue devoted to EW. There are also a relatively large number of books on EW and signature reduction. A Web site with a tutorial on EW is located at http://www.goldcrows.org/ewtutor1.htm, and a series of tutorials on radar and EW that appeared in the *Journal of Electronic Defense* is available online at http://www.jedonline.com under the link ResourceGuide/EW 101 Archives.

Go to Problems 4.4.1 to 4.4.6.

4.4.2 Threat Warning

Learning	**4.4.4**	**Describe the advantages of threat warning.**
Objectives	**4.4.5**	**Describe the types of threat warning equipment.**

Knowledge of the location, type, and status of the threat elements during the planning of a mission and during the execution of that mission is extremely important to an aircraft's survival. When planning the mission with a knowledge of the enemy's air defense weapon locations, the routes, altitudes, and ordnance can be selected to avoid the most effective or numerous threats, and supporting assets, such as standoff electronic jamming aircraft and fighter escorts, can be assigned as needed. While on the mission, if the pilot knew that enemy air interceptors were on their way he/she could prepare for battle. If the pilot knew that a missile was approaching from a particular direction, he/she could eject radar-reflecting chaff or IR flares and make an evasive maneuver in an attempt to significantly increase the miss distance. Or if he/she knew that the aircraft were being tracked by a particular type of fire control system, jamming could be initiated and expendables deployed to cause the tracker to lose 'sight' of the aircraft, thus breaking the tracker's lock on the aircraft. Passive and active onboard threat warning devices are designed to provide that kind of information. Passive, onboard threat warning devices for many of the hostile radar detection, tracking, and missile guidance systems have been developed and are referred to as radar homing and warning receivers (RHAW), radar warning receivers (RWR), and intercept receivers. The need for similar warning devices for the IR, visual, and laser tracking and guidance systems and for the warning of a missile launch and approach, known as a missile warning system (MWS) or a missile approach and warning system (MAWS), is apparent. Not all threat warning requires electronic sensors, for example, the radio call from a wingman who has spotted a missile heading toward your aircraft, and not all threat warning is passive, for example, the pulse Doppler radar that detects approaching missiles is an active system.

4.4.2.1 Radar warning. Radar warning of the presence of radar-directed air defenses requires two capabilities for maximum effectiveness. They are the timely detection of the radiating threat elements and the accurate location and status of the weapon delivery systems intent on destroying the aircraft. Because of the extent and capabilities of the early warning radar networks, the assumption is sometimes made that a nonstealthy aircraft will be under observation by the early warning radars long before it reaches its destination, and thus there is generally no need to warn the aircrew of this fact. Consequently, the radar warning is usually associated with the tracking and fire control radars, and the basic radar warning functions are to provide the crew with a map of the hostile radar-directed weapons that surround the aircraft and their status. The radar warning receiver provides this map by detecting the radar emissions impinging on the aircraft, and from this information it determines the classification (radar type), location (range and bearing), and status of the weapon system with respect to the aircraft (searching, tracking, illuminating, or actively guiding a missile). A prioritization of the threats based upon their status might also be indicated. If the response is not automatic, the aircrew must then decide what to do with this information, such as attempt to mask the aircraft behind terrain, eject a bundle of chaff, turn on a radar jammer or deceiver, and/or initiate a missile evasive maneuver if a missile is on the way.

Equipment. All RWR systems contain the same basic components to perform the functions of signal detection and identification and of emitter location or direction-finding (DF). These components consist of one or more antennas, a receiver, a signal analyzer, and a display. A control panel for operator input and one or more auxiliary outputs, such as warning lights or audio tones, are often provided. The display associated with most RWRs consists of a cathode-ray tube (CRT) or a flat-panel head-up display. In hardware RWRs the direction to the radar is usually indicated by a strobe or radial line; the type of radar can be denoted by the type of line, such as solid, dashed, or flashing; and a rough approximation of the range to the radar is given by the length of the strobe. Software RWRs typically use symbols to denote the type of radar, and the position of the symbol on the screen might indicate the radar bearing, range, and status. A blinking symbol or audible signal can be used to inform the crew as to the status of the system. The aural output makes it unnecessary for the crew to constantly monitor the display because the modulation and volume of the audio signal indicate to the crew the particular status of the threat. For example, when the radar is searching wide variations in the signal amplitude will take place as the radar beam scans back and forth across the aircraft. This could be indicated by a relatively soft and slowly varying tone. When the radar is in the track mode, the signal could be a loud tone with a modulation frequency equal to the PRF of the tracking radar. The fact that a missile is being command guided toward the aircraft could be indicated by a very loud warbling tone. Some modern systems may provide (Bitchin' Betty) voice alerts. (http://www.geocities.com/Athens/forum/6682/erica.html.

Because it might be difficult for the crew to react in time to the warning provided by the RWR, and because only a limited amount of electronic power is available for radar jamming, many modern EA systems incorporate a power management processor. This processor examines the output from the intercept receiver and optimally allocates the available electronic and expendable countermeasures to defeat the threat. The power manager often shares the same physical unit with the receiver to save on costs and space. The primary functions of power management are the allocation of jamming and expendable resources to priority targets, the pointing of any rotatable jamming antennas, the optimization of the jamming by the selection of modulation techniques and frequency setting to match the measured radar characteristics, and a reallocation, if required, based on controlled 'look-through' of the jamming signals by the RWR. Furthermore, because the jamming is under complete control of the manager the jamming duty cycle can be adjusted for both maximum jamming effectiveness and system power consumption. An unmanaged system will attempt to jam all radars, including those that are not a threat to the aircraft. The managed system will jam only those radars that are a threat and, consequently, can use the available power selectivity to jam more of the threat radars. The use of time-gated noise allows the jammer to nearly simultaneously jam several radars in succession, thus controlling the system power consumption without reducing the jamming effectiveness. The power manager can also control the deployment of expendables. Just as in the case of jamming, prestored priority rules can be used by the processor to select the radars against which to deploy chaff, either alone or in conjunction with jamming.

Design considerations. The selection or design of an RWR for a particular aircraft is influenced by the aircraft mission requirements, the aircrew complement and duties, and the aircraft itself. Each mission places certain requirements upon the RWR system. For example, an attack mission might require relatively good emitter location information, particularly in the forward direction. If the aircraft flies very low, the surveillance radars might not interfere. However, for aircraft that operate at higher altitudes the nonthreatening radars must be sorted out from the actual threats. Strike cover and threat suppression, on the other hand, have the requirement to identify and accurately locate radar systems that are threatening other aircraft. Multimission aircraft can pose a more difficult design problem than single mission aircraft.

The number and duties of the aircrew dictate the degree of automation required for the RWR. In a single-placed aircraft the RWR must not add appreciably to the pilot's tasks, but it nevertheless must keep the pilot aware of the total threat situation. In aircraft with two crew members, the person not flying the aircraft might have more time to monitor the data from the RWR. Aircraft with many members might have an electronic warfare officer (EWO) devoted to the survivability problem. This concentrated assignment permits an increased latitude in the automation, the amount of data that can be presented and interpreted, and the degree of control that can be exercised.

The aircraft itself also influences the requirements for the RWR system. The available space and weight are obvious considerations, and the decision whether to centralize or to scatter the various electronic components plays a major role. The location of the antennas is influenced by the aircraft shape and stealth requirements and by the location of other emitters on the aircraft, such as the jammer and other radars.

4.4.2.2 Infrared/laser/visual warning. The need for warning devices for the IR, laser, and visual detection, tracking, illuminating, and missile guidance systems is becoming increasingly apparent. The laser threat warning receiver operates on the same principle as the radar warning receiver because the laser is an active system; it must transmit radiation. Illumination of the aircraft by a laser for the purpose of determining range or for the guidance of a beam-rider or semiactive homing missile is no different in principle than illuminating or tracking the aircraft with radar; only the signal characteristic values are different.

4.4.2.3 Missile launch and approach warning. The determination that a missile has been launched, possibly toward the aircraft, can be made using either an active radar tracking system or a passive staring or scanning sensor that detects the electromagnetic radiation associated with the missile launch and flyout. The radar system detects and tracks the approaching missile as radars do. The passive sensor can detect the UV radiation from the missile's rocket flare or the IR radiation from the missile hot parts and rocket flare and plume.[25] These sensors can be located around the aircraft or only in the expected missile approach direction. For example, if IR homing missiles are expected to approach the aircraft from the rear only (which may not be a good assumption), the launch warning system would be installed in the tail of the aircraft. Because there are several common features shared between the target to be detected and the background clutter to be rejected, care must be given to the design of the system to ensure a very low false alarm rate, particularly those systems that employ IR detectors. The MAWS can input the appropriate information regarding the type of the missile and the time-to-go (intercept) into a central countermeasures computer, which will then turn on a jammer, deploy expendables, and automatically maneuver the aircraft to avoid the oncoming missile. The pilot just goes along for the ride.

4.4.2.4 Some threat warning equipment. Table 4.7 lists some of the RWRs and MAWSs in production or late development. Considerably more information on this equipment can be found in Ref. 26 and online at http://www.fas.org/man/dod-101/sys/ac/equip/.

Go to Problems 4.4.7 to 4.4.10.

4.4.3 Noise Jammers and Deceivers

One of the most important countermeasures concepts that should be considered in any survivability program is the use of either onboard, offboard, or standoff active electronic equipment to degrade the effectiveness of the various nonterminal threat elements. Radiation emission equipment carried onboard an aircraft for defensive electronic countermeasures (DECM) is usually referred to as a self-screening or self-protection jammer, such as the airborne self-protection jammer (ASPJ). Offboard equipment can be carried by an unmanned combat aerial vehicle.

Table 4.7 Some threat warning equipment[26]

Equipment (aircraft)	Description (manufacturer)
AN/APR-39[27] (variety of fixed- and rotary-wing aircraft)	Radar warning receiver (BAE Systems)
AN/ALR-45 (USN aircraft)[a]	Radar warning receiver (Litton Advanced Systems Div.)
AN/ALR-46/69 (USAF aircraft and several other NATO countries)[b]	Radar warning receiver (Litton Advanced Systems Div.)
AN/ALR-66 (variety of maritime patrol aircraft, both fixed and rotary wing)	Radar warning receiver (Litton Advanced Systems Div.)
AN/ALR-67 (USN front-line aircraft)	Radar warning receiver (Raytheon Co.)
AN/AAR-44 (large number of aircraft, including U. S. SOCOM C-130s)	Passive missile approach warning system for rapid warning of ground and air-launched missile attack (Cincinnati Electronics)
AN/AAR-47 (Several helicopter types and C-130, C-141, C-5, and C-17 transports)	Passive missile approach warning system intended for battlefield helicopters and strike aircraft (BAE Systems)
AN/AAR-54 (Production ongoing for numerous programs)	Passive missile approach warning system that is part of the Directional Infrared Countermeasures (DIRCM) program (Northop Grumman ESSS)
AN/AAR-56 (will be deployed on the F-22)	Missile approach warning system (BAE Systems)
AN/AAR-57 CMWS (might be deployed on USN/USAF tactical aircraft and on a number of foreign aircraft)	Common Missile Warning System (CMWS) is a missile approach warning system for rotary-wing, transport, and tactical aircraft that is part of the Advanced Threat Infrared Countermeasures (ATIRCM) program (BAE Systems)
AN/ALQ-156 (on 15 different aircraft including CH-47s and C-130s)	Active pulse Doppler missile approach warning system (BAE Systems)
AN/AVR-2[27] (on USA, USN, and USMC helicopters)[c]	Laser detector of range finders, target designators, and beam rider missiles (Raytheon Co.)

[a] USN = U. S. Navy. [b] USAF = U. S. Air Force.
[c] USA = U. S. Army and USMC = U. S. Marine Corps.

Standoff jamming is usually accomplished by a special purpose ECM support aircraft, such as the Navy's EA-6B Prowler aircraft.

There are two major radiation emission techniques used to reduce the susceptibility of the aircraft: noise or denial jamming and deception. Noise jamming can be described as a 'brute force' method in which the jammer simply 'outshouts' or masks the echo from the aircraft. The objective of noise jamming, or simply jamming, is to impair the ability of the enemy's detection and tracking equipment. Deception techniques are more subtle and complex than noise jammers because they transmit signals designed to fool, confuse, or mislead the threat system by appearing as one or more false targets. Deceivers are often referred to as deception jammers, which is technically incorrect because they do not 'jam,' or as deception repeaters or spoofers. References 28–37 contain a considerable amount of information on radar noise jamming and deceiving. Although jamming and deceiving are normally associated with radar, there are devices for jamming and deceiving in the other portions of the electromagnetic spectrum, such as the infrared.

4.4.3.1 Radar noise jamming.

Learning Objectives	**4.4.6**	**Describe the three types of noise jamming.**
	4.4.7	**Compute the J/S and R_B for self-screening jamming.**
	4.4.8	**List the advantages and the disadvantages of dedicated support jammer aircraft.**

Radar noise jamming consists of the generation and directed transmission of a noise-like signal that has the characteristics of radar receiver noise. The purpose of this noise is to mask or obscure the target echo. The noise can be continuous (CW) or intermittent. The radar operator sees the noise on a plan position indicator (PPI) as a relatively large area of clutter. Figure 4.32 illustrates the effects of CW noise jamming on a surveillance radar PPI for three different jammer power levels. Because the surveillance radar continuously listens for the echo, the CW noise is continuously received, and the noise lights up a strobe on the PPI corresponding to the direction of the antenna when the noise is received. Note that for the low-power jammer, the noise is above the threshold only when the main lobe axis of the antenna is pointing at the jammer. For the medium- and high-power jammers the jamming effect is much wider because the noise has sufficient power to be 'seen' off of the main lobe axis of the antenna. Thus, even though the antenna is not pointing directly at the jammer, noise is received, possibly in the side lobes, and the PPI lights up whenever the threshold is exceeded.

There are three general frequency techniques used by radar noise jammers to obscure the aircraft echo. One is called broadband or barrage jamming. It consists of jamming a spectrum of frequencies much wider than the operating bandwidth of the radar. Barrage jamming is normally used when the radar frequency is either unknown or changing, or to cover the operating frequencies of more than one radar. Spot jamming is noise jamming in a relatively narrow frequency band centered at the radar frequency and usually somewhat larger than the radar bandwidth. This type is used when the radar frequency is known. Swept jamming is the rapid, repetitive sweeping of a narrow bandwidth noise signal across the range of frequencies to be jammed and is sometimes used in place of barrage jamming.

Jam-to-signal ratio. One of the most important parameters affecting the effectiveness of noise jamming is the jam-to-signal or J/S ratio. This is the ratio of the power of the noise J to the power of the echo S at the aircraft and at the radar receiver (Note 32). The power of the jammer within the bandwidth of the radar receiver is denoted here by P_j. Because the frequency bandwidth of the jammer can be anywhere from slightly larger than the bandwidth of the radar to very much

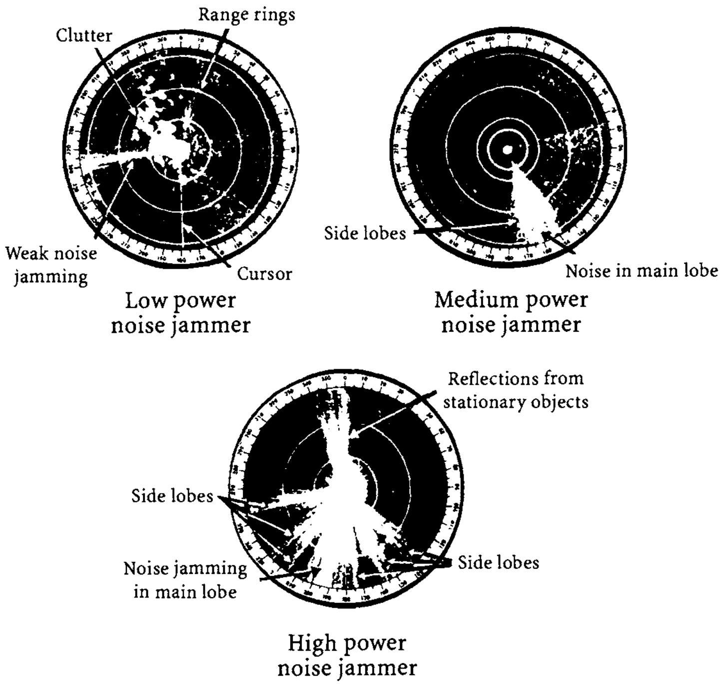


Fig. 4.32 Examples of continuous noise jamming effects on a PPI.

larger than the radar bandwidth, depending upon the type of jamming, P_j is only that portion of the total jammer power intercepted by the radar receiver. The power of the generated noise directed toward the radar depends upon the jammer antenna gain in the direction of the radar antenna G_j and is given by

$$\begin{aligned}\text{Noise power at the target } J &= P_j G_j \\ &= \text{Jammer effective radiated power (JERP)} \quad (\text{W})\end{aligned} \tag{4.55a}$$

For the self-screening situation the power in the echo at the target is given by Eq. (4.5c) when losses are neglected. Hence

$$\text{Echo power at the target } S = \frac{P_r G_r \sigma}{4\pi R^2} \quad (\text{W}) \tag{4.55b}$$

In the self-screening situation both the reflected echo and the jamming signal travel the same distance from the target to the receiver. Therefore, the jam-to-signal ratio is established at the target and remains constant all of the way back to the radar. Thus, the J/S ratio at the radar receiver can be given in the form

$$\frac{J}{S} = \left(\frac{P_j G_j}{P_r G_r}\right)\left(\frac{4\pi}{\sigma}\right) R^2 \tag{4.55c}$$

Burn-through range. Note that the J/S ratio given by Eq. (4.55c) is directly proportional to R^2. This means the jammer has a range advantage because the radar signal has to traverse twice the distance traveled by the jamming signal. However, looking at this feature from a different point of view, the echo power S at the aircraft increases as the target approaches the radar receiver (R decreases), whereas the jammer power remains constant. This is analagous to the S/N ratio as a function of R shown in Fig. 4.12c; S increases and N is constant as R decreases. Eventually, a range can be reached where the target echo has increased to the point that it can be detected by the radar operator in the presence of the jamming signal. This distance is called the burn-through range R_B because the echo has 'burned through' the jamming signal. Thus, when $R > R_B$ the aircraft is not detected, and when $R \le R_B$ it is. (R_B in the presence of jamming is analagous to $R_{\max}$ with no jamming.) Define a 'camouflage factor' C as the largest J/S ratio for which the aircraft can be detected. Thus, when $J/S > C$ the aircraft is not detected, and when $J/S \le C$ the aircraft is detected. Substituting C for J/S in Eq. (4.55c), replacing R with R_B, and solving for the burn-through range gives

$$R_B = \left(\frac{P_r G_r \sigma C}{P_j G_j 4\pi} \right)^{\frac{1}{2}} \tag{4.56}$$

In reality, there is no one value for the burn-through range because of the fluctuations in σ and G_j that occur in a typical scenario.

Example 4.14 Burn-Through Range

In Example 4.3, $R_{\max} = 56.3$ km (considering losses) for a radar with $P_r = 100$ kW and $G_r = 40$ dB and an aircraft with a 1 m^2 RCS. Suppose the aircraft turns on a noise jammer with $P_j = 100$ W in the band of the radar and an omnidirectional antenna at 60 km. The camouflage factor $C = 10$ dB. Thus, the burn-through range is

$$R_B = \left[\frac{(100{,}000\ \text{W})(10{,}000)(1\ \text{m}^2)(10)}{(100\ \text{W})(1)4\pi} \right]^{\frac{1}{2}} = 2.82\ \text{km}$$

using decimals. Using decibels

$$\begin{aligned} R_b &= (50\ \text{dBW} + 40\ \text{dB} + 0\ \text{dBsm} + 10\ \text{dB} - 20\ \text{dBW} - 0\ \text{dB} - 11\ \text{dB})/2 \\ &= 34.5\ \text{dBm or } 2.82\ \text{km}. \end{aligned}$$

Support jamming. Noise jammers can be carried on supporting manned aircraft or UCAVs rather than on the aircraft to be protected. The supporting aircraft, known as a standoff jammer, usually stands off at a distance from both the target aircraft and the radar, out of range of the air defenses, whereas the EA UCAV can accompany the aircraft to be protected and can even get closer to the radar to be jammed than the protected aircraft. There are several advantages in the use of dedicated support jammers compared with self-protection jammers. These are the following:

1) A dedicated jammer can protect several attack vehicles.
2) A dedicated jammer may have higher power.
3) A dedicated jammer might be able to use one or more directional antenna.
4) A dedicated jammer might be able to operate at optimum altitude to maximize the jammer-to-radar propagation factor.
5) Use of standoff jammers can prevent the enemy's use of home-on-jam tracking of target aircraft's onboard jammer.
6) Two or more jammers can sometimes be used simultaneously for maximum protection.
7) The precise direction to the attack vehicles is not revealed before burn-through.

Disadvantages in the use of support jammers are as follows:

- The standoff jammer-to-radar range is relatively large; hence, high jamming power is required for a desired J/S.
- It might be difficult for the standoff jammer to provide enough protection by remaining behind the strike aircraft.
- The jamming aircraft itself becomes a high-value target, and its loss could be detrimental to the survivability of the aircraft it was supposed to protect.

The jam-to-signal ratio and burn-through range equation for the support jammer can be derived in a manner similar to that used for the self-protection jammer, except the ratio must also account for the fact that the jammer and the target are not coincident. The J/S ratio for the standoff electronic jamming (SOJ) situation can be given in the form

$$\frac{J}{S} = \left(\frac{P_j G_{\mathrm{jr}} G_{\mathrm{rj}}}{P_r G_r^2}\right)\left(\frac{4\pi}{\sigma}\right)\left(\frac{R_t^4}{R_j^2}\right) \tag{4.57}$$

where R_t is the radar to target range, R_j is the radar to jammer range, G_{jr} is the gain of the jammer antenna toward the radar, and G_{rj} is the gain of the radar antenna in the direction of the jammer. The burn-through range R_B is obtained by setting $J/S = C$, replacing R_t with R_B, and solving Eq. (4.57) for the burn-through range. Thus,

$$R_B = \left(\frac{P_r G_r^2 \sigma C R_j^2}{P_j G_{\mathrm{jr}} G_{\mathrm{rj}} 4\pi}\right)^{\frac{1}{4}} \tag{4.58}$$

Design and operational considerations. In designing a noise jammer for optimum performance, the burn-through range given by Eqs. (4.56) and (4.58) shows that to minimize the burn-through range the engineer should design for the maximum possible power per unit bandwidth, obtain as much antenna directivity toward the victim receiver as possible, and select a jamming waveform that will minimize the camouflage factor.

Maximum jamming power output might be limited by the ratings of the available devices, by the power supply and environmental limitations (such as the available cooling) on the aircraft, by safety considerations for personnel, and by power limitations of waveguides, antennas, or other components. To maximize the power per unit bandwidth, the jammer bandwidth should be made as narrow as possible (spot jamming), and the spectrum should be matched to the victim receiver bandwidth. In most cases the jammer bandwidth must be somewhat greater than the receiver bandwidth to allow for frequency set-on tolerances and drift of the jammer and radar receiver, or in order to jam several receivers on different frequencies simultaneously. Normally, the designer tries to obtain as uniform a jamming spectrum over the jammer bandwidth as possible so that jamming effectiveness will not be a function of the location of the receiver bandwidth within the jamming spectrum.

To obtain antenna gain greater than unity toward the radar receiver, directional antenna must be used. If either the jammer or the receiver is moving, the antenna beam must be steered. This can be accomplished manually if personnel are available, or it can be accomplished automatically. When designing self-protection jammers, it might be desirable to employ radiating systems that are completely omnidirectional if jamming coverage is required during hard maneuvers.

If the characteristics of the radar receiver were known exactly, it would be possible to select an optimum waveform to use against that receiver. Such an optimum choice is generally not possible for several reasons. Even if the receiver characteristics were known exactly, the enemy might temporarily change the receiver circuitry to reduce the effectiveness of the jamming signal. Moreover, the jammer must be able to operate against several radar systems with receivers having different characteristics, and sometimes two or more systems must be jammed simultaneously.

There are, of course, other problems in designing a jamming system. The enemy radar signals must be detected and identified before they can be jammed. A jamming system could be useless if the user does not know which frequencies need to be jammed. Intelligence information is not enough, for radars can change frequency or go off the air. Furthermore, it would be pointless and possibly dangerous to jam a radar that was not radiating for two reasons. One, a missile with a home-on-jam tracking capability could be on its way; and two, although a nonradiating radar cannot directly measure the range to a target it can determine the direction to a jammer, and two such radars can obtain a position fix on the jammer. Thus, most jammers have an intercept receiver or RWR capability.

Detecting the impinging radar signals while jamming (the look-through problem) can be difficult. The received radar signal can be in the order of -35 dBm, while the jammer output can be $+55$ dBm or more. Thus, isolation between the jamming transmitter and the intercept receiver in the order of 90 dB or more is required for detection of the victim signal while jamming. It is not always possible to obtain this degree of isolation, particularly with an omnidirectional transmitting antenna. Alternate solutions to the look-through problem are to either turn the jammer off or to detune it for a very short time.

Threat priorities must be established in order to jam effectively. Electronic warfare support measures are therefore needed to obtain up-to-date information on operating radars so that the most dangerous threats can be jammed. The jammer must be set on the radar frequency and jamming initiated at the proper time. These functions can be provided by a power-managed ECM suite. It has already been shown that the J/S ratio increases as the square of the range. Therefore, the jammer can be detected by the radar at ranges much greater than the range at which the jamming aircraft can be detected by the radar. Thus, the jammer should not be turned on beyond the maximum detection range of the radar. To do so might give the enemy information they could not obtain with their own radar at that range, such as the direction of the jammer.

Sometimes, when a very wide band of frequencies must be jammed, a swept jammer is used. In this case the jamming is swept over the band of frequencies at a relatively slow rate so that each radar is jammed intermittently. Thus, the target aircraft is seen intermittently by the radar, but the blip-scan ratio (the single scan detection probability) is reduced below its value without any jamming. It is also more difficult to determine the direction to the jammer from the radar PPI display because jamming strobes appear on the display in various directions, depending on the direction the radar antenna is pointing at the times when the jammer signal is received.

All forms of noise jamming are generally most effective if several jammers are scattered geographically and used simultaneously. With several jammers in different directions, the PPI picture can be so confusing that the radar operator has difficulty determining the direction to any one of the jammers. This is particularly true at short-to-moderate ranges where the jamming can enter the radar antenna through the main and the side lobes.

Enemy electronic counter-countermeasures. The ECCM against noise jamming includes optical tracking, low-antenna side lobes or side-lobe cancellation, automatic gain control (AGC), moving target indicator, and frequency agility or frequency hopping. For considerably more information on ECCM, see Refs. 38 and 39.

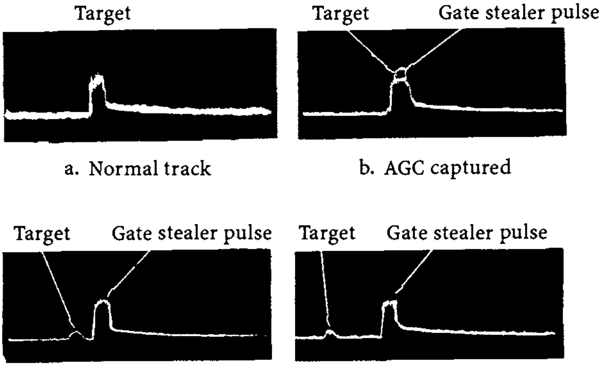
Go to Problems 4.4.11 to 4.4.18.

4.4.3.2 Radar deception.

Learning Objective	**4.4.9**	**Describe the radar deceiving approaches in general and the range gate pull-off and inverse con-scan deception techniques in particular.**

Deception of a surveillance or weapon control radar system consists of those electronic techniques that present false target information to the radar. In some cases it might be possible to cause the break-lock of a tracking radar, causing it to become completely unlocked from the target. The radar must then attempt to reacquire the aircraft. The general approaches for deception are as follows: 1) to generate a large number of false targets that are indistinguishable from the real target and that overload the system by subtle means rather than by brute force and 2) to provide incorrect target bearing, range, or velocity information to the radar. In general, many deception signals can be unmasked by a properly designed radar with ECCM, but they can be very effective if not accounted for by the radar.

Deception techniques. There are a great many deception techniques available today, and many more will probably be developed to counter the changing threat environment. In general, they all modify or modulate the echo received by the radar in some manner. Because of the power limitations on self-protection jammers, most self-protection jammers rely heavily on deception for their effectiveness. The



a. Normal track b. AGC captured

c. Deceiving pulse delayed d. Range gate pulled off

Fig. 4.33 Range gate pull-off.

deception methods can be divided into the following four categories according to the type of echo modulation used: time, amplitude, phase or frequency, and polarization. Two of the most common deception techniques, range gate pull-off and inverse con-scan, are described in the following paragraphs to give the reader an indication of the nature of this beast.

Range gate pull-off (RGPO): This time modulation deception technique, also known as range gate walk-off and range gate stealer, is a DECM that can work with automatic range tracking pulse radars using automatic gain control. The procedure and effects of RGPO are illustrated in Fig. 4.33. The pull-off of the range gate is accomplished by the deceiver by first detecting the impinging radar pulse and as quickly as possible transmitting a relatively small deceiving signal as identical to the target echo as possible. The radar then sees both the target echo and the gate stealer pulse almost simultaneously. As this superposition procedure continues, the power of the deceiving signal is continually increased. The radar's automatic gain control will turn the gain down as the combined echo plus deceiver signal increases in magnitude. Eventually, the gate stealer pulse becomes sufficiently large compared to the target echo so that the radar is in fact tracking the deceiving signal. The deceiver has captured the radar's target tracker. Now the radar is tracking the stronger deceiving signal, and it cannot see the target echo. Next, the deceiving signal is slowly delayed, causing the automatic range tracking circuit to move the presumed target (the false target) beyond the range of the actual target. The deceiver has now pulled the range gate off of the target. Eventually, the deceiving signal can be shut off, causing the radar to lose sight of the false target. Because the radar gain control is now so low and because the actual target is out of the range gate, the radar must go into its acquisition mode to reacquire the target. Its lock on the target has been broken. RGPO is not always effective. An operator watching this spoofing start to happen on a PPI scope may be able to detect the RGPO and prevent it from breaking lock, and there are ECCM techniques that will degrade or eliminate its effectiveness, such as leading-edge tracking. In leading-edge tracking the range gate always tracks the leading edge of the pulse, and thus the delayed

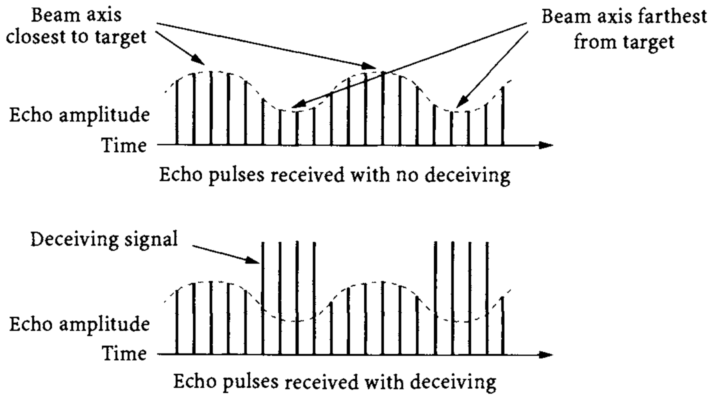


Fig. 4.34 Inverse con-scan.

deceiving signal will not capture the tracking gate. Because the EA community knows about leading-edge tracking, range gate pull-in is used in place of pull-off; the deceiving signal is transmitted before the arrival of the radar pulse. However, the enemy knows about range gate pull-in, and they can use PRF jitter (The time between successive pulses is allowed to vary in a random manner.) or PRF stagger (a periodic pattern of changes in the PRF) as an ECCM to defeat the deceiver. (http://www.goldcrows.org/ewtutor2.htm#sec2_2_3.)

Inverse con-scan: This is an amplitude modulation technique for deceiving conical-scan tracking radars and is illustrated in Fig. 4.34. It works by determining both the scan rate of the radar and when the scanning beam is closest to the aircraft. When the scanning beam is pointed away from the aircraft, the deceiver transmits a relatively strong signal so that the radar sees both the echo and the deceiving signal. As the beam approaches the aircraft, the deceiver stops transmitting so that only the target echo is received. When the combination of the faint target echo and the strong deceiving signal (when the beam is farthest from the target) is stronger in amplitude than the return from the target alone (when the beam is closest to the target), the radar will interpret the inverse modulation pattern to mean that the aircraft is in the direction indicated when the deceiving signals were received, which is of course in the wrong direction. This can cause a break-lock of the radar. There are ECCM techniques to defeat inverse con-scan, such as lobe-on-receive-only, in which the radar lobes only the receiving antenna. With LORO the jammer does not know the scan rate or when the receiver is looking away from the aircraft. The use of monopulse also defeats this technique because only one pulse is required to determine the angle to the aircraft.

Comparison of radar noise jammers and deceivers. The noise jammer is universal in that it can degrade the performance of any radar if it knows the radar frequency. With adequate noise power available, range, and possibly angle, information is denied to the radar. However, relatively high power is required for noise jammers because they can operate with a 100% duty cycle. Furthermore, directional information might not be denied by a single low-power jammer used for self-protection. Also, the noise jammer can serve as a beacon for home-on-jam missiles. The deceiver for a pulse radar usually requires relatively small average power output because its duty cycle is comparable to the radar duty cycle. To be effective, its modulation must be carefully tailored to the characteristics of the victim radar. Like the noise jammer the deceiver can serve as a beacon, although it is somewhat harder to detect. It can be programmed to give false range information and false angular information. However, angular deception against certain types of radars, such as monopulse, is much more difficult.

Go to Problems 4.4.19 to 4.4.22.

4.4.3.3 Radar proximity-fuze jamming. Many modern missiles are detonated by some sort of proximity fuze that senses the presence of the target and detonates the warhead at a location along the flight path to maximize damage (see Fig. 4.27). Proximity fuzes can sometimes be affected by countermeasures. In general, the best countermeasure procedure will either prevent fuzing or cause the warhead to detonate outside of the detonation zone at a range great enough to reduce the probability of damage to the target and to other aircraft in the vicinity to near zero.

4.4.3.4 Infrared jammers and deceivers.

Learning Objective 4.4.10 Describe the operation of an IR deceiver.

Infrared countermeasure (IRCM) devices that either introduce large amounts of IR noise into threat IR tracking systems or fool the IR trackers by sending false target information can also be important to the survivability of an aircraft. The first type of device is referred to as a saturation jammer. This device generates an amount of IR radiation in the bandwidth of the seeker that is sufficient to saturate or possibly damage the detector or the optics, causing the seeker to go blind.

The second type of device is the smart IR jammer or deceiver. In general, smart IRCM deceivers are either nondirectional or directional (DIRCM). One particular example of a nondirectional IR deceiver is shown in Fig. 4.35. This type of jammer can use jet engine fuel or electricity to heat a ceramic source or IR lamp. The IR radiation from the hot source is mechanically modulated to provide the signal that deceives reticle-based IR seekers. The IR seeker on an approaching missile will see the combination of the relatively steady aircraft signature and the pulses of IR energy from the hot source. Further modulation of the fluctuating incoming signal by the seeker reticle to determine the aircraft's angular location will create false information on that location. The deceiver modulations will be processed with the reticle-caused target modulations, and the computed location of the target will be wrong, causing the missile to go astray. A laser can also be used to generate the modulated deceiving signal in the appropriate wavelengths, such as 1 to 2 and 3 to 5 μm. Two recent directional laser IRCM developments for helicopters and the Special Operation Forces MC-130 and AC-130 are the DIRCM (by Northrop

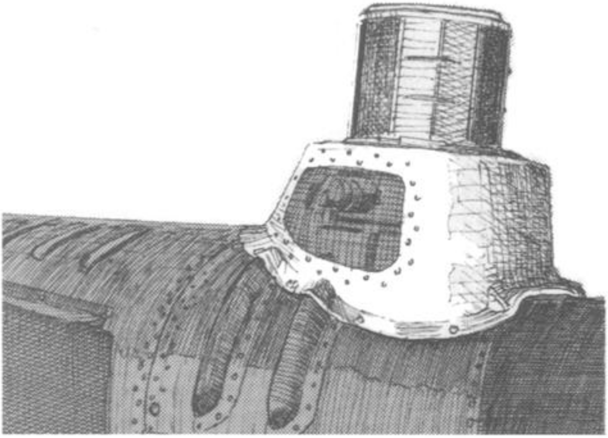


Fig. 4.35 Nondirectional IR deceiver.

Grumman) and the Advance Threat Infrared Countermeasures (ATIRCM by BAE Systems) programs.[40–44] A program similar to DIRCM/ATIRCM for fixed-wing tactical aircraft is TADIRCM. (http://www.defense-aerospace.com/data/communiques/archives/1999Nov/data/1999Nov1016/ and http://www.northgrum.com/news/news_releases/089-114_DIRCM-flt-tests.html.)

There are several design considerations for the smart jammer. Besides being fast, light, inexpensive, and reliable, it must have an adequate radiation pattern or directed beam around the aircraft to deceive missiles approaching from any direction. It must have sufficient signal strength to be seen by the missile in combination with the aircraft signature; it should be capable of operating as long as the aircraft is in the hostile environment; and it should have a filter that removes the visible radiation so the device cannot be seen at night. Associated with the use of a pointable laser as a DIRCM device is the requirement to quickly detect the launch and approach of the missile, identify the missile, slew the laser to the missile, track the missile, and then transmit the deceiving signal, quickly. The effectiveness of any IRCM device against advanced IR missiles must be evaluated because, like the radar jammer, it could be a beacon that more sophisticated IR trackers can home in on.

Go to Problem 4.4.23.

4.4.3.5 Some noise jamming and deceiving equipment. Table 4.8 lists some of the noise jammers and deceivers in production or late development. Considerably more information on this equipment can be found in Ref. 26 and online at http://www.fas.org/man/dod-101/sys/ac/equip/.

4.4.4 Signature Reduction

The ability of a threat system to quickly detect, locate, identify, and accurately track an airborne target has a significant influence upon the survivability of the target. Features that reduce the apparent size of the target observables or

Table 4.8 Some noise jammers and deceivers[26]

Equipment (aircraft)	Description (manufacturer)
AN/AAQ-24 (USSOCOM aircraft)	NEMESIS, a DIRCM system (Northrop Grumman Electronics and Systems Integration International, Inc.)
AN/ALQ-99 (EA-6B)	Standoff radar jammer/deceiver (AIL Systems)
AN/ALQ-119/184 (USAF aircraft)	Dual-mode radar jammer in an external pod (Northrop Grumman ESSS/Raytheon Co.)
AN/ALQ-126B (USN aircraft)	Multimode, deceptive radar ECM system (BAE Systems)
AN/ALQ-131 (USAF aircraft)	Dual-mode, multitechnique deception radar jammer in an external pod (Northrop Grumman ESSS)
AN/ALQ-144[27] (both fixed and rotary-wing aircraft)	Nondirectional IRCM deceiver (BAE Systems)
AN/ALQ-157 (Large troop-carrying helicopters and C-130s)	Nondirectional IRCM deceiver (BAE Systems)
AN/ALQ-162 Shadowbox (both fixed- and rotary-wing aircraft)	Continuous wave radar jammer (Northrop Grummàn ESSS)
AN/ALQ-165 ASPJ (USN aircraft)	Airborne self-protection jammer (ITT Industries, Avionics Div./Northrop Grumman ESSS)
AN/ALQ-211 SIRFC[27] (USA and USAF platforms)	Suite of integrated RF countermeasures (ITT Industries, Avionics Div.)
AN/ALQ-212 ATIRCM[27] (USA aircraft)	Advanced threat infrared countermeasures directed IRCM suite (includes the CMWS) (BAE Systems)
AN/ALQ-214 RFCM (will be deployed on USN/USAF tactical aircraft and strategic aircraft)	Integrated defensive electronic countermeasures (IDECM) RF countermeasures (RFCM) system with the towed decoy (BAE Systems/ITT Industries, Avionics Div.)

signatures degrade the ability of the threat system to accomplish these functions. These features are therefore extremely important and should be a major consideration in the design of an aircraft. When the signatures (or observables) of an aircraft are reduced to a low level, the aircraft is said to be a low observable or stealthy aircraft (Note 33).

There are several detectable observables utilized by threat systems for target detection and tracking. Currently, they are the radar echo, the IR radiation, the visual radiation, and the acoustic pressure. Associated with each of these observables is a signature. The two general methods used to make an aircraft more difficult to be seen by detection and tracking systems are 1) reduction of the aircraft signature to a level that is below the sensor threshold, and 2) masking of the aircraft signature by minimizing the aircraft-to-background contrast. Both of these methods are passive. The particular method used to enhance survivability depends upon the type of threat system sensors expected to be encountered. A considerable amount of information on how to reduce the radar signature is given in Refs. 45–54, and Refs. 45, 46, 49–51, 55, 56 contain information on how to reduce the infrared signature. References 57–67 cover the general topic of stealth. More data are available online at http://www.sais-jhu.edu/umt/07_invisible/Understanding%20Stealth.pdf.

4.4.4.1 Radar signature.

Learning Objectives	**4.4.11**	**Describe how to reduce the RCS of an aircraft.**
	4.4.12	**Explain the ways that radar absorbent material absorbs the impinging radar signal.**
	4.4.13	**Determine the benefits of RCS reduction.**

The radar observable is the radar echo, and the radar echo power is directly proportional to the radar cross section. Reducing the radar signature means reducing or camouflaging the RCS. The major contributors to the radar cross section are described in Sec. 4.3.2.1. Briefly, the two major features that determine the RCS of any aircraft for a given radar are 1) its geometry (size and detailed shape) and 2) the electromagnetic properties of the aircraft surface materials. The major sources of the radar echo from aircraft surfaces are the smooth surfaces, which return the signal in a specular or mirror-like manner, and the intersections of surfaces, panel gaps, and the cavities, which scatter the return over broad angular regions. Thus, for fixed-wing aircraft, the return from the fuselage, the fuselage-wing-empennage interfaces, the leading and trailing edges, the cockpit interiors, the antennas and compartments, the engine propellers or inlet and exhaust cavities, the external stores and associated suspension equipment, and any other protuberances should be controlled. For rotary-wing aircraft, additional sources are the fuselage-sponson interfaces, the main rotor mast, hub, and blades, the tail rotor drive, hub, and blades, and the landing gear.

The general method of RCS control is the reduction in the magnitude of the signature. This has the effect of decreasing the signal-to-noise ratio. This reduction can be accomplished in three ways: 1) reflection of the radar signal away from any receiving antenna, 2) absorption of the radar signal by attenuation or interference, and 3) active interference with the surface currents. The following is a list of the RCS reduction techniques presented in the next subsections:

1) Reflect by shaping and orienting conducting surfaces.

2) Reflect by locating cavities, reflecting antennas, ordnance, etc. out of the radar line-of-sight.

3) Reflect by aligning all edges in a few directions.

4) Reflect by covering all properly shaped radar transparent surfaces or cavities with a conducting material.

5) Reflect by eliminating any electrical discontinuities on the surface.
6) Absorb by covering directly exposed surfaces with radar absorbent material (RAM).
7) Absorb by covering travelling wave surfaces with RAM.

Reflection. Reflection of the impinging radar signal away from the receiving antenna of a monostatic radar can be accomplished by shaping and orienting the conducting aircraft surfaces to eliminate the backscatter from both the large flat surfaces and the surface intersections and cavities. This approach leads to an aircraft with either a properly oriented faceted shape or a smooth, electrically continuous, curved shape with blended surface intersections at locations, such as the wing root and the weapon pylon attachments. The backscatter is also reduced by locating cavities, ordnance, and other glitter points out of the radar line-of-sight. For example, locating the engine inlets on the upper surface of the wing might remove them from the line-of-sight to ground-based radars (but might put them in the view of higher-flying aircraft). Another example is the storage of all ordnance, such as air-to-ground bombs and air-to-air missiles, inside the aircraft.

Another reflection technique is the alignment of all wing, tail, and panel edges in a few directions such that the impinging signal is reflected away from the receiving radar antenna even when the aircraft is manuevering. Reflection of the impinging signal away from the receiving antenna can also be accomplished by covering and orienting cavities, such as engine inlets, and radar transparent materials, such as radomes and cockpit canopies, with a thin layer of conducting material that is opaque to the impinging radar signal but transparent to other frequencies, such as the radar's operating frequency and light. This prevents the signal from being backscattered by internal surfaces, such as engine fans, bulkheads, and other components. Ensuring that there are no electrical discontinuities in the aircraft's surface eliminates diffraction from panel edges.

The objective of the reflection technique is to reflect the radar signal away from the receiving antenna. This objective presupposes a knowledge of the direction of the receiver. For monostatic radars the transmitter and receiver are collocated, and consequently the impinging radar signal should be directed away from the approach direction. However, this could actually increase the RCS of the aircraft for a bistatic radar because the receiver may be in the direction of the reflected signal. In general, shaping is most effective when the radar wavelength is short compared with the dimensions of the individual reflecting surfaces.

Absorption. Absorption of the impinging radar signal is accomplished using special radar absorbent materials called RAM or radar absorbent structures called RAS. RAM/RAS can 'absorb' the echo either by admitting and then internally attenuating the strength of the impinging signal or by internally generating reflections that interfere with the reflection from the front surface. The former type is referred to as attenuating or broadband RAM, and the latter type is known as interference, tuned, or resonant RAM. A number of RAM types have been developed that provide a selection of weights, thicknesses, costs, and structural properties. These include the attenuating dielectric gradients and magnetics and the resonant tuned RAM and circuit analogs. The effectiveness of RAM is greatly dependent upon its electromagnetic impedance, which is usually frequency dependent.

When a radar signal traveling through the atmosphere strikes the surface or skin of an aircraft, some of it will be reradiated at the interface by the aircraft material, and the remainder will travel partly or completely through the material, as shown in Fig. 3.53. The strength of the nonscattered portion will decay somewhat as the signal passes through the material until the signal strikes the rear face of the skin. Some of this portion will be reflected at the interface, and the remainder will pass through. The internally reflected portion will again pass through the material, continuing to decay in strength as it propagates, until it reaches the front interface where the reflection-transmission phenomenon occurs again. This process continues until the signal within the material has totally decayed. The backscatter echo is the sum of the backscattered reflection from the front face and the internal backscattered reflections.

The amount of signal that is reradiated by the induced electric charge oscillations on the surface of the skin and the remaining amount that passes through the air-skin interface are dependent upon the relative electromagnetic impedances of the air and the skin. The electromagnetic characteristic impedance of a material η is given by

$$\eta = \sqrt{\mu/\varepsilon}$$

where μ and ε are the permeability (the magnetic parameter) and permittivity (the electrical parameter) of the material, respectively. In lossy (energy absorbing) materials μ and ε are complex numbers, and the imaginary part is the lossy part. In air, $\eta = 377\,\Omega$. In metals (which are electrical conductors) μ is very small except for iron, and ε is very large compared to μ, hence $\eta \approx 0$. In a dielectric or semiconductor material μ is very small, and ε is small and slightly imaginary. When the radar signal travels through one medium with an impedance of η_1 and strikes (at normal incidence) another medium with an impedance of η_2, the absolute value of the reflected portion $|\rho|$ is given by

$$|\rho| = |\eta_2 - \eta_1|/|\eta_2 + \eta_1| \tag{4.59}$$

For the typical air-metal interface $|\rho| \approx 1$ because of the large impedance mismatch at the interface ($377\,\Omega$ vs $0\,\Omega$). Hence, nearly all of the impinging signal is reflected.

For a material to be effective as attenuating RAM, it must reflect very little of the incident signal; hence, its electromagnetic impedance must be approximately that of air. Another requirement for attenuating RAM is that it rapidly absorbs the energy in the radar signal as the wave propagates though the material. This can be accomplished using lossy dielectrics (often carbon based) or lossy magnetics (often iron based). The amount of absorption in a lossy material depends upon the particular properties of the material's impedance, the radar frequency, the thickness of the material, and the angle of incidence of the signal. For broad coverage over a wide range of frequencies, several layers of different lossy dielectric materials can be bonded together, making a dielectric gradient. Typical lossy materials are carbon or ferrite particles in a thin layer or mesh of synthetic rubber or plastic, foams, and hair mats (Note 34).

Examples of RAM that work by interference absorption are the Dällenbach layer and the circuit analog. In the Dällenbach-layer technique a homogeneous, lossy layer is placed in front of a conducting ground plane, such as the aircraft skin.

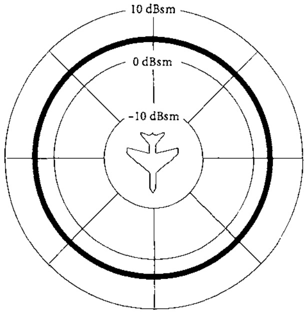
Absorption by destructive interference between the front face echo and the ground plane echo occurs when the radar wavelength (in the Dällenbach layer) is four times the distance of the layer front face from the ground plane (Note 35). As a consequence of the limited frequency coverage of the Dällenbach layer, circuit analog interference absorbers have been developed to broaden the frequency coverage. In the circuit analog several thin sheets of material with specific surface impedances are separated by loss-less dielectric layers. The Salisbury screen, consisting of a thin layer of lossy material (the screen) separated from a conducting ground plane by a loss-less dielectric, is perhaps the simplest example of a circuit analog. The reflection from the front face of the circuit analog absorber is the net result of the reflections of the signal from the front face and the interfaces between the sheets and the layers. The behavior of this type of construction can be represented analytically by an electrical circuit analog consisting of impedances, resistors, and capacitors.

Typically, the lossy dielectrics are light and thick, the lossy magnetics are thin and heavy, and the circuit analogs, which might be the most effective RAM, are thick and expensive.

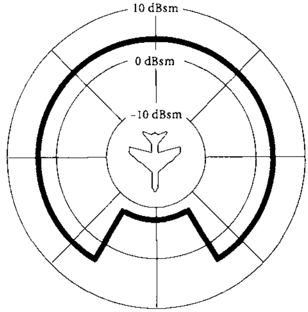
RAM is used on surfaces directly exposed to the radar signal, where the attenuation occurs as the wave proceeds through the thickness of the RAM, to reduce the specular reflection. This type of RAM is known as specular RAM because it reduces the specular reflection. For example, the leading edge of wings and helicopter rotor blades can be covered with specular RAM. To avoid using a reflecting covering over an engine inlet, a serpentine or S-shaped inlet coated with RAM can be used. The radar signal entering into the engine inlet will undergo multiple bounces off of the inlet walls as it propagates toward the engine face and back out again. Each bounce off of the RAM-covered wall results in a reduction in echo. If the inlet is short, radar blockers can be used.[45,46] RAM can also be used on surfaces not directly exposed, such as the upper surface of a wing, to attenuate traveling waves.

Interference with the surface currents. The use of shaping and RAM is most effective when the radar wavelength is short compared with the dimensions of the target scatterer. A method that can be used when the radar wavelength is approximately the same length as or larger than the dimensions of the scattering surfaces is to interfere with the electric charge flow on the surface of the scatter. This is accomplished by introducing impedances at various locations over the aircraft surface, and consequently the method is referred to as reactive loading. Reactive loading cannot only modify the RCS, it can be used to actively control the RCS by opening and closing switches that alter the amount of interference.

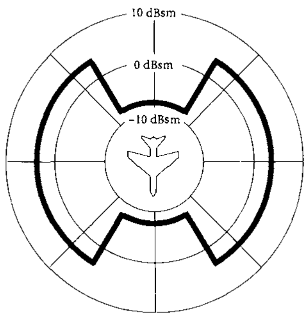
Some examples of RCS reduction. The general public got its first look at a stealth aircraft in 1988 when the F-117 fighter and B-2 bomber were introduced. Since then, the F-18E/F and F/A-22 fighters, the RAH-66 helicopter, and the F-35 Joint Strike Fighter have been designed to reduce the RCS. There are at least four general types of RCS polar plots used in survivability assessments to represent the reduction.[68] These are the fuzzball, the Pacman, the bowtie, and the spider man shown in Fig. 4.36. Each one represents a particular pattern of RCS reduction. In the fuzzball the RCS is an idealized uniform value around the aircraft. This pattern is usually used in baseline studies. In the Pacman the RCS has been reduced only in the front section, and in the bowtie the reduction occurs in both the front and the



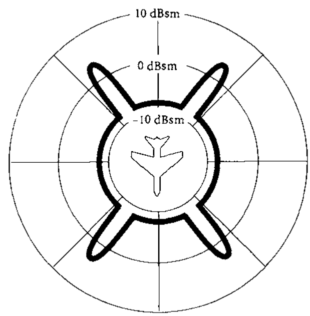
Fuzzball



Pacman



Bowtie



Spider man

Fig. 4.36 Four general types of RCS polar plots.

back sections. In the spider man the RCS is prominate in only four (or more) narrow lobes as a result of edge alignment, where each lobe is normal to an edge direction.

Benefits of RCS reduction. The benefits of reducing the radar signature include 1) a decrease in the radar detection range $R_{\max}$, an increase in the radar's tracking error ε_t, and a degradation in radar fuze capabilities; 2) an increase in the effectiveness of any RF countermeasures; and 3) a decrease in the required size and power of the countermeasures for a given level of effectiveness.

Reduction of the RCS of an aircraft reduces $R_{\max}$, the range at which the aircraft is first detected by a radar system according to Eq. (4.5i). When comparing the maximum detection ranges of two aircraft, the ratio of the $R_{\max}$ of a given radar for an aircraft with an RCS of σ_2 to the $R_{\max}$ for an aircraft with an RCS of σ_1 is

$$\frac{R_{\max}(\text{aircraft with } \sigma_2)}{R_{\max}(\text{aircraft with } \sigma_1)} = \left(\frac{\sigma_2}{\sigma_1}\right)^{1/4} \tag{4.60}$$

according to Eq. (4.5i). Also important is the impact on the burn-though range, Eq. (4.58), and the power required for a given jam-to-signal ratio, Eq. (4.57), for both the individual aircraft carrying a radar jammer and a standoff jammer. The reduction in these three parameters (for the same camouflage factor) is as follows: 1) the detection range $R_{\max}$ varies as $(\sigma)^{1/4}$, 2) the burn-through range R_B for an

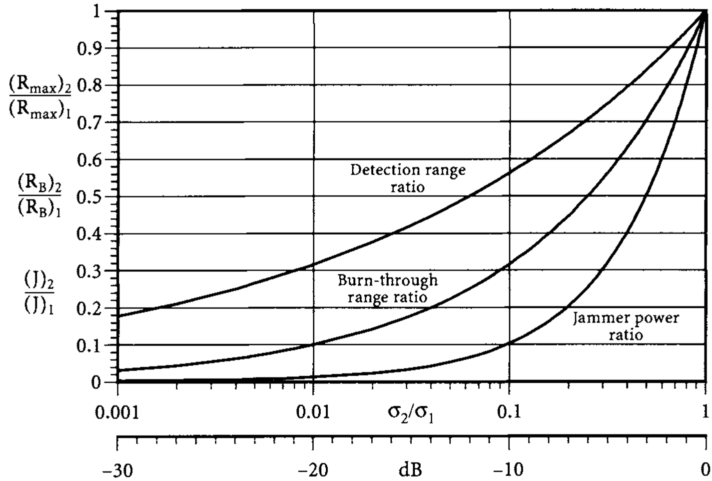


Fig. 4.37 Effects of a reduction in the RCS.

aircraft with a self-protection jammer varies as $(\sigma)^{1/2}$, and 3) the required self-protection jammer power J varies as σ. Figure 4.37 shows these three relationships. The baseline and new values are denoted by the subscripts 1 and 2, respectively.

A reduction in RCS also also increases the radar's tracking error. For example, according to Eq. (4.16), the standard deviation of the radar noise is inversely proportional to the square root of the radar echo (and hence the RCS), provided the echo is large compared to the noise. When the RCS is reduced to such a value that the echo strength is not large compared to the radar noise, other factors must be considered.

Example 4.15 Benefits of RCS Reduction

Suppose the designers of a new fighter increase the wing sweep angle and thereby reduce the RCS to 50% of the baseline RCS, that is, a –3 dB reduction. According to Fig. 4.37, the aircraft with the reduced RCS is detected in free space at 84% (or –3/4 dB) of the baseline detection range, the burn-through range is reduced to 71% (or –3/2 dB) of the baseline burn-through range, and the jammer power required to achieve the same J/S ratio is only 50% (or –3 dB) of that required by the jammer on the baseline aircraft. Additional treatments to the canopy, the radome, and some surface treatments increase the reduction of the RCS to 10% (or –10 dB) of the baseline. This aircraft's detection range is 56% (or –10/4 dB) of that of the baseline aircraft, and the burn-through range is 32% (or –10/2 dB) of the baseline, and the jammer power is 10% (or – 10 dB) of the baseline. Although this example uses reduction factors of 1/2 and 1/10, reductions by a factor of 1/50 or 1/100 or more might not be uncommon with present day technology, and the cost and other penalties when the RCS is controlled early in the development stage of the aircraft can be relatively low.

Combinations of signature reduction and onboard jamming. One of the major decisions to make when combining radar signature reduction with onboard jamming is the selection of the best combination of RCS and jammer power. At least two aspects of this selection should be considered: the effectiveness achieved and the associated cost. The effectiveness of the combination can be measured by the ability of an aircraft to close to within a certain distance of an enemy aircraft or surface-based threat R_C without being targeted or engaged, that is, effectiveness is measured by the combinations of σ and J that result in $R_B = R_C$. Substituting R_C for R_B in Eq. (4.56) and replacing $P_r G_r$ with ERP and $P_j G_j$ with JERP results in

$$\frac{\text{JERP}}{\text{ERP}} = \frac{\sigma C}{4\pi R_c^2} \tag{4.61}$$

Example 4.16 Study of Jamming and Signature Reduction Effectiveness

In a recent theoretical study for the best combination of σ and J for a new fighter/attack aircraft against an enemy fighter with an air-to-air missile, the air-to-air radar parameters were[69]

$$\mathrm{P}_r = 5\,\mathrm{kW} \quad G_r = 3500 \quad \mathrm{ERP} = (5\,\mathrm{kW})(3500) = 1.75 \times 10^7\,\mathrm{W}$$

$$\lambda = 0.03\,\mathrm{m} \quad N = 2 \times 10^{-19}\,\mathrm{W} \quad (S/N)_{\min} = 20$$

The goal was to achieve a closure distance $R_C = 35$ km before detection by the enemy's radar. The baseline RCS was 10 m^2.

The radar's $R_{\max}$ for the aircraft with $\sigma = 10\,\mathrm{m}^2$ and no jamming is 513 km according to Eq. (4.5h). To reduce $R_{\max}$ to 35 km, the reduction factor of approximately 0.07 (35 km/513 km or −11.7 dB) would require a reduction factor in σ of $0.07^4 = 0.000024$ or $0.00024\,\mathrm{m}^2$ ($a - 4 \cdot 11.7$ dB $= -46.8$ dB reduction factor). This level of σ might be difficult to achieve at an acceptable cost. Hence jamming should be available if closure to 35 km without being targeted is to be achieved.

To determine the jamming power required, three values of C were selected (4, 10, and 100) to study the effect of the ability of the jamming signal to cover the echo pulse or deceive the radar. Thus, in this simple analysis

$$\mathrm{JERP/ERP} = (10\,\mathrm{m}^2)C/[4\pi(35,000\,\mathrm{m})^2] = 6.50 \times 10^{-10}C$$

$$= 26.0 \times 10^{-10},\ 65.0 \times 10^{-10},\ \text{and}\ 650 \times 10^{-10}$$

according to Eq. (4.61) with $C = 4$, 10, and 100. The ERP of the radar is 1.75×10^7 W. Hence,

$$\mathrm{JERP} = 0.05\,\mathrm{W},\ 0.1\mathrm{W},\ \text{and}\ 1.0\,\mathrm{W}$$

These values are relatively easy to obtain. Thus, the tactical requirement can be achieved with no signature reduction and a relatively small amount of jamming.

In a similar analysis for the attack mission against a radar-directed SAM, the radar parameters were[69]

$$P_r = 1.5\,\text{MW} \quad G_r = 11,500 \quad \text{ERP} = (1.5\,\text{MW})(11,500) = 1.73 \times 10^{10}\,\text{W}$$
$$\lambda = 0.06\,\text{m} \quad N = 3 \times 10^{-17}\,\text{W} \quad (S/N)_{\min} = 10$$

The goal was to achieve a closure distance $R_C = 11$ km before detection by the SAM's radar. The baseline RCS was 10 m^2.

The radar's $R_{\max}$ for the aircraft with $\sigma = 10\,\text{m}^2$ and no jamming is 1860 km according to Eq. (4.5h). To reduce $R_{\max}$ to 11 km, the reduction factor of approximately 0.006 (or more than -22 dB) would require a reduction in σ of 0.006^4 (or more than –88 dB). This extremely low level of σ is impossible today. Hence jamming must be available if closure to 11 km without being targeted is to be achieved (Note 36).

To determine the jammer power required, $C = 4$, 10, and 100. Thus, in this simple analysis

$$\begin{aligned}\text{JERP/ERP} &= (10\,\text{m}^2)C/[4\pi(11,000\,\text{m})^2] = 6.58 \times 10^{-9}C \\ &= 26.3 \times 10^{-9},\ 65.8 \times 10^{-9},\ \text{and}\ 658 \times 10^{-9}\end{aligned}$$

The ERP of the radar is 1.73×10^{10} W. Hence,

$$\text{JERP} = 454\,\text{W},\ 1138\,\text{W},\ \text{and}\ 11,380\,\text{W} \quad (\sigma = 10\,\text{m}^2)$$

These jammer power requirements are very high.

Note that neither jamming nor signature reduction alone will satisfy the tactical requirement. However, if σ is reduced to 0.1 m^2 (a -20 dB reduction) the values for JERP also reduce by a factor of 0.01 according to Eq. (4.61) and Fig. 4.37. Thus,

$$\text{JERP} = 4.54\,\text{W},\ 11.38\,\text{W},\ \text{and}\ 113.80\,\text{W} \quad (\sigma = 0.1\,\text{m}^2)$$

which are easily obtained. Therefore, an achievable combination of signature reduction of –20 dB with onboard jamming satisfies the tactical requirement in this very simple analysis.

The second aspect of the combination of signature reduction and onboard jamming is the total impact of the combination. Careful attention to the radar cross section in the initial design stages can result in considerable savings in total weight and dollar cost penalties because of the resultant reduction in the size and power of the jammer required to protect the aircraft. Figure 4.38 illustrates a hypothetical relationship between the increase in weight as a result of the addition of RCS reduction techniques and the decrease in jammer weight required to achieve a specific J/S (or R_B or R_C) ratio. When the RCS is large, a relatively large, heavy,

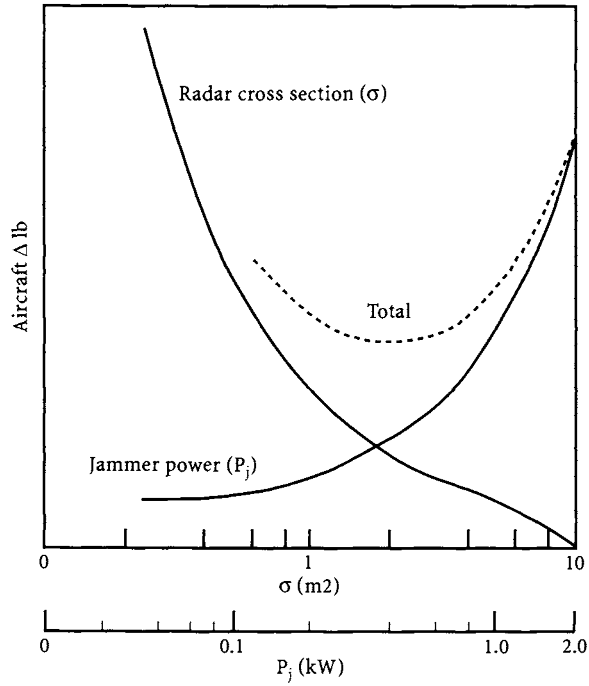


Fig. 4.38 Hypothetical RCS reduction/jammer power total weight trade for fixed J/S.

and expensive jammer system might be required. Reducing the RCS adds weight and costs associated with the control technology, but also allows a lighter and less expensive jammer to be used. The reduction in jammer weight and costs might be larger than the increases associated with the RCS control for certain levels of RCS. The designer should look for the optimum combination of RCS control and jammer size to minimize the weight and/or cost of the total system for the desired J/S value. In the hypothetical example shown in Fig. 4.38, the minimum weight penalty occurs when the aircraft RCS has been reduced from 10 to 2 m^2. A 400-W jammer is required for this value of RCS vs the 2000 W jammer required for the baseline aircraft.

Go to Problems 4.4.24 to 4.4.34.

4.4.4.2 Infrared signature.

Learning	**4.4.14**	**Describe how to reduce the IR signature of an aircraft.**
Objectives	**4.4.15**	**Determine the benefits of IR reduction.**

The infrared observable is the radiation in the IR portion of the electromagnetic spectrum, and the IR signature is *I*, the radiant intensity (W/sr) at the aircraft in the direction of the IR sensor and in the bandwidth of the sensor. Reducing the

IR signature means reducing or camouflaging I. The principal sources of infrared radiation from an aircraft, as described in Sec. 4.3.2.2, are the emitting surfaces and the reflecting surfaces. The emitting surfaces consist of the hot parts of the airframe and the propulsion system and the hot exhaust plume from the engine(s) and other power equipment. The reflecting surfaces are generally on the airframe. Reduction of the IR signature is accomplished in the following ways: 1) reduce the temperature of the hot parts, 2) reduce the surface emissivity of the hot parts, 3) reduce the temperature of the exhausts 4) reduce or mask the observable surface radiating area, and, 5) for the reflecting surfaces reduce the surface reflectivity. The specific application of these four techniques depends upon the particular IR source being controlled.

Propulsion sources. The number and the type of engines on the aircraft have a major impact on the IR signature. The three major engine types are, in order of IR signature level intensity, the turbojet, the turbofan, and the turboprop/turboshaft. Of these three types of engines, only the turbofan with its bypass air has an inherent available coolant source. The other two engine types must obtain ambient air for the cooling. In general, two small high-bypass turbofans will have a smaller IR signature in the MWIR than one large turbojet. Cooling of the engine hot metal parts and the exhaust plume is a potentially effective technique for controlling the IR radiation level in the bandwidth of an IR detector, as illustrated in Fig. 3.65b. For example, reducing the temperature of a hot part from 800 to 300 K reduces the spectral radiant emittance by a factor of more than 1/1000 for a 3- to 5-mm detector. The utility of cooling depends upon the type of engine. The engine exhaust system components that can be cooled are the exhaust frame centerbody, the flame holders, the tail pipe, and the nozzle walls. Cooling air for these parts can be obtained by either external blowers or ejectors in the case of turboshaft engines or obtained from the fan flow in turbofan engines. The cooling air is generally applied to the surface through cooling slots that combine impingement and convective cooling. For components, such as the turbine blades which remain hot, cooled shields that block the view of the component to an IR observer external to the exhaust system can be used. Another method of shielding the hot components from view is to incorporate a turn in the exhaust duct. Further IR radiation reduction can then be accomplished by coating the masking surfaces with IR absorbent materials, provided the increased radiation from the coated surfaces is at a wavelength outside of the bandwidth of the IR detector.

Suppression of the engine exhaust plume IR radiation level is most efficiently accomplished by reducing the gas temperature either before it leaves the exhaust system or as soon thereafter as possible. One technique used on turbofan engines that have a hot gas generator or core stream and a much cooler surrounding bypass or fan airstream is to employ a mixer to bring the hot and cool streams into contact just downstream of the turbine discharge plane and to force these gases to mix in the duct prior to exit from the nozzle. A similar technique for turbojet and turboshaft engines is to use ejectors that pump either engine bay compartment cooling air or ambient ram air into a coannular stream surrounding the hot core gas stream. The ejector pump can utilize the residual energy of the engine exhaust gases to pump the cooling air into the exhaust plume. Still further plume radiation reduction can be obtained under flight conditions by turning the exhaust gas at an angle to the flight direction, which puts the plume in a crossflow. This cross flow

Fig. 4.39 Black Hole IR suppressor (Reproduced with permission of the Boeing Company, Seattle, WA).

will cause rapid mixing of the cooler ambient air with the plume as the exhaust gas stream is turned back into the direction of the cross flow. An additional advantage of turning the exhaust duct is that it can shield the hot engine parts from view. Another technique for reducing exhaust plume radiation is to make the exhaust duct transition from a round cross-sectional shape near the turbine discharge plane to an elliptical or rectangular (two-dimensional) shape at the exhaust exit plane, as was done on the F-117. The two-dimensional exit shape gives more perimeter for the hot exhaust flow to mix with the surrounding ambient air, and the corners of the two-dimensional nozzle can cause turbulence to improve the mixing. The horizontal duct might have a lip on the lower edge that hides the hot parts from the ground, for example, the F-117. On helicopters, the exhaust duct may point to the side, as on the AH-64, or downward, as on the RAH-66. One example of an IR suppressor is the Black Hole Ocarina used on the AH-64 illustrated in Fig. 4.39. Note the two-dimensional nozzles and the turn in the duct path.

Airframe sources. Radiation from the airframe consists of the emissions from the relatively cool surfaces in the LWIR band; from the aerodynamically heated surfaces, the hot metal spots, and the aircraft lights in the LWIR and MWIR bands; and of the reflection of incident radiation or sun glint in all three bands. No efficient technique currently exists to reduce the aerodynamic heating effects. This contributor to the IR signature in the LWIR and MWIR bands may be significant for supersonic aircraft and for aircraft flying low level at very high subsonic speeds. Infrared radiation from hot spots caused by other than the propulsion system and aerodynamic heating, such as oil coolers, heat exchangers, and rotary-wing aircraft main rotor transmissions and gearboxes, can be reduced by reducing the surface emissivity, by inserting insulation between the hot part and the skin, by masking, or by cooling flow techniques. The weight penalty associated with these techniques can be minimized by judicious placement of these hot components during the conceptual/preliminary design phase.

Sun glint off of the airframe opaque surfaces and transparencies can be a potential source of radiation for an IR tracker. If the surface is very round, the glint can be observed from a wide range of angles, and this continuous IR source can be used by a seeker for tracking, even as the aircraft moves. The effect of the sun glint off of the aircraft transparencies can be reduced by using flat or nearly flat surfaces (to reduce the vibration). The nearly flat surface provides a specular return in a limited direction, and as the aircraft moves any IR seeker will only see a highly sporadic signal that either degrades tracking accuracy or eliminates tracking entirely. Reflection of sunlight off of the aircraft skin can be reduced by using a paint that has a very low reflectivity in the IR band of interest. This IR-absorbing paint is referred to as IRAP. Because the paint absorbs the incident radiation, the surface temperature will rise. This could be a problem for parked aircraft that require a relatively cool environment in certain areas, such as around electronic equipment.

Benefits of IR signature reduction. The benefits of IR signature reduction are similar to those associated with the reduction of the radar signature just presented. The reduction of the IR signature 1) degrades detection and tracking; 2) increases the effectiveness of IR countermeasures, such as the IRCM deceivers and expendable flares; and 3) decreases the required size and power of the deceivers and flares for a given level of effectiveness.

Reducing the IR signature I reduces R_{LO}, the lock-on range where the IR tracker locks on to the target signature according to Eq. (4.8c). When comparing the maximum lock-on ranges of two aircraft, the ratio of the R_{LO} for a given IR tracker for an aircraft with a signature I_2 to the R_{LO} for an aircraft with a signature of I_1 is

$$\frac{R_{LO}\ \text{(aircraft with } I_2)}{R_{LO}\ \text{(aircraft with } I_1)} = \left(\frac{I_2}{I_1}\right)^{1/2} \tag{4.62}$$

according to Eq. (4.8c). Thus, the reduction in lock-on range varies as $(I)^{1/2}$. The radar burn-through range ratio curve in Fig. 4.37 can be used to determine the R_{LO} ratio for a given IR signature ratio. For example, an order-of-magnitude reduction in I from 100 W/sr to 10 W/sr reduces R_{LO} by a factor of 0.32. If R_{LO} is 10 km for the baseline signature, the lock-on range for the reduced signature is 3.2 km.

Go to Problems 4.4.35 to 4.4.40.

4.4.4.3 Visual signature.

Learning Objective 4.4.16 Describe how to control the visual signature of an aircraft.

The control of the visual signature is based upon the method of minimizing the contrast between the aircraft and the background with respect to the four parameters: luminance, chromaticity, clutter, and movement. Those areas that require attention are the engine exhaust and glow, the glint off of the canopy and any rotor blades, the airframe signature, and the aircraft lighting.

Engine exhaust and glow. Engine exhaust contributors to visual detection include smoke, contrails, and, at night, exhaust glow. Until recently, chemical additives were used to catalyze the oxidation of carbonaceous particles, thus eliminating the carbon particles in the plume (the smoke), by lowering the fuel ignition temperature. The use of chemical additives has since been abandoned because it shortened engine life, was ineffective at low altitudes of flight, and was toxic. Current emphasis is directed toward improved combustor design for a smoke-free exhaust. To minimize hot parts glow, an asymmetric or turned exhaust nozzle can be utilized. Hot parts glow reduction can be an inherent fringe benefit of an IR engine suppressor.

Canopy glint. Canopy glint is most effectively controlled at the present time by the use of flat or relatively flat transparencies. The use of flat transparencies reduces the frequency of glint occurrence to the threat observer. Because the flat surfaces act like a mirror, the sun will be reflected at angles equal to the domain of incident angles, which is small. Highly curved surfaces, on the other hand, will reflect the sunlight into a much larger angle, thereby allowing the glint to be observable at many locations simultaneously and at one location over a large range of aircraft rotation. The objective of glint reduction is not to reduce it to zero necessarily, but to reduce it to the level of the next most dominant visual cue. Note that glint observability does not necessarily lead to glint detectability, and glint detection does not necessarily lead to target acquisition. For accurate weapon platform pointing and target tracking, the glint must be almost continuously (not momentarily) discernable to the naked eye or other sensor. Flat-plate transparencies make this unlikely to occur.

Rotor blade glint flicker. In rotary-wing aircraft rotor blade flicker detection has been found to be higher with two blade configurations than with four or more blades. The blade frequency should be above 16 Hz to avoid the apparent brightness that is observed at lower frequencies. Helicopter rotor heads have also been found to be a significant source of reflected light. Consideration should be given to finishes or coatings that will minimize or subdue such reflective surfaces. Rotor blade tip markings can provide visual clues to the enemy, but elimination of such markings must be evaluated with personnel safety factors.

Airframe. The technique to control the visual signature of a given airframe is the application of some form of paint or coating. Its effectiveness is dependent upon the successful suppression of any visible cues from the engine smoke and canopy glint. For in-flight visual signature control of aircraft, the paint application categories include glint suppression, luminance contrast minimization, countershading, pattern matching to structured backgrounds, and other concepts in paint schemes. When the aircraft's background is generally uniform, such as a clear sky, minimizing the luminous contrast of the aircraft with the background minimizes its detectability. Because the visual environmental parameters will usually encompass a range of luminous values, no one paint can be optimum. Therefore, the reflectance value of the paint should be chosen to minimize, on a frequency of occurrence basis, the possibility of large contrasts. For low-altitude flight profiles, generally associated with rotary-wing aircraft, other backgrounds should be considered. Most helicopter flight profiles include either discernable terrain as the background or are so low as to preclude any significant illumination on the aircraft undersides. In such cases, paints with reflectances simulating foliated terrain should be used. Aircraft that fly only at night are usually painted black.

If the application of paints is insufficient to remove the luminance contrast between the various surfaces of an aircraft and a clear sky background, a further reduction can be obtained by lighting up the darker-appearing portions of the aircraft with 'Yehudi' lights. (http://www.sew-lexicon.com/gloss_uz.htm#YEHUDI.) If the intensity and location of the lights are properly controlled, the aircraft can be made more difficult to see.

In addition to matching the luminance of the background, contrasts over the exterior surface at such locations as the wing-fuselage intersection and around any inlet ducts should be eliminated through the use of countershading or Yehudi lights. Countershading is a painting technique for controlling the overall luminance (or brightness) of aircraft by removing internal contrasts while achieving the desired average apparent brightness of the overall surface. It consists, generally, of specifying paints darker than the overall paint for normally highlighted surfaces and lighter paints for surfaces normally in shadow. The dramatic contrast caused by the traditional insignias, identification markings, and safety/warning notices are strong visual clues that should be subdued or eliminated where possible.

Aircraft flying over cluttered background or parked on the ground should be camouflaged using pattern painting, a technique that has been used for many years. By using a disruptive pattern, the aircraft will be indistinguishable from the background clutter. The use of several different paints increases the likelihood that at least part of the aircraft will be of negligible luminance or chromatic contrast to its immediate background. However, the use of pattern matching can be disadvantageous if the aircraft is used in a different type of background. Other paint concepts include paint formulations with seasonal features and paint schemes to give a false perception of the aircraft as to its type or its course of movement. One example of deception is the painting of a false canopy on the underside of a fighter aircraft. Enemy trackers trying to anticipate the heading of the fighter may be misled by the false canopy.

Aircraft lighting. To minimize nighttime visual cues from the aircraft lighting system, exterior lights should be masked from ground angles to the greatest degree practical while maintaining adequate safety for formation flying. The capability of anticollision light installations to reflect moonlight or any other light source should be minimized. Care should be exercised to minimize the direction and intensity of instrument lighting as well as reflections from cockpit interior surfaces.

Go to Problems 4.4.41 to 4.4.42.

4.4.4.4 Aural signature.

Learning Objective **4.4.17** **Describe how to reduce the aural signature of an aircraft.**

The aural signature is the only important signature that is not electromagnetic radiation. The aural signature can be very important to survivability on certain missions. The two major aspects of the signature are the frequency distribution and the power level within each frequency band. The two general approaches to reducing the aural signature are to reduce the power level of noise within the bands and to change the distribution characteristics. The specific approaches include reducing the acoustic power in the audible frequency range; modifying the noise spectra (amplitude and frequency) of the radiated noise to increase the attenuation through the atmosphere, through any atmosphere-to-water interface, and through the ocean; and shielding and absorption. The aural signature of military rotary-wing aircraft increased in importance with the advent of the acoustic antihelicopter mine. Another factor that has drawn more attention to the aural signature of aircraft is the increased emphasis by governments worldwide on noise abatement procedures and noise reduction technology for civilian aircraft.

Acoustic power reduction. Fan inlet radiated noise can be reduced by the use of an accelerating inlet with a high subsonic throat Mach number. Because jet engine exhaust radiates noise to approximately the eighth power of the jet velocity, a small reduction in velocity results in a large reduction in acoustic power. With respect to aerodynamic noise, air turbulence and vibrations caused by the motion of the wing and fuselage and air movement across a cavity or other airframe protuberances should be kept to a minimum.

Spectrum shaping. During the conceptual design phase, spectrum shaping of noise to where the human ear is less sensitive should be a consideration. Also, at the higher frequencies additional reduction in noise is achieved through excess atmospheric attenuation, and at the very low frequencies background noise levels can mask the aircraft noise. Another possible shaping concept is directing the engine exhaust through a number of small-diameter, remotely placed nozzles to produce a much higher noise frequency than that of a single exhaust pipe. Although no undersea detection criteria for the detection of aircraft by submerged vessels have been established, such criteria can allow high tone levels at some frequencies, while requiring very low tone levels at other frequencies. Therefore, it is important to consider tradeoffs between amplitude and frequency of tones in the development of undersea detection criteria.

Shielding and absorption. The application of shielding techniques or absorbing panels can result in significant reductions in aural detectability. Shielding methods involve placing a physical barrier in the path of the noise so that a lower intensity of noise is propagated to the receiver. An example is the placement of engines or the engine exhaust nozzles above the wing. The effectiveness of shielding is greater for higher frequency tones and when the shielding is located close to the noise source. Absorbing materials involve the use of sound-absorbent materials or resonators that absorb the incident acoustic energy. These materials include fiberglass batting and open-cell polyurethane. The engine cowling can be designed to form a labyrinth for the cooling air and noise, and fan inlet radiated noise can be reduced by the application of acoustic materials. Likewise, exhaust noise can be reduced by using acoustic materials and by the use of acoustic treatment downstream of the low-pressure turbine stage; and properly designed mufflers or resonators can be used as a combination mechanism for shielding and absorbing noise in duct walls of turboprop and turbofan engines.

Rotor noise reduction. Rotor blade/propeller radiated noise can be reduced by increasing the diameter and the number of blades, by decreasing the tip velocity, by sweeping or tapering the blade tips, by decreasing shaft horsepower, or by phasing the propellers of a multipropeller aircraft to minimize the noise through phase cancellation of the noise from each propeller. Slowing or sweeping the main rotor blade tips and replacing the traditional tail rotor with a fan-in-duct (fenestron), a fantail (RAH-66), or the no-tail-rotor vector-thrust antitorque/yaw control system eliminates the interaction between the vortices from the main rotor and the tail rotor, which is a significant source of the aural signature. Another noise reduction technique is to reduce the impulsive or slapping noise caused by blade-vortex interaction. Reference 70 describes many of the techniques used to reduce the rotor noise on the RAH-66 Comanche.

Go to Problem 4.4.43.

4.4.4.5 Other signatures. There are other aircraft observables that are potential sources for detection, tracking, and home-on-jam. These include the active electromagnetic emissions by the aircraft as it conducts its mission and those electromagnetic emissions that are inadvertent. Active emissions include radars for navigation and weapons delivery, altimeter radars for height finding, communications, and active countermeasures, such as jammers and deceivers. Inadvertent emissions include emissions from equipment on standby status. These observables should not be overlooked. They should be examined to determine if they can be used by the enemy as a source for detection, tracking, and guidance.

4.4.5 Expendables

Expendables are materials or devices designed to be ejected from an aircraft for the purpose of denying or deceiving threat tracking systems for a limited period of time. As the name implies, they are not intended to be recovered after they are deployed. Because they are not reusable, they must be of low cost when compared to the cost of the aircraft they are designed to protect. Expendables can be used by an aircraft for self-protection or for mutual support between several aircraft. A dedicated aircraft can also deploy expendables to provide either a predeployed saturation screen or decoys for many aircraft. If the signature of the aircraft that the expendable is supposed to protect is too large, it will be difficult, if not impossible, to design an effective expendable system.

Expendables come in many forms. Four of the simplest are chaff and retroreflectors (for radar systems), aerosols (for IR and visual systems), and flares (for IR systems). For radar systems, active deception jammers and unpowered and powered small, air-launched decoy aircraft constitute more complex forms of expendables. Some of the design and operational considerations regarding onboard expendables are 1) which expendables to carry and how many of each type; 2) the expendable ejection locations, and directions, the number of expendables in a salvo and their distribution around the aircraft, and the time between salvos; 3) when to eject the expendables; and 4) what to do next. Most expendable systems have a cockpit control unit that is used to select one of the expendable programs built into the system and the dispensing mode, such as manual or automatic.

4.4.5.1 Radar expendables.

Learning	**4.4.18**	**Describe the expendables used against radar systems.**
Objectives	**4.4.19**	**Describe how they degrade detection and tracking.**

Chaff: One of the oldest forms of expendables is chaff. Code-named Window by the British, it was first used in World War II to confuse German air defense radars. It is still considered by many to be one of the most effective countermeasures for radar systems. However, the increasing sophistication of moving target indicator processing and other ECCM techniques may eventually render it ineffective.

Chaff dipoles: A chaff cloud consists of a large number of dipoles. A typical dipole consists of a very thin strip of aluminum foil or a very thin glass fiber coated with aluminum or zinc. The fibers can easily be ingested by an aircraft engine with no adverse effects. Each dipole exhibits a radar return or backscatter cross section that depends on the radar wavelength λ and hence frequency f according to Eq. (3.17). A typical example of the variation of σ with respect to frequency is shown in Fig. 4.40. For dipoles with very large length-to-width ratios, the peak return occurs in the resonance region at the radar wavelength that is approximately twice the physical length of the fiber. Resonances also occur at higher integer multiples of

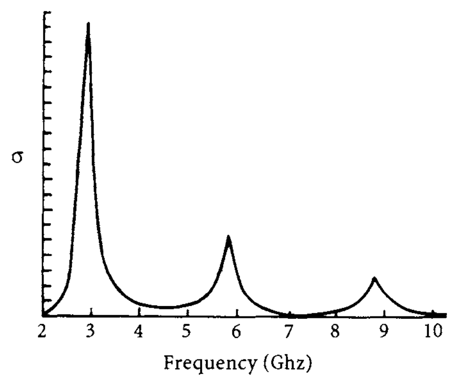


Fig. 4.40 RCS of a single dipole.

the fiber length. The magnitude of the backscatter RCS of the dipole also depends upon its orientation with respect to the electric field of the illuminating radar and the conductivity of the foil or coating. Viewed end on, the return is essentially zero, whereas from the side it could have a maximum RCS of approximately $0.87\lambda^2$ when the electric field is parallel to the fiber. When averaged over all aspects, the return from a single dipole is approximately $0.16\lambda^2$ at the resonant wavelength.

Chaff bundles and corridors: Chaff for short- and medium-wavelength radars is usually dispensed in individual bundles or continuously. The bundle chaff results in a roughly spherically shape cloud. When the chaff is continuously dispensed from a fast-moving aircraft, the cloud very rapidly grows into a corridor along the flight path. The composite echo received by a radar from the chaff cloud or corridor is the vector sum of the individual echoes received from each dipole within the radar range gate, accounting for the phase and polarization relationships between the return from each dipole. To affect a particular radar operating at one wavelength, each dipole should be cut to one-half of that wavelength. For example, for a 3-GHz radar with a wavelength of 10 cm the dipoles should be 5 cm long. When more than one radar frequency must be countered, the dipoles can be cut into several lengths, with each length optimized to a particular frequency. The theoretical minimum number of dipoles required to give an average RCS of σ is $\sigma/(0.16\lambda^2)$. Thus, an average RCS of 10 m^2 at 3 GHz requires at least 6000 dipoles. The actual number required is larger than the minimum number as a result of dipole shielding, uneven distribution, and breakage.

The effects of chaff on a surveillance radar PPI and a range scope are illustrated in Figs. 4.41 and 4.42. The radar return of a fully developed chaff cloud is not a constant value with time. The pulse-to-pulse variation of the RCS can be quite large. In general, chaff clouds at high altitudes tend to grow in physical size and RCS from several minutes to several hours after deployment, with most of the growth in the direction of the prevailing winds, whereas chaff dispensed from helicopters close to the ground can settle within a minute in calm air. The RCS of the mature cloud depends to a large extent on the geometry of the cloud to the radar, the cloud position, and the wind direction.

Ropes: For the long radar wavelengths the glass fibers and aluminum foil become impractical, and rope chaff is used. Rope chaff is metal or metal-coated fiber streamers that is very long compared with the frequency to be countered.

Chaff dispensers: Dipole chaff is packaged and deployed in several ways. These include discrete rectangular or circular cylindrical containers, known as bundles or cartridges, and continuous rolls. The cylindrical containers are stored in a dispenser and are ejected by electromechanical, pneumatic, or pyrotechnical methods. A typical chaff cartridge and dispenser are illustrated in Fig. 4.43. Three chaff cartridges are the RR-129/AL (E, G, I bands), the RR-170/AL (E, G-J bands), and the RR-180 Dual.[71] (More data are available online at http://www.denix.osd.mil/denix/Public/Library/Rfchaff/Images/images.htm, http://www.denix.osd.mil/denix/Public/Library/Rfchaff/Docs/gaochaff.pdf, and http://www.fas.org/man/dod-101/sys/ac/equip/). The rolled chaff can be precut fibers packaged between two sheets of plastic, or it can be a spool of continuous fibers that are cut to the desired length by the dispenser.

The location and orientation of the dispenser on the aircraft has a major impact on the effectiveness of chaff in the self-protection role. For self-protection the chaff cloud must bloom very rapidly so that the radar sees both the aircraft and the chaff

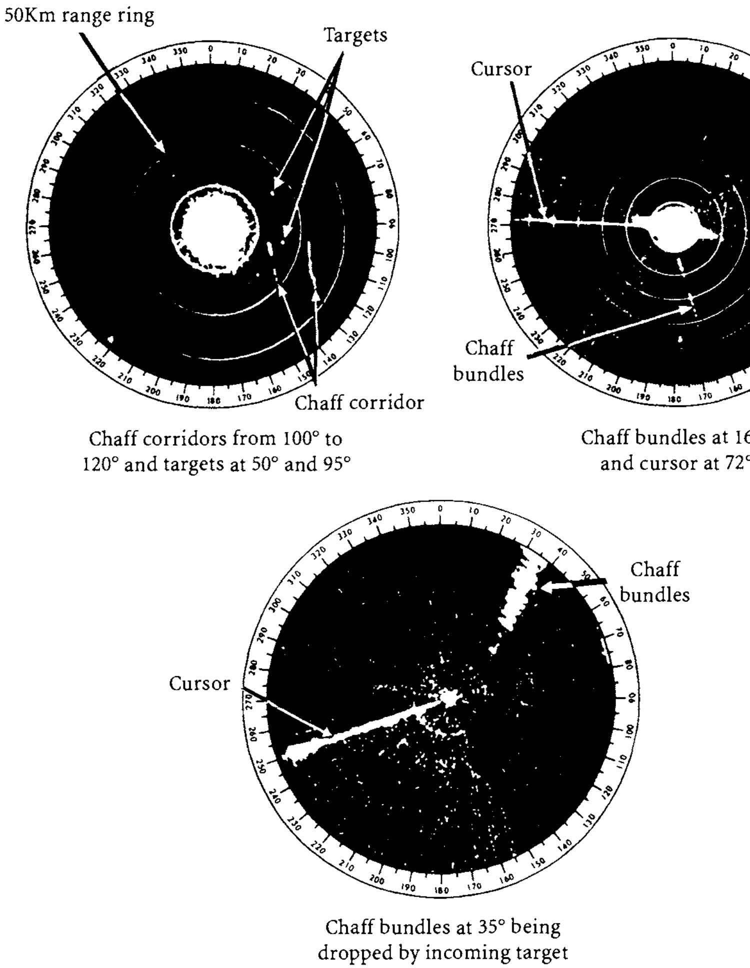


Fig. 4.41 Appearance of chaff on a PPI.

in the same range bin. Rapid growth is enhanced when the chaff is ejected into a very high turbulent flow. Consequently, forward of, but not in line with, wing roots and the engine exhaust are good locations for the dispenser. Furthermore, the chaff is usually dispensed rearward, as illustrated in Fig. 4.43, although some chaff dispensers eject the chaff forward of the aircraft to confuse radar trackers that automatically reject a second echo that suddenly appears toward the rear of the target aircraft. For a number of reasons, some chaff dispensers have been built to also carry and dispense IR flares and active jammers for decoying missiles. Smooth airflow conditions are desirable for the flares and jammers. This is, however, the least desirable environment for the chaff. Consequently, the location of the dispenser is often a compromise. The chaff is typically dispensed under the control of a programmer unit according to the settings on a control panel. The most recent

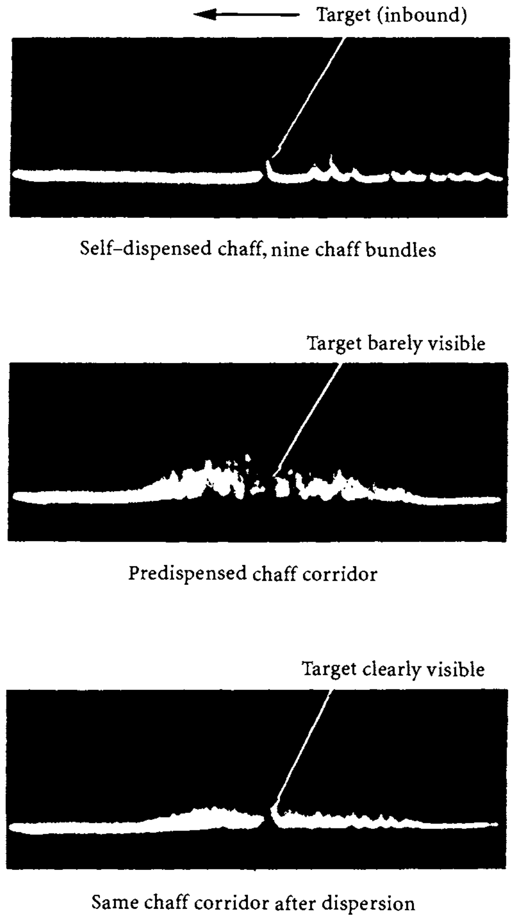


Fig. 4.42 Chaff on a range scope.

countermeasures dispensing systems connect the dispensing unit with a warning receiver. Several current chaff (and flare) dispensers, also known as decoy systems, are listed in Table 4.9. Considerably more information on this equipment can be found in Ref. 26 and online at http://www.fas.org/man/dod-101/sys/ac/equip/.

Uses and effectiveness: Chaff can be used against the long-range early warning radars, ground-controlled intercept radars, and acquisition radars in the predeployed saturation mode or the mutual support mode. Against airborne weapons systems and ground-based weapon control radars, these two modes and the self-protection mode can be effective. Chaff can also be used as a countermeasure for radar proximity fuzes. Figure 4.44 illustrates three techniques for chaff deployment. The flight path of the aircraft subsequent to the ejection of chaff will influence the effectiveness of the chaff in breaking the radar lock-on.

The requirements on chaff are that it must grow rapidly, it must provide the necessary RCS, it should remain aloft, and it should move to provide a Doppler

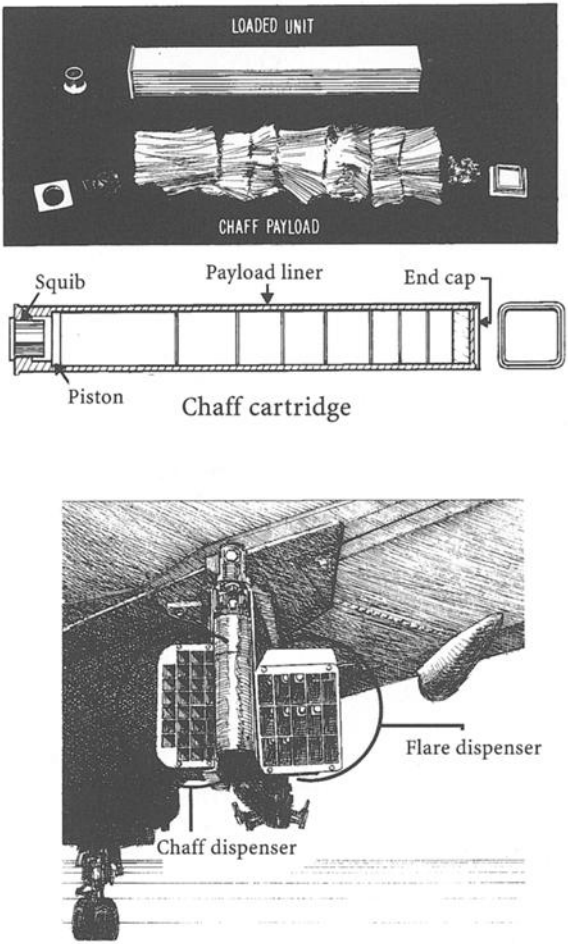


Fig. 4.43 Chaff cartridge, chaff dispenser, and flare dispenser.

frequency shift. In general, chaff is effective when the aircraft is within the very large cloud or corridor and the chaff echo masks the target's echo or when a small cloud decoys a radar tracker, causing a break-lock. However, if the radar employs ECCM against chaff, such as pulse-Doppler or MTI signal processing, the moving echo from the aircraft can be identified by the radar operator in the presence of the relatively stationary echo of the chaff cloud. Skilled operators can track aircraft through the chaff, but the tracking accuracy will most likely be degraded. Aircraft that are behind the cloud can be detected if a sufficient amount of the radar signal passes through the cloud, just as an object can be observed by the human eye behind a smoke screen if the smoke is not totally opaque to light. Another counter to the chaff countermeasure is the switch to EO tracking when the chaff is first detected.

Table 4.9 Some decoy systems[26]

System	Definition
M-130 general purpose dispensing system (USA aircraft)	Lightweight chaff and flare dispensing system based upon the AN/ALE-40 (BAE Systems, formerly Tracor/ Marconi NA)
AN/ALE-39B (USN fighter and attack aircraft)	Internally mounted system that can dispense mixed loads of chaff (RR-129/AL) flares, and active expendables (POET and GEN-X) (BAE Systems, formerly Tracor/ Marconi NA)
AN/ALE-40 (USAF fighter and attack aircraft)	Internally, semi-internally, pylon, or skin-mounted system that can dispense mixed loads of chaff (RR-170/AL) and flares (BAE Systems, formerly Tracor/Marconi NA)
AN/ALE-47 (USAF and USN fighter and attack aircraft)	Form fit replacement for both the AN/ALE-39B and the AN/ALE-40 that dispenses all 39 and 40 expendables plus the RR-180 Dual chaff cartridge (BAE Systems, formerly Tracor/Marconi NA)

Radar reflectors. In addition to chaff, other reflective devices are used, primarily in decoys, to create target-like radar echoes. These reflective devices can be used either to make a small false target appear large or to create clutter and confusion on the radar screen. The reflective device can be as simple as a corner reflector or as exotic and complicated as a Luneberg lens or Van Atta array. The main requirements are that the echo be the appropriate size in the band of the radar and that the extent of the viewing angle for the RCS decoy is appropriate. The corner reflector provides a relatively large return over a wide range of angles caused by the multiple reflections of the incident signal off of the angled faces back in the direction of the receiver, as shown on Fig. 4.4f. Table 4.4 gives the formula for the maximum radar cross section for the triangular corner reflector. The triangular corner reflector is generally used because it can easily be manufactured and handled. For example, three thin circular plates that intersect at right angles form eight corners that can be seen from any direction. When coverage wider than that provided by a single corner reflector is desired, the use of a Luneberg lens or Van Atta array can be considered.

Active expendable deceivers. The active expendable deceiver or decoy is an expendable radar transmitter designed to deceive tracking radars. There are two types of expendable jammers: those that are ejected from a dispenser on the aircraft, such as the Primed Oscillator Expendable Transponder (POET) and its replacement GEN-X, and those that are towed behind the aircraft for self-protection,[72,73]

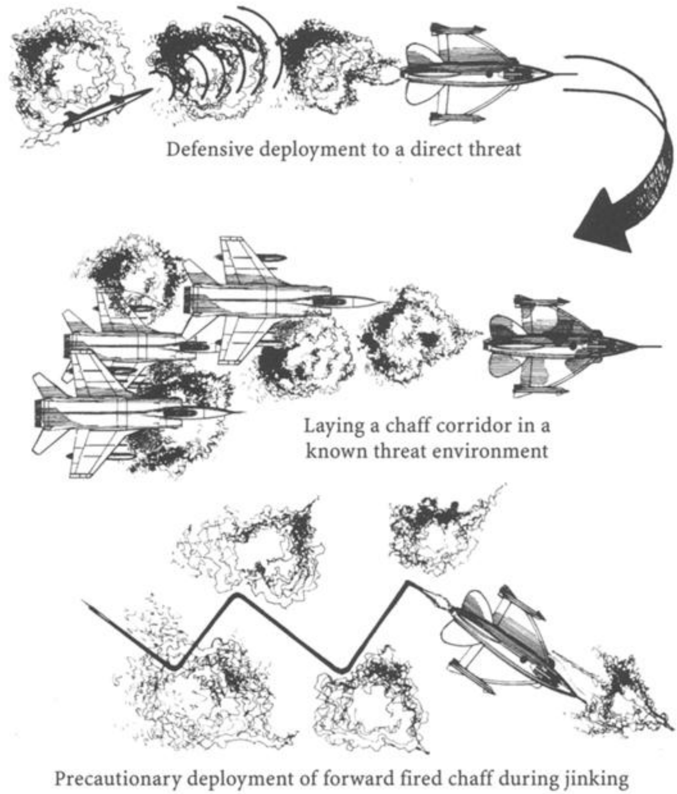


Fig. 4.44 Chaff deployment.

such as the AN/ALE-50 Towed Decoy System.[74] (http://www.raytheon.com/products/ale50/.) Deceiving signals emitted by the decoy are designed to seduce the approaching missile away from the target aircraft and toward the decoy. The signals emitted by the towed decoy are generated either by the decoy itself (a repeater decoy) or by an onboard countermeasures device linked to the decoy by a fiber-optic cable. The towed decoy may or may not be recoverable. If recoverable, perhaps this description should be in Sec. 4.4.3: Noise Jammers and Deceivers.

Air-launched decoys. Air-launched decoys are expendable unpowered or powered air vehicles that are launched from aircraft before or during an air strike. They can be passive decoys that simulate a tactical aircraft's characteristics, such as flight path, speed, and RCS; or they can also carry an active radar jammer/deceiver. Their goals are to saturate and confuse the enemy air defense, tempt the defense to turn on their radars and thus make them targets for SEAD/DEAD aircraft, and to draw enemy fire away from the strike aircraft. Two current air-launched decoys are the unpowered ADM-141A Tactical Air-Launched Decoy (TALD) and the powered ADM-141C Improved TALD (ITALD). (http://www.fas.org/man/

dod-101/sys/ac/equip/.) A decoy under development is the Miniature Air-Launched Decoy (MALD). (http://www.darpa.mil/tto/Programs/mald.html.)

Go to Problems 4.4.44 to 4.4.50.

4.4.5.2 IR and visual expendables.

Learning	**4.4.20**	**Describe the expendables used against IR and visual systems.**
Objectives	**4.4.21**	**Describe how they degrade detection and tracking.**

Infrared and visual expendables include aerosols, IR flares, and the towed IR decoy.

Aerosols. Mists, fogs, smokes, clouds, and similar atmospheric disturbances have been used in warfare since the beginning of recorded history. Until recent times the main use of these disturbances was to provide a screen to prevent the enemy from seeing the friendly forces. However, aerosols can be used to hide aircraft from IR and other electromagnetic wave sensors, as well as visually. They can also be used to generate false targets and to modify the target signature.

An aerosol consists of many relatively small particles dispensed into the atmosphere to form a cloud. These particles will scatter, absorb, and transmit a portion of any incident electromagnetic wave. The amount of scattering, absorption, and transmission depends on the size and properties of the particles. When the aerosol cloud lies between the aircraft and the sensor, the amount of obscuration of the target signature will depend upon the level of reduction in the transmitted intensity of the incident electromagnetic wave as it passes through the aerosol, which is known as the extinction. The extinction is caused by the absorption and scattering of the incident wave, and the larger the extinction, the more effective the aerosol is at hiding the aircraft.

In principle, a light ray or any similar electromagnetic wave passing through a medium is unperturbed so long as the refractive index of the medium is unchanged. When the wave strikes an aerosol cloud, the extinction of the wave by the aerosol particles depends upon the wavelength of the incident wave, the particle size, and the refractive index of the particle. The refractive index is a measure of both the scattering and the absorption properties of the particle. There are three ranges of particle sizes: small sizes, where the particles are much smaller than the wavelength; intermediate sizes, where the particles and wavelength are of comparable magnitude; and large sizes, where the particles are much larger than the wavelength (see Fig. 4.2a). The amount of scattering by a particle for a given wavelength is not a simple function of the particle shape and size, and the angular intensity is very variable and depends on the particle size and refractive index. An aerosol cloud designed for optimum performance must use particles matched to the physical and electromagnetic constraints of the application. Aerosol generation is ultimately a process of generating particles from a liquid, or separating discrete particles that tend to cling together, and dispersing them into a cloud of the right size, using various explosive or depressurization techniques.

Infrared flares. An IR flare is a pyrotechnic solid, or pyrophoric liquid or metal, self-protection device, designed to be ejected from an aircraft, that emits a large amount of radiation in the sensor bandwidth of an IR homing missile. (http://www.bristol.ca/PyrophoricIRFlare.html and http://www.fas.org/man/dod-101/sys/ac/equip/mju-52.htm.) It is supposed to be a more attractive target to the IR seeker. The seeker on an approaching IR missile will detect the presence of both the flare and the aircraft in its field of view and hopefully will home in on the flare because of its IR signature. Because the flare is moving away from the aircraft, the missile will be decoyed away from the aircraft, possibly causing a miss distance sufficiently large to prevent a warhead detonation. Some current flares are the MJU-27A/B, the MJU-46B, the MJU-49B, and the M-206.[25] More data are available online at http://www.fas.org/man/dod-101/sys/ac/equip/.

Flare intensity: There are several factors to be considered in the design and utilization of flares. For example, the flare must be of sufficient intensity (relative to the target signature) in the bandwidth of the IR detector to be seen as a more attractive target. It must be launched at the right time, in the right direction, and must reach full intensity quickly if it is to draw the missile away from the aircraft. It must also burn long enough to prevent the seeker from reacquiring the aircraft. The fact that the pyrotechnic flare is a relatively small or point source of IR intensity, whereas the aircraft and exhaust plume are distributed sources, may have an influence on the effectiveness of the flare in decoying the missile. The amount of influence will depend upon the type of target tracker in the missile.

A typical flare energy spectra is shown in Fig. 4.45 for sea-level conditions. In general, the flare will radiate as a very hot blackbody (Fig. 3.65a); the dips in intensity at 2.7 and 4.3μ are caused by the absorption by the CO_2 in the atmosphere (Fig. 3.67). The flare intensity is affected by both the aircraft altitude and its velocity. There is a decrease in intensity for increasing altitude and a decrease in intensity for increasing velocity. The aircraft velocity has the most significant effect on the intensity because the high-velocity air passing around the flare reduces the size of the fireball and cools the surrounding air, thus reducing the intensity of the radiation.

Flare ejection: Flares, like chaff, are ejected from a dispenser. A flare dispenser is illustrated in Fig. 4.43. Attention must be given to the location, direction, and velocity of flare ejection. Whereas chaff should be ejected into turbulent airflow, flares should be ejected into nonturbulent airflow in order to minimize the decrease in intensity caused by velocity effects. Generally, flares are ejected down and slightly to the rear of the aircraft, as shown in Fig. 4.43. This allows gravity to maintain the flare at the ejected velocity away from the aircraft and also draws the missile down and behind the departing aircraft. Flare ejection velocity should not be so low that the miss distance is insufficient to prevent warhead detonation, nor so high that the seeker will not respond to the rapidly moving flare and the lock-on will not be broken as the flare transits the seeker's field of view.

Flares are usually ejected in a salvo (several at a time) with a set time between salvos. The number of flares in a salvo and the time interval between salvos can be automatically set or crew selected. Aircraft maneuvers after flare ejection must be considered in the development of a successful flare system. Sharp turns in the horizontal plane accompanied by reductions in engine power reduce the aircraft IR emissions in the field of view of the seeker, thus allowing the flare to be seen. The

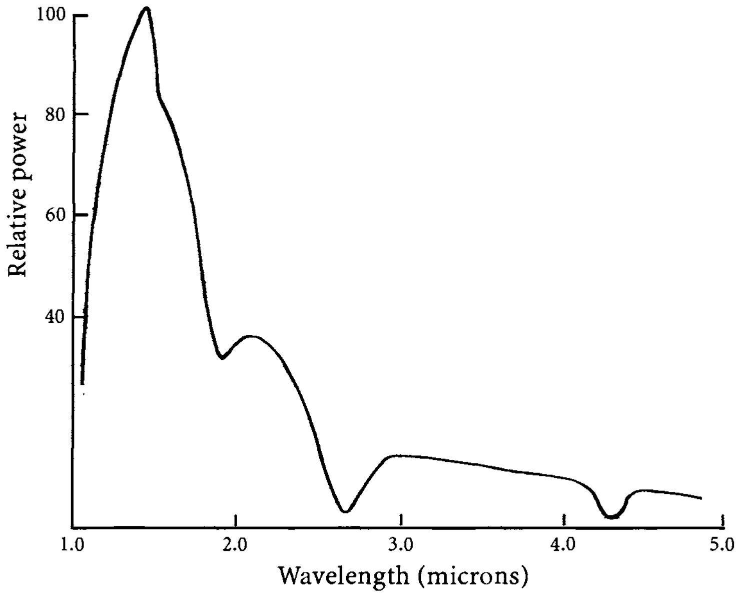


Fig. 4.45 Example of a flare spectra.

desire to use the engine afterburner for additional power after a missile sighting and flare ejection can be self-defeating because of the large increase in the IR emission.

Flare effectiveness: The effectiveness of the IR flare as a countermeasure depends on the flare parameters of rise time, burn time, power output, and spectral distribution; the number of flares carried; the ejector locations; the time of ejection; the number of flares in a salvo, the distribution of the flares in the salvo around the aircraft, and the interval between salvos; the flare trajectories; and the subsequent aircraft maneuvers. Many modern IR missiles have built-in flare rejection capabilities. For example, note that the flare spectral distribution in Fig. 4.45 does not match that of an aircraft shown in Fig. 4.11a. Because the flare must be very hot in order to develop enough radiant flux, most of the flare energy is in the short wavelengths below 2 μm. This feature could be used by a two-color IR detector to reject a flare as a target. The seeker could measure the spectral radiant intensity in two wavelengths from the aircraft and the flare. By comparing the relative intensity in each wavelength, it could make a decision as to whether it was tracking a flare or an aircraft.[75]

Go to Problems 4.4.51 to 4.4.56.

Towed IR decoy. A towed IR decoy works by slowly dispensing a pyrophoric material in a plume behind the aircraft. The radiation from the material is similar to that from the engine exhaust plume, and so a missile's IR tracker would have to contend with two IR targets. The most recent evolution of the towed decoy is by Raytheon and is known as the Comet. (http://www.knowlesreport.com/sample.htm.)

4.4.6 Threat Suppression

Learning Objective 4.4.22 Describe some of the techniques for threat suppression.

Threat suppression consists of actions taken by friendly forces with the intent to physically damage or destroy part or all of a threat system. The actions can be taken by supporting elements, such as a fighter escort, SEAD aircraft, or supporting artillery; or they can be taken by an aircraft in jeopardy for self-protection. For example, missiles and guns carried by utility helicopters, ASW aircraft, and bombers for self-defense are threat suppression weapons. Degradation of the threat effectiveness can also occur through intimidation; the presence of armed helicopters escorting an airborne troop assault can discourage an attack on the troop carriers and the potential use of an antiradiation missile (ARM) that homes in on the transmissions from a radar antenna might make the enemy reluctant to turn the radar on. Often the threat suppression does not have to destroy all of the threat elements. The use of an ARM can render a radar-guided threat useless by causing sufficient damage to the radar antenna or the supporting mechanical and electronic equipment. The concept of threat suppression has been around for a long time (get them before they get you) and is a major survivability factor in many scenarios. Quick destruction of the hostile air defense systems is a primary goal in any conflict.

Go to Problems 4.4.57 to 4.4.59.

4.4.7 Weapons and Tactics, Flight Performance, and Crew Training and Proficiency

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Learning Objective 4.4.23 Describe the contributions of weapons and tactics, flight performance, and crew training and proficiency to survivability.

This last concept is somewhat of a catch-all concept. It combines all of the operational aspects of combat except threat suppression.

4.4.7.1 Weapons and tactics. The weapons carried by a shooter aircraft and the associated tactics used have a very large effect on the survivability of an aircraft in combat (Note 37). Suppose the target assigned to an attack aircraft is heavily defended by AAA and SAMs out to a range of 10 n miles. The aircraft has a much better change of surviving the mission if the target can be detected at 40 n miles (or it is a fixed target with known geographical coordinates) and the weapon is effective when launched from high altitude at 20 n miles than if the weapon is a dumb bomb that must be dropped from low altitude close to the defended target.

Tactics is the employment of units in combat, and the development of tactics is normally the responsibility of the operational and test units. Typically, the tactics consist of the flight profiles, operations, and formations used to accomplish the mission. The tactics employed in a particular combat operation are influenced by many factors, such as the intensity and effectiveness of the air defenses, the urgency of the mission, the type of aircraft for the mission, the availability of supporting elements (FE, SOJ, etc.), and the terrain and weather. Those in charge of choosing the tactics should take into account the susceptibility and vulnerability of the aircraft at their disposal and plan the operation accordingly. Many missions are planned by mission planning systems, such as TAMPS and AFMSS. Usually, those tactics are selected that minimize the susceptibility of the aircraft, either by eliminating the threat or by reducing the exposure time to the various threat elements (threat avoidance). However, the tactics must account for the aircraft's performance and weapon delivery capabilities. Some of the current susceptibility reduction tactics are as follows: jinking maneuvers to defeat fire control flight-path predictors and cause large miss distances, evasive maneuvers to avoid approaching propagators, avoidance of known locations of threat sites, the use of high altitude standoff weapons, nap-of-the-Earth flight, terrain masking, adverse weather operations, saturation attacks, attacks at night, and the use of every available friendly unit for support of one kind or another.

4.4.7.2 Flight performance. Speed is life, or so the saying goes. This adage may not be as true today as it was in the past. It also overlooks the primary reason for the aircraft being in hostile territory in the first place: the accomplishment of the mission objectives. Can the objectives be accomplished at high speed? Turning performance, maneuverability, and agility have been important flight performance parameters for fighter aircraft for nearly 100 years. But they will not help much when the fighter with a large RCS is engaged from long range by an enemy fighter with a beyond visual range (BVR) air-to-air missile. Comparing the effectiveness of two aircraft as a total weapon system today requires consideration of all of the operational attributes of the aircraft, not just the aerodynamic performance specifications. Is that extra *g* of maneuverablity worth the accompanying increase in radar and IR signatures (Note 38)?

4.4.7.3 Crew training and proficiency. Train as you are going to fight is the current training doctrine. History has shown time and again that the proficient aircrew will survive in combat more often than those with little or poor training and inadaquate proficiency. Flying a modern, high-technology aircraft is not a simple task, particularly when the enemy is trying to kill you as you try to do your job. A well-designed cockpit layout and a forgiving flight control system can allow the trained and proficient pilot to concentrate on accomplishing the mission objectives and avoiding the enemy's guns and missiles. Although this aspect of survivability enhancement is not usually considered to be a part of designing for survivability, it nevertheless must be included among the concepts for survivability enhancement.

Go to Problems 4.4.60 to 4.4.63.

Endnotes

1. There is a close parallel between the use of the E^3A in the susceptibility program to determine the essential events and elements in the scenario and the use of the fault tree analysis to determine the aircraft's critical components in the vulnerability program described in Chapter 5, Sec. 5.2.2.8. Both analyses start with an undesired event (a hit on the aircraft or an aircraft kill) and then determine what events either can or are required to cause the undesired event.
2. The reader who is unfamiliar with the general subject of radar should read the material in Chapter 3, Secs. 3.6.1 and 3.6.2.
3. The power density in the radar beam is analogous to the IR radiant exitance from a body, illustrated in Fig. 3.64, where the surface of the body represents the beam.
4. The standard mathematical definition of σ is the limit of $4\pi R^2 \cdot |E_s|^2/|E_i|^2$ as R goes to infinity, where E_i is the strength of the electric field in the incident wave at the scatterer and E_s is the strength of the spherically scattered wave at a distance R from the scatterer.
5. There are two parts to the solution to Maxwell's equations. One part, known as the far-field part, decays very slowly as the reflected wave propagates away from the scatterer. This is the part of interest in most radar-aircraft situations. The other part, the near field part, decays very rapidly as the wave propagates away from the body and consequently is insignificant in the far field. In the near field, which is the field of interest to fuze designers, both parts are important. These two parts are analogous to the phugoid and short period oscillation modes of an aircraft. When a flying aircraft receives a gust input, the initial response is a combination of both the phugoid (a relatively slow wings level oscillation in altitude) and short period (a rapid angular rotation about the aircraft's center of gravity) modes. The short period mode quickly decays, and the subsequent motion of aircraft consists of only the phugoid mode.
6. Shine a flashlight on a mirror such that the beam of the flashlight is normal to the surface of the mirror and you will see a very bright light, but it will not blind you.
7. More complex theories that account for edge effects are the Geometrical Theory of Diffraction (GTD) and the Physical Theory of Diffraction (PTD).
8. The RCS pattern with respect to the angle of incidence is analogous to the gain pattern from an antenna. Both exhibit a strong main lobe with smaller side lobes. Hence, an aircraft is simply a complex antenna when illuminated by a radar signal.
9. One simplistic way to interpret diffraction from a sharp edge as illustrated in Fig. 4.4d is to consider the sharp edge to be a wire antenna. If the edge is vertical and the polarization is vertical, the electrons in the wire can easily oscillate along the wire as a result of the impinging oscillating electric field and will efficiently reradiate a signal around the wire, as shown in Fig. 4.4d. However, if the wave is horizontally polarized the electrons are forced to oscillate around the circumference of the wire, which they do not do efficiently, and very little scattering will occur.
10. When the radar wavelength is short, any discontinuity in the skin of the aircraft can be the source of a large echo. An example of this phenomenon is described in *Skunk Works, A Personal Memoir of My Years at Lockheed*, written by Ben R. Rich and Leo Janos and published by Little, Brown and Company in 1994. In the chapter entitled "The Silver Bullet," they describe the development of the first stealth fighter, the F-117. The following excerpts are taken from p. 69:

    Ultimately I had to guarantee that the stealth fighters would meet the identical radar cross section numbers achieved by our thirty-eight-foot wooden model at the White

> Sands radar range in 1975 . . . I was feeling particularly skittish on that score because a few weeks before the contract negotiations began, I received an urgent call from Keith Beswick, head of our flight test operation out at the secret base. 'Ben' he exclaimed, 'we've lost our stealth.' He explained that Ken Dyson had flown that morning in Have Blue (the subscale prototype of the F-117) against the radar range and was lit like a . . . Christmas tree. 'They saw him coming from fifty miles.' Actually, Keith and I both figured out what the problem was. Those stealth airplanes demanded absolutely smooth surfaces to remain invisible. That meant intensive preflight preparations in which special radar-absorbent materials were filled in around all the access panels and doors. This material came in sheets like linoleum and had to be perfectly cut to fit. About an hour after the first phone call, Keith phoned again. Problem solved. The heads of three screws were not quite tight and extended above the surface by less than an eighth of an inch. On radar, they appeared as big as a barn door!

11. One problem with outdoor ranges is the lack of security. Overhead surveillance satellites may be able to observe the tests.
12. The reader who is unfamiliar with the general subject of infrared radiation should read the material Chapter 3, Secs. 3.6.1 and 3.6.3.
13. The losses in the power of the echo are accounted for by introducing the 'greater than one' loss factors L_a and L_s in the denominator, rather than numbers 'less than one' in the numerator. The reason the losses are represented by a number in the denominator is because any number in the denominator is subtracted from the total when the maximum range is computed using decibels. A number in the numerator would be added. However, intuitively, losses should subtract, not add. The numerical result would be the same if the numerator approach with numbers less than one is used, but the procedure would be counterintuitive.
14. In some publications the noise power N is represented by the total interference power I, and the power ratio S/I is used rather than S/N .
15. The radar detection envelope shown in Fig. 4.12f is a more detailed description of the general detection envelope shown in Fig. 3.5. However, note that the coordinate axes and scales are different. For example, the altitude in Fig. 4.12f is the normal distance above the Earth's surface, whereas the altitude in Fig. 3.5 is the vertical distance above the 0-deg elevation.
16. The four Swerling cases are defined as follows. Case 1 is the situation where the aircraft consists of a large number of relatively equal amplitude scatterers. The aircraft echoes on any one scan are of constant amplitude, but the amplitude changes independently on each scan. This is referred to as slow fluctuation. Case 2 is the situation where the individual echo pulses change independently during each scan. This is fast fluctuation. Case 3 is similar in fluctuation to case 1, but the aircraft has one dominant scatterer and a number of smaller scatterers. The aircraft in case 4 is similar to the aircraft in case 3, and the fluctuation is similar to case 2.[76]
17. Note the absence of 4π in the denominator of Eq. (4.8a). The reason for the absence is that the aircraft's signature is given in watts/steradian, not watts as in radar.
18. Note that R is usually in meters or kilometers, whereas NEFD is usually in W/cm^2. Consequently, the units of NEFD must be changed to meters or kilometers when computing R_{LO} in meters or kilometers.
19. Many tracking systems apply mathematical filters, such as a Kalman filter, to measured data to obtain a better estimate of the target's true parameters.[77]
20. The normal PDF is described in detail in Appendix B, Sec. B.7.2.
21. The circular normal PDF is described in detail in Appendix B, Sec. B.7.4.

22. Equations (4.45a) through (4.45c) for the deceleration of a fragment can also be used to determine a projectile's deceleration as a result of drag.
23. The intercept shown in Fig. 4.19 is modeled when 90 deg $< \Psi_P <$ 180 deg, as shown in the diagram in the lower right corner of Fig. 4.20b.
24. Your calculator most likely would show −40.9 deg rather than 139.1 deg. They are the same angle because the negative sign means the angle is clockwise from the negative x axis as shown in the figure in the example. When both $(v_p)_x$ and $(v_p)_y$ are negative, ψ_p provided by a calculator will be a positive number less than 90 deg, when it should be that number plus 180 deg.
25. The situation when there is a correlation between the N miss distances is referred to as round-to-round correlation. For example, suppose the first round miss distance is in the upper right-hand quadrant. If there is round-to-round correlation, the miss distance of the second round is more likely to be in the upper right-hand quadrant because that is the location of the first round. Thus, the effect is to exhibit a mean error for a small sample size.
26. Reference 78 contains considerably more detail on the types of errors associated with AAA and their effect on P_H.
27. If the fragment's velocity decay is accounted for, the fragment path in Fig. 4.25b would curve counter clockwise—the larger the decay, the larger the curvature.
28. In general, Eqs. (4.46a), (4.46b), and (4.46c) apply for any value of Ψ_P. However, the value of ϕ obtained from Eqs. (4.46c) and (4.46d) by a calculator might not correspond to the correct value of ϕ (see Note 24).
29. Because the fragment paths shown in Fig. 4.26 are relative to the target, the actual distance a fragment travels from the detonation point to the target is not the length of the path in the figure. However, the time to impact is the same in both the local and the global coordinate systems. Thus, the actual distance equals the relative distance times (V_F/V_f).
30. The words passive and active are often used to describe the various countermeasure techniques. Passive refers to any technique that does not require any action that would alert the enemy as to the presence of the aircraft, whereas active does require such action. For example, threat warning and signature reduction are usually passive techniques, whereas noise jamming, expendables, and threat suppression are usually active techniques.
31. In a subtle way susceptibility reduction can appear to reduce an aircraft's vulnerability to a proximity-fuzed HE warhead. For example, the value of the $P_{K|F}$ for a SAM warhead that detonates 200 ft from the aircraft will most likely be less than the corresponding value for a warhead that detonates 20 ft away. The reduction in vulnerability is apparent rather than real, however, because the true measure of the vulnerability of an aircraft to the proximity-fuzed warhead is the $P_{\mathrm{K|F}}$ function, illustrated in Fig. 3.11, rather than any specific value of $P_{K|F}$.
32. Sometimes, if the jammer power at the radar receiver is approximately the same size as the radar internal noise power N_0, the total power ratio I/S is used at the radar receiver rather than J/S, where the interference power I is the sum of the jammer power J at the radar and the radar noise power N_0.
33. The more general view of signature reduction is signature control, which is "the manipulation of a platform's emission and physical characteristics, such as radar cross section, infrared modulation, radar pulse repetition rate, etc., in order to reduce an adversary's ability to detect, track, and engage friendly units during combat

operations. It is synonymous with signature management and low observables." (http://www.sew-lexicon.com/gloss_s.htm#SIGNATURE_CONTROL).

34. The chicken you cook in your 2.45-GHz microwave oven is a good example of attenuating RAM. The impedance of the chicken skin is close to that of air, so that most of the impinging radiation goes into the meat of the chicken. The meat is composed mainly of water, which exhibits an electric moment in the same manner as the CO_2 molecule examined in Note 80 in Chapter 3. Consequently, the oscillating electric field in the radar signal at 2.45 GHz induces internal oscillations of the atoms in the water molecule. These internal oscillations convert the electromagnetic energy into heat. And the chicken cooks.
35. The velocity of the radar signal in the conductive layer can be much slower that in air. Hence, the radar wavelength in the conductive layer, which is directly proportional to the velocity, can be much shorter than the radar wavelength in air, particularly for ferrite-loaded materials. Thus, the Dällenbach layer is usually much thinner than one-fourth of the wavelength in air.
36. Another possible solution is for SEAD aircraft to take the SAM radar out before the strike.
37. For aircraft that use electronics rather than weapons to achieve their mission objectives, such as SOJ, photoreconnaissance, and long-range targeting aircraft, the ability of the electronics to work effectively at long ranges or very high altitudes increases the survivability of the aircraft.
38. One phrase applied to the F/A-22 is 'hot and stealthy,' indicating that the aircraft designers have achieved a stealth design without sacrificing high performance.

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Problems

4.1.1 Describe susceptibility.

4.1.2 List the three major factors that determine the level or degree of susceptibility?

4.1.3 Describe the three major tasks in a susceptibility program.

4.2.1 Why is the E^3A conducted?

4.2.2 Conduct a simple E^3A for a single soldier with a rifle and a passing helicopter.

4.3.1 What is a susceptibility assessment?

4.3.2 The two categories of susceptibility assessment are the flyout and the endgame. What events does the flyout include, and what events does the endgame include?

4.3.3 List five major measures of susceptibility.

4.3.4 Susceptibility assessment includes all of the endgame events: True or False.

4.3.5 Describe what happens to a radar signal when it strikes and passes over an aircraft.

4.3.6 What distinguishes the backscatter RCS from the bistatic scattering cross section?

4.3.7 Because an aircraft has a fixed physical size, it has only one value of RCS: True or False.

4.3.8 Describe the three regions of RCS for a perfectly conducting sphere.

4.3.9 The RCS of a bomber for a 1-cm radar signal is in the Rayleigh region: True or False.

4.3.10 The theory of geometrical optics and the theory of diffraction optics are used to compute the RCS of large scatterers for small wavelengths: True or False.

4.3.11 The RCS of a flat plate is equal to the cross-sectional area when the ray is normal to the plate: True or False.

4.3.12 The RCS of a flat plate is 0 m^2 when the ray is not normal to the plate: True or False.

4.3.13 Explain your answer to Problem 4.3.9.

4.3.14 A vertically polarized signal will be diffracted by a vertical edge: True or False.

4.3.15 The RCS of a flat plate will be nearly 0 m^2 when the angle of incidence of the radar signal is very small: True or False.

4.3.16 What is a retroreflector?

4.3.17 What is the difference between a creeping wave and a traveling wave?

4.3.18 Composite materials do not reflect radar signals: True or False.

4.3.19 A radar signal passes over an irregular body. List the four generic contributors to the RCS.

4.3.20 List the specific locations on an aircraft that might contribute significantly to the aircraft RCS.

4.3.21 What particular feature of the RCS of a helicopter can be utilized by threat radar systems to enhance detection and tracking?

4.3.22 Describe target RCS scintillation.

4.3.23 Describe the cause of target glint.

4.3.24 The RCS values of three glitter points on a scatterer are 4 m^2, 25 m^2, and 49 m^2. What is the maximum value for the RCS of the scatterer?

4.3.25 What are the three general sources of an aircraft's infrared signature?

4.3.26 An IRST system operating in the LWIR band has the potential to detect slow-flying aircraft: True or False.

4.3.27 An IR detector with a cutoff (maximum) wavelength of 4 μm can detect the radiation from the skin of an aircraft traveling at Mach 2 at sea level: True or False.

4.3.28 What is the wavelength band associated with the hot parts in the engine exhaust when the engine is not in afterburner?

4.3.29 Which gas contributes the most to the engine exhaust plume radiation, and at what wavelength does it occur?

4.3.30 An engine goes into the afterburner mode, and the exhaust plume temperature goes from 700 to 1500 K. What is the peak wavelength of the radiation from the plume?

4.3.31 Reflected sunlight can be a significant source of IR radiation, particularly for the 1- to 3-μm detectors: True or False.

4.3.32 What are the blue spike and the red spike?

4.3.33 When a dark, single-engine, fixed-wing aircraft is viewed at night from the front and sides, the plume radiation is usually the primary source of the IR signature: True or False.

4.3.34 What are the four parameters that influence the detectability of the visual signature, and which one is the most important?

4.3.35 Turbojet engines are usually noisier than turbofan engines: True or False.

4.3.36 A radar has an antenna height of 16 ft. What is the radar horizon for an aircraft flying at 100 and 10,000 ft?

4.3.37 Given the following parameters of a radar system and target aircraft:

$$f = 10\,\text{GHz} \quad P_r = 200\,\text{kW} \quad G_r = 43\,\text{dB} \quad \text{PRF} = 1000\,\text{PPS}$$
$$L_s = 2\,\text{dB} \quad L_s = 4\,\text{dB} \quad (S/N)_{\min} = 15\,\text{dB} \quad N = 2 \times 10^{-16}\,\text{W}$$

Compute the free-space maximum range and the maximum range with multipath effects for an aircraft with an RCS of 1 m^2. What is $R_{\max}$ if the aircraft's RCS is reduced to 0.1 m^2? Use both the decimal and the decibel approach.

4.3.38 Lowering the threshold for detection increases P_D and reduces P_{fa}: True or False.

4.3.39 What is the required $(S/N)_{\min}$ to achieve $P_D = 0.98$ and $P_{fa} = 1 \times 10^{-10}$?

4.3.40 What is the range at which the radar described in Example 4.3 has a probability of detecting a 1-m^2 RCS aircraft of 0.6. Assume the P_{fa} is 1×10^{-10}.

4.3.41 What is the P_{fa} associated with a 15-min false-alarm time? Assume $B =$ 1 MHz.

4.3.42 What is the probability an aircraft is detected at least once on 20 pulses if the probability of detection on one pulse is 0.2.

4.3.43 What is the S and the N in S/N for an IR seeker?

4.3.44 Why is $R_{\max}$ for a radar system proportional to the fourth root of the aircraft radar signature, whereas R_{LO} for an IR system is proportional to the square root of the IR signature?

4.3.45 The lock-on range of an IR missile R_{LO} is proportional to the square root of the radiance of the aircraft: True or False.

4.3.46 R_{LO} is independent of the aircraft's aspect with respect to the seeker: True or False.

4.3.47 What are some of the factors that influence radar tracking accuracy that can be affected by the aircraft and its tactics?

4.3.48 Given the following set of 21 tracking errors in mrad, develop the histogram with seven bins and a bin width of 1 mrad. Determine the sample mean and sample variance using both the given error values and the histogram values. Determine the normal mean, standard deviation, and error probable based upon the given error values: $-1.3, -4.6, 0.4, -0.3, -1.2, -2.7, 1.9, -2.3, -1.9, -2.6, -1.9, -3.5, -1.2, -0.4, -3.3, -2.8, -1.5, -0.8, -2.5, -1.4, 0.1$.

4.3.49 Two sources of error contribute to the total tracking error: ε_{noise} and ε_{glint}. The variance of the total error is equal to sum of the variances of the noise and the glint: True or False.

4.3.50 Describe the CEP.

4.3.51 The following set of error values for the circularly symmetric error are possible: (0.2, 1.2, 0.7, 0.9, 1.5, −0.5, 1.4, 0.1, 0.5): True or False.

4.3.52 Given the following set of 11 circularly symmetric errors, determine the CEP using two procedures: 0.3, 0.7, 0.9, 0.4, 1.2, 1.7, 0.3, 1.1, 0.5, 1.0, 0.5.

4.3.53 A projectile is fired from a gun with a muzzle velocity of 2500 ft/s. Assuming no deceleration caused by drag, how far has the round traveled, and how far has it dropped after 2 s?

4.3.54 Long-range guided missiles typically fly a direct-line flight path to the target: True or False.

4.3.55 An aircraft is flying straight and level, from left to right, and a missile is approaching from in front and above in the (X, Z) plane. The two-dimensional intercept conditions are as follows:

$$T_X = 1000\,\text{ft}, \quad T_Z = 1000\,\text{ft}, \quad P_X = 1500\,\text{ft}, \quad P_Z = 1500\,\text{ft}$$

$$V_T = 1200\,\text{ft/s}, \quad V_P = 2000\,\text{ft/s}$$

$$\Psi_P = 230\,\text{deg} \quad \Omega_P = 0\,\text{deg}$$

What is the miss distance? Is the missile an early bird or a late bird?

4.3.56 List three aerodynamic factors that affect the miss distance of a guided missile.

4.3.57 Tracking errors caused by target glint and target scintillation increase as the missile approaches the target: True or False.

4.3.58 Consider a visually directed gun that is firing at an aircraft 3 km away. Assume circular symmetry. The variance of the radial tracking error is estimated to be 1.44 mrad^2, and the variance of the propagator radial flyout error is estimated to be 144 mrad^2. What is the estimated standard deviation of the total miss distance error at the target in m?

4.3.59 The shoe-box aircraft shown in Fig. 4.22a has the dimensions $\xi_0 = 40$ ft and $\zeta_0 = 12$ ft. The bivariate normal PDF for the miss distance for a particular gun in a particular firing situation is given by $\mu_\xi = -20$ ft, $\mu_\zeta = 12$ ft, $\sigma_\xi = 50$ ft, and $\sigma_\zeta = 12$ ft. Determine the probability the target is hit using the cookie-cutter hit function.

4.3.60 Determine the probability the shoe-box aircraft in Problem 4.3.59 is hit using the Carlton hit function.

4.3.61 Determine the probability the aircraft in Problem 4.3.59 is hit assuming circular symmetry with the average standard deviation $\sigma_\rho = 31$ ft. Assume the aircraft's presented area is the same as in Problem 4.3.59. Use both the cookie-cutter and the Carlton hit functions.

4.3.62 Consider a cubic steel fragment 0.30 in. on a side traveling at 3000 fps at 10,000 ft altitude. The Gurney velocity is 7000 ft/s, and the Taylor angle is 83 deg. Assume the fragment travels face-on. What is the global velocity of the fragment at the detonation point, and at 50, 100, 150, and 200 ft from the detonation?

4.3.63 Given a 40-ft-long aircraft flying straight and level with a velocity of 600 ft/s. Determine the four detonation zones and the extent of zone II for a late bird missile with an elevation angle of 60 deg. The missile velocity is 2000 ft/s. The warhead parameters are $V_0 = 8000$ ft/s, $\alpha_1 = 84$ deg, and $\alpha_2 = 89$ deg.

4.3.64 Suppose the late bird missile in Problem 4.3.63 detonates in zone II at 30 ft and in zone IV at 150 ft. There are 2000 fragments in the warhead. How many fragments from each detonation hit the aircraft if the aircraft's bottom area is approximated by $L = 40$ ft and $W = 15$ ft?

4.3.65 Fuzing is a stochastic process: True or False.

4.3.66 Define the shotline.

4.3.67 A gunner on a hill fires due east and horizontally at an aircraft at the same elevation flying straight and level from southeast to northwest at 800 fps. The muzzle velocity of the projectile is 2000 fps.

(a) What is the impact velocity on the aircraft? Neglect the effects of gravity and air drag.

(b) What is the direction of the shotline of the impacting projectile?

(c) Suppose the projectile hits a location on the aircraft, where $\psi_n = 0$ and $\omega_n = 90$ deg. What is the angle of obliquity?

4.4.1 Why is the term countermeasures used for susceptibility reduction?

4.4.2 What is the difference between active and passive countermeasures?

4.4.3 The three major subdivisions of EW are electronic attack, electronic counter-countermeasures, and electronic warfare support: True or False.

4.4.4 Electronic countermeasures (ECM) are a part of electronic attack: True or False.

4.4.5 Give an example of a particular technique for each susceptibility reduction concept and describe how it affects P_H and P_F.

4.4.6 What would an AAR-99 be used on and for?

4.4.7 How is threat warning used for mission planning?

4.4.8 RHAW is an example of passive threat warning: True or False.

4.4.9 Why is laser warning important?

4.4.10 What is a MAWS?

4.4.11 Describe the difference between noise jamming and deceiving.

4.4.12 List the three frequency techniques used by radar noise jammers and when they are used.

4.4.13 What is one of the most important parameters affecting the effectiveness of noise jamming?

4.4.14 The jam-to-signal ratio is established at the target and remains constant all of the way back to the radar: True or False.

4.4.15 The interference-to-signal ratio is established at the target and remains constant all of the way back to the radar: True or False.

4.4.16 Define burn-through range (in words).

4.4.17 What is the burn-through range for a radar with $P_r = 50\,\text{kW}$ and $G_r = 36\,\text{dB}$ and an aircraft with a 10-m^2 RCS and a 200-W jammer with an antenna gain of 3 dB? Assume $C = 13\,\text{dB}$. Calculate R_b using both decimals and decibels.

4.4.18 What are the advantages and disadvantages of a dedicated support jammer aircraft?

4.4.19 What are the two usual approaches for deception?

4.4.20 What are the four categories of deception methods?

4.4.21 Range gate pull-off is defeated by monopulse radars: True or False.

4.4.22 Inverse con-scan is defeated by monopulse radars: True or False.

4.4.23 How does an IRCM device deceive a reticle-based IR tracker?

4.4.24 List the three ways that the RCS of an aircraft can be reduced.

4.4.25 Why does shaping not necessarily work against bistatic radars?

4.4.26 Describe the two types of RAM.

4.4.27 The use of shaping and RAM is most effective when the radar wavelength is short compared with the dimensions of the target scattering surface: True or False.

4.4.28 Why is the electromagnetic impedance η of the surface of an aircraft important to radar detection?

4.4.29 For air, $\eta \approx$ ______ Ω. For typical aircraft metals (electrical conductors) $\eta \approx$ ______ Ω.

4.4.30 For a material to be effective as attenuating RAM, it must reflect very little of the incident signal; hence, its electromagnetic impedance must be close to zero: True or False.

4.4.31 What does "lossy material" mean?

4.4.32 Why is a chicken in a microwave oven like RAM?

4.4.33 An aircraft with an RCS of 10 m^2 can be detected at 200 km by a radar with an ERP $= 1 \times 10^8$ W. What value of the RCS is required to reduce the detection range to 50 km?

4.4.34 A jammer is added to the baseline aircraft in Problem 4.4.33. What must the JERP be to achieve a closure range of 50 km? Assume $C = 10$.

4.4.35 What are the four ways in which the the IR signature can be reduced?

4.4.36 Cooling the engine hot metal parts is a potentially effective technique for lowering the IR signature because I is generally proportional to T^2: True or False.

4.4.37 List three methods for the suppression of the engine exhaust plume IR radiation level.

4.4.38 A round canopy is not good for susceptibility against IR missiles because?

4.4.39 What is a potential problem with using IR-absorbing paint?

4.4.40 An aircraft with an IR signature of 80 W/sr in the band of an IR seeker can be detected at 9 km. What must the signature be reduced to in order to reduce the detection range to 3 km?

4.4.41 How is the control of the visual signature of an aircraft accomplished?

4.4.42 What four areas require attention?

4.4.43 What are the two general approaches to reducing the aural signature?

4.4.44 What are the major expendables for radar systems?

4.4.45 Chaff clouds consist of a large number of uncoated glass fibers: True or False.

4.4.46 To affect a particular radar operating frequency, each chaff dipole should be one-fourth of that wavelength: True or False.

4.4.47 Aircraft located behind a chaff cloud cannot be detected by the radar: True or False.

4.4.48 What types of ECCM techniques used by radars will degrade the effectiveness of chaff?

4.4.49 Chaff for short- and medium-wavelength radars is dispensed in __________ or ____________ .

4.4.50 The GEN-X is an active radar expendable ejected from a dispenser: True or False.

4.4.51 List the expendables used against IR and visual detection and tracking systems

4.4.52 Describe what an aerosol consists of and its function.

4.4.53 Why is a flare more effective against an IR tracker within the 1–3 μm band than one in the 3–5 μm band?

4.4.54 Aircraft velocity has a significant effect on flare intensity: True or False.

4.4.55 Describe a technique that an IR seeker might use to discriminate between a flare and an aircraft.

4.4.56 Why is the location of chaff and flare dispensers often a compromise?

4.4.57 List three supporting elements that can provide threat suppression.

4.4.58 Degradation of threat effectiveness can occur through intimidation: True or False.

4.4.59 'Get them before they get you' is a threat suppression technique: True or False.

4.4.60 An aircraft has a much better chance of surviving the mission if the target can be detected at 40 n miles and the weapon is effective when launched from high altitude at 20 n miles than if the weapon is a dumb bomb that must be dropped from low altitude close to the defended target: True or False.

4.4.61 An aircraft jinks to avoid an approaching IR missile: True or False.

4.4.62 Comparing the effectiveness of two aircraft as a total weapon system today requires consideration of all of the operational attributes of the aircraft, not just the aerodynamic performance specifications: True or False.

4.4.63 History has shown time and again that the proficient aircrew will survive in combat more often than those with little or poor training and no proficiency: True or False.

Chapter 5
Vulnerability ($P_{K|H}$ and $P_{K|F}$)

5.1 Vulnerability and the Vulnerability Program

Learning Objective	**5.1.1**	**Describe the three major tasks in a vulnerability program.**

Aircraft vulnerability refers to the inability of the aircraft to withstand the damage caused by the man-made hostile environment, to its vincibility, to its liability to serious damage or destruction when hit by enemy fire. Aircraft that are more vulnerable are softer, whereas those that are less vulnerable are harder, tougher, or more rugged. The more vulnerable an aircraft is, the more likely it will be killed when hit by one or more damage mechanisms (Note 1).

The vulnerability of an aircraft depends upon the vulnerability of the components that compose the aircraft. Each of the aircraft's components has a level, or degree, or amount of vulnerability to the damage mechanisms, and each component's vulnerability contributes in some way to the vulnerability of the aircraft. Some components contribute more than other components. The critical components on an aircraft are those components whose kill, either individually or jointly, result in an aircraft kill. The kill of some critical components, such as a pilot or single engine, might result in a quick attrition kill of the aircraft, whereas the loss of other critical components, such as a navigation computer or weapon sensor, can result in a mission abort kill because the pilot decides to return to base before achieving the mission objectives. Thus, the set of critical components on an aircraft depends upon the type of kill considered.

The first task in a vulnerability program is the identification of the critical components on the aircraft and the ways these components can be killed, that is, their kill modes, for a selected type of kill. This task is referred to as the Critical Component Analysis.

Once the critical components and their kill modes have been identified, the second task in a vulnerability program is the quantification of the measures of vulnerability of the individual critical components and of the entire aircraft to the warheads that are a threat to the aircraft. This task is known as a vulnerability assessment. A vulnerability assessment is a required survivability program task. It should be initiated early in the life cycle of any aircraft development program, and it should be continually updated as the design evolves.

While the vulnerability of each of the critical components and of the aircraft are being assessed or quantified for the threat warheads, actions should be taken during the early design process to reduce the vulnerability of the aircraft to its lowest possible value within the constraints of cost, flight performance, weight, maintainability, and the other important attributes that contribute to aircraft effectiveness (Note 2). This process is the third task in a vulnerability program and is known as designing for low vulnerability using vulnerability reduction technology. In essence, designing for low vulnerability consists of preventing the kill modes from occurring, thus reducing the likelihood that one or more of the critical components will be killed if the aircraft is hit. Vulnerability reduction is most effectively accomplished early in the design of the aircraft when component sizes, locations, materials, construction, and redundancies are being studied and selected.

Table 5.1 contains a list of the major subtasks in each of the three vulnerability program tasks. The remainder of this chapter will describe these subtasks in some detail (Note 3).

Much of the general procedure and many of the databases used to identify the critical components on an aircraft, quantify the aircraft's vulnerability, and reduce the vulnerability of the aircraft to an acceptable level are not unique to the vulnerability community. The aircraft system safety community must conduct hazard analyses in which they identify the hazards to the aircraft, classify the hazards in terms of severity and probability of occurrence, and eliminate those hazards that are unacceptable. The reliability community must identify those aircraft components that are essential for mission completion, quantify the failure rates of those components and the readiness rate of the aircraft, and improve the reliability of those components that degrade readiness to an unacceptable level.

In the past these communities typically have conducted their studies independently from each other. For example, the failure mode and effects analysis, which is subtask 5 within task I in the vulnerability program shown in Table 5.1, is also used by the system safety organization to determine those components that are potential hazards and by the reliability community to determine those components that have the most potential to degrade reliability. To create a more effective and efficient environment for accomplishing the goals of the vulnerability, system safety, and reliability communities, Ref. 1 identifies those tasks that are similar in each community and describes a process in which an integrated survivability, vulnerability, system safety, and reliability technical group can perform those common tasks using common databases (Note 4).

Go to Problems 5.1.1 to 5.1.5.

5.2 Task I: Identify the Critical Components and Their Kill Modes

The first of the three major tasks in the vulnerability program is to determine what makes an aircraft vulnerable. This is accomplished by identifying the critical components and their kill modes. The identification process includes the study of combat data, the testing of components, systems and the full-up aircraft, and the performance of the Critical Component Analysis.

5.2.1 Combat Data Analysis

Combat data analysis is the study of actual battle damage reports and loss statistics to determine the effectiveness of the enemy's weapon systems, the susceptibility

Table 5.1 Tasks in a vulnerability program

Vulnerability program task	Subtasks
Task I: Identify the critical components and their kill modes (What makes the aircraft vulnerable?)	1) Select the type of aircraft kill. 2) Gather information on the technical description and functional operation of the aircraft. 3) Determine the flight and mission essential functions. 4) Determine the system and subsystem functions that contribute to the essential functions. 5) Conduct a failure mode and effects analysis (FMEA) and identify the critical components and their kill modes 6) Conduct a damage mode and effects analysis (DMEA) and identify the kill criteria for the kill modes; and/or 7) Conduct a fault tree analysis (FTA) and identify the critical components and their kill modes. 8) Develop the kill tree for the critical components and write the kill expression.
Task II: Perform a vulnerability assessment (How vulnerable is the aircraft?)	1) Select the threat warhead and the measure of aircraft vulnerability. 2) Select the critical component kill criteria. 3) Compute the vulnerability of the critical components and the aircraft for one or more of the following threats: a single hit by a nonexplosive penetrator or fragment, multiple hits by a nonexplosive penetrator or fragment, a single hit by a contact-fuzed HE warhead, a proximity-fuzed HE warhead.
Task III: Design for low vulnerability using vulnerability reduction technology (What can be done about it?)	1) Examine the kill modes of each of the critical components, particularly those that make a major contribution to the aircraft's vulnerability. 2) Propose VR features that prevent or minimize the effects of each of the kill modes on the essential functions using the six VR concepts. 3) Conduct trade studies to determine the payoffs and impacts of each of the VR features proposed.

and vulnerability of the aircraft involved, and the effectiveness of any survivability enhancement techniques. There are many variables that affect each combat incident; and a reliable, accurate, and complete description of the circumstances surrounding the incident is very difficult to obtain in the hectic combat environment. Nevertheless, much data have been gathered, and many analyses have been made. Because almost all of the data and analyses are classified, very little of this material can be presented here. However, some of the vulnerability data are described in the following subsection to give the reader a general idea of the wide use of combat data. The interested reader can obtain most of the available combat data from SURVIAC, which is described in Chapter 1, Sec. 1.3.6.

5.2.1.1 Some typical combat damage incidents.

Learning Objective	**5.2.1**	**Describe some typical nonlethal and lethal combat damage incidents.**

To give the reader a general understanding of the kinds of damage that can be expected from the various types of threat propagators and damage mechanisms, a description of several nonlethal and lethal combat damage incidents that occurred during the Southeast Asia conflict are given next. The comment within the parentheses following a damage description is the author's opinion of what happened or what could have happened.

Nonlethal damage. The following descriptions are from fixed- and rotary-wing aircraft that were able to return to base; the damage was not sufficient to cause a loss of the aircraft.

Small arms fire: Some typical examples of nonlethal damage from small arms fire are as follows:

1) There was a hole in port aft fuselage, and the elevator control cable was damaged. (If this was the only elevator control cable and if it had been severed rather than damaged, the pilot could have lost the ability to control pitch with trim tabs alone, and the aircraft would have fallen out of control.)

2) There was a hole in rear cockpit canopy. (Members of the aircrew can be killed by metallic penetrators and fragments when hit.)

3) A hit in ammunition case in right wing caused one 20-mm round to go off. (The ordnance carried by an aircraft is a source of vulnerability, particularly if stored inside the fuselage. If several 20-mm rounds had sympathetically detonated, rather than just one, the aircraft most likely would have been lost as a result of a major fire or explosion.)

4) There was a hole in rudder. (A hit in a nonvulnerable area of the aircraft.)

5) There was a hit in center section of wing, and fuel was lost. (If the fuel tank that was hit and holed was the only feed tank, the tank would have eventually emptied, and the engine would have stopped as a result of a loss of fuel supply. Also, note that a fire did not occur.)

6) The oil cooler air scoop was hit. (If this damage had been sufficient to prevent the oil from being adequately cooled, the oil would have overheated, possibly

resulting in an engine shutdown and subsequent loss of the aircraft as a result of a loss of thrust.)

7) The port horizontal stabilizer was hit, and a small section of rear spar web shattered. (Most major aircraft structures are relatively rugged and can withstand extensive damage.)

8) The port drop tank ruptured. (Possibly as a result of hydrodynamic ram if the tank was full or internal combustion if the tank was empty.)

9) There was a one-inch hole through starboard aileron. (A hit in a non-vulnerable area).

10) There was a one-quarter-inch hole in left wing fuel cell, but no fire. (The occurrence of a fire or explosion in the ullage of a fuel tank is dependent upon the fuel vapor, oxygen, and temperature conditions in the vicinity of the hit. In this particular situation the conditions were not right for combustion.)

11) The hydraulic lines were severed. (Apparently, the spewing hydraulic fluid did not catch fire, and the aircraft had a redundant source of hydraulic power.)

12) A bullet hit in the bottom of the port wing. An internal fire resulted, and was extinguished in flight. (Combustion can be quenched by cooling.)

13) A bullet went through the right wing inlet duct and into the engine. (Either the hit did not kill the engine, or this was a multiple-engine aircraft.)

14) The radome was hit. All electrical power was lost. (If this aircraft had required electrical power to maintain control of flight, it would have been killed by this hit.)

15) Aircraft sustained numerous small holes approximately 3/8 in. scattered along the left side of aft fuselage section, with some fragments going through both sides of vertical stabilizer. Three holes were in left horizontal stabilizer. Small holes were in both right and left leading-edge flaps; three holes were in left wing. (Luckily for this pilot, none of these hits killed a critical component.)

16) A projectile entered the wing leading edge followed by an explosion that ruptured utility hydraulic lines, with a subsequent fire. (Most likely the projectile penetrated the leading-edge spar and entered into the wing fuel tank. Fuel from the wing tank might have migrated into the leading-edge dry bay. Perhaps incendiaries in the projectile ignited the leaking fuel, causing the explosion in the dry bay, which ruptured the hydraulic line. The flammable hydraulic fluid might also have been ignited, contributing to the fire. Apparently the fire was eventually extinguished before it caused fatal damage to the aircraft.

17) Copilot was hit in leg. (Members of the aircrew can be killed by metallic penetrators and fragments when hit.)

18) Helicopter was hovering when it received heavy ground fire. One crewman was hit. Aircraft took one hit in a fuel cell, one in a fuel filter, two hits in rotor blades, and 16 hits total. (Apparently none of the 16 hits killed a critical component. Neither the hit on the fuel cell nor the fuel filter resulted in a fire, and the rotor blades withstood the two hits.)

High-explosive AAA projectiles: The damage from the HE projectiles is usually much more severe than that from the penetrators. Some typical examples are as follows:

1) There was major damage to right wing. Projectile entered bottom of right wing just aft of leading-edge flap near fuselage. There was a hole in bottom of wing and

a 16-in. hole in top. There were six holes in fuselage ranging in size from $\frac{1}{2}$ to 2 in. One fragment entered engine intake and was ingested by engine. Engines and right wing will have to be changed. (Most major aircraft structures are relatively rugged and can withstand extensive damage. Apparently none of the fuselage hits killed a critical component, and most likely the aircraft was able to return to base because it had two engines.)

2) A projectile struck left-hand (LH) wing and exploded, causing 4-in. holes and fuselage damage. The port engine was secured, and the aircraft returned on one engine. (Most major aircraft structures are relatively rugged and can withstand extensive damage. This aircraft was able to return to base because it had two engines.)

3) A shell exploded in port-wing wheel well and caused fire. (A fire in a wheel well usually resulted in an aircraft kill because fuel and hydraulic lines typically passed through the well. Once a fire started, it would overpressurize the fuel and hydraulic fluid in these lines, causing the lines to rupture. The spewing fuel and hydraulic fluid would feed the flames. For most aircraft there was no way to put the wheel well fire out, and the crew would be forced to eject.)

4) A 12-in. section was removed from LH elevator. (Most modern aircraft structures are relatively rugged because of multiple load paths and can withstand extensive damage.)

5) Aircraft lost 12–18 in. of wing panel. (Most major aircraft structures are relatively rugged and can withstand extensive damage.)

6) Right wing suffered internal explosion with a 2-in. bulge from front to rear spar with multiple popped rivets top and underside wing. Fire was indicated for 10 s. (Most major aircraft structures are relatively rugged and can withstand extensive damage. Fortunately, the fire quickly died out.)

7) A hole approximately 40 × 27 in. on left engine duct; 1- and 3-in. holes on right side of fuselage. Holes went through right engine duct. Wires were cut, hydraulic and fuel lines were broken, and further undetermined damage occurred (no fire, and no loss of thrust or control).

Missiles: Two sample incidents where the aircraft returned are as follows:

1) Approximately 150 holes were made in fuselage, port inner and outer wing, empennage, and control surfaces. The port outer wing stiffener ruptured, with a 5-in. hole in outer wing rib, and a 8-in. hole in port forward fuselage keel. (Lots of holes were made, but no critical components were killed.)

2) Port engine was damaged and secured. Aircraft returned on one engine (again, the advantage of a second engine).

Lethal damage. Some typical descriptions of the events leading to an aircraft loss are given here for several incidents to illustrate the various kinds of lethal damage:

1) Aircraft received a hit in the belly. Controls vibrated violently. There was a fire in the left engine. (Apparently the fire eventually killed both engines.)

2) Aircraft exploded in midair. (Either a direct hit by a large HE warhead or an explosion inside of a fuel tank.)

3) Aircraft was hit by several rounds of AAA fire. Large hole and flames were observed in right wing. Aircraft started porpoising, and control was lost. (Control

could have been lost because of the severance of the control signal path or the loss of control power.)

4) Pilot felt a thump, fire warning and overheat lights came on, and controls became mushy. Hydraulic pressure decreased and engine stopped. (A single engine aircraft may have two or more sources of hydraulic power, but if the engine shaft stops turning, those sources that are dependent upon the rotating engine shaft for their input power will cease to provide hydraulic pressure.)

5) An internal detonation by a contact-fuzed HE AAA shell caused excessive fuel loss and engine flameout. (This aircraft had a single feed tank that could not contain the fuel because of the damage caused by the detonation of the HE shell. Either the tank was not self-sealing, or the self-sealing was defeated by the penetration and hydrodynamic ram damage processes caused by the explosion and the fragments from the warhead.)

6) Aircraft was hit by ground fire and lost airspeed and utility hydraulic system. Electrical fire, smoke, and heat were observed in cockpit. (Crew members usually eject from an aircraft when fire and smoke are observed in the cockpit.)

7) Aircraft was hit in rear of right engine and then burst into flames. Four minutes later, the left engine was on fire, and control was lost. (Here is a situation where having two engines made the aircraft more vulnerable rather than less vulnerable. Although only the right engine was hit, and subsequently killed, the left engine was also eventually killed because of cascading damage in the form of a fire that spread from the hit engine to the other engine. Conceivably, the same process could have occurred if the hit had been on the left engine. Thus, a hit on either engine could result in a kill of both engines as a result of cascading damage.)

8) Pilot was fatally hit. Navigator assumed control of aircraft and departed target area. (The pilot and copilot are redundant critical components.)

9) Aircraft was hit in right horizontal stabilizer. Pilot lost control. (The essential function of control of flight was lost as a result of a loss of a major control surface.)

10) Aircraft was hit in right wing by medium-caliber AAA. There was immediate hydraulic system failure and fire in wing near forward edge of flap. Fire burned forward for 15 min until it reached the main wing spar. Aircraft became impossible to control, and crew ejected. (This is an example of an attrition kill that occurred 15 min after the hit. It also is an example of a kill caused by an internal wing fire that could not be extinguished.)

11) Aircraft was hit in starboard wing. Fuel streamed from hit. Hydraulic power PC-1 failed, and PC-2 was unstable initially, then stabilized when the emergency power package (EPP) was extended into airstream. Starboard aileron was jammed full up, and full left aileron required for level flight. Fire in wing (hydraulic fluid and burning metal) all of the way back to base. As aircraft slowed to land, the fuel vapor ignited, and flames spread to aft of aircraft. Aircraft touched down, missed short field gear, broke midfield gear, pilot ejected, and aircraft left runway. (There is much to learn from this incident. Note that there was no fuel fire caused by the hit in the wing tank, but the tank did lose fuel. One of the two primary hydraulic power subsystems remained operational, but at a reduced capability—redundancy in action. The EPP was a third source of hydraulic power that activated when the other two systems were damaged; this is an example of vulnerability reduction using the active damage suppression concept. The starboard aileron was most likely not jammed full up, as reported; instead, the mechanical linkage from the

pilot's control stick to the aileron actuator was probably severed, thus allowing the pilot to control the aircraft with the left aileron. Had the right aileron been jammed, the control stick would have been locked in place, and the pilot would have lost the ability to control the aircraft. Finally, note that the hydraulic fluid was very flammable, resulting in an intense fire that ignited the metal in the wing.)

12) Aircraft was hit on bomb run. Pilot completed bomb run and egressed target area while climbing to altitude. Wingman reported damage in starboard aft section of aircraft. After 25 min engine seized, and aircraft went out of control. (When the single engine of an aircraft seizes, the functions of thrust and control are lost.)

13) Aircraft was hit by AAA in area aft of cockpit. Fire was in aft fuselage, probably fuel, possibly hydraulics, and smoke was in cockpit. Aircraft lost electrical power to instruments and communications, lost normal oxygen, but engine continued to operate. Crew ejected 3 min after hit because of fire. (Another kill caused by an internal fire.)

14) Aircraft took a direct hit by SAM under starboard wing. Wing was blown off. (A direct hit by a large SAM will kill most aircraft.)

15) Crew felt a thump underneath cockpit, followed by immediate utility hydraulic failure, followed by sloppy controls and throttles stuck at full military power. Egressed target area using rudders. Aircraft was on fire. Weapons officer ejected; pilot could not because of loss of canopy emergency jettison air bottle. (Several functions were eventually lost because of a hit that appeared at first to be relatively minor. Note that both the loss of hydraulic power and fire played a role, again. Also note the inability of the pilot to vary the throttle setting; apparently the mechanical connection from the throttles in the cockpit to the engines was severed.)

16) Aircraft was on strike mission. AAA hit in nose and starboard engine area, followed by fire warning in starboard engine and smoke in cockpit. Starboard engine was secured. Ordnance could not be jettisoned, and aircraft could not maintain flight on port engine. Crew ejected. (Here is an example of an aircraft with two engines that could not fly on one engine while fully loaded with ordnance. The combination of the loss of one engine and the inability to jettison the ordnance resulted in the loss of sufficient lift to maintain altitude.)

17) Helicopter received intense fire from small arms. At 1 ft off of the ground, the aircraft rolled to the left and landed in a slightly nose-down attitude. A fuel cell was ruptured, and the aircraft was destroyed by fire. Suspect multiple rounds severely damaged the tail rotor blades. (The fuel system was not designed to survive even a minor crash. Also, the loss of the tail rotor blades resulted in the loss of control.)

18) Helicopter was in a 100-ft hover. Pilot felt loss of power. Helicopter settled into the trees, rolled left, inverted, caught fire, and burned. (The helicopter probably lost its one engine. Again, the fuel system was not crash-worthy.)

19) Helicopter was touching down in the landing zone when it received heavy small arms fire. Helicopter would not respond to controls, crashed into the side of a hill, and was consumed by fire. (Another example of the loss of a helicopter and its crew as a result of a combination of a loss of control and a fragile fuel system.)

20) Helicopter was 1500 ft over the landing zone when hit by 0.50-cal fire. It descended on fire, landed, and exploded 15 sec later. (Another helicopter lost because of fire.)

21) Aircraft hit in cockpit by small-caliber bullet. Pilot suffered wound in shoulder and began to lose consciousness. Crew ejected. (The pilot is a critical component on an aircraft.)

Go to Problems 5.2.1 to 5.2.2.

5.2.1.2 Combat data on the World Wide Web. There are a number of sites online the World Wide Web that contain descriptions of U. S. Army helicopters damaged in combat in SEA. Among them are http://www.gorilla.net/~118AHC/Incidents.htm for the 118th Assault Helicopter Company, http://www.170thahc.org/GoldBook/temp.html for the 170th Assault Helicopter Company, http://www.129th.net/helicopters.html for the 129th Assault Helicopter Company, and http://www.a101avn.org/ for the 101st Airborne Division. You might have to go to one or more links within each site to find the combat incident descriptions.

5.2.1.3 Loss–cause relationships.

Learning Objective **5.2.2 Describe a loss–cause network and its purpose.**

Determining the critical components and systems on an aircraft and their kill modes is one of the most important aspects of combat data analysis. This information can be used to design less vulnerable aircraft. Consequently, when the SEA conflict ended, the U. S. Navy tasked the Center for Naval Analyses (CNA) to determine the reasons the Navy lost so many tactical, carrier-based aircraft in the conflict. The CNA established eight different reasons-for-crash or loss–cause categories to assist in this determination. These are as follows: fire intensity, pilot incapacitation, pilot error, explosion, loss of control, engine failure or loss of thrust, loss of stable flight (structural), and unknown (Note 5). Many of the Navy aircraft losses in the SEA conflict were studied, and the ultimate cause for the loss of each aircraft was attributed to one of the eight categories. An example of one form of examination for the ultimate loss–cause is the CNA loss–cause evaluation form shown in Fig. 5.1.

A detailed study of the sequence of events from the hit on the aircraft to the eventual loss of the aircraft can often help in the identification of the critical components of the aircraft and their kill modes. Consequently, loss–cause failure sequences were prepared by the CNA from loss review panel evaluations for several aircraft types operating in Southeast Asia from 1965 through January 1973. The pertinent sequence of events from the hit to the loss for all of the aircraft whose loss was attributed to a particular loss–cause category were combined into a network of failure paths leading eventually to the loss–cause. These networks are called loss–cause networks. Figures 5.2 and 5.3 show the loss–cause networks for 20 aircraft of one particular type (a single-engine aircraft) whose loss was ultimately attributed to loss of control. Figure 5.2 contains the gross network, showing essentially all

Aircraft Type:
Squadron:
Call Name:
Carrier:

DATE:

PILOT/STATUS:

MOST DETAILED SOURCE OF DATA:

SUMMARY OF EVENTS:

Aircraft was alpha strike lead. Multiple SAM firing, medium 85mm AAA barrage fire. While in process of evading SAMs, pilot observed one go overhead and one underneath followed immediately by explosion under tail of aircraft from either SAM or AAA. Master (hydraulic) caution light. PC–1 failure almost immediately. Pilot egressed to feet wet. PC–2 surge followed by failure. PC–3 fluctuation with "mushy" controls. Successful ejection and pickup by destroyer.

CONFLICTING DATA, IF ANY, AND SOURCE:

None.

RECONSTRUCTION:

SAM or AAA HIT close to tail. Loss of PC–1 system probably due to holes in lines or pump damage. No fire. PC–2 surge followed by failure. Subsequent loss of control as third PC system failed.

EVALUATION OF PRIMARY AND CONTRIBUTORY CAUSES OF LOSS:

Multiple PC failure followed by loss of control. Apparently failure of PC system was caused by holes in all system lines and/or pump damage.

OTHER COMMENTS/UNCERTAINTIES:

None

Fig. 5.1 CNA loss–cause evaluation form.

failures identified in the loss–cause failure sequence. Eliminating from Fig. 5.2 the component or system failures that did not contribute directly to the loss and combining similar specific failures into common broad failure types give the refined network shown in Fig. 5.3.

The sequence of events for each aircraft proceeds along a path of the network from the damaging agent on the far left to the ultimate cause of loss on the far right. Each node in the network represents a component or system failure or kill. The paths between the nodes depict the progression of component or system failures to the ultimate loss–cause. The number of occurrences of each component or system failure is presented within the node, and the number of aircraft that had a particular sequence is indicated by the number along that path.

Consider the gross network shown in Fig. 5.2. The loss incident described in the loss–cause evaluation form in Fig. 5.1 is indicated by the horizontal dashed line from the SAM damaging agent on the left (a total of 10 aircraft were killed by a SAM) directly to the hydraulic failure node in Fig. 5.2. Note that another aircraft

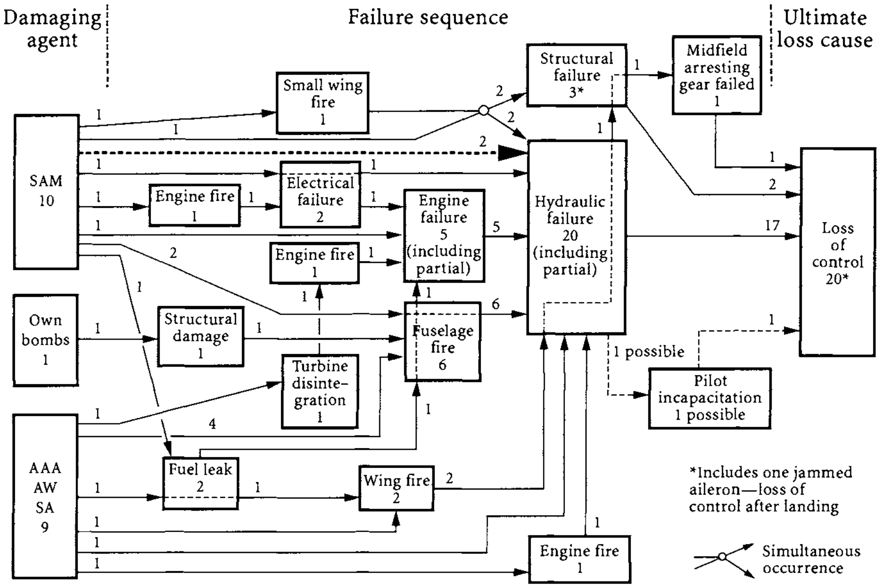

Fig. 5.2 Loss-of-control losses (gross).

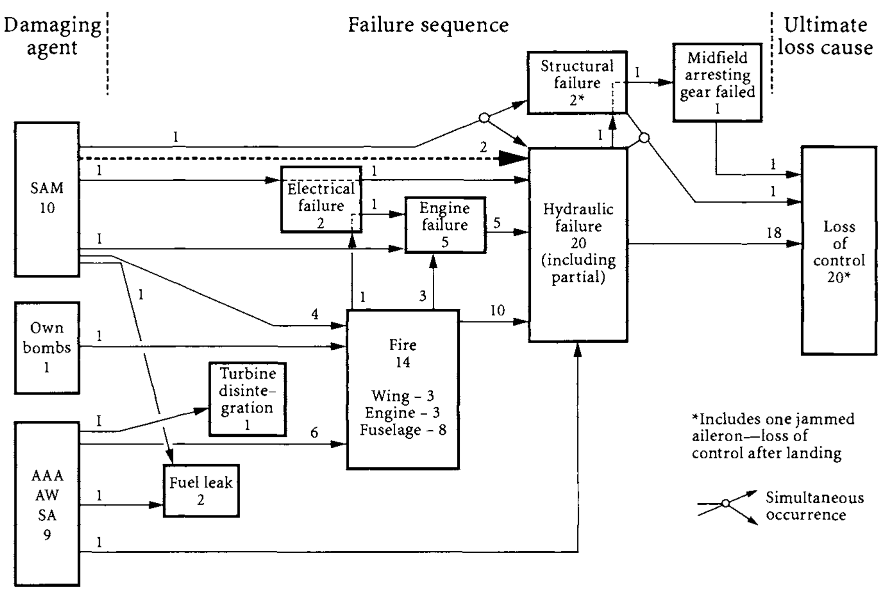

Fig. 5.3 Loss-of-control losses (refined).

had a similar sequence of a SAM hit leading directly to a hydraulic failure. Also note that all 20 of the aircraft sequenced through the hydraulic failure node on their way to the ultimate loss of control. Consequently, this loss–cause category for this aircraft type was equivalent to a loss of control as a result of a loss of hydraulic power.

Conclusions on aircraft vulnerability drawn from the attributed ultimate cause-of-loss must always be seasoned with intuition. For example, according to the networks shown in Figs. 5.2 and 5.3 all 20 aircraft suffered hydraulic failure prior to the loss. Consequently, one might conclude that failure of the hydraulic subsystem was the primary cause of the 20 losses. On the other hand, further examination of these two figures reveals that 14 of the 20 aircraft were on fire. Had they not been on fire, the hydraulic subsystem might not have failed; or perhaps many of the 20 aircraft would have eventually been lost because of fire intensity, even if the hydraulic subsystem had not failed. Thus, perhaps fire was the primary reason for the loss of 14 out of these 20 aircraft, not the ultimate loss of hydraulic power. Adding an additional source of hydraulic power might not have saved any of these 14 aircraft; using a nonflammable hydraulic fluid might have. Furthermore, this aircraft had just one engine, and five of the 20 aircraft had an engine failure. Most likely these five aircraft would have eventually been lost even without the loss of hydraulic power.

Go to Problems 5.2.3 to 5.2.4.

5.2.1.4 Summary of the combat data.

Learning Objective	**5.2.3**	**List the critical aircraft systems in WW II and the Southeast Asia conflict based upon combat data.**

Examination of the combat data for World War II has revealed that damage to the engines, the cooling and lubrication subsystems, the fuel system, and the flight control system would most likely lead to an aircraft loss (in that order) and that the majority of aircraft lost were on fire.

With the change over to gas turbine engines after World War II, the aircraft in Korea and Southeast Asia were lost mainly as a result of hits on the fuel system, which now occupies a much larger volume within the aircraft, on the engine, on the flight controls and hydraulics, and on the crew. Again, fire played a major role.

A study of the Southeast Asia combat data for the most frequent causes of helicopter adverse reactions concluded that helicopter crashes were caused mainly by hits on the engine, the flight controls, the crew, and the fuel system. Forced landings were caused most often by hits on the fuel system, the lubrication subsystem, the engine, the flight controls, and the main rotor. Mission aborts occurred because of hits on the crew, the fuel system, the main rotor, and the hydraulic subsystem.

Go to Problems 5.2.5 to 5.2.7.

5.2.2 *Critical Component Analysis*

The critical component analysis is the identification of the critical components on an aircraft and their kill modes. The tasks in the analysis are listed in Table 5.1, under task I, and are described in the following subsections.

5.2.2.1 *Task 1: Select the type of aircraft kill.*

Learning Objective	**5.2.4 Define the aircraft kill categories and levels.**

The first task in the analysis for the critical components on an aircraft is the selection of the type(s) of kill of interest. There are several types of aircraft kill that are considered in vulnerability programs. These types can be divided into categories that measure the degree to which the aircraft suffers performance degradation. The category most often used in vulnerability assessments is the attrition kill category. Associated with the attrition kill category are several periods of elapsed time after the hit, known as kill levels. Three other categories that are occasionally used in vulnerability programs are the mission kill, the mission abort kill, and the mission denial kill. There are other categories that are used in special circumstances, such as the landing kill for fixed-wing aircraft and the forced landing kill for helicopters.

Attrition kill category.[2] Attrition kill is a measure of the degree of aircraft damage that prevents it from returning to base, or renders it incapable of being repaired or uneconomical to repair if it does return, so that it is lost from the inventory. The elapsed time between the time when the aircraft is hit and the time when the aircraft is declared killed is an important variable of vulnerability because the longer the damaged aircraft can continue to fly, the more likely the crew can eject from the aircraft and be recovered. Consequently, four different levels of attrition kill have been defined based upon the elapsed time between hit and kill. They are the KK, K, A, and B levels. These four attrition kill levels do not consider where the aircraft was within the mission profile at the time of the hit, for example, on its way into the target, over the target, or egressing from the target. The C level attrition kill specifically addresses the situation where the aircraft is killed before it achieves the mission objectives. These five attrition kill levels are defined in Table 5.2.

Note that the four levels of attrition kill, KK, K, A, and B, are inclusive as the time limit increases. Damage that causes the aircraft to fall out of control within 30 s, the K kill level, also satisfies the time limit definitions of 5 and 30 min for the A and B level kills, respectively. Thus, if a component kill results in a K kill it also qualifies as a critical component for the A and B kill levels. Examples of component kills that result in each of the four attrition kill levels are given in Table 5.3.

From an operational (aircrew) point of view, the KK attrition kill level implies a loss of the crew as well as the aircraft; the damage is catastrophic, and the crew

Table 5.2 Attrition kill levels

Kill level	Definition
KK	Damage that causes an aircraft to disintegrate immediately upon being hit. (This kill level is sometimes referred to as a catastrophic kill.)
K	Damage that causes an aircraft to fall out of control within 30 s after being hit.
A	Damage that causes an aircraft to fall out of control within 5 min after being hit.
B	Damage that causes an aircraft to fall out of control within 30 min after being hit.
C	Damage that causes an aircraft to fall out of control before completion of the mission objectives. This kill level is sometimes referred to as a mission kill.

Table 5.3 Attrition kill levels and examples of component kills

Kill level	Examples of component kills
KK	The following events cause an immediate kill: 1) Destructive fuel tank explosion 2) Catastrophic engine failure 3) Loss of a wing or a main rotor blade
K	All of the preceding events plus the following occur within 30 s: 1) Pilot incapacitation 2) Loss of hydraulic pressure at the flight control actuators 3) Ingestion of fuel from a hydrodynamically ruptured fuel tank by the engine, resulting in the destruction of the engine
A	All of the preceding events plus the following occur within 5 min: A fire that burns for several minutes, eventually destroying flight control rods, or killing both engines, or causing smoke that migrates into the cockpit, forcing the crew to eject within 5 min of the hit
B	All of the preceding events plus the following occur within 30 min: 1) Eventual seizing of a helicopter's main transmission that has lost lubrication 2) Loss of primary electrical power to the flight control computer followed by the eventual depletion of the power from the battery that provides the backup electrical power to the computer

does not have time to eject. On the other hand, the 30-s K attrition kill level might give the crew time to eject.

The attrition kill category is often used in the design requirements for the vulnerability of an aircraft. For example, the vulnerability requirement for the U. S. Army's Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) in the 1970s was safe flight for at least 30 min after a single hit by a 7.62- and 12.7-mm API projectile, respectively. In the vernacular of vulnerability, these helicopters were designed to prevent a B level attrition kill as a result of a single hit by an API projectile.

Mission abort kill category.[2] A mission abort kill is the measure of that degree of aircraft damage that prevents an ingressing aircraft from completing its designated mission, but is not sufficient to cause a loss of the aircraft to the inventory; minimum flying qualities remain after the hit. A mission abort kill can occur when the ingressing aircraft is damaged by an enemy weapon and the pilot or plane commander decides that the damage jeopardizes continued safe flight and aborts the mission. This type of kill is referred to as a mission abort kill caused by safety of flight. A mission abort kill can also occur when a component essential for mission completion has been killed. For example, a mission abort kill occurs when a pilot aborts the mission during ingress to the target area because the weapons computer is killed. An aircraft that has reached the target area and is hit and damaged while returning to base is not a mission abort kill.

Note that those components whose kill mode will result in an attrition kill cannot also be components whose kill mode results in a mission abort kill. The attrition kill category and the mission abort kill category are mutually exclusive, that is, an attrition kill is defined as the loss of the aircraft from the inventory, whereas the mission abort kill is defined as damage that does not result in the loss of the aircraft from the inventory. Thus, a critical component for an attrition kill, such as the single engine on an aircraft, cannot also be a critical component for a mission abort kill. If the engine is killed, the aircraft will eventually crash before it can return to base. However, one engine on a two-engine aircraft is a critical component for a mission abort kill, and both engines are redundant critical components for an attrition kill.

Mission denial kill category. A mission denial kill is a combination of kills and occurs when an ingressing aircraft is hit and the pilot either is unable to control the aircraft (a C level attrition kill) or aborts the mission because of damage to the aircraft (a mission abort kill). In either event the mission objectives are not accomplished. As an example of the mission denial kill, suppose 100 aircraft are on a mission to bomb a certain target. While ingressing to the target area, the air defense kills one aircraft and sufficiently damages two other aircraft such they immediately return to base. Thus, on this mission there were three mission denial kills, one of which was a C level attrition kill and two were mission abort kills.

Landing kill category.[2] The landing kill category is used in special circumstances. A carrier-based aircraft far out to sea that is able to return to the carrier but cannot land because of damage to the tail hook is an example of a landing kill. For another example, consider an aircraft with a short takeoff, vertical landing (STOVL) capability, such as the AV-8B Harrier, that is based on a ship equipped with only a vertical landing pad. If the aircraft returns to the ship with damage such that it cannot land vertically, for example, one of the air jet nozzles at the wing tips cannot be rotated to the proper position, the aircraft must be abandoned if there are no conventional landing fields in the vicinity. A third example of a landing kill is an aircraft with large propellers and rotating engines, such as the V-22 Osprey. If the engines cannot be rotated to the vertical position prior to landing, the aircraft cannot land without risking serious damage.

Forced landing kill category.[2] A forced landing kill is a helicopter kill category in which damage to the helicopter causes the pilot to land (powered or unpowered) because he/she receives some indication of damage, such as a red light, low-fuel-level warning, difficulty in operating the controls, or loss of power. The extent of damage might be such that very little repair is required to enable the pilot to fly the helicopter back to base; however, if the pilot decided to continue flying and not repair the damage the helicopter would crash before reaching its destination. The forced landing kill category includes a forced landing at any time after damage occurs, but before the expenditure of the aircraft fuel load.

Summary. The definitions of the types of kills described here have evolved since WWII as the assessment of vulnerability has evolved. They are not intended to cover all possible combat situations. Instead, they are used to design less vulnerable aircraft. For example, one of the goals of survivability is to delay the inevitable loss of a damaged aircraft. This is achieved by designing the aircraft for low vulnerability such that attrition kills as a result of a hit are moved from a KK or K level to an A level, or possibly to a B level or beyond. For example, prior to the 1970s some helicopter rotor blades would fail immediately when hit by small arms projectiles, causing the helicopter to immediately fall out of control, which is a KK level attrition kill. The single-hit vulnerability requirement for the U. S. Army's UTTAS and AAH eliminated that possibility and moved the attrition kill to beyond the B level for the specified threats (Note 6).

Go to Problems 5.2.8 to 5.2.14.

5.2.2.2 Task 2: Gather information on the technical description and functional operation of the aircraft. The second task in the critical component analysis is the description of the aircraft as a total weapon system consisting of major systems (e.g., fuel), subsystems (storage), assemblies (wing tank), subassemblies (inboard half of tank), and parts (upper surface of inboard half of tank). Each of these entities can be categorized by an indenture level based upon the relative complexity of the item, progressing from the most complex (the aircraft as a weapon system) to the most simple (the part). In the vernacular of vulnerability, each of these entities can be considered to be a component.

At the beginning of any vulnerability program, as much of the aircraft's technical description and functional operation as possible must be gathered on each of the major systems of the aircraft. The technical description of each system should include information on the size, location, material, and construction of all components. In today's computer-based design environment a geometric model of the aircraft, developed using a program such as CATIA, is an essential part of the database.

The operation of the aircraft should be defined by the functions provided by each component and the interfaces between the component and other components in the form of functional and reliability block diagrams, including all functional redundancies.

For existing aircraft the manufacturer and the operator and maintenance manuals are sources of some of this information. They usually provide complete descriptions of the components of the aircraft, how they function, and how they relate to the overall operation of the aircraft. For aircraft in development, it is very important to obtain and use as much of the preliminary design information as possible. The importance of using current technical and functional information in the vulnerability program in all stages of aircraft development cannot be overemphasized.

5.2.2.3 Task 3: Determine the flight and mission essential functions.

Learning Objective	**5.2.5**	**Describe the flight and mission essential functions and the contributing systems.**

The ability to fly and to complete mission objectives requires specific capabilities or functions. An aircraft is killed when it loses one or more of those functions that are essential for flight or for mission completion. For the attrition kill category the essential functions are those contributing to continuous, controlled flight. For the mission abort kill category the essential functions are those associated with mission capabilities. The other kill categories also have functions that are essential for successful operation. The third task in the critical component analysis is to identify the essential functions for each of the kill types of interest. The attrition and mission abort kill categories are usually the ones of most interest, and consequently the procedure for the identification of the essential functions for flight and for mission completion is described next. Similar procedures are followed for the other types of kills.

Flight essential functions are those system and subsystem functions required to enable an aircraft to sustain controlled flight. Controlled flight of the aircraft requires 1) structural integrity, and adequate 2) lift, 3) thrust, and 4) directional control. Loss of one or more of these four flight essential functions will result in an attrition kill of the aircraft. Mission essential functions are those system and subsystem functions required to enable an aircraft to perform its designated mission. Loss of any one or more of the mission essential functions can result in a mission abort.

The analysis for the essential functions should consider each phase of the mission. For example, a mission for an attack aircraft could include such phases as takeoff, climb, cruise out to the vicinity of target area, descend, enter the target area, locate the target, deliver the ordnance, exit the target area, climb, cruise back to base, descend, and land. The function of directional control of flight is essential for all of these phases. On the other hand, although the functions provided by the onboard weapons computer are not essential for flight for any phase of the mission they are essential for the ordnance delivery phase. Thus, they are a mission essential function.

The essential functions for the attrition or mission abort kill could be qualified by requiring a particular level of operation. For example, loss of one engine on a two-engine helicopter might not cause a total loss of lift and thrust, but could lead to a reduction of flight performance capabilities. If this reduction in flight performance is not acceptable under certain flight conditions, such as when the helicopter is very close to the ground, or if the helicopter is in a particularly hostile environment where it is much more susceptible because of the degradation in flight performance, then the power from both engines might be deemed essential. Special functions, such as those required for vertical or arrested landing, must also be identified for the other kill types.

A chart identifying the required flight and mission essential functions for each of the mission phases of an attack helicopter is given in Fig. 5.4 (Note 7).

Go to Problem 5.2.15.

5.2.2.4 Task 4: Determine the system and subsystem functions that contribute to the essential functions. The ability of the aircraft to fly and to conduct its mission depends upon the continued operation of those systems that provide or contribute to the flight and mission essential functions listed in Fig. 5.4. If the aircraft is damaged in combat, the operation of the damaged components can be impaired or stopped, and one or more essential functions might be lost. The rapidity of the loss of any function essential for flight is directly related to the attrition kill level. A general examination of each system and subsystem on the aircraft must be conducted to determine its specific contributions to the essential functions identified in the preceding task for each phase of the mission. Figure 5.5 presents a sample tabulation of those systems on an attack helicopter that contribute to the essential functions shown in Fig. 5.4.

Note in Fig. 5.5 that the electrical system contributes to the essential functions of lift and thrust and of control. The primary flight control system on this particular helicopter is mechanical, with an electrical backup system. The mechanical flight control system consists of push–pull rods, cables, and other components that form a mechanical path from the pilot's controls to the servoactuators that position the rotor blades. The electrical system contributes to flight control by providing a second or redundant path from the pilot's controls to the servoactuators. Thus, when identifying the contributions of each system to the essential functions the contribution of any system component to an essential function must be accounted for, even when that contribution is not a primary contribution.

Figure 5.6 illustrates a detailed tabulation of the subsystem functions performed by the electrical system for each of the flight and mission essential functions.

ITEM	ESSENTIAL FUNCTIONS	MISSION PHASES: ALERT	TAKEOFF	CRUISE TO LAAGER AREA*	CRUISE TO HOLDING POSITION	CRUISE TO ASSAULT POSITION	ENGAGE TARGETS	RETURN CRUISE	LAND
	FLIGHT:								
1	Provide structural integrity	X	X	X	X	X	X	X	X
2	Provide lift and thrust		X	X	X	X	X	X	X
3	Provide controlled flight		X	X	X	X	X	X	X
	MISSION:								
4	Communications								
	• secured voice		X	X	X	X	X	X	
	• unsecured voice	X	X						X
	• internal (ICS)								
5	Start systems	X						X	X
6	Monitor systems	X	X	X	X	X	X	X	X
7	Provide air data intelligence		X	X	X	X		X	
8	Maintain terrain clearance		X	X	X	X	X	X	
9	Employ IFF/ECM			X	X	X	X	X	
10	Navigate			X	X	X	X	X	
11	Locate/identify targets					X	X		
12	Employ weapons						X		

*The laager area is similar to a staging or rendezvous area and is located between the logistics support center and the FLOT.

Fig. 5.4 Some flight and mission essential functions vs mission phases for an attack helicopter.

5.2.2.5 Examples of some critical components and their kill modes.

Learning Objective 5.2.6 Describe nonredundant and redundant critical components and their loss of function and cascading-damage kill modes.

The critical component analysis has now progressed to the point where the system and subsystem functions that contribute to the flight and mission essential functions have been identified for each phase of the mission. These system and subsystem functions are provided by literally thousands of components. Those components whose kill, either individually or jointly, results in the loss of an essential function

ITEM	ESSENTIAL FUNCTIONS	SYSTEM: ELECTRICAL	FLIGHT CONTROL	PROPULSION	FUEL	STRUCTURAL	CREW	AVIONICS	ARMAMENT
	FLIGHT:								
1	Provide structural integrity					X			
2	Provide lift and thrust	X	X	X	X	X	X	X	
3	Provide controlled flight	X	X	X	X	X	X	X	
	MISSION:								
4	Communications								
	• secured voice	X					X	X	
	• unsecured voice	X					X	X	
	• internal (ICS)	X					X	X	
5	Start systems	X	X		X		X	X	
6	Monitor systems	X					X	X	
7	Provide air data intelligence	X					X	X	
8	Maintain terrain clearance	X	X	X	X	X	X	X	
9	Employ IFF/ECM	X					X	X	
10	Navigate	X					X	X	
11	Locate/identify targets	X					X	X	
12	Employ weapons	X				X	X	X	X

Fig. 5.5 System/essential function relationships.

for a particular aircraft kill category and level are the critical components for that particular kill. Thus,

$$\text{Critical component(s) kill} \Rightarrow \text{loss of an essential function} \Rightarrow \text{aircraft kill}$$

Not all of the components on an aircraft are critical. Consequently, the next task in the critical component analysis is to determine which components are critical and the ways these components can be killed by conducting the failure mode and effects analysis (FMEA), followed by the damage mode and effects

ITEM	ESSENTIAL FUNCTIONS	ELECTRICAL SYSTEM FUNCTIONS							
		Generate electrical power	Provide automatic control and protection of power generation	Distribute electrical power	Provide power conversion	Provide battery power	Control subsystem loads	Provide controls and displays	Provide illumination
	FLIGHT:								
1	Provide structural integrity								
2	Provide lift and thrust	X	X	X	X	X	X	X	X
3	Provide controlled flight	X	X	X	X	X	X	X	X
	MISSION:								
4	Communications								
	• secured voice		X	X	X	X	X	X	
	• unsecured voice	X	X						X
	• internal (ICS)								
5	Start systems	X						X	X
6	Monitor systems	X	X	X	X	X	X	X	X
7	Provide air data intelligence		X	X	X	X		X	
8	Maintain terrain clearance		X	X	X	X	X	X	
9	Employ IFF/ECM			X	X	X	X	X	
10	Navigate			X	X	X	X	X	
11	Locate/identify targets					X	X		
12	Employ weapons						X		

Fig. 5.6 Subsystem functions/essential functions relationships.

analysis (DMEA), and/or the fault tree analysis (FTA). Before the FMEA, DMEA, and FTA are described, some additional terminology and several examples of critical components and their kill modes are given to illustrate the various ways a component's kill can result in an aircraft kill.

Component dysfunction, damage, failure, fault, or kill. The inability of a component to provide the function(s) it was designed to provide is referred to variously as a component dysfunction, damage, failure, fault, or kill depending upon the type of analysis being performed and the performing organization. When a component failure is the result of an internal dysfunction, the failure is referred to as a mechanical or hardware failure. When a component fails to provide the design function as a result of the kill of another component that provides a necessary input to that component, the fault is referred to as functional. The seizing of a tail rotor gear box as a result of overheat is an example of a mechanical failure, and the inability of a flight control computer to determine the necessary control signals caused by the loss of electrical power is an example of a functional failure of the computer.

Component kill modes. The ways in which a component can fail or be killed are referred to here as the component kill modes. Component kill modes can be categorized as failure modes when the failure is the result of the normal operational environment or as damage modes when the cause and effect are directly related to combat damage. Two examples of mechanical failure modes are a submerged fuel pump that fails to transfer fuel from the feed tank to the engine because the fuel filter in the pump becomes clogged and an electrical switch that fails to make the proper electrical connection because of corrosion. Note that there is no warhead damage mechanism or damage process associated with the failure of these components; these two component failures can occur during normal flight. However, the term failure mode is also used in the vulnerability program when a component dysfunction usually associated with the normal operating environment is the result of combat damage. For example, the impact and penetration of a metallic penetrator into the fuel pump or the electrical switch can also result in the inability of the pump to transfer the fuel or the switch to make the proper contact because of mechanical damage to these components. The essential point here is that the component no longer provides the function(s) for which it was designed.

Component damage modes. Component damage modes are the result of the combat damage processes caused by the warhead damage mechanisms. For example, a damage mode of the submerged fuel pump is crushing, and one possible cause of the crushing is the hydrodynamic ram loading on the pump caused by a metallic penetrator penetrating the fuel in the tank. A damage mode of the electrical switch could be arcing, and one possible cause of the arcing is the impact on the switch by a metallic penetrator. If the switch was simply broken because of the hit by the penetrator, and the result of the hit was that the switch fails to make the proper electrical connection, the component dysfunction or kill would usually be referred to as a failure mode even though the cause was combat related. When examining the possible kill modes of most components in the critical component analysis, the term failure mode is typically used even though the failure is assumed to be caused by a damage mechanism or process.

System kill modes. The component kill mode (failure or damage) can result in a system kill mode. A system kill mode is a particular loss of an essential function provided by the system. In Example 3.1, the control rod kill (or mechanical failure) mode of breaking results in a flight control system kill mode of disruption of the control signal path, which leads to the loss of the flight essential function of directional control. When two control paths are available, for example, the mechanical and electrical paths in Example 3.1, the single component kill mode of a severed rod

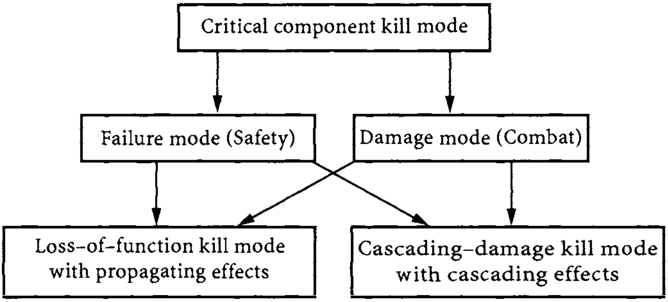

Fig. 5.7 Kill mode terminology connections.

does not result in a system kill mode. The electrical signal path must also be killed to cause a system kill. Thus,

$$\text{Critical component(s) kill mode(s)} \Rightarrow \text{system kill mode} \\ \Rightarrow \text{loss of an essential function} \Rightarrow \text{aircraft kill}$$

Note how the kill of one or more components creates functional effects that propagate from the killed component(s) to the system to the loss of an essential function to the kill of the aircraft. This is referred to as a propagating functional effect.

Loss of function and cascading-damage kill modes. Component kill modes can result in a loss-of-function kill of the component, with the resulting propagating effects on subsystem and system functions, or they can result in the kill of adjacent components caused by cascading damage (Note 8). Figure 5.7 illustrates the relationship between the types of kill modes. The distinction between these two types of kill modes, loss of function and cascading damage, and some other important aspects of critical components and their kill modes are described in the following paragraphs.

Loss-of-function kill mode: A component can be a critical component because it provides or contributes to an essential function. If the component is killed by a loss-of-function kill mode, the essential function provided by the component is lost. If the function of this component is to provide an essential function to another component, the loss-of-function kill is said to propagate to the supported function, resulting in a loss-of-function kill of that component. Eventually, the loss-of-function kill of one or more critical components can result in the loss of a mission or flight essential function, and the aircraft is killed. Thus,

$$\text{Critical component(s) loss-of-function kill} \Rightarrow \text{loss of an essential function} \\ \Rightarrow \text{aircraft kill}$$

As an example of a component that is critical because its loss-of-function kill mode leads to an aircraft kill, consider the single pilot on an aircraft. The essential function of the pilot (the component) is to fly or control the aircraft. If the pilot is unable to control the aircraft because he/she has been killed or incapacitated (the component loss-of-function kill mode) for any reason (heart attack, falling asleep, or killed by a fragment), the control signal path from the pilot to the control servoactuators is disrupted (the system kill mode). If the aircraft falls out of control within 30 s of a hit on the aircraft, the aircraft kill is referred to as a K level attrition kill. Thus, the pilot is a loss-of-function critical component for a K level attrition kill because he/she is an essential contributor to control, one of the essential functions for flight.

For the next example, consider the control stick or column in the cockpit. The pilot uses the stick to steer the aircraft. Thus, the function of the stick is to provide a physical connection between the pilot and the downstream parts of the control signal path. If the stick breaks for any reason, a loss-of-function kill mode has occurred, and the control signal issued by the pilot is unable to proceed beyond the pilot; he/she has nothing with which to steer the aircraft. This is another example of a disruption in the control signal path that leads to an aircraft attrition kill because of loss of control. Thus, the control stick is another critical component caused by a loss-of-function kill mode. Note that the control stick provides an essential function to the pilot. This function is the transmission of the control signal from the pilot to the downstream control components. Consequently, when the stick is killed, control is lost, but the pilot is *not* killed. The pilot could steer the aircraft if there were something available with which to steer. The effect of the kill of the stick has propagated from the stick to the pilot, who is still alive but is unable to steer the aircraft because the stick is dead. The pilot is referred to as nonfunctional because of the kill of the stick.

The engine on a single-engine aircraft is another critical component for an attrition kill because its loss-of-function kill mode, the loss of engine thrust for any reason, results in the loss of the flight essential function of thrust. The amount of time delay from the time of the hit on the aircraft to the time the aircraft falls out of control as a result of a loss of thrust will determine the specific level of attrition kill. For example, if the engine stops producing thrust 20 s after the hit on the aircraft, but the aircraft can glide for another 4 min before falling out of control, the engine is an A level attrition kill critical component.

The engine-mounted main fuel pump that provides high-pressure fuel to the engine fuel manifold is also a critical component because the fuel it provides to the engine combustor is essential for continued combustion. Without combustion there is no thrust, and the aircraft is killed as a result of fuel starvation. The fuel pump is similar to the cockpit control stick because the effect of its loss-of-function kill propagates to another component, the engine, which is now unable to provide the essential function of thrust. Note that the engine was not killed. If there was another source of high-pressure fuel, the engine could keep on burning. Thus, the engine is said to be nonfunctional when it has no fuel to burn.

For another example of a propagating effect, consider the flight essential functions of a modern tactical aircraft, which achieves stable flight using control computers and aircraft motion sensors. If a component that provides electrical power to one of the flight essential motion sensors is killed, the sensor could report either inaccurate data or no data to the flight control computer. This lack of correct motion data could cause the flight control system to misposition the control surfaces. If the aircraft is unstable, mispositioning a control surface in response to a pilot command could result in an aircraft kill. In this example, the propagating effect is the subsequent functional failures that begin with the loss of electrical power to the motion sensor and end with the loss of control of the aircraft caused by incorrect control surface positioning. Note that neither the servoactuator, nor the hydraulic components that provide high-pressure hydraulic fluid to the servoactuator, nor the control surfaces were physically damaged or killed; they became nonfunctional because of the loss of correct motion data.

To illustrate the critical component dependence on the kill category selected, consider the high-pressure liquid oxygen (LOX) converter on a high-flying aircraft. The function of the LOX converter is to provide oxygen to the pilot so he/she can fly at high altitude. If the LOX converter loses its ability to provide oxygen to the pilot for any reason, that is, a loss-of-function kill, the pilot can quickly descend to a lower altitude and continue flying. Thus, the LOX converter is not a critical component for an aircraft attrition kill because of a component loss-of-function kill mode. Sufficient lift, thrust, and control are available after the loss-of-function kill of the LOX converter. However, because of the increase in susceptibility at the lower altitude, the pilot might decide to abort the mission as a result of the kill of the LOX converter. Thus, the LOX converter is a loss-of-function critical component for a mission abort kill because one of the essential functions for mission capability (flying high) has been lost.

Cascading-damage kill mode: A component can be a critical component not because it is providing or contributing to an essential function, but because its kill mode results in cascading damage that causes either the physical or the loss-of-function kill of another critical component that does provide an essential function. Thus,

Critical component cascading-damage kill $\Rightarrow$ kill of another critical component
$\Rightarrow$ loss of an essential function $\Rightarrow$ aircraft kill

For example, suppose the high-pressure LOX converter just described is located in the cockpit near the pilot. Vulnerability tests conducted on the LOX converter reveal that the converter can shatter when hit by a high-speed fragment. The shattering is a cascading-damage kill mode, and the converter fragments are new damage mechanisms. Suppose the fragments from the shattered converter hit and kill the pilot, who is a loss-of-function critical component. In this situation the LOX converter is deemed a critical component for an attrition kill when the kill mode of shattering occurs because this particular kill mode can result in cascading damage that kills another component which is providing an essential function, the pilot. Note in this example, the cascading-damage kill of the LOX converter killed the pilot, as contrasted with the loss-of-function kill of the control stick, which did not kill the pilot. However, in both examples the aircraft was killed. If the cascading-damage kill mode of shattering does not result in the kill of any critical components, the LOX converter is not a critical component for an attrition kill.

Another example of a component that could be critical because of a cascading-damage kill mode is the liquid coolant for the radar electronic components on the aircraft. Loss of the ability of the coolant to cool the radar equipment, a loss-of-function kill mode, will not cause an attrition kill of the aircraft because the radar is not required for sustained flight (Note 9). However, the coolant is thought to be flammable. Vulnerability testing of the coolant under realistic conditions reveals that coolant escaping from a hole in one or more of the components in the cooling subsystem can result in a coolant fire. This fire could destroy nearby components that are critical to flight. Thus, the radar coolant is a critical component for an attrition kill when the cascading-damage kill mode of coolant fire occurs and results in the kill of one or more loss-of-function critical components.

Fuel tanks are major sources of cascading-damage kills. For example, consider an aircraft with one engine located inside the fuselage. The inlet duct that provides air to the engine starts beneath the nose of the aircraft and continues through the interior of the fuselage, ending at the engine fan face. A fuel tank is located within the fuselage above the duct, and the duct wall is common to both the inlet and the fuel tank. Penetration of the fuel in the tank by a metallic fragment or penetrator can result in hydrodynamic ram damage to the duct wall, which can allow fuel to spew into the duct and eventually be ingested by the engine. The engine can be killed by this ingested fuel, resulting in an aircraft kill. Another example of cascading damage associated with fuel tanks is when fuel leaks from a hit-caused hole in a tank wall into an adjacent dry bay. If the fuel is ignited by an incendiary, arcing electrical lines, or hot surface in the dry bay, the resultant fire can kill components located in that bay, resulting in an aircraft kill if those components are critical.

Nonredundant and redundant critical components. Some components on an aircraft individually provide or uniquely contribute to one or more flight or mission functions. These components are referred to here as nonredundant components (Note 10). For example, the single pilot, single control stick, single engine, and single-engine-mounted main fuel pump just described above are examples of nonredundant components. There are no other components that duplicate or backup the functions provided by these components. Because their loss-of-function kill results in an aircraft kill, they are also nonredundant critical components. The LOX converter and the radar coolant are also nonredundant critical components because their cascading-damage kill mode can eventually kill other critical components, resulting in an aircraft kill. Although these last two components are referred to as nonredundant critical components, their kill individually is not sufficient to kill the aircraft. Other critical components must also be killed as a result of their cascading-damage kill mode. A shattering LOX converter in the cockpit that can not kill the pilot is not a critical component.

On the other hand, many of the components on an aircraft are redundant. When two or more components on an aircraft are redundant, each of the redundant components contributes to a flight or mission function. The contribution might be in the form of a simultaneous contribution or a backup contribution. The loss of one or more of the redundant components will not result in the loss of the function when the remaining redundant component(s) can provide the function. For example, the four spars in a wing torque box are referred to as redundant components when any two of the spars can maintain the structural integrity of the box.

Redundant components are referred to as redundant critical components when the function they contribute to is an essential function (Note 11). In this situation

$$\begin{aligned}&\text{Redundant critical components loss-of-function kill}\\&\quad\Rightarrow \text{loss of an essential function} \Rightarrow \text{aircraft kill}\end{aligned}$$

For example, consider an aircraft with two engines. The engines are redundant critical components for an attrition kill when either engine can provide sufficient thrust to maintain flight. For example, if the port engine is killed by a loss-of-function kill mode, the aircraft can still fly with the thrust from the starboard engine. Both of the engines must be killed to result in the loss of the flight essential function of thrust (Note 12). Other typical redundant critical components on aircraft are the pilot and copilot, the major structural members, the fuel storage tanks, and many of the avionics and flight control components.

Major redundant critical components, such as engines, can contain both nonredundant and redundant components that are critical to the major component. For example, each engine on a two-engine aircraft might have only one engine-mounted main fuel pump. Because the pump is essential for the continued operation of the engine on which it is mounted, the pump is referred to as a nonredundant critical component for the engine, which is a redundant critical component for the aircraft. From an aircraft point of view, the pumps are redundant critical components because a loss-of-function kill of only one pump will not result in a kill of the aircraft. On the other hand, consider a single-engine aircraft with two pumps that provide high-pressure fuel to the combustor. The two pumps are redundant critical components for an engine kill, but the engine is a nonredundant critical component for an aircraft kill. Thus, the terms nonredundant and redundant are relative to the end result, that is, a component kill or an aircraft kill.

Because the critical components are dependent upon the selected kill type, components can be nonredundant for one type of kill and redundant for another type. For example, in a twin-engine helicopter if the kill of either engine results in a mission abort the engines are said to be nonredundant critical components for the mission abort kill. On the other hand, if the kill of both engines results in a helicopter crash the engines are said to be redundant for the attrition kill. If the helicopter is capable of autorotation when both engines are killed, the two engines are said to be redundant critical components for a forced landing kill. If the helicopter is heavily loaded at high altitude on a hot day, a kill of either one of the engines might force it to land. Thus, under these conditions the engines are nonredundant critical components for a forced landing kill.

Nonredundant and redundant critical components have been referred to in the past and elsewhere as singly vulnerable components and multiply vulnerable components, respectively. Thus, the single engine on an aircraft is a singly vulnerable (nonredundant) critical component, and the two engines on an aircraft are multiply vulnerable (redundant) critical components. This terminology is counterintuitive (if vulnerability is bad, then a multiply vulnerable component must be multiply bad), obscure, and unfamiliar to most people. Consequently, it is not used here. Nevertheless, because this terminology has been around since the early 1950s some practitioners of vulnerability assessment still use it, and hence the student of vulnerability must know what it means.

Multiple kill modes of one component. When one component has several possible loss-of-function and/or cascading-damage kill modes, each of the kill modes must be examined when determining the consequence of the component kill on the essential functions. For example, consider the left-wing integral fuel tank in an aircraft with one engine in the fuselage. The function of the fuel tank in the wing is to store fuel. When the aircraft is in combat, most of the fuel in the wing tank has been burned off, and the tank is nearly empty. Suppose the wing is hit from the bottom by a penetrator and the tank wall is penetrated. If the hydrodynamic ram damage to the tank wall is minimal because of the low level of fuel, there might be a slow fuel leak through the entry hole and eventual fuel depletion from the damaged tank. There will be no substantial effect on the ability of the aircraft to continue to fly because of the loss of fuel from the damaged wing tank; there is sufficient fuel remaining in the other tanks to complete the mission (Note 13). The fuel tanks are redundant components with respect to fuel storage, and consequently, the fuel system kill mode of fuel supply depletion will not occur. For this loss-of-function kill mode, the wing tank is a redundant critical component for an attrition kill because there are other fuel tanks available to provide the necessary fuel (Note 14).

On the other hand, suppose the wing tank was nearly full of fuel, and the penetrator caused severe hydrodynamic ram damage to major components of wing structure, such as the spars, ribs, stiffeners, and skin. This damage could result in the failure of the wing torque box and the subsequent loss of the aircraft because of the loss of structural integrity. For this hydrodynamic ram cascading-damage kill mode of the fuel tank, the damage cascaded from the fuel in the tank to the surrounding wing structure, rendering the structure incapable of carrying the flight loads and resulting in an attrition kill of the aircraft. Thus, the wing fuel tank is a nonredundant critical component for an attrition kill when the hydrodynamic ram cascading-damage kill mode occurs.

A similar situation exists when there is a possibility of an explosion in the ullage of the wing fuel tank. Fuel leaking from a small hole in the bottom of the wing tank most likely will not cause an aircraft kill, but an explosion inside the tank can. Thus, the wing fuel tank is a nonredundant critical component for an attrition kill if the in-tank explosion cascading-damage kill mode results in the loss of the aircraft.

Multiple engines on aircraft that are normally redundant for loss-of-function kill modes can be nonredundant critical components if an engine cascading-damage kill mode results in a kill of one or more nearby nonredundant critical components. For example, consider a two-engine aircraft with both engines in the fuselage. Nonredundant flight control rods run from the cockpit along the top of the aircraft, between and above the two engines, and back to the differential tail planes and rudders. Suppose the engines have a cascading-damage kill mode, such as 'thrown' fan or compressor blades that can cause damage to the engine fuel system, resulting in a engine bay fuel fire that destroys the flight control rods that pass through the engine bay. The loss-of-function kill of the flight control rods results in a loss of control kill of the aircraft. Thus, a kill of either engine by this cascading-damage kill mode can result in a kill of the aircraft as a result of the subsequent kill of the nonredundant flight control rods. Consequently, the engines are nonredundant critical components for this cascading-damage kill mode because a kill of either engine can lead to the kill of the aircraft. A similar situation can exist for aircraft with multiple turboprop engines. Loss of a propeller from one engine might result in either major damage to the engine that lost the propeller, possibly resulting in an aircraft kill. Or the thrown propeller might cause damage to components in other parts of the aircraft, such as the cockpit.

One confusing situation with redundant critical components and multiple kill modes occurs when a cascading-damage kill mode of one redundant critical

Table 5.4 Critical components and their kill modes

Critical component (CC)	Description	Examples
Failure mode	Type of component dysfunction or kill related to the normal flying environment	Failure to operate, out-of-tolerance operation
Damage mode	Type of component dysfunction or kill related to combat damage	Explosion, fire, penetration, hydrodynamic ram
Nonredundant, loss-of-function	Nonredundant component whose kill mode can result in the loss of essential function (If the component provides an essential function to another component, the loss of function of the supported component is referred to as a propagating effect. The affected component is said to be nonfunctional.)	Tail rotor drive shaft, tail boom, rotor blade, single engine, single fuel pump, single pilot, cockpit control stick, single control signal, wing, fuselage
Redundant, loss-of-function	Redundant component whose kill mode will not result in the loss of essential function because of the remaining redundant CCs	Two engines, pilot and copilot, hydraulic components, avionics components, major structural components
Cascading damage	Component whose kill mode can result in cascading damage that kills one or more loss-of-function critical components, leading to an aircraft kill	Fuel tanks, fuel lines, LOX converter, flammable avionics coolant, flammable hydraulic fluid

component leads to a loss-of-function kill of the remaining redundant critical components. For example, consider the two-engine aircraft just described. Suppose the thrown blade cascading-damage kill mode for one of the engines results in a loss-of-function kill of the second engine. The kill of both engines will result in an attrition kill of the aircraft. Thus, although the engines are still redundant critical components for this cascading-damage kill mode because a kill of both engines is required for an aircraft kill, a hit on one engine could result in a kill of both engines.

Table 5.4 summarizes the material just presented on critical components and their kill modes.

Go to Problems 5.2.16 to 5.2.25.

5.2.2.6 Task 5: Conduct a FMEA and identify the critical components and their kill modes.

Learning Objective **5.2.7 Describe and conduct a FMEA.**

Several examples of the critical components on an aircraft and their kill (failure or damage) modes have been described in the preceding section to illustrate the concept of a critical component and the types of kill modes that can occur. A formal, systematic procedure for identifying all of the critical components on an aircraft and their failure modes first appeared in the aircraft industry in the late 1950s. This procedure, now known as the failure mode and effects analysis, 1) identifies and documents all possible failure modes of a component, and 2) determines the effects of each component failure mode upon the capability of the component or subsystem and the system to perform its functions. If an estimation of the severity of the effects of the failure mode identified in the FMEA and of the relative frequency of occurrence of the failure mode are made, the process is sometimes referred to as the criticality analysis (CA) (Note 15). The combination of the FMEA and CA is the failure mode, effects, and criticality analysis (FMECA). The FMECA process and requirements are defined in MIL-STD-1629A, Procedures for Performing a Failure Mode, Effects, and Criticality Analysis.[3] These two analyses are described in the following subsections (Note 16).

FMEA.[3] There are two primary approaches for accomplishing an FMEA: the hardware approach and the functional approach. In the hardware approach hardware failures are assumed, typically at the lowest level of hardware complexity, for example, the part level. This is referred to as a bottom-up approach. In the functional approach failures of the functions provided by the component are assumed. The assumed failure can be at a low level and proceed upward or at a high level and proceed downward. In complex systems both approaches might be used.

All possible component failure modes should be identified and described in the FMEA. The probable causes of each of these failure modes are also identified and described. According to MIL-STD-1629A, the types of component failure modes generally considered in the FMEA include, as a minimum, 1) premature operation, 2) failure to operate at a prescribed time, 3) intermittent operation, 4) failure to cease operation at a prescribed time, 5) loss of output or failure during operation, 6) degraded output or operational capability, and 7) other unique failure modes.

The consequences of each assumed component failure mode on the continued operation, function, and status of the failed component, known as the local effects, are identified and documented. In addition, the effect of the component failure upon the continued operation, function, and status of the higher levels all of the way up to the aircraft containing the component are identified and documented. The ultimate effect a particular component failure has upon the operation, function, and status of the aircraft is referred to as the end effect. If the end effect is the loss of an essential function for flight or for mission completion, the component is a critical component based upon the assumed failure mode.

In general, each individual component failure is considered to be the only failure in the aircraft, and any aircraft kill resulting from the single component failure is referred to as a single-point kill. However, multiple component failures that can result in an aircraft kill must also be identified in the FMEA. The consideration of multiple component failures is extremely important when the failure is caused by combat damage because of the likelihood that more than one component is killed when the aircraft is hit.

The examination of the effects of a component failure should also include the consideration of any transients that might occur when the failure occurs. For example, consider a single-engine, fly-by-wire, statically unstable aircraft, with no mechanical flight controls for backup. Suppose the engine-driven generator that supplies the electrical power to the flight control computer was to cease operation immediately. Suppose further that the computer relies on an emergency ram-air turbine (RAT) or a hydrazine-fueled electrical generator for backup electrical power. The RAT is designed to be deployed into the airstream when the electrical power failure is sensed, and the generator is designed to burn hydrazine, which turns a turbine and generates electrical power. However, this takes time. While the RAT is being deployed or the hydrazine generator starts up, the computer could be without sufficient power. This might cause problems with the fly-by-wire control system, such as the loss of the stability augmentation subsystem or the issuance of hard-over commands to the control surfaces, that could cause the aircraft to become uncontrollable, leading to an aircraft loss. Thus, the assumption of redundancy in the electrical power system is, in fact, erroneous.

Examples 5.1 and 5.2 describe the FMEA process. The FMEA worksheet format given in MIL-STD-1629A is shown in Fig. 5.8 for the two flight control rod failure modes described in Example 5.2.

Example 5.1 One Example of an FMEA

Consider the battery mounted inside a helicopter on a vertical bulkhead near the tail rotor drive shaft. There are three bolts holding the battery in place. Assume one bolt breaks. This is the hardware failure mode during operation. The functional failure mode is the inability of the bolt to restrain the battery. The cause of the break is fatigue (reliability/safety), or the break is caused by a hit by a 7.62-mm API (vulnerability). Regardless of the cause, the bolt is broken. Analysis, and possibly testing, reveals that the remaining two bolts cannot restrain the battery from breaking away from its mount.

Further analysis and testing reveal that the loose battery can strike the tail rotor drive shaft. The drive shaft can bend as a result of the impact of the battery. The bent shaft can flail and eventually break. This results in the loss of shaft power to the tail rotor, which then stops turning. There no longer is sufficient yaw force to prevent a loss of control of a hovering helicopter, and the helicopter crashes. The elapsed time between the time of the hit and the time the helicopter is out of control is estimated to be less than 30 s. Thus, the end effect of this failure mode is a K level attrition kill. Consequently, the bolt is a nonredundant critical component

SYSTEM ____________
INDENTURE LEVEL ____________
REFERENCE DRAWING ____________
MISSION ____________

DATE ____________
SHEET ______ OF ______
COMPILED BY ____________
APPROVED BY ____________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	FAILURE EFFECTS			FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY CLASS	REMARKS
					LOCAL EFFECTS	NEXT HIGHER LEVEL	END EFFECTS				
3127	Rod	Transmit Pilot's lateral stick motions to starboard side aileron	Sever	Normal flight	Aileron hardover up	Control stick free. Hardover effect can be balanced with port aileron	No loss of control	None	None	No attrition kill Possible mission abort kill	
			Jam	Normal flight	Aileron hardover up	Control stick jammed	Loss of control	None	None	KK level attrition kill	

Fig. 5.8 Example of an FMEA worksheet format (Example 5.2, Ref. 3).

for the K level attrition kill. The failure mode of breaking is a loss-of-function failure mode that results in a cascading-damage kill of the tail rotor drive shaft.

Suppose the designer added a fourth bolt. Again, assume one of the bolts breaks. Analysis and testing reveal that the three remaining bolts are sufficient to hold the battery in place. Thus, the end effect of this particular component failure is no loss of any essential function and hence no aircraft kill. However, if any two bolts were to break, the break-away battery situation just described could occur. Hence, the four bolts are redundant critical components for the K level attrition kill, and a kill of any two of the four bolts could result in an aircraft kill.

Example 5.2 Another Example of an FMEA

Consider the mechanical flight controls in a fixed wing aircraft that form a mechanical path from the pilot's stick along the centerline of the aircraft to a three-arm bellcrank located at the centerline of the trailing edge of the wing. Push–pull rods run from the bellcrank out along the trailing edge of each wing to the aileron servoactuator. When the pilot moves the stick laterally to roll the aircraft, the three-arm bellcrank moves the rods in each wing in the opposite direction, causing the two ailerons to move in opposite directions, one up and one down. The ailerons contribute to the flight essential function of control.

Assume the component failure mode is a break of one of the rods along the trailing edge of the port wing. The break could be because of corrosion or a hit by a warhead fragment. When the pilot moves the control stick laterally, the control signal to the port servoactuator is disrupted at the break. Analysis reveals that the port aileron servoactuator will automatically extend outward as a result of the loss of the control signal. The extension of the servoactuator will cause the aileron to move upward. The roll force on the aircraft caused by the port aileron in the up position can be balanced by the pilot moving the stick so that the starboard aileron is also up. Thus, the end effect of this failure is that control of flight is maintained. Thus, the rod is not a critical component for the failure mode of breaking.

On the other hand, suppose the failure mode was a jam of one of the rods in the port wing. The cause of the failure could be as a result of a nut that had come loose from a nearby bolt and fallen between the rod and the trailing edge spar web, or it could be caused by the impact of a warhead fragment. In either situation the jammed rod prevents the three-arm bellcrank from moving in any direction. Thus, the entire mechanical path from the pilot's stick to both ailerons is jammed. Now, neither aileron can be moved, and roll control of the aircraft is immediately lost. Thus, the end effect of this failure is a KK level attrition kill. Consequently, the control rods in the trailing edge of both wings are nonredundant critical components for a KK level attrition kill for the failure mode of jamming.

Suppose the designer of the flight control system decided to put a safety spring cartridge on both sides of the three-arm bellcrank in the mechanical path along the trailing edge of each wing. Analysis reveals that a jam of any of the rods outboard of the safety spring will not cause a jam of the three-arm bellcrank because the spring allows relative displacement along the path. Thus, the spring frees the jam and allows the pilot to move the stick freely; control of flight is maintained. In this situation the rods are not critical components as a result of the failure mode of jamming.

Criticality analysis. The FMEA just described identifies the end effects caused by an assumed component failure mode. Of considerable interest in reliability and safety studies is the severity of the end effect and the relative frequency of occurrence. For example, if a particular failure of a component, such as the loss of thrust from the single engine on an aircraft, results in the loss of an essential function for flight, such as thrust, the severity of the end effect is catastrophic. When the frequency of occurrence of the failure mode that leads to a catastrophic end effect is more than extremely unlikely, the component failure mode is deemed critical.

The formal examination of the severity of the end effects and the frequency of occurrence of each of the failure modes identified in the FMEA is known as the criticality analysis. The categories of the severity of the end effects from a failure mode and the relative frequency of occurrence of the failure mode given in MIL-STD-1629A are essentially the same as those used by the system safety community for the hazard analysis. These categories are defined in MIL-STD-882D and listed in Table 1.6.

In the vulnerability program the level of severity of the end effect is related to the type of aircraft kill. For example, a component failure mode that results in a KK level attrition kill is considerably more severe than one that results in a mission abort kill. The frequency of occurrence of the component failure (kill) mode is determined in the vulnerability assessment task, where the likelihood a particular component kill occurs when the aircraft is hit is determined.

Go to Problem 5.2.26.

5.2.2.7 Task 6: Conduct a DMEA and identify the kill criteria for the kill modes.

Learning	**5.2.8**	**Describe and conduct a DMEA.**
Objectives	**5.2.9**	**Describe the kill modes for the major systems.**

DMEA. In an FMEA conducted by the reliability or system safety community, the cause of the component failure is usually related to the normal, peacetime operational environment. In the vulnerability program, which is concerned with component kills as a result of combat damage, the peacetime component failures identified in the FMEA must be supplemented with component failures caused by combat damage. The procedure for identifying the component dysfunction as a result of combat damage is known as the damage mode and effects analysis. The DMEA is also defined in MIL-STD-1629A[3].

The DMEA builds upon the results of the FMEA. In the DMEA the potential component or subsystem failures identified in the FMEA, as well as other possible damage-caused failures, such as mechanical damage to components caused by the impact of one or more projectiles or fragments on the component and damage caused by a fire or explosion, are associated with the damage mechanisms and the damage processes. The end effects of the damage modes are evaluated to determine their relationship to the selected kill level. The quantification of the component kill criteria is also part of the DMEA, but this procedure is described in the vulnerability assessment presentation in Sec. 5.3 of this chapter. The possibility of any secondary hazard or cascading damage that might be caused by the primary damage mode is also identified in the DMEA. Examples of cascading damage are ingestion of fuel by an engine and the seepage of toxic fumes from a fuselage fire into the cockpit.

According to MIL-STD-1629A,[3] the following examples of damage modes shall be considered, as a minimum: 1) penetration; 2) severing; 3) shattering, cracking; 4) jamming; 5) deforming; 6) igniting, detonating; 7) burnout (e.g., electrical overload); and 8) burn-through (e.g., by a fire).

The worksheet format of the DMEA given in MIL-STD-1629A is shown in Fig. 5.9. This worksheet is very similar to the FMEA worksheet format shown in Fig. 5.8. The effects of a particular component damage mode are identified, starting with the local effects on the operation of the component itself, progressing to the effects on the operations and functional capabilities of the next higher level, and finishing with the end effects on the aircraft flight and mission essential function capabilities. Emphasis is placed upon the identification of any cascading damage from the damaged component to other components. A disablement diagram can add to the understanding of the DMEA output by graphically showing the locations of the component and stating the effects of each of the component kills.

Some important kill modes of critical components and systems. There are many different types of nonredundant and redundant critical component kill modes (failure or damage, loss of function or cascading damage) that can occur within each of the systems of an aircraft. These critical component kill modes result in subsystem or system kill modes that eventually lead to the loss of one or more flight or mission essential functions. Several examples of different kill modes have already been described. Over the years, studies of combat data, lessons learned, and aircraft vulnerability have identified many of these component and system kill modes. Some of the most important kill modes that can result in the loss of one or more of the four flight essential functions (structural integrity, lift, thrust, and control) are listed in Table 1.4 and repeated in Table 5.5 for the major systems on aircraft. These system kill modes are briefly described in the following paragraphs. The order of the systems is somewhat indicative of their relative contribution to the total aircraft vulnerability. A thorough understanding of these system kill modes is essential if vulnerability is to be reduced because vulnerability reduction is, in essence, either the prevention of these kill modes from occurring or the mitigation of their end effects.

Fuel system kill modes: The following is a listing and brief description of the fuel system kill modes.

1) The *fuel supply depletion* kill mode results in an aircraft kill because of a loss of thrust. It is caused by hydrodynamic ram or penetration damage to fuel storage

SYSTEM ______________
INDENTURE LEVEL ______________
REFERENCE DRAWING ______________
MISSION ______________

DATE ______________
SHEET ______ OF ______
COMPILED BY ______________
APPROVED BY ______________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	SEVERITY CLASS	DAMAGE MODE	DAMAGE EFFECTS			REMARKS
							LOCAL EFFECTS	NEXT HIGHER LEVEL	END EFFECTS	

Fig. 5.9 Example of a DMEA worksheet format.[3]

Table 5.5 List of component and system kill modes

Component/System	Kill mode

Fuel	Fuel supply depletion
	Fire/explosion
	  In-tank ullage
	  Void space
	Hydrodynamic ram

Propulsion	Air inlet flow distortion
	Engine failure
	  Fuel ingestion
	  Foreign object damage
	  Fan/compressor damage
	  Combustor damage
	  Turbine damage
	  Exhaust duct or afterburner damage
	Engine fire
	Engine subsystem or control failure
	  Loss of lubrication
	  Engine controls and accessories failure

Flight control	Disruption of control signal path
	  Loss of pilot
	  Loss of control lines
	  Computer failure
	  Sensor damage
	Loss of control power
	  Hydraulic failure
	  Electrical failure
	  Actuator damage
	Damage to control surface/hinges
	Hydraulic fluid fire

Structural	Fracture/removal Pressure overload Thermal weakening Delamination/fiber buckling Connection failure
Power train and rotor blade/propeller	Mechanical/structural damage Loss of lubrication
Electrical power	Severing/grounding Mechanical damage Overheating
Avionics	Mechanical damage Fire/overheat
Armament	Fire/explosion
Crew	Injury/death Life support failure

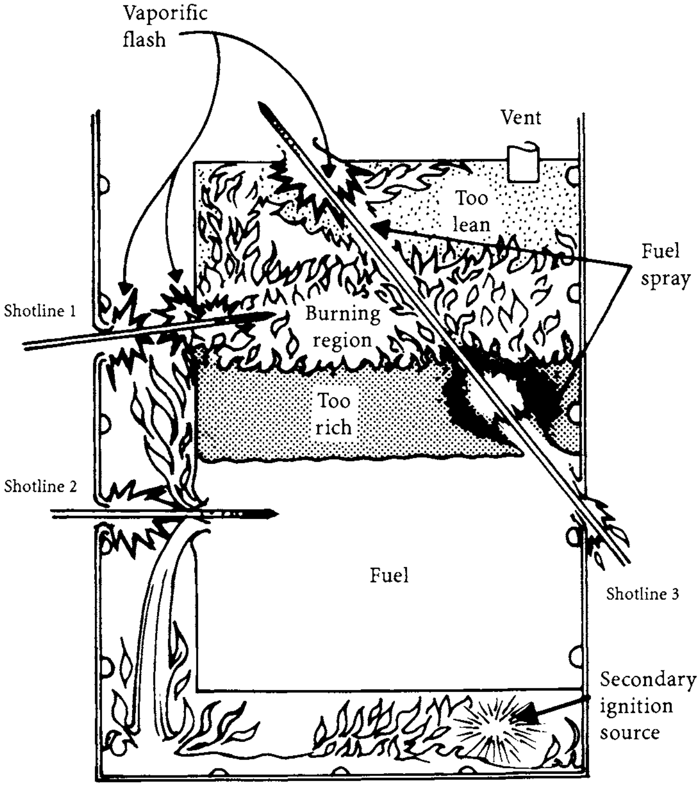

Fig. 5.10 Possible combustion incidents in and around a fuel tank (Note 17).

components that results in excessive leakage or by damage to fuel pumping and transfer components that prevents fuel from reaching the engine(s).

2) The *fire/explosion kill* mode is the combustion damage process, and it can result in a loss of structural integrity of the airframe or in the kill of other critical components caused by cascading damage, such as control lines, hydraulic lines, and flight critical avionics.

Figure 5.10 illustrates several possible combustion conditions for different penetrator or fragment shotlines. As shown in the illustration, the fire or explosion can occur in two general locations: within the fuel tank ullage and in the void spaces or dry bays around the tanks and lines. The in-tank fire and explosion is caused by ignition of the fuel-air mixture in the ullage of the tank caused by incendiary particles, or a hot wall, or some other ignition source. In general, there will be regions in the ullage where the ullage gas is too lean, such as the volume near the vent at the top of the tank, and regions where it is too rich, such as the gas near the sloshing fuel surface. The void space fire and explosion is caused by to a leakage of fuel from a damaged tank or line into the adjacent void spaces and dry bays and the subsequent ignition of the leaked fuel. The possible sources of ignition in the void spaces include incendiary particles, vaporific flash, and secondary ignition sources, such as hot gases from penetrated bleed air lines or engine combustors, hot metallic surfaces, and arcing electrical lines.

Shotline 1 in Fig. 5.10 (from left to right into the ullage) shows the direct encounter of a penetrator with the flammable vapor in the ullage. The small clouds along the shotline are typical ignition sources. For incendiary projectiles these flashes represent burning incendiary mixtures. These incendiary clouds can also be locations of flashes caused by the high-speed impact of a penetrator or fragment upon metallic tank surfaces. For HE and HE-I projectiles the location of each detonation and incendiary flash is determined by the fuze delay employed and the impact conditions. For this particular shotline the flammable region could be ignited, and an in-tank fire or explosion could occur.

For shotline 2 (from left to right into the fuel) the flashing external to the tank is caused by effects similar to shotline 1. Although no combustion can occur within the liquid fuel itself, the hydrodynamic ram can grossly increase the wall damage and fuel leakage. Another possibility with this shotline is the ignition of the fuel that is spurting from the entry hole by either an incendiary or a metal impact flash. An independent hazard is indicated by the lower fire, where leaking fuel and vapor have found an onboard secondary ignition source. These primary and secondary void space fires and explosions caused by shotline 2 can be the most prevalent means by which the smaller incendiary projectiles can cause fuel-system-related aircraft kills.

Shotline 3 (from lower right to upper left) is an impact upon a fuel tank wall that is integral with the airframe skin. Even though fuel escapes into the atmosphere through the entry hole, the slipstream can prevent a sustained exterior fire on the tank wall. However, if there is severe petaling the jagged edges could act as flame holders, and a sustained exterior fire could occur. The second flash along shotline 3 in the ullage denotes the delayed detonation of an HE round or the delayed activation of an incendiary round. The third flash is caused by penetration or impact with the top of the tank. As a result of the fuel spray caused by the penetrator or fragment exiting the liquid surface, a substantial mist is generated, which follows the shotline and can reach the incendiary flash at the exit. The mist can convert the too lean zone into a just-right zone for combustion to occur.

Both in-tank and void space fires can quickly spread to other parts of the aircraft, killing components as they go. Explosions that occur within enclosed spaces can cause significant damage to surrounding structure and components caused by blast and heat effects, and any fire can quickly spread to other parts of the aircraft. A fire can create smoke and toxic fumes that can migrate to crew stations, causing a possible mission abort, forced landing, or aircraft abandonment.

Ignition of fuel leaking out of the aircraft can lead to a sustained exterior fire. Sometimes the exterior fire is snuffed out by the airflow over the surface; however, the condition of the damaged surface, the altitude, and the flight speed might prevent this from occurring.

3) The *hydrodynamic ram* kill mode is also the hydrodynamic ram damage process. It can result in the rupture of the fuel tank walls, and the subsequent leakage of fluid, and the failure of major structural elements of the airframe, resulting in the loss of structural integrity, lift, and control.

Propulsion system kill modes: Critical component kill modes associated with the propulsion system usually result in the loss of the aircraft as a result of loss of thrust from the engine. Many aircraft have more than one engine, and consequently the engines are redundant critical components. Nevertheless, each engine has the same potential kill modes. The kill modes of the propulsion system that have been observed are briefly described in the following paragraphs. They are divided into the categories of air inlet failure, engine failure, engine fire, and engine subsystems and controls failure.

1) *Air inlet flow distortion* to the engine can be so severe as a result of combat damage to the inlet that uncontrollable engine surging or engine failure occurs.

2) Engines have the following kill modes.

Fuel ingestion is caused by fuel entering the engine air inlet following penetration of, or hydrodynamic damage to, fuel tank walls that are near the inlet. Fuel ingestion effects normally include compressor surge, severe stall, unstable burning in the inlet and the tail pipe, and/or engine flameout. (The fuel ingestion kill can also occur during in-flight refueling.)

Foreign object damage (FOD) is caused by foreign objects that consist of metallic penetrators and fragments and pieces of damaged aircraft components which enter the engine inlet and subsequently damage the fan and compressor blades. This could cause either an engine failure or the throwing of blades through the engine case, resulting in damage to components in the vicinity of the engine.

The fan or compressor case damage kill mode is caused by penetrator or fragment penetration through the case of the fan or compressor, possibly causing distortion or caving in of the case or breaking the compressor disk or blades. The broken disk or blades can exit through the case at several hundred feet per second and can impact and penetrate adjacent parts of the aircraft, causing cascading damage.

Combustor damage is caused by penetrator or fragment penetration and holing of the combustor case or cracks caused by blast effects, which can result in subsequent hot gas emission or torching through the hole. This gas, torch, or streak can cause secondary damage effects, such as severe heating of turbine blades and guide vanes, and adjacent fuel tanks and control rods. The holes and cracks can also cause a combustion pressure drop that might result in a significant loss of engine power. A damaged combustor case (and liner) can result in turbine damage and a subsequent engine kill as a result of the disruption of the cooling flow around the liner, and a hot streak of gas out of the combustor can burn up the turbine blades and guide vanes.

Turbine failure can be caused by penetrator or fragment damage to the turbine wheels, blades, and case. This results in a loss of engine power or secondary perforation and possible fire damage.

Exhaust duct or afterburner damage is caused by penetration by penetrators and fragments into the exhaust duct that can result in damage to nozzle fuel lines and actuator mechanisms and possible fuel spillage and a secondary fire if an augmentor is operating at the time of hit. For those aircraft equipped with fuel-powered thrust vectoring, fuel leakage and a possible secondary fire can be caused by the penetration of thrust vector control lines and actuator mechanisms. This kill mode can also fall under flight control systems if the failure leads to a loss of controlled flight.

3) An *engine fire*, either in the fuselage or a nacelle, can occur if any of the components containing fuel intended for the combustor, such as the fuel boost pump, main fuel pump, and fuel manifold, are penetrated and the leaking fuel ignites. This fire can quickly destroy the engine and spread to adjacent components, compounding the damage.

4) *Engine subsystem or control failure* can be caused by loss of lubrication or engine controls and accessories failure.

Penetrator, fragment, or fire damage to the lubrication circulation and cooling subsystem can result in the *loss of lubrication* and subsequent deterioration and seizing of the bearing surfaces. This is followed by movement of the engine spools with subsequent collision with the stator vanes and engine case.

A kill of many of the *controls and accessories* associated with the engine operation can lead to a kill of the engine. The kill can be caused by penetrator, fragment, or fire damage. This kill mode can result in the loss of the pilot's ability to control of the engine, resulting in engine loss or over speed and eventual failure. Some engines are controlled by computer. Therefore, this kill mode can also be caused by damage to the computers and avionics controlling the engine's operation.

Flight control system kill modes: The flight control system is the third major system that contributes to an aircraft's vulnerability. Failures within the flight control system usually lead to a loss of control. Of particular concern are those locations on the aircraft where a single hit could cause a kill. These locations are referred to as single-point kills, and no modern military aircraft should have any single-point kills. Some of the most important flight control kill modes are given in the following paragraphs.

1) *Disruption of the control signal path* kill mode is caused by either an incorrect or no control signal from the pilot, or the component flying the aircraft, through the control signal lines to the flight control computer to the servoactuators that power the control surfaces. It can be caused by the loss of the pilot(s), the severance of the electrical or optical control signal line(s), the jamming or severing of a mechanical path, and by the generation of an incorrect control signal (Note 18). For statically unstable aircraft, damage to the flight control computer or loss of the data from the aircraft motion sensors can quickly lead to an out of control aircraft. Damage to the aircraft motion sensors or to the sensor data signal paths to the flight control computer can prevent the autopilot and the stability augmentation system from properly controlling the motion of the aircraft. The result can vary from a partial loss of control, leading to a mission abort, to the loss of an out of control aircraft. These components are relatively soft and are easily damaged or severed by metallic penetrators and fragments and may be quickly destroyed by fire.

2) *Loss of control power* kill mode occurs when there is insufficient power to position the control surfaces. This power loss can be caused by damage to the hydraulic power generation components, the hydraulic lines and reservoirs, and the servoactuators. If the control power is electrical, loss of control power can occur as a result of damage to the electrical power generation system, the electrical transmission lines, and the electrical actuators. Examples of power system component kill modes include thermal degradation caused by fire, penetration of hydraulic lines, reservoirs, and servoactuators, leading to a loss of hydraulic fluid,

and deformation of hydraulic components, servoactuators, or lines that cause a hydraulic lock or jammed condition.

3) *Damage to control surfaces/hinges* can be caused by penetrators, fragments, blast, and fire damage, which can result in the physical removal of part or all of a flight control surface or in the jamming of the hinges, rods, and other linkages between the servoactuators and the control surfaces. The removal or jamming of a control surface can create problems for an unstable fly-by-wire aircraft. The control gains in the flight control laws might need to be changed when a particular surface is no longer available. If the control system is unable to recognize the loss of a surface, it might not be able to control the stability of the aircraft's flight, and control is lost.

4) *Hydraulic fluid fire* kill mode occurs when a hydraulic component is penetrated, and the high-pressure hydraulic fluid escapes as an atomized mist. A fire can result if the fluid is flammable and there is an ignition source in the vicinity, such as the incendiaries from an API. Any smoke or toxic fumes from the hydraulic fluid fire might migrate into the cockpit, forcing the aircrew to eject.

Structural system kill modes: The structural system is usually the toughest system on the aircraft. However, structural damage as a result of hydrodynamic ram or internal or external blast can be sufficient to cause an aircraft kill caused by loss of structural integrity. Typically, a kill of the structure results in the loss of one or more lifting or control surfaces.

1) *Fracture, tearing, or complete removal* of large portions of the load-carrying aircraft structure caused by multiple penetrators and fragments, internal or external blast, fire, or hydrodynamic ram effects can result in either an immediate or a delayed aircraft loss.

2) *Pressure overload* is the immediate failure, or subsequent failure under maneuver loads, that can be caused by external or internal blast effects or by hydrodynamic ram that result in the buckling or crushing of the load-carrying structure.

3) *Thermal weakening* is a structural failure that can occur to portions of the load-carrying structure as a result of internal void space fires or externally sustained fires.

4) *The delamination/fiber buckling* kill mode occurs with fibrous composite materials, such as graphite epoxy, and is caused by the breakdown of the load-carrying capability of the material by blast, hydrodynamic ram effects, or penetration of the structural member.

5) *Connection failure* is a major vulnerability problem that can occur when composite materials are used as walls of a fluid container, such as a fuel tank. Impact into the tank and penetration through the fuel by a metallic penetrator or fragment can create very large hydrodynamic pressure on the composite walls and internal structure of the tank. If the connections between the various composite components, such as the lower skin and substructure of a wing fuel tank, are not designed to carry the large transverse shear loads created by the fluid pressure acting normal to the tank walls, the connections can fail.

Power train and rotor blade/propeller system kill modes: Some of the possible damage-caused failures within the power train and rotor blade system of helicopters and propeller-driven fixed-wing aircraft are described next.

1) *Mechanical or structural failure* of power train components can be caused by fragment and penetrator impact or penetration, or by fire. Bearings, gears, and shafts are prone to damage and failure when hit, shafts can be severed, and bearings and gears can jam. Chips and debris from damaged components or structures can jam the oil pump, causing loss of the lubrication. Rotor blades and propellers when hit can result in rotor unbalance, blade instability, blade out-of-track, and loss of lift. Rotor unbalance is perhaps the most critical consequence of ballistic damage and occurs when a portion of the blade is removed. This loss of mass in one blade can cause large, alternating hub forces and intense cockpit and control vibrations, leading to structural failure or loss of control. Blade instability is caused by a reduction of blade stiffness as a result of damage and can result in severe flutter or divergent pitch oscillation that can be catastrophic. Blade out-of-track is usually a less severe result of the reduction of blade stiffness, but it could result in blade contact with the fuselage. Although some loss of lift normally accompanies any ballistic damage, the consequences are usually not as catastrophic as those associated with the other types of blade reactions.

2) *The loss of lubrication* kill mode can occur as a result of projectile or fragment perforation of oil- or grease-containing components, with subsequent loss of the lubrication oil or grease. Lubrication starvation is especially critical in oil-cooled helicopter transmissions, where the oil systems are not self-contained and usually consist of externally mounted components, such as sumps, filters, coolers, and interconnecting lines and hoses. Loss of lubrication prevents the removal of heat and lubrication of rubbing surfaces, which eventually results in component seizure. In helicopter transmissions and gearboxes failures are often catastrophic, causing case rupture and fire after input pinion failures and rotor blade seizure after planetary assembly failures.

Electrical power system kill modes: The failure of electrical system components is caused by the severing or grounding of electrical circuits and mechanical damage as a result of the destruction or unbalancing of rotating components, such as generators and alternators and the penetration or overheating of batteries.

Avionics system kill modes: Avionics components are usually very soft and are easily damaged by penetrators and fragments, blast, and thermal hazards, such as a fire from a leaking flammable coolant or hot gas torching. Their failure mode is usually failure to operate, although a degraded operation can occur.

Armament system kill modes: Several major reactions can occur when gun ammunition, bombs, rockets, and missiles are hit by a damage mechanism, such as a metallic penetrator or fragment. The impact can cause the deflagration of a propellant or explosive, possibly resulting in a sustained fire that could cause cook-off or detonation of other nearby propellants or explosives. More energetic reactions to the impact include an explosive pressure burst of a munition case or an instantaneous consumption of the propellant or explosive when the shock created by the impact intiates a detonation. This prompt shock to detonation phenomenon occurs in milliseconds and liberates all of the chemically stored energy as a blast, which is accompanied by fragments and debris radiating with high velocities.[4]

Crew system kill modes: The inability of the pilot and his or her backup, for example, a copilot, to operate the aircraft because of injury, incapacitation, or death will usually lead to an aircraft kill in a very short period of time. Also, the loss of the life support system can result in smoke in the cockpit or a loss of oxygen that either incapacitates the pilot or leads to the decision by the pilot to eject from the aircraft, resulting in the loss of the aircraft.

Go to Problems 5.2.27 to 5.2.31.

5.2.2.8 Task 7: Conduct a FTA and identify the critical components.

Learning	**5.2.10**	**Describe and conduct a FTA.**
Objectives	**5.2.11**	**List some of the typical critical components on an aircraft.**

The FMEA and DMEA are usually bottom-up approaches for determining the critical components; the failure or damage of a component is assumed, and the consequences identified. Another procedure for identifying the critical components is the fault tree analysis.[5] This is a top-down approach that starts with an undesired outcome or event (a fault) and then determines what event or combination of events can cause the undesired event. It is one of the principal methods of system safety analysis and can include both hardware failures and human effects.

Fault tree. The FTA and its logic symbology are illustrated by the generic fault tree shown in Fig. 5.11. The undesired event U can only occur when both intermediate event A and intermediate event B occur. (This is the logical AND gate.) Event A can occur when either basic event C occurs or basic event D occurs or both occur. (This is the inclusive OR gate.) Intermediate event B can occur when basic event E occurs or when basic event F occurs, but not when both occur. (This is the exclusive OR gate.) Note the symbology for the basic and intermediate events and the logic gates; basic events are at the bottom of the tree and are ellipses here (or circles in general), intermediate events are between the basic events and the top level undesired event and are rectangular boxes, and each gate has its own particular shape.

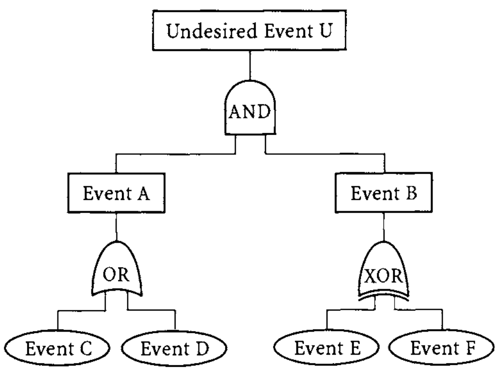

Fig. 5.11 Generic fault tree.

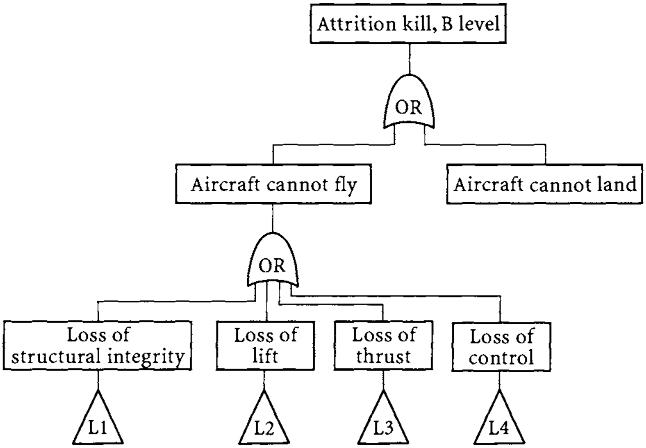

Fig. 5.12a Fault tree for a two-engine aircraft.

In the vulnerability program the undesirable event is an aircraft kill, and the faults that result in the aircraft kill are the kills of the critical components by one or more kill modes. Figures 5.12a–5.12d illustrate portions of the fault tree for a two-engine aircraft. The triangles below the bottom line intermediate events indicate a continuation of the fault tree. The undesirable event shown in Fig. 5.12a is an aircraft attrition kill at the B level. An attrition kill occurs if the aircraft can neither fly nor land. The aircraft cannot fly if it loses structural integrity, lift, thrust, or control. The loss of structural integrity (L1) refers to the failure of one or more major structural assemblies, such as a wing, fuselage, or tail boom, and is usually caused by an internal or nearby external explosion (Note 19). The loss of lift (L2) is usually caused by the loss of a wing or a rotor blade, both of which can also result in the loss of control. However, in fixed-wing aircraft with a vertical takeoff or landing capability the loss of lift might not be accompanied by the loss of any other essential function. The loss of thrust (L3) and loss of control (L4) faults are described next.

Loss of thrust: The loss of thrust depends upon the number of engines and the fuel supply design. The two-engine aircraft in Fig. 5.12a has a single fuel feed tank that supplies fuel to both engines and two fuel storage tanks that supply fuel to the feed tank. Examining the continuation of the fault tree in Fig. 5.12b for the loss of thrust event (L3) reveals that total thrust is lost when both the left engine AND the right engine are killed as a result of damage to both engines OR the engine fuel subsystems (an engine or engine subsystem failure) OR when the fuel supply to both engines is lost (a fuel supply depletion kill). The fuel supply to both engines is lost when the common feed tank is killed OR when both the left AND the right supply tanks are killed (Note 20). All fuel tanks can be killed as a result of leakage from damage caused by the basic events of penetration or hydrodynamic ram, as illustrated for the loss of the feed tank (Note 21).

The loss of thrust from either engine can occur as a result of a loss of the local engine fuel supply (E1) OR to engine damage (E2). Continuing the fault tree at

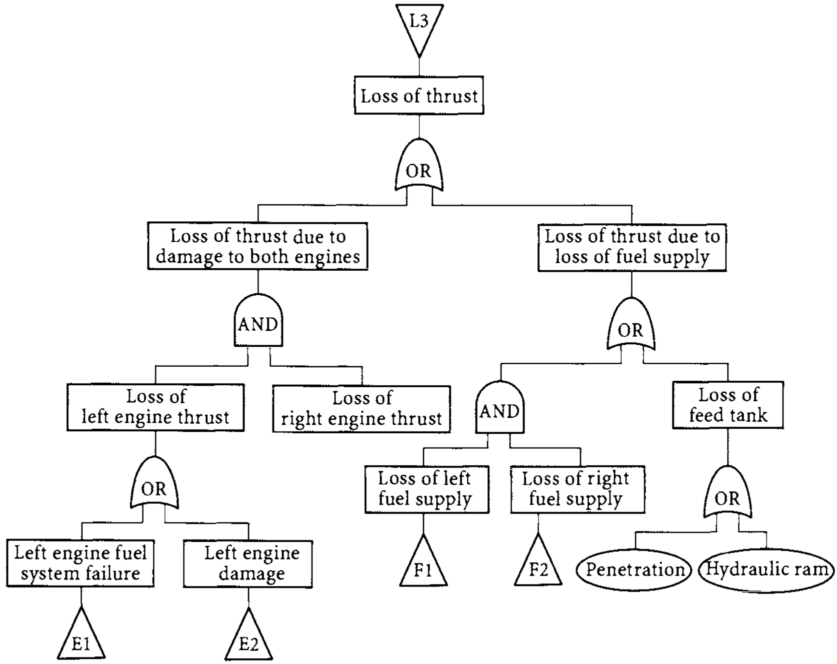

Fig. 5.12b Loss of thrust portion of a fault tree for a two-engine aircraft.

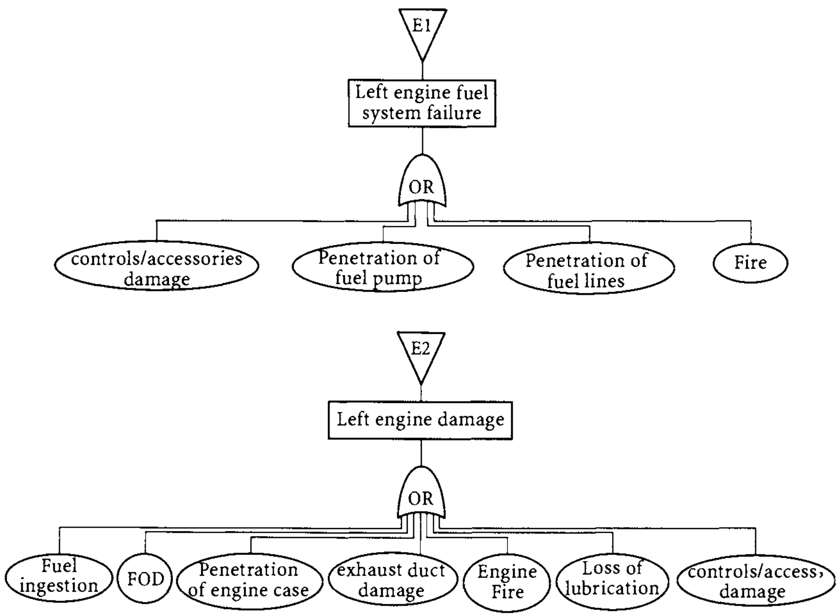

Fig. 5.12c Loss of left engine portion of a fault tree for a two-engine aircraft.

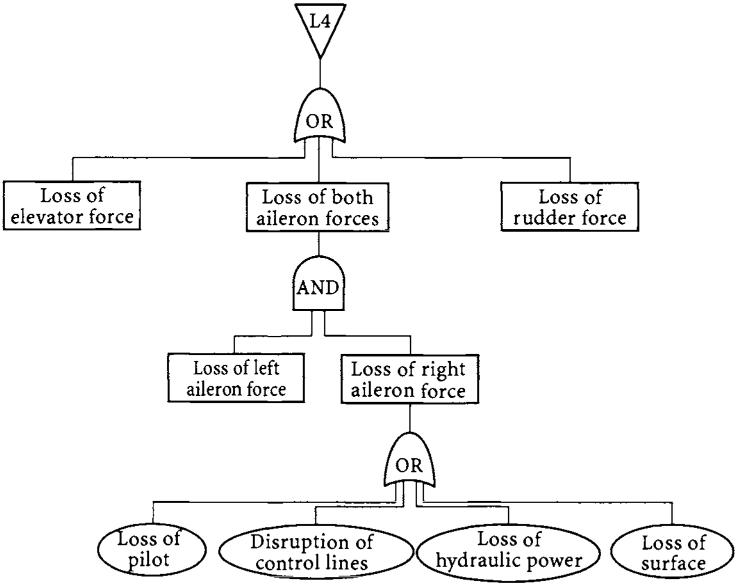

Fig. 5.12d Loss of control portion of the fault tree for a two-engine aircraft.

(E1) in Fig. 5.12c, the engine kill can occur because of penetration of the input signal to the fuel pump OR penetration of one of the fuel transfer components from the feed tank line to the engine combustor, such as the fuel pump itself OR the fuel lines, OR these components can be killed because of fire caused by leaking fuel, leaking hydraulic fluid, or a holed combustor. Continuing the tree at (E2) in Fig. 5.12c for the kill of the left engine as a result of damage to the engine itself, the kill can be the result of fuel ingestion; FOD; penetration of the fan, compressor, combustor, or turbine; exhaust duct damage; engine fire caused by leaking fuel; loss of lubrication; OR damage to the engine controls or accessories (the kill modes listed in Table 5.5).

Loss of control: As the final example of the construction of the fault tree, consider the loss of control portion of the fault tree (L4) shown in Fig. 5.12d. The aircraft relies on the forces developed on several surfaces around the aircraft for control. It has a very simple control system consisting of one hydraulic power supply; one control path from the pilot to the control actuators; and two ailerons for roll control, an elevator for pitch control, and a rudder for directional control (Note 22). According to Fig. 5.12d, if the force developed on the elevator OR the left aileron AND the right aileron OR the rudder is lost control in the corresponding axis is lost, and the aircraft is killed because of loss of control. As shown in the fault tree, the force on every control surface depends upon the availability of the correct control signal input, adequate power to position the surface, and a movable surface with adequate area.

Critical components. The fault trees shown in Figs. 5.12a–5.12d proceed from the undesirable event (an aircraft attrition kill at the B level) down to the basic events consisting of the individual component or system kill modes caused by the damage processes. Once the FTA has reached the basic events at the lowest level of interest in the fault tree, an examination of the path from each component kill up through the logical OR and AND gates to the final undesired event reveals which of the components are critical and any redundancy relationships between components. If the path from a component kill proceeds upward to the loss of an essential function through only OR gates, such as the loss of the feed tank in Fig. 5.12b, the component is a nonredundant critical component. If the path from the component kill passes through an AND gate before reaching the top of the tree, such as the control or accessories damage in Fig. 5.12c, the component is part of a redundant set of components. For example, if the left-engine accessory gearbox is cracked or holed because of ballistic impact or penetration, the gearbox could lose the lubrication oil. Eventually, the gearbox might seize or self-destruct because of the loss of lubrication, leading to a loss of power to several essential engine functions. According to the fault tree, this individual component kill would result in the loss of the thrust from the left engine. Thus, the gearbox is a nonredundant critical component for the left engine. However, moving up the fault tree from a kill of the left engine reveals that the engine is a redundant critical component for the attrition kill because of loss of thrust, that is, both engines must lose thrust to lead to a propulsion system and eventual aircraft kill as a result of a loss of thrust. Thus, the loss of only the accessory gearbox on the left engine would result in a loss of thrust from the left engine, but would not lead to an attrition kill of the aircraft because the gearbox is a part of the redundant engines.

Care must be taken when a component kill appears in several locations in the fault tree. For example, in Fig. 5.12d both the loss of pilot and the loss of hydraulic power appear in the loss of every control surface force. Hence, these common components could have been moved from below the loss of the individual surfaces to separate branches from the OR gate at the top of Fig. 5.12d on the same level with the loss of the four surfaces. Particular attention should be given to components (like the pilot and the hydraulics) that contribute to all members of a set of redundant components. The loss of the common component could result in the nonfunctioning of the all of the redundant components. The common feed tank in Fig. 5.12b is an example of this effect. If the fuel supply components had been included in the branches below the engines instead of separated as in Fig. 5.12b, the fact that the feed tank is a nonredundant critical component would not be so obvious.

Another example of components appearing in different locations in the tree is when the components have different kill modes. For example, the fuel supply depletion kill mode caused by the loss of the left and right fuel supply tanks appears in the loss of thrust branch (L3) shown in Fig. 5.12b, whereas the in-tank explosion kill mode caused by an explosion in either supply tank would appear in the loss of structural integrity (L1) or loss of lift (L2) branches. Consequently, critical components that are members of sets of redundant components might appear as nonredundant components if one of their kill modes causes the loss of an essential function. This feature has particular application to the fuel system components that might be redundant for fuel storage and transfer, but because of the possibility of fire or explosion they are also treated as nonredundant critical components.

Some typical critical components. Some of the major critical components for a helicopter and a fixed-wing aircraft are given in the following paragraphs.

Helicopters: For a two-engine helicopter with a single pilot, the following nonredundant components are potential critical components for an attrition kill: 1) flight control system components (rods, rod ends, bellcranks, pitch links, swashplate, hydraulic actuators, collective lever, and control pedals); 2) rotor blade and power train components (blades, drive shafts, rotor heads, main transmission, and gearboxes); 3) fuel system components (fuel cells, the sump, lines, and valves); 4) pilot; and 5) tail boom.

The potential redundant critical components for an attrition kill can include 1) propulsion system components (engines and engine mounts), 2) hydraulic subsystem components, and 3) structural elements.

Fixed-wing aircraft: Some potential redundant and nonredundant critical components for an A level attrition kill of a single-engine, single-pilot, fixed-wing aircraft are as follows: 1) pilot; 2) flight control components throughout the aircraft; 3) hydraulic reservoirs, lines, components, and actuators; 4) all fuel tanks, components, lines, and shutoff valves; 5) engine fan, compressor, turbine, and combustor sections, drive shaft and bearings, engine mounts, the engine accessory drive, and the lubrication and fuel supply components; 6) major structure, such as the wing box spars, the fuselage longerons, and the horizontal and vertical stabilizer spars and attachments; 7) external ordnance and the ammunition storage drum; 8) liquid oxygen converter and components; and 9) liquid-cooled avionics with a flammable coolant.

Go to Problems 5.2.32 to 5.2.33.

5.2.2.9 Task 8: Develop the kill tree and write the kill expression.

Learning Objective 5.2.12 Describe and construct a kill tree and write a kill expression and a survival expression.

Kill tree. A list of critical components, such as those just given, is generally insufficient when assessing the vulnerability of an aircraft. Therefore, a visual illustration of the critical components and all component redundancies is provided by the kill tree (Note 23). An example of a kill tree for the attrition kill of a helicopter is given in Fig. 5.13.

Each of the critical components in the kill tree is indicated by an oval and is located in the kill tree (horizontally) according to any redundancy relationships. The tree proceeds from the top left downward to A. It continues from A at the top middle downward to B, which continues from B at the top right downward to the bottom of the tree. The vertical location of the components along the tree is not important. For example, the nonredundant drive train just above A at the bottom left could have been located below the four nonredundant main rotor (MR) blades at the top of the kill tree. However, any redundancies among components, such as the left and right engines, are indicated by a horizontal lines containing the redundant components. In essence, each vertical line in the tree is an OR separation between components or groups of components, and each horizontal box represents an AND redundancy connection between the critical components (Note 24).

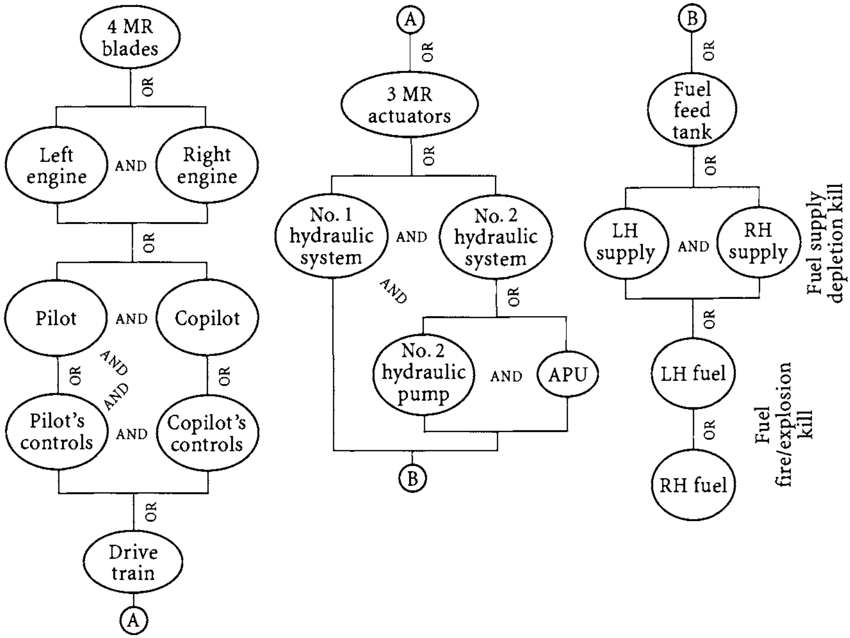

Fig. 5.13 Example attrition kill tree for a two-engine, pilot/copilot helicopter.

A complete horizontal cut through the tree trunk is required to kill the aircraft. For example, according to Fig. 5.13, a kill of any of the four nonredundant MR blades will kill the aircraft, OR a kill of the left engine AND the right engine will kill the aircraft. Examining the redundancy relationships in the cockpit, note that a kill of the pilot AND the copilot will kill the aircraft, which is obvious. So is the kill of the pilot's controls AND the copilot's controls. However, what is not so obvious is that a kill of the pilot AND the copilot's controls also will kill the aircraft. The assumption was made in the critical component analysis for this helicopter that if the pilot AND the copilot's controls were killed, the copilot could not fly the helicopter using the pilot's controls. The same situation exists for a kill of the pilot's controls and the copilot. If this assumption were not true, the box containing the four components would be broken into two boxes, one containing the pilot and the copilot and the other containing the pilot's controls and the copilot's controls. The two boxes would be separated by a OR vertical line. The two situations are different.

Note in Fig. 5.13 that the left hand (LH) and right hand (RH) fuel storage tanks appear twice in the kill tree: once as redundant critical components and once as nonredundant critical components. This is because of the possibility of an aircraft kill caused by fuel supply depletion and a kill caused by a fire or explosion inside either tank. The two tanks provide a redundancy for the fuel supply depletion kill mode because either tank can provide fuel to both engines through the common (nonredundant) fuel feed tank. However, the storage tanks are nonredundant critical components when the fire/explosion kill mode is considered because of the possibility that a fire or explosion in either tank will lead to the kill of the aircraft.

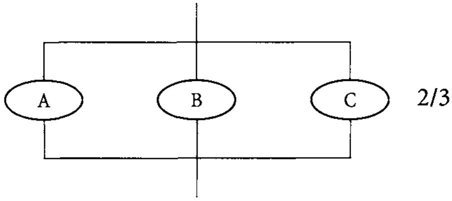

Fig. 5.14 Aircraft kill as a result of a kill of any two of three redundant critical components.

When not all of the redundant critical components must be killed to cause a kill of the aircraft, the required fraction of component kills is indicated on the kill tree next to the box containing the components. For example, suppose an aircraft has three engines, A, B, and C. If a kill of any two of the three engines on the aircraft will cause a kill of the aircraft, that is, the aircraft cannot sustain level flight on only one engine, the fraction $\frac{2}{3}$ is located next to the box containing the components, as indicated in Fig. 5.14.

Kill expression and the survival expression. The relationship between a component kill and an aircraft kill illustrated in the kill tree can also be expressed using the logical OR and AND statements. This expression is known as the kill expression. For example, the kill tree given in Fig. 5.13 can be expressed in the logical form:

> Aircraft kill = (MR blade #1) .OR. (MR blade #2) .OR. (MR blade #3) .OR. (MR blade #4) .OR. (Left engine .AND. Right engine) .OR. [(Pilot. OR. Pilot's controls) .AND. (Copilot .OR. Copilot's controls)] .OR. (Drive train) .OR. (MR actuator #1) .OR. (MR actuator #2) .OR. (MR actuator #3) .OR. [(No. 1 Hydraulic system) .AND. [(No. 2 Hydraulic system) .OR. [(No. 2 Hydraulic pump) .AND. (APU)]]] .OR. Fuel feed tank .OR. [(LH supply) .AND. (RH supply) fuel supply depletion] .OR. (LH fuel fire/explosion) .OR. (RH fuel fire/explosion)

In the preceding kill expression the appearance of a component's name indicated a kill of that component. Looking at the aircraft from a survival point of view, all of the nonredundant critical component's must survive, and not all of the redundant critical components can be killed. A survival expression can be developed from the kill expression by replacing the logical OR with AND and the AND with OR statements and by changing the implication of a component's name from kill to survival. Thus, the survival expression for the kill tree shown in Fig. 5.13 is

> Aircraft survival = (MR blade #1) .AND. (MR blade #2) .AND. (MR blade #3) .AND. (MR blade #4) .AND. (Left engine .OR. Right engine) .AND. [(Pilot. AND. Pilot's controls) .OR. (Copilot .AND. Copilot's controls)] .AND. (Drive train) .AND. (MR actuator #1) .AND. (MR actuator #2) .AND. (MR actuator #3) .AND. [(No. 1 Hydraulic system) .OR. [(No. 2 Hydraulic system) .AND. [(No. 2 Hydraulic pump) .OR. (APU)]]] .AND. Fuel feed tank .AND. [(LH supply) .OR. (RH supply) fuel supply depletion] .AND. (LH fuel fire/explosion) .AND. (RH fuel fire/explosion)

In words, in order for the aircraft to survive the MR blade #1 must survive AND the MR blade #2 must survive AND the left engine OR the right engine must survive AND the pilot AND the pilot's controls must survive OR the copilot AND the copilot's controls must survive AND the drive train must survive ... AND the RH fuel tank must not have a fire or explosion. Both the kill expression and the survival expression are used in the assessment of the vulnerability of an aircraft.

Probability of an aircraft kill given a component kill. The conduct of the FTA and the development of the kill tree just described assumed that the kill of a component always resulted in an aircraft kill, either directly as a nonredundant component or indirectly as one of a set of redundant components. For example, in the kill tree shown in Fig. 5.13 a kill of the drive train means the ability of one or more of the drive train components to transfer torque from the main transmission to the tail rotor is lost. This results in an aircraft kill, for sure; the probability of an aircraft kill given the kill of the component is unity. Similarly, for a kill of the pilot and the copilot, the probability of an aircraft kill given a kill of the pilot AND the copilot is unity. However, there are some situations where a component's kill will not always result in an aircraft kill; it depends upon the situation. Thus, a component might not always be a critical component. For example, consider the air-to-air missile. It can be carried on the wing tips and on the fuselage. If a missile is hit by a fragment or penetrator, there could be a major reaction, such as those just described in the armament system kill modes. If the missile is on the wing tip, the reaction most likely will not result in an aircraft attrition kill, and the component is not a critical component for an attrition kill. However, if the missile is carried on the fuselage the reaction could cause significant cascading damage that could result in the loss of the aircraft—same missile, different results depending upon the location of the missile attachment. This feature can be accounted for by assigning a number less than unity to the probability an aircraft is killed given a component kill.

5.2.2.10 Society of Automotive Engineers ARP4761 guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment. In late 1996 the Society of Automotive Engineers (SAE) published ARP4761. This document describes guidelines and methods of performing the safety assessment for certification of civilian aircraft. In ARP4761, the Safety Assessment Process is composed of three major tasks: the functional hazard assessment (FHA), the preliminary system safety assessment (PSSA), and the system safety assessment (SSA). The FHA is a systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity. The PSSA is used to complete the failure conditions list and the corresponding safety requirements, and the SSA is a systematic, comprehensive evaluation of the implemented system to show that relevant safety requirements are met. From an aircraft vulnerability FMEA/DMEA/FTA point of view, the FHA generates the failure conditions leading to the selected kill, such as an attrition kill because of loss of thrust. The PSSA develops qualitative fault trees using these failures as the undesired event, such as the fault tree shown in

Figs. 5.12b and 5.12c for the loss of thrust. The SSA applies the FMEA to the basic events at the bottom of the fault trees developed in the PSSA. For example, the basic event of penetration of the fuel pump shown in Fig. 5.12c would be one of the failure modes examined. The effects this failure mode has upon the continued operation of the aircraft is determined, and the probability this failure would occur, or its failure rate, is quantified. Quantitative fault trees are then developed from the qualitative fault trees using the probability or frequency of occurrence values for the basic events determined in the FMEA (or FMECA). The probability or predicted frequency of occurrence of the mishap is computed using the basic event probabilities or failure rates in the quantitative fault tree.[5] In the aircraft vulnerability discipline all of the basic events that result in an aircraft kill, either individually or jointly, are contained in the kill tree, and the probability the aircraft is killed given a hit is computed in the vulnerability assessment (described in the following section) using the kill tree rather than the fault trees.

Go to Problems 5.2.34 to 5.2.37.

5.3 Task II: Perform a Vulnerability Assessment

5.3.1 What Is a Vulnerability Assessment, and How Is It Performed?

Learning Objective	**5.3.1**	**Describe the vulnerability assessment process and the levels of assessment.**

A vulnerability assessment is the process of determining numerical values for the measures of vulnerability. This is accomplished using vulnerability assessment techniques. The assessment can be carried out entirely by hand, or one or more computer programs can be used. Assessments are usually conducted to help the designer evaluate the vulnerability of his/her design, or to help the military in evaluating competing designs, or to help the field commander make operational decisions regarding the use of his/her aircraft. The tasks in a vulnerability assessment are common to all studies regardless of the type of threat considered. They are listed in Table 5.1. The tasks in Task I have been described in the preceding section. A presentation of the three tasks in Task II is given next.

The assessment can be carried out at one of three general levels of detail. These levels consist of estimates, evaluations, and analyses. Estimates typically use simple equations for the aircraft vulnerability measures that are functions of a few major parameters of the aircraft, the damage mechanisms, and the terminal effects parameters. When these equations are fitted to historical data on several aircraft or to the results from several engineering studies, they are referred to as regression equations. Evaluations are more detailed assessments that can include such items as the individual component locations, sizes, and vulnerability measures. (For convenience, use of the word 'component' hereafter will imply a critical component.) Analyses are very detailed studies that use specific technical and functional information about the components and their vulnerability. Analyses are usually conducted on a digital computer using complex geometric models.

The computational methodology used in the assessment should have the capability to account for the six VR concepts presented in Table 1.3 in order to properly reflect the benefits associated with the application of VR techniques. These six concepts are component redundancy, component location, passive damage suppression, active damage suppression, component shielding, and component elimination. These six concepts will be examined in detail in the vulnerability reduction presentation given in Sec. 5.4 of this chapter. The degree to which these concepts are accounted for in the computation of the vulnerability measures will depend to some extent upon the level of the assessment.

Go to Problems 5.3.1 to 5.3.3.

5.3.2 Task 1: Select the Threat Warhead and the Measure of Aircraft Vulnerability

Learning	**5.3.2**	**Describe the four threats usually considered.**
Objectives	**5.3.3**	**Describe the vulnerability measures.**

5.3.2.1 Select the threat. Because of the many and diverse terminal effects of the various damage mechanisms, each vulnerability assessment is usually made considering either a specific threat or a specific damage mechanism. The threats and damage mechanisms that are typically considered are 1) a nonexplosive penetrating projectile or fragment; 2) the fragments, incendiaries, and blast from contact-fuzed HE warheads; 3) external blast; and 4) the fragments, penetrators, incendiaries, and missile debris from proximity-fuzed HE warheads.

5.3.2.2 Select the measure of aircraft vulnerability. The measures of the vulnerability of an aircraft vary with the type of threat. For example, if a hit on the aircraft must occur in order for a threat to be effective, such as a small arms projectile and a contact-fuzed HE warhead, one measure of vulnerability is the conditional probability that the aircraft is killed given a random hit on the aircraft $P_{K|H}$. Another measure of vulnerability to impacting threats is the aircraft's single-hit vulnerable area A_V. This is a theoretical, nonunique area presented to the threat that, if hit by the threat, would result in an aircraft kill. On the other hand, when damage is caused by the effects of a nearby HE warhead detonation the vulnerability measure can be expressed in the form of a one-dimensional probability of kill given fuzing curve (Fig. 3.11) or a three-dimensional $P_{K|F}$ envelope around the aircraft (Fig. 3.10). The envelope represents a kill probability contour about the aircraft on which a specified detonation will result in a certain probability of aircraft kill. If only the blast from the exploding warhead is considered, the envelope represents the aircraft's vulnerability to external blast.

Go to Problems 5.3.4 to 5.3.6.

5.3.3 Task 2: Select the Critical Component Kill Criteria

Learning Objective **5.3.4 Describe the four critical component kill criteria.**

Given the set of critical components for an aircraft, the damage or kill criteria for each of the kill modes of these components must be determined for the selected threats and vulnerability measures. A kill criterion is the specific descriptive characteristic or quantification of a component failure or kill. Very few kill criteria are precisely known, nor can they easily be determined. Combat damage reports are an important source of component damage effects information. The results of laboratory and field tests conducted on all types of aircraft components and subsystems provide another increasingly important and expanding source of data.

The result of this task is the specification of numerical values for the kill criteria for each failure mode for each critical component for each threat to be considered. Three specific kill criteria are currently in use for the impacting damage mechanisms (metallic penetrators and fragments). They are the probability of component kill given a hit (the $P_{k|h}$ function), the area removal criterion, and the energy density criterion. A fourth criterion applies to the blast damage mechanism.

5.3.3.1 $P_{k|h}$ function. The $P_{k|h}$ function defines the probability of a component kill when the component is impacted at a random location by a fragment or penetrator. This criterion can be presented graphically as a function of the mass and velocity of the damage mechanism, or it can be expressed in an analytical form. Figure 5.14a is a sample of $P_{k|h}$ data for a flight control rod. The $P_{k|h}$ criterion is normally used for components that can be killed by a single hit, such as servoactuators, crew members, control rods, and electronic equipment. These components are sometimes referred to as single-fragment vulnerable components. It can also be used for some of the larger components, such as engines and fuel tanks. In this instance the area of the large component is usually divided into several smaller areas, and a different numerical value of $P_{k|h}$ is assigned to each area. For example, a fuel tank could be divided into the ullage, fuel, and external void spaces, and a turbojet engine could be subdivided into the major sections illustrated in Fig. 5.14b.

The determination of the $P_{k|h}$ for each component or part of a component is a very difficult undertaking. It requires a combination of critical component analysis data and sound engineering judgment. Although limited gun-fire testing provides some insight into the effects of projectile and fragment damage potential, there is no universal methodology for arriving at a numerical value for $P_{k|h}$. In general, the $P_{k|h}$ function for most components depends upon the shotline aspect and obliquity angle. Consequently, each critical component must be examined carefully to assess the effects on the component of the striking velocity, the striking obliquity, and the mass and shape of the penetrator or fragment. The presence of incendiary particles or flashes must also be accounted for. The larger components, such as the fuel tanks and engines, are especially difficult to evaluate because of the multitude of local environments, the constantly changing operating conditions, and the many different kill modes. Numbers for $P_{k|h}$ are eventually assigned based upon a

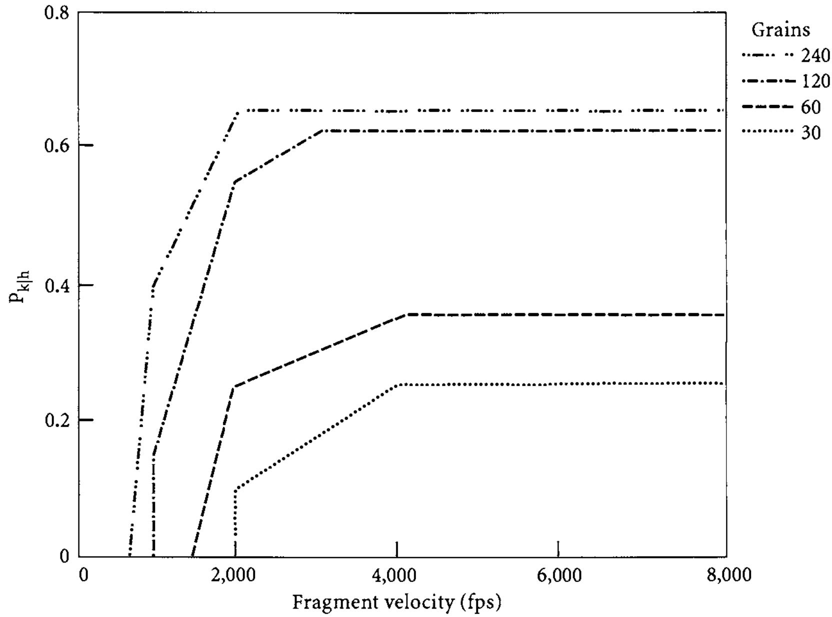

Fig. 5.14a Typical $P_{k|h}$ data for a flight control rod.

combination of empirical information, engineering judgment, and experience. For many components only one $P_{k|h}$ function is determined for each damage mechanism, as illustrated by the control rod in Fig. 5.14a (Note 25).

The impact velocity of the damage mechanism on the aircraft V_i is given by Eq. (4.25b). However, this is not the impact velocity on components behind the aircraft skin. The location of the component inside the aircraft will have an influence on

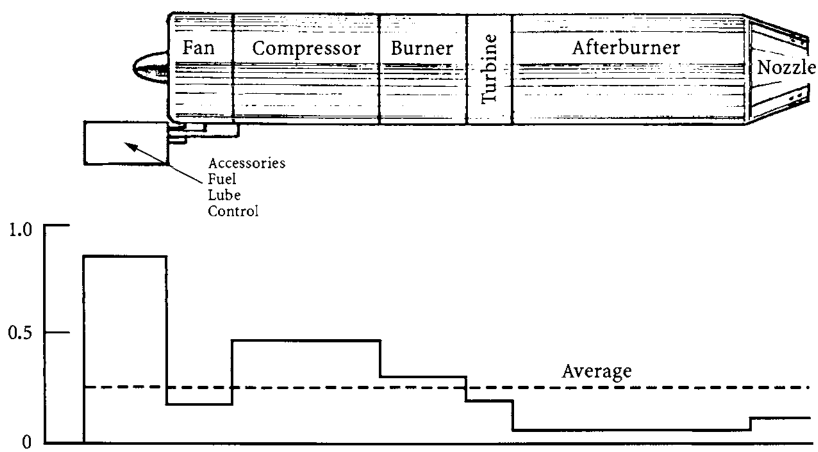

Fig. 5.14b Subdivision of a large component.

the ultimate numerical value for the probability of kill given a hit, but not on the $P_{k|h}$ function. Components located behind thick structure or dense equipment will receive a level of protection because of the slowdown of the damage mechanism as it attempts to penetrate the masking or shielding components. The numerical value of the $P_{k|h}$ for the lowered velocity of impact will generally be less than the $P_{k|h}$ value for the impact of a penetrator or fragment that was not slowed down. For example, a 30-grain fragment that impacts the control rod of Fig. 5.14a at 5000 ft/s will have a probability of killing the rod of 0.25, but the $P_{k|h}$ will drop to 0.0 if the fragment is slowed down to less than 2000 ft/s by intervening components. Other considerations, such as spall and fragment breakup caused by the intervening components, also might become important.

5.3.3.2 Area removal. The area removal criterion defines a specific amount of area that must be removed from a component in order to kill that component. This criterion is applicable to large penetrators, such as rods, and to the closely spaced hits from many fragments. The total component damage from a collection of closely spaced hits can be greater than the sum of the individual damages from the same number of widely spaced hits, as illustrated in Fig. 3.46. There often is a synergism of damage because of the cracking and petaling between the individual holes, and large areas of component structure can be removed or destroyed. This criterion is used mainly for large structural components.

5.3.3.3 Energy density. In this criterion a component kill is expressed in terms of a required minimum component surface area that must be exposed to a threshold level of the kinetic energy density of the impacting damage mechanisms. This criterion is applicable to multiple, closely spaced fragment hits and is used for the structural components, as well as for other large components, such as the fuel tanks and engines. For some components there might be a minimum mass of the damage mechanism below which the criterion is not applied.

5.3.3.4 Blast. The kill criterion for blast is generally the critical values of pressure and impulse on an aircraft surface necessary to cause the specific component damage level associated with the assumed kill level. For example, a dynamic overpressure of 2 lb/in.^{2} over the upper surface of a horizontal tail for 1 ms might be sufficient to cause crushing of the skin, leading to a loss of stiffness and an inability to support the flight loads. Although this criterion is usually applied to the structural components and control surfaces, the effects of the blast can extend into the interior of the aircraft and can damage electrical wiring, hydraulic lines, fuel tank walls, and other internal components located close to the aircraft skin.

Go to Problems 5.3.7 to 5.3.9.

5.3.4 Task 3: Compute the Vulnerability of the Critical Components and the Aircraft for Selected Threats

On any given combat mission an aircraft will either not be hit, or will be hit once, or will be hit more than once. The no-hit situation is, of course, not of interest here in the vulnerability chapter. The single-hit case is not only of interest itself, but it also lays the groundwork for the multiple-hit case. In both cases the influence of nonredundancy and redundancy of components on the $P_{K|H}$ and the vulnerable area must be examined. Overlap of components is an important consideration as well. The procedures used to compute the vulnerability of an aircraft and its components to the threats of 1) a single hit by a nonexplosive penetrator or fragment, 2) multiple hits by a nonexplosive penetrator or fragment, 3) a single hit by a contact-fuzed HE warhead, or 4) a proximity-fuzed HE warhead are described in the following subsections. (The reader who is unfamiliar with probability theory may want to read Appendix B first.)

5.3.4.1 Vulnerability to a single hit by a nonexplosive penetrator or fragment ($P_{K|H}$ and A_V).

Learning Objective	**5.3.5**	**Compute an aircraft's single-hit vulnerable area for aircraft with nonredundant, redundant, nonoverlapping, and overlapping critical components.**

When computing the vulnerability of an aircraft to a single impacting penetrator or fragment, the assumptions are usually made that there is no capability by the enemy to direct hits to any one particular component, subsystem, or part of the aircraft, and that the damage mechanisms travel along parallel shotlines, as illustrated in Fig. 4.28. Under these assumptions, the vulnerability of the aircraft (for a particular aspect or shotline direction) is usually expressed as the probability the aircraft is killed given a random (equally likely or uniformly distributed) hit anywhere on the presented area of the aircraft $P_{K|H}$, or as the single-hit vulnerable area of the aircraft A_V (Note 26). The component kill criterion used is the probability the component is killed given a random hit anywhere on the component, which is denoted by $P_{ki|hi}$ for the ith component. (If the subscript i is omitted, the k and the h apply to the same component.) The vulnerable area of the ith component is denoted by A_{vi}. To assist the reader in keeping track of the notation used in this presentation, the variable and subscript definitions are summarized in Table 5.6. Note that a distinction is made between component and aircraft designated variables by using lower- and upper-case subscripts, respectively. The upper-case subscript version of the variables will also be used to refer to the generic term.

Both the total aircraft and all of its critical components have a vulnerable area. The vulnerable area of the ith component is defined as the product of the presented area of the component in the plane normal to the approach direction of the penetrator (the shotline) A_{pi} and the probability of kill of the component given a random hit on the component $P_{ki|hi}$. Thus,

$$A_{vi} = A_{pi} P_{ki|hi} \tag{5.1a}$$

Equation (5.1a) can be rewritten in the form

$$P_{ki|hi} = A_{vi}/A_{pi} \tag{5.1b}$$

Table 5.6 Vulnerability variable definitions

Definition	ith component	Aircraft
Probability of kill of the ith component (or aircraft) given a hit on the ith component (or aircraft)	$P_{ki\|hi}$	$P_{K\|H}$
Probability of kill of the ith component given a hit on the jth component	$P_{ki\|hj}$	—
Probability of a hit on the ith component given a random hit on the aircraft	$P_{hi\|H}$	—
Probability of kill of the ith component given a hit on the aircraft	$P_{ki\|H}$	—
Probability of survival of the ith component (or aircraft) given a hit on the aircraft	$P_{si\|H}$	$P_{S\|H}$
Vulnerable area of the ith component (or aircraft)	A_{vi}	A_V
Presented area of the ith component (or aircraft)	A_{pi}	A_P

Because both A_{pi} and $P_{ki|hi}$ are generally functions of the threat direction or aspect, the vulnerable area will also vary with aspect. In the presentation that follows, it is important to recall that the probability of killing a component (or aircraft) plus the probability of survival of that component (or aircraft) is unity. Hence, given that the ith component (or aircraft) is hit,

$$P_{si|hi} = 1 - P_{ki|hi} \tag{5.2a}$$

for the component, and

$$P_{S|H} = 1 - P_{K|H} \tag{5.2b}$$

for the aircraft.

Aircraft hits and component kills. An aircraft is killed when one or more of its critical components is killed. Consequently, if an aircraft gets hit from a particular direction and the location of the hit is uniformly distributed, what is the probability the ith critical component is killed given the equally likely located hit? To answer that question, consider the generic aircraft and ith component shown in Fig. 5.15. Because the hit is uniformly distributed, the probability the ith component is hit is

$$P_{hi|H} = A_{pi}/A_P \tag{5.3}$$

The probability the ith component is killed given the random hit on the aircraft $P_{ki|H}$ is the product of the probability the ith component is hit given the hit on the

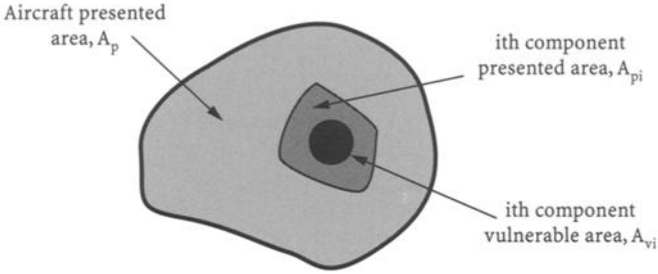

Fig. 5.15 Generic aircraft and the *i*th component.

aircraft $P_{hi|H}$ and the probability the *i*th component is killed given a hit on the *i*th component $P_{ki|hi}$. Thus,

$$P_{ki|H} = P_{hi|H} P_{ki|hi} = (A_{pi}/A_P)(A_{vi}/A_{pi}) = A_{vi}/A_P \tag{5.4a}$$

according to Eqs. (5.3) and (5.1b). Or $P_{ki|H}$ is simply the probability the vulnerable area of the *i*th component is hit

$$P_{ki|H} = A_{vi}/A_P \tag{5.4b}$$

which is equivalent to Eq. (5.4a).

The numerical value for $P_{ki|H}$ depends upon the presented area of the critical component A_{pi} and of the aircraft A_P and upon the component kill criterion $P_{ki|hi}$. The presented area of the critical components and of the aircraft can be obtained from the available technical description of the aircraft. The procedure for determining the numerical value for $P_{ki|hi}$ is described in the preceding presentation on the $P_{k|h}$ function.

Note that in this assessment for $P_{ki|H}$ a component is assumed to be either operating and performing all of its functions or is killed; no degradation of component capabilities is considered (Note 27). Furthermore, at this step in the assessment only the component hit can be killed. This assumption will be modified later.

The aircraft models developed in this section are assumed to receive only one hit, and both a nonredundant aircraft model and a redundant aircraft model are considered. The critical nonredundant aircraft model is composed of only nonredundant critical components. Thus, the loss of any one critical component will cause the loss of the aircraft. In the redundant aircraft model some of the essential functions are provided by redundant critical components. The effects of the overlapping of both nonredundant and redundant critical components are also examined.

Aircraft composed of only nonredundant components with no component overlap. This aircraft consists of *N* critical components whose functions are not duplicated by any other component. The critical components are arranged in such a manner that no one critical component overlaps any other critical component when viewed from a given aspect. Any hit on the aircraft takes place along a shotline that passes completely through the aircraft. Thus, no more than one critical component can be hit on any one shotline. As an example of such a model, consider the aircraft

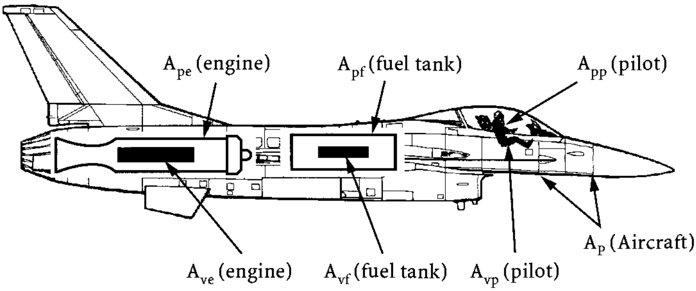

Fig. 5.16 Nonredundant aircraft model with no component overlap.

shown in Fig. 5.16. This aircraft consists of three critical components ($N = 3$): a pilot, one fuel tank, and one engine. None of the critical components overlap from this aspect.

The probability of killing this aircraft, given a random hit on the presented area shown in Fig. 5.16, can be derived using the kill expression and Eqs. (5.4a) or (5.4b). Recall from the preceding kill expression presentation that the logical AND and OR statements are used to define an aircraft kill in terms of component kills. For an aircraft composed of N nonredundant critical components, the kill expression uses only the logical OR statement and is given in the form

$$\text{Aircraft Kill} = (\text{nrcl}) .\text{OR}. (\text{nrc2}) .\text{OR}. \ldots .\text{OR}. (\text{nrcN}) \tag{5.5}$$

where nrci refers to a kill of the ith nonredundant critical component. In other words, the aircraft kill is defined by the kill of nonredundant component 1 OR nonredundant component 2 OR ... OR nonredundant component N.

Because of the assumption that only the component hit can be killed and because none of the components overlap in this model, the kills of the components are said to be mutually exclusive, that is, only one component can be killed by the single hit. Hence, the union of the N mutually exclusive kills given by Eq. (5.5) can be given in the probability form

$$P_{K|H} = P_{kl|H} + P_{k2|H} + \cdots + P_{kN|H} \tag{5.6a}$$

according to Eq. (B. 22) (Note 28). Substituting Eq. (5.4a) for $P_{ki|H}$ into Eq. (5.6a) gives

$$P_{\text{K|H}} = \frac{A_{v1}}{A_P} + \frac{A_{v2}}{A_P} + \cdots + \frac{A_{VN}}{A_P} = \frac{1}{A_P}\sum_{i=1}^{N} A_{vi} = \frac{A_V}{A_P} \tag{5.6b}$$

where A_V is the vulnerable area of the aircraft and is given by

$$A_V = \sum_{i=1}^{N} A_{vi} \tag{5.6c}$$

Example 5.3 presents the computations for $P_{K|H}$ and A_V for the aircraft shown in Fig. 5.16.

Example 5.3 Single-Hit Vulnerable Area of an Aircraft

For the aircraft shown in Fig. 5.16, the kill expression is

$$\text{Aircraft kill} = (\text{Pilot}) .\text{OR}. (\text{Fuel}) .\text{OR}. (\text{Engine})$$

Thus, according to Eqs. (5.6a) and (5.6c)

$$P_{K|H} = P_{kp|H} + P_{kf|H} + P_{ke|H}$$

and

$$A_V = (A_{vp} + A_{vf} + A_{ve})$$

where the subscripts p, f, and e denote the pilot, the fuel tank, and the engine, respectively. The individual component vulnerable areas are given by

$$A_{vp} = A_{pp} P_{kp|hp}, \quad A_{vf} = A_{pf} P_{kf|hf} \quad A_{ve} = A_{pe} P_{ke|he}$$

according to Eq. (5.1a).

As a numerical illustration, consider the assumed values for the component and aircraft presented areas and the component kill criteria given in Table 5.7 for a generic penetrator. The computed values for A_{vi}, $P_{ki|H}$, A_V, and $P_{K|H}$, are indicated in the table. The values used in this and the following examples are not intended to represent a real life scenario, but instead are chosen for their educational value.

Table 5.7 Assumed values for a nonredundant aircraft model

Critical component	A_p, ft^2	$\times P_{k\|h} =$	A_v, ft^2	$P_{k\|h}$
Pilot	4	1.0	4.0	0.0133
Fuel	60	0.3	18.0	0.0600
Engine	50	0.6	30.0	0.1000
Total	$A_P = 300$	—	$A_V = 52$	$P_{k\|h} = 0.1733$

The kill of one critical component as a result of damage caused by a hit on another critical component $P_{ki|hj}$ and the consideration of multiple kill modes of one critical component can be indirectly accounted for in this model by increasing the numerical value of the kill criterion for the component hit. For example, suppose the probability that the fuel tank of an aircraft is destroyed by a fire when the fuel tank is hit, leading to a loss of the aircraft, is taken as 0.3. Suppose further that the probability that the fuel tank is penetrated and that hydrodynamic ram damage causes fuel to be dumped into the air inlet and ingested by the engine, leading to a loss of thrust and the loss of the aircraft, is taken as 0.1. (Hit the fuel tank and kill the engine with a 0.1 probability.) The assumption is made that the two kill modes are independent, that is, both kill modes can occur when the fuel tank is hit, and the occurrence of one does not affect the occurrence of the other. The aircraft will survive a hit in the fuel tank only if there is neither a fire kill nor a fuel ingestion kill. The probability that neither of these kill modes will occur when the fuel tank hit is given by the product of the probability that there is no fire kill $(1 - 0.3)$ and the probability that there is no fuel ingestion kill $(1 - 0.1)$, or 0.63. Therefore, the probability that there will be a fire kill OR a fuel ingestion kill, given a hit on the fuel tank, is given by $(1 - 0.63)$, or 0.37, which is equivalent to the union of the two independent kills $0.3 + 0.1 - 0.3 \cdot 0.1 = 0.37$ according to Eq. (B.20). Thus, accounting for the fuel ingestion kill of the engine as a result of a hit on the fuel tank increases the fuel tank $P_{k|h}$ from 0.3 to 0.37. This same procedure can be used to compute the $P_{ki|hi}$ caused by multiple kill modes of one critical component.

An Aircraft with nonredundant components that overlap. The model will now be extended by allowing two or more nonredundant critical components to overlap in an arbitrary manner. Figure 5.17 illustrates an overlap for the example aircraft, where A_{po} is the overlap area. A hit in the overlap area can kill one or more of the components intersected by the shotline. Thus, the component kills along the shotline are not mutually exclusive. Assume there are C nonredundant critical components along all shotlines within the overlap area. This overlap area, with its C components, can be considered to be a composite nonredundant critical component and is denoted by the subscript o. When assessing the vulnerability of the overlap component, the survival expression is more appropriate than the kill expression. The survival expression for the C overlapping, nonredundant components is

$$\text{Aircraft survival} = (\text{nrc1})\ .\text{AND}.\ (\text{nrc2})\ .\text{AND}.\ \ldots\ .\text{AND}.\ (\text{nrc}C) \qquad (5.7)$$

where the appearance of a component name implies the survival of that component. Because all of the components are nonredundant, only the AND statement appears in the survival expression, that is, the composite nonredundant component will survive a hit along the shotline within the overlap area only when all of the nonredundant critical components along the shotline survive.

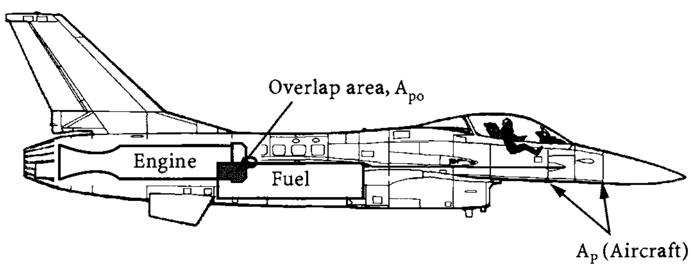

Fig. 5.17 Component overlap.

The probability all C components survive the hit $P_{so|ho}$ is given by the joint probability that each of the C components survives the hit. If the assumption is made that the kills of the C components are independent, then,

$$P_{so|ho} = P_{s1|ho} P_{s2|ho} P_{s3|ho} \ldots P_{sC|ho} = \prod_{i=1}^{C} (1 - P_{ki|ho}) \tag{5.8a}$$

according to Eq. (B.19c), where $P_{si|ho}$ is given in terms of $P_{ki|ho}$ by Eq. (5.2a). Hence, the probability the composite component is killed is given by

$$P_{ko|ho} = 1 - \prod_{i=1}^{C} (1 - P_{ki|ho}) \tag{5.8b}$$

The vulnerable area of the overlap area is the product of the overlap presented area and the probability of overlap component kill. Therefore,

$$A_{vo} = A_{po} P_{ko|ho} \tag{5.8c}$$

The vulnerable area of the overlap area contributes to the aircraft vulnerable area in the same manner as the vulnerable areas of the nonoverlapped components. However, overlapping also requires that the overlap area be subtracted from the total presented area of each overlapping component contributing to the overlap. The component area outside of the overlap is treated in the usual way.

Example 5.4 Single-Hit Vulnerable Area of an Aircraft with Component Overlap

This example extends the analysis presented in Example 5.3 to include component overlap. Assume that the overlap area in Fig. 5.17 is 10 ft^2. In the overlap area the fuel tank is in front of the engine, and the $P_{kf|ho}$ is taken as 0.3, the same as that for the nonoverlap region. The $P_{ke|ho}$ for the overlapped engine is conservatively taken as 0.6, the same as in the nonoverlap engine area; the fuel is assumed to slow the penetrator down, but not enough to change the engine $P_{k|h}$. Because the $P_{k|h}$ values are the same as in the nonoverlapping situation in Example 5.3, any reduction in the vulnerable area of the aircraft is caused only by the component overlap.

In the overlap region the $P_{ko|ho}$ is

$$P_{ko|ho} = 1 - (1 - 0.3)(1 - 0.6) = 0.72$$

according to Eq. (5.8b), and the overlap vulnerable area is

$$A_{vo} = (10 \text{ ft}^2)(0.72) = 7.2 \text{ ft}^2$$

according to Eq. (5.8c).

Table 5.8 Vulnerable area with overlap

Critical component	A_p, ft^2	$\times P_{\mathrm{k|h}} =$	A_v, ft^2
Pilot	4	1.0	4.0
Fuel	60 − 10	0.3	15.0
Engine	50 − 10	0.6	24.0
Overlap	10	0.72	7.2
Total	$A_P = 300$	——	$A_V = 50.2$

The vulnerable areas of the four components (pilot, fuel tank, engine, and overlap) and the aircraft are presented in Table 5.8. Note that locating two of the critical components such that one overlaps the other reduces the aircraft vulnerable area from 52 to 50.2 ft^2. Thus, this is one example of how location of the critical components can reduce an aircraft's vulnerable area.

If the assumption is made that the fuel slows the penetrator down to a velocity that does not result in a penetration of the tank wall next to the engine, the engine $P_{k|h}$ in the overlap area reduces to 0.0 and $P_{ko|ho}$ becomes 0.3. Thus, the vulnerable area of the overlap area reduces to 10 ft$^2 \cdot 0.3 = 3.0$ ft^2, and A_V reduces to 46 ft^2.

Example 5.5 Single-Hit Vulnerable Area of an Aircraft with Component Overlap—Revisited

This example extends the analysis presented in Example 5.4 to include additional effects of component overlap. The net effect of component overlap can be a desirable reduction in aircraft vulnerable area, as demonstrated in Example 5.4, provided the damage inflicted by the hit in the overlap area does not cause other problems. For example, reconsider the shotline through the fuel tank that overlaps the engine. Fuel could leak from the punctured tank to hot engine parts, causing a fire. Or even if the tank wall were not penetrated, hydrodynamic ram could result in damage to the wall with subsequent fuel leakage. Thus, the probability the engine is killed by the hit could be higher than 0.6 because of the overlapping fuel tank. The computation of the vulnerable area with the possibility of an engine fire is presented in Table 5.9. The overlapping area is assumed to be 10 ft^2; the fuel tank $P_{k|h}$ is taken as 0.3, as before; and the $P_{k|h}$ for the overlapped engine area is now taken as 0.9 because an engine fire is assumed to nearly always occur as a result of a hit on the overlapping fuel tank. Thus,

$$P_{ko|ho} = 1 - (1 - 0.3)(1 - 0.9) = 0.93$$

and the aircraft's vulnerable area goes from 50.2 to 52.3 ft^2 because of the possibility of an engine fire. Thus, overlapping nonredundant critical components can reduce vulnerability provided that no undesirable cascading damage occurs. If such damage occurs, the aircraft could be more vulnerable.

Table 5.9 Vulnerable area with overlap and an engine fire

Critical component	A_p, ft^2	$\times\ P_{k\|h} =$	A_v, ft^2
Pilot	4	1.0	4.0
Fuel	60 − 10	0.3	15.0
Engine	50 − 10	0.6	24.0
Overlap	10	0.93	9.3
Total	$A_P = 300$	——	$A_V = 52.3$

Another facet of the overlap situation is the change in the vulnerable area of the overlap area that occurs when one of the components along a shotline has its vulnerability reduced by one of the many techniques presented in Sec. 5.4 of this chapter. For example, suppose the overlapping fuel tank has its $P_{k|h}$ reduced from 0.3 to 0.0. The vulnerable area of the overlap area without a fire will be reduced from 7.2 to 6.0 ft^2 as a result of this change. This amount of reduction appears to conflict with the fact that 10 ft^2 of fuel tank with a $P_{k|h}$ of 0.3, and hence a vulnerable area of 3 ft^2, has been made invulnerable. The reason for this apparent contradiction is, of course, the fact that the fuel tank is only one of two overlapping components. In general, when the vulnerability of one component is reduced the vulnerability of another component along the shotline will become more important. To distinguish between the 3 ft^2 of vulnerability reduction of the fuel tank and the net reduction of 1.2 ft^2 in the aircraft vulnerable area, the vulnerable area of each component along the shotline is referred to as the true vulnerable area, and the component's contribution to the overlap vulnerable area is referred to as the incremental vulnerable area. Both the true and the incremental vulnerable areas are computed considering the velocity decay and mass degradation caused by successive component penetrations. Thus, using the data given in Table 5.10, the true vulnerable areas are 3 and 6 ft^2 for the overlapping fuel tank and engine areas, whereas the incremental vulnerable areas of these two overlapping components are 1.2 and 4.2 ft^2, respectively.

Aircraft composed of redundant and nonredundant components with no overlap. The nonredundant aircraft model just described will now be expanded by adding a second, separated engine, as shown in Fig. 5.18. The kill expression for the

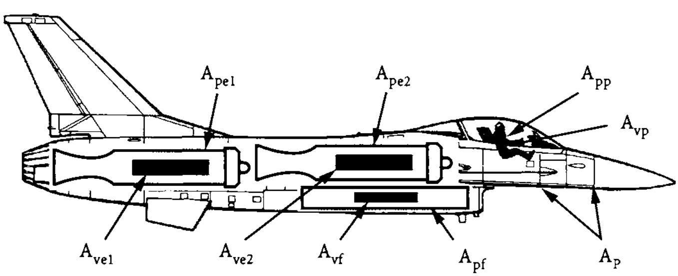

Fig. 5.18 Redundant aircraft model with no overlap.

redundant aircraft model is

$$\text{Aircraft kill} = (\text{Pilot}) \text{ OR. } (\text{Fuel}) \text{ OR. } [(\text{Engine } 1) \text{ AND. } (\text{Engine } 2)] \tag{5.9a}$$

If the assumption is made that the single hit cannot kill both engines (recall the assumption that only the component hit is killed), then all of the component kills are mutually exclusive, and the single hit cannot kill engine 1 AND engine 2. Hence, the aircraft is killed only if the pilot is killed OR if the fuel tank is killed, and $P_{K|H}$ and A_V are given by

$$P_{K|H} = P_{kp|H} + P_{kf|H} \quad \text{and} \quad A_V = A_{vp} + A_{vf} \tag{5.9b}$$

according to Eqs. (5.6a) and (5.6c).

Example 5.6 Single-Hit Vulnerable Area of an Aircraft with Redundant Components

A second engine has be added to the aircraft in Example 5.4. Table 5.10 presents the values for the vulnerability parameters for this two-engine aircraft. The second engine is assumed to have the same presented area as the first engine, 50 ft^2, but its $P_{k|h}$ is taken as 0.7 because of presence of an additional accessory drive. (The larger vulnerable area of engine 2 will help to distinguish it from engine 1 in the following presentation.) The presented area of the aircraft is assumed to remain at 300 ft^2 for the purpose of comparison. Note in Table 5.10 the significant reduction in A_V as a result of the absence of the vulnerable area of the propulsion system.

In general, only those components whose loss or damage can cause a kill of the aircraft on a single hit will contribute their vulnerable area to A_V. If the single-hit kills only one of the redundant components, the aircraft is not killed; hence, nothing is contributed to the vulnerable area. Thus, the total vulnerable area of an aircraft for this case is just the sum of vulnerable areas for each of the nonredundant critical components. For the aircraft defined in Table 5.10, the single-hit vulnerable area reduces from 52 to 22 ft^2 because of the addition of the second engine. Thus, redundancy can significantly reduce the vulnerable area of the aircraft.

On the other hand, if the damage to the struck redundant component creates secondary damage mechanisms or damage processes that propagate to another redundant component and kill that component (cascading damage), causing a loss

Table 5.10 Example of a redundant aircraft model

Critical component	A_p, ft^2	$\times\ P_{k\|h} =$	A_v, ft^2	$P_{k\|h}$
Pilot	4	1.0	4.0	0.0133
Fuel	60	0.3	18.0	0.0600
Engine 1	50	0.6	30.0	0.1000
Engine 2	50	0.7	35.0	0.1167
Total	$\mathbf{A_P = 300}$	—	$\mathbf{A_V = 22.0}$	$\mathbf{P_{K\|H} = 0.0733}$

of the aircraft, the redundant components will contribute to the aircraft vulnerable area. For example, suppose the probability that a hit on one of the engines will cause that engine to throw blades into, or torch, or burn the other engine is 0.1. Thus, the addition to the aircraft's vulnerable area as a result of a hit on engine 1 killing it and also killing engine 2 is $(50\ \text{ft}^2)(0.1) = 5\ \text{ft}^2$. Another $(50\ \text{ft}^2)(0.1) = 5\ \text{ft}^2$ is added to A_V because this can also happen if engine 2 is hit and both engines are killed. Thus, this cascading damage kill mode increases the aircraft's vulnerability by $10\ \text{ft}^2$.

Redundant critical components with overlap. If redundant critical components are now allowed to overlap one another, as shown by the aircraft in Fig. 5.19, the computation of the vulnerable area must account for the fact that a single hit in the overlap region can kill both engines, resulting in a kill of the aircraft. Thus, it will be necessary to add the vulnerable area of the redundant component overlap region to that of the nonredundant critical components. In essence, the overlap region shown in Fig. 5.19 contributes to the A_V just like the nonredundant critical components.

For a more general overlap model consider an overlap area with C components, two of which are redundant. The survival expression given by Eq. (5.7) and the expressions for $P_{so|ho}$ given by Eqs. (5.8a) and (5.8b) must be modified as follows. Suppose the two redundant components among the C components are components 2 (rc2) and 3 (rc3). One or the other, or both, of the two engines must survive for the aircraft to survive. Thus, the survival expression given by Eq. (5.7) becomes

$$\text{Aircraft survival} = (\text{nrc1})\ .\text{AND.}\ [(\text{rc2})\ .\text{OR.}\ (\text{rc3})] \ldots .\text{AND.}\ (\text{nrcC}) \tag{5.10a}$$

The probability that rc2 OR rc3 survives is given by the union of the two survival probabilities, which is

$$\begin{aligned} P(\text{rc2 .OR. rc3}) &= (1 - P_{krc2|ho}) + (1 - P_{krc3|ho}) - (1 - P_{krc2|ho})(1 - P_{krc3|ho}) \\ &= 1 - P_{krc2|ho} P_{krc3|ho} \end{aligned} \tag{5.10b}$$

according to Eq. (B.20) when the redundant component kills are independent

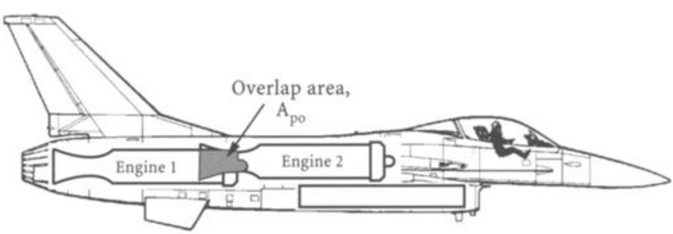

Fig. 5.19 Redundant aircraft model with overlap.

(Note 29). Thus, $(P_{s2|ho}P_{s3|ho})$ in Eq. (5.8a) must be replaced with $(1 - P_{k2|ho}P_{k3|ho})$, the probability that both engines are not killed. This procedure can be extended to the situation where there are more than two redundant overlapping components.

The nonoverlapping areas of each of the redundant components are not used in the vulnerable area computations for the same reason as that used in the no-overlap case. A single shotline through any one of the redundant components outside of the overlap region causes only a kill of that component, not of the aircraft, and hence no contribution is made to the aircraft vulnerable area.

Example 5.7 Single-Hit Vulnerable Area of an Aircraft with Overlapping Redundant Components

The aircraft in Example 5.6 has been redesigned, and engine 2 now overlaps engine 1, as illustrated in Fig. 5.19. If the $P_{k|h}$ values for the two engines in the overlap region are taken as 0.7 for the first engine hit and 0.2 for the overlapped engine (the overlapping engine slows the penetrator down), the probability the aircraft will survive a hit on the overlap region is

$$1 - 0.7 \cdot 0.2 = 0.86$$

Thus, the probability of an aircraft kill given a hit in the engine overlap region is

$$1 - 0.86 = 0.14$$

If the overlap area is assumed to be 10 ft^2, the A_V increases by

$$(10 \text{ ft}^2)(0.14) = 1.4 \text{ ft}^2.$$

Go to Problem 5.3.10.

5.3.4.2 Vulnerability to multiple hits by nonexplosive penetrators or fragments

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Learning Objective	**5.3.6**	**Determine the probability that an aircraft or an aircraft component is killed when hit by more than one penetrator or fragment using the binomial, Poisson, tree diagram, Markov, and simplified approach.**

The analysis will now progress to the situation where the aircraft will receive more than one hit by a penetrator or fragment. The random distribution of these hits over the aircraft is assumed to be uniform, and all hits are assumed to travel along parallel shotlines from the same direction. (The second assumption is not required, but is taken for ease of explanation.) Five different approaches to determine the probability an aircraft is killed after multiple hits are described next. In each of these approaches, the number of penetrator hits is either a known integer N, such as 1, 2, or 25, or an expected number E, such as 1.2, 2.4, or 24.7.

Binomial approach for N hits. Equation (B.40), developed using the binomial approach in Appendix B, Sec. B.6.3.2 can be used to determine the probability an aircraft is killed when it is hit by N penetrators, where N is an integer. The binomial approach is based upon the assumptions that there are two outcomes for each hit, kill and survival, the outcomes for each hit are independent from the outcomes for the preceding hits, and the probability of each outcome, $P_{K|H}$ and $P_{S|H}$ respectively, is constant for each hit. According to Eqs. (B.39) and (B.40),

$$P_S \text{ (after } N \text{ hits)} = (1 - P_{K|H})^N \tag{5.11a}$$

$$P_K \text{ (after } N \text{ hits)} = 1 - P_S \text{ (after } N \text{ hits)} = 1 - (1 - P_{K|H})^N \tag{5.11b}$$

Equations (5.11a) and (5.11b) also can be used to determine the probability a component survives or is killed after N hits on the component by replacing $P_{K|H}$ with $P_{k|h}$.

The assumption that $P_{K|H}$ and $P_{S|H}$ are constant for each hit is not correct if the aircraft has redundant components. In the redundant model the $P_{K|H}$ for the ith shot is dependent upon the outcomes for the preceding shots. This feature will be examined in the presentations on the tree diagram and the Markov chain given next.

Poisson approach for E expected hits. The Poisson approach, developed in Appendix B, Sec. B.6.3.3 is also applicable to the multiple-hit problem. In the Poisson approach the number of hits is a random variable, and the statistical parameter that describes the variable is the expected number of hits E. The Poisson process is applicable to the situation shown in Fig. 4.21, where M shots are fired (or warhead fragments are ejected) toward the aircraft. From 0 to M of those shots (or fragments) can hit the aircraft. The M penetrators shown in Fig. 4.21 are assumed to be uniformly distributed over a spray zone with an area A_S, where $A_S \geq A_P$. The penetrator spray density ρ, the number of penetrators per unit spray area, is given by

$$\rho = M/A_S \tag{5.12a}$$

When the penetrator spray hits the entire aircraft, the expected number of hits on the aircraft E is given by

$$E = \rho A_P = M(A_P/A_S) \tag{5.12b}$$

according to Eq. (5.12a). Given the expected E hits on the aircraft, the expected number of times the aircraft is killed is $EP_{K|H}$ (Note 30). The Poisson probability function given by Eq. (B. 44) can be used to determine the probability the aircraft survives (is killed 0 times) when it is expected be killed $EP_{K|H}$ times. Thus,

$$\text{Probability of 0 kills of the aircraft when } EP_{K|H} \text{ kills are expected} = e^{-EP_{K|H}} \tag{5.12c}$$

Equation (5.12c) can also be given in terms of the aircraft's single-hit vulnerable area A_V. Using Eq. (5.6b) to replace $P_{K|H}$ and Eq. (5.12b) to replace E in Eq. (5.12c) results in

$$\text{Probability of 0 kills of the aircraft when } \rho A_V \text{ kills are expected} = e^{-\rho A_V} \tag{5.12d}$$

where ρ is given by Eq. (5.12a). Note that ρA_V is the expected number of hits on A_V, where $P_{K|H} = 1$. The probability the aircraft is killed by the multiple hits is the complement of the probability it is not killed. Hence,

$$P_K = 1 - e^{-EP_{K|H}} = 1 - e^{-\rho A_V} \tag{5.12e}$$

Equations (5.12b–5.12e) also can be used to determine the survival of a component in a spray zone by replacing A_P with A_p, A_V with A_v, and $P_{K|H}$ with $P_{k|h}$.

Example 5.8 Multiple Hit Vulnerability

The nonredundant aircraft presented in Example 5.3 has a $P_{K|H}$ of 0.1733 for a generic penetrator. Assume the aircraft is hit by five penetrators. Using the binomial approach

$$P_K = 1 - (1 - 0.1733)^5 = 0.614$$

according to Eq. (5.11b).

Suppose the aircraft is subjected to a burst of 10 rounds. The spray zone of 600 ft^2 covers the 300-ft^2 aircraft. Using the Poisson approach, the aircraft is expected to be hit

$$E = 10(300 \text{ ft}^2)/(600 \text{ ft}^2) = 5$$

according to Eq. (5.12b). Thus, the aircraft is expected to be killed $5 \cdot 0.1733 = 0.8665$ times.

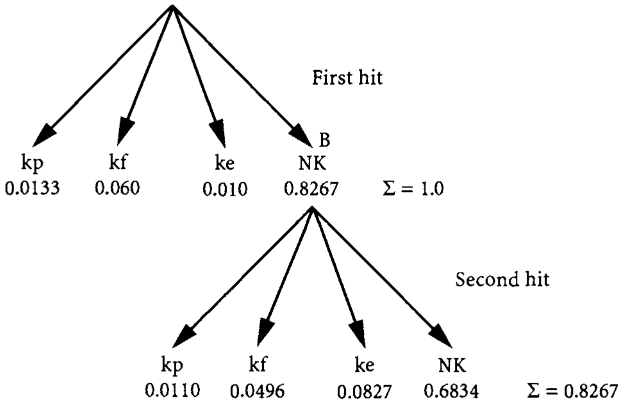


Fig. 5.20 Tree diagram after two hits, nonredundant model.

The probability the aircraft survives when it is expected to be killed 0.8665 times is

$$\text{Probability of 0 kills of the aircraft when 0.8665 kills are expected} = e^{-0.8665} = 0.420$$

according to Eq. (5.12c). Hence, the probability the aircraft is killed by the burst is

$$P_K = 1 - 0.420 = 0.580$$

Tree diagram. The tree diagram, described in Appendix B, Sec. B.5 and used in Secs. B.5 and B.6, can be used here to determine the probability both nonredundant and redundant aircraft models are killed as a result of N hits.

Tree diagram, nonredundant model: Figure 5.20 presents the tree diagram for the aircraft shown in Fig. 5.16 after two hits. The probabilities in the figure are from Table 5.7. The kill expression for this nonredundant aircraft model is (Pilot) .OR. (Fuel Tank) .OR. (Engine). The four mutually exclusive outcomes of each hit are as follows: the kill of the pilot $kp = P_{kp|H}$, the kill of the fuel tank $kf = P_{kf|H}$, the kill of the engine $ke = P_{ke|H}$, and the no critical component kills (and hence no aircraft kill) $NK = 1 - (kp + kf + ke) = 1 - P_{K|H}$. The probability the aircraft is killed after the first hit is

$$P_K \text{ (after 1 hit)} = kp + kf + ke = P_{K|H} = 0.1733 \tag{5.13}$$

The only addition to the kill probability of the aircraft caused by the second hit comes from the branch NK, where no critical components were killed on the first hit. The probability the aircraft is killed after two hits is

$$\begin{aligned} P_K \text{ (after 2 hits)} &= P_K \text{ (after 1 hit)} + NK(kp + kf + ke) \\ &= P_{K|H} + (1 - P_{K|H})P_{K|H} = 2P_{K|H} - (P_{K|H})^2 = 0.3166 \end{aligned} \tag{5.14a}$$

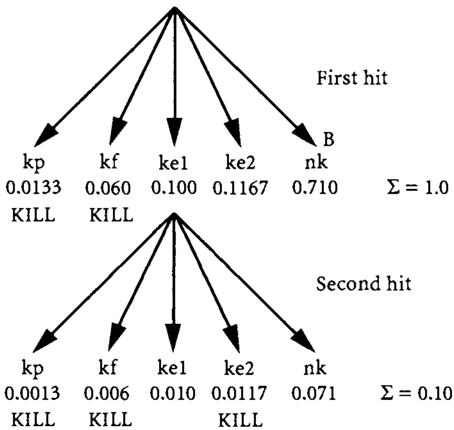


Fig. 5.21 Tree diagram after two hits, redundant model.

According to the tree diagram, the probability the aircraft survives the two hits is

$$P_S \text{ (after 2 hits)} = (1 - P_{\mathrm{K|H}})^2 = 0.6834 \tag{5.14b}$$

which is the complement of Eq. (5.14a), as it should be. The tree diagram shown in Fig. 5.20 can be extended for additional hits as necessary.

Tree diagram, redundant model: Now consider the redundant aircraft model shown in Fig. 5.18 and defined in Table 5.10. An evaluation for P_K and P_S after two hits can be determined using the tree diagram in a manner similar to the that for the nonredundant model. The kill expression for this redundant model is (Pilot) .OR. (Fuel Tank) .OR. [(Engine 1) .AND. (Engine 2)]. Although the engines are redundant critical components, each must be shown as a separate branch in the tree diagram because a kill of either engine is a possible outcome of an aircraft hit, and any engine kill will have an effect on the aircraft's vulnerability to subsequent hits. Accordingly, the tree must contain the additional branch for a kill of engine 2, where $ke2 = P_{ke2|H}$. Furthermore, the NK condition in the nonredundant model is changed to nk here because not all component kills cause an aircraft kill. Part of the tree diagram for two hits on the redundant model is shown in Fig. 5.21, where the five mutually exclusive outcomes branch from a kill of engine 1 after the first hit. Similar branches occur below the kill of engine 2 ($ke2$) and the no component kill (nk) after the first hit.

The outcomes for the two hits shown in Fig. 5.21 that lead to an aircraft kill are labeled KILL in the figure. Note that a kill of only engine 1 or engine 2 does not result in an aircraft kill because the components are redundant. Consequently, the probability that the aircraft is killed after the first hit is just the sum of the kill probabilities for each of the two nonredundant critical components (pilot and fuel). Thus,

$$P_K \text{ (after 1 hit)} = kp + kf = 0.0733 \tag{5.15}$$

Now consider all possible outcomes of the second hit (Note 31). Three of the branches shown in Fig. 5.21 following the kill of engine 1 result in an aircraft kill: the kill of the pilot (0.00133), the kill of the fuel (0.0060), and the kill of engine 2 (0.01167). Similar kill outcomes occur for the branches below the kill of engine 2 and the no component kill. Thus, after two hits,

$$\begin{aligned} P_K \text{ (after 2 hits)} &= 0.0733 + (ke1 = 0.100)(0.0133 + 0.060 + 0.1167) \\ &+ (ke2 = 0.1167)(0.0133 + 0.060 + 0.100) \\ &+ (nk = 0.710)(0.0133 + 0.060) = 0.1646 \end{aligned} \tag{5.16a}$$

and hence,

$$P_S \text{ (after 2 hits)} = 1 - 0.1646 = 0.8354 \tag{5.16b}$$

Note the significant increase in survivability as a result of the addition of the second engine (0.8354 vs 0.6834) The tree diagram can be continued indefinitely, as in the nonredundant case, but it is obvious that the computations quickly become overwhelming in complexity. The Markov chain described next is better suited to handle this assessment.

Markov chain. The Markov chain, or state transition matrix method, is described in Appendix B, Sec. B.8.3. The redundant aircraft consisting of a pilot, a fuel tank, and two engines can exist in five distinct states:

1) One or more of the nonredundant critical components (the pilot and the fuel tank) have been killed, resulting in an aircraft kill, denoted by *Knrc*.
2) Only engine 1 has been killed, denoted by *ke*1.
3) Only engine 2 has been killed, denoted by *ke*2.
4) Both engine 1 and engine 2 have been killed, resulting in an aircraft kill, denoted by *Krc*.
5) None of the nonredundant critical components and neither of the engines are killed, denoted by *nk*.

States *Knrc* and *Krc* are called absorbing states because the aircraft cannot transition from these two kill states to any of the other three nonkill states.

The transition matrix of probabilities $[T]$ that specifies how the aircraft will transition from one state to another as a result of a hit on the aircraft will now be constructed. Table 5.11 presents the elements of the $[T]$ matrix for the example redundant aircraft model defined in Table 5.10. Each element of the matrix represents the probability of transitioning from the state defined by the column location to the new state defined by the row location. Thus, the probability of the aircraft transitioning from the *Knrc* state to the *Knrc* state is unity (300/300) because *Knrc* is an absorbing state. The probability of transitioning from the *ke*l state to the *Knrc* state (kill of a nonredundant component) is the sum of the conditional probabilities of kill of the two nonredundant components, that is, $kp + kf$, or $(4 + 18)/300$. The probability of transitioning from *ke*l to *ke*l (remaining in kel) is the sum of engine 1's probability of kill given a hit on the aircraft, $ke1$, and that of the *nk* area of the aircraft, or $(30 + 213)/300$. The probability of transitioning from *ke*l to *ke*2

Table 5.11a State transition matrix [T]

	Probability of transitioning from this state					
$1/A_p$	*Knrc*	*ke*1	*ke*2	*Krc*	*nk*	To this state
	300	(4 + 18)	(4 + 18)	0	(4 + 18)	*Knrc*
	0	(30 + 213)	0	0	30	*ke*1
1/300	0	0	(35 + 213)	0	35	*ke*2
	0	35	30	300	0	*Krc*
	0	0	0	0	213	*nk*

is zero because *ke*2 is the state where only engine 2 is killed. Transitioning from *ke*l to *Krc* occurs when engine 2 is killed (35/300), and transitioning from *ke*1 to *nk* is zero because *nk* is the state where no components are killed. The elements in the remaining columns are determined in the same manner.

The state vector $\{S\}^{(j)}$, given by

$$\{S\}^{(j)} = \begin{Bmatrix} Knrc \\ ke1 \\ ke2 \\ Krc \\ NK \end{Bmatrix}^{(j)} \tag{5.17a}$$

consists of the probabilities that the system is in each of the five states after the jth hit, $j = 0, 1, \ldots J$. Note that the sum of the elements in $\{S\}^{(j)}$ is always unity; the aircraft must exist in one of these five states. The state transition matrix $[T]$ transforms the state vector $\{S\}^{(j)}$ to $\{S\}^{(j+1)}$ in the form

$$\{S\}^{(j+1)} = [T]\{S\}^{(j)} \tag{5.17b}$$

An aircraft kill is defined by those states that specify either a kill of any of the nonredundant components (*Knrc*) or a kill of the members of the sets of redundant components (*Krc*), such as both engines. Hence, the probability the aircraft is killed after j hits is given by

$$\bar{P}_{K|H}^{(j)} = Knrc^{(j)} + Krc^{(j)} \tag{5.18}$$

Table 5.11 contains the transition probabilities for the redundant aircraft model shown in Fig. 5.18. Prior to the first hit, the aircraft is entirely in the *nk* state. Thus, according to Eqs. (5.17a) and (5.17b),

$$\begin{Bmatrix} Knrc \\ ke1 \\ ke2 \\ Krc \\ NK \end{Bmatrix}^{(1)} = [T]\begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{Bmatrix}^{(0)} \tag{5.19a}$$

Carrying out the matrix multiplication gives

$$\begin{Bmatrix} Knrc \\ ke1 \\ ke2 \\ Krc \\ NK \end{Bmatrix}^{(1)} = [T] \begin{Bmatrix} 0.0733 \\ 0.1000 \\ 0.1167 \\ 0 \\ 0.7100 \end{Bmatrix}^{(1)} \tag{5.19b}$$

Thus, the probability the aircraft is killed after the first hit is

$$P_K \text{ (after 1 hit)} = 0.0733 \tag{5.19c}$$

which is the same result obtained using the tree diagram. Substituting Eq. (5.19b) into Eq. (5.17b) and carrying out the matrix multiplication leads to

$$\begin{Bmatrix} 0.1413 \\ 0.1520 \\ 0.1793 \\ 0.0233 \\ 0.5041 \end{Bmatrix}^{(2)} = [T] \begin{Bmatrix} 0.0733 \\ 0.1000 \\ 0.1167 \\ 0 \\ 0.7100 \end{Bmatrix}^{(1)} \tag{5.19d}$$

Note that the sum of the elements of $\{S\}^{(2)}$ is unity, as it should be. The $\{S\}^{(2)}$ vector results reveal that after the second hit there is a 0.1413 probability that either the pilot or the fuel tank or both have been killed, a 0.1520 probability that engine 1 has been killed, a 0.1793 probability that engine 2 has been killed, a 0.0233 probability that both engines have been killed, and a 0.5041 probability that none of the critical components have been killed. Thus, the probability the aircraft is killed after the second hit is

$$P_K \text{ (after 2 hits)} = 0.1413 + 0.0233 = 0.1646 \tag{5.19e}$$

This value is the same as that obtained using the tree diagram, as it should be.

This process can easily be continued for as many hits as desired. Figure 5.22 shows the aircraft P_K as a function of j for both the redundant aircraft model and the nonredundant aircraft model given in Table 5.7 using the binomial approach. The difference between the two curves is the reduction in vulnerability caused by redundancy. As the number of hits becomes large, the effect of the engine redundancy on the aircraft's survivability is diminished. This is because of the increased likelihood that the larger number of hits has killed both engines.

In the preceding presentation the transition matrix was assumed to be the same for all hits. This assumption is not necessary. If multiple penetrators hit the aircraft from several different aspects, a transition matrix can be constructed for each aspect of interest. The computation of the state vector for the $j + 1$ hit, given by Eq. (5.17b), would use the transition matrix for the approach direction of that particular hit. Another possible modification is the consideration of an increase in the ith component probability of kill $P_{ki|H}$ as a result of multiple hits. Again, $[T]$ could be changed from one hit to the next.

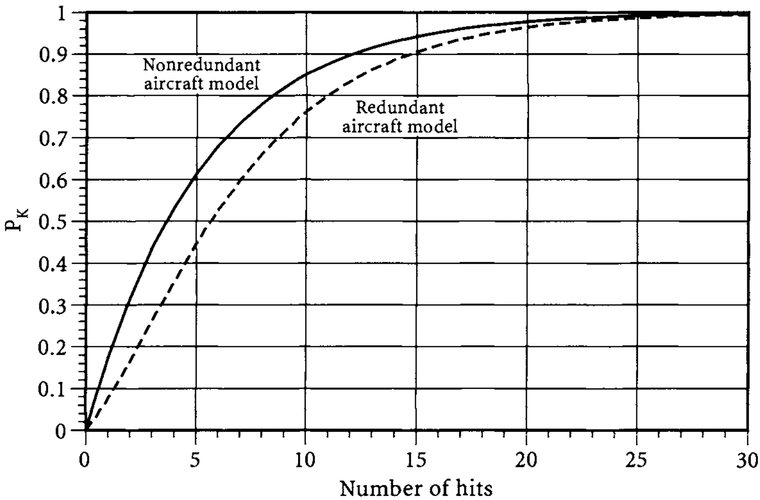


Fig. 5.22 P_K **for the redundant and nonredundant aircraft models vs the number of hits.**

Simplified approach for the P_K. An approximation for the probability that an aircraft has been killed after N hits (or E expected hits) can be obtained by neglecting the mutually exclusive feature of the individual, nonoverlapping component kills on any one hit and assuming all component kills are independent. Effectively, this means that more than one component can be killed by one hit and the kill of one component has no effect on the kills of the other components. Using this assumption, the probability an aircraft survives N hits (or E expected hits) can be approximated by the joint probability that all of the nonredundant critical components survive, and not all of the redundant critical components are killed by the N hits. The appropriate expression for this simplified approach is the survival expression. For the redundant aircraft models shown in Figs. 5.18 and 5.19, the survival expression is

$$\text{Aircraft survival} = (\text{Pilot}) \text{ AND } (\text{Fuel}) \text{ AND } [(\text{Engine 1}) \text{ OR } (\text{Engine 2})] \tag{5.20}$$

where the appearance of a component name implies the survival of that component.

Using the binomial approach for N random hits on the aircraft given by Eq. (5.11a), the probability each component survives after N hits on the aircraft is given by

$$P_{\text{sp}}\,(\text{after } N \text{ hits}) = (1 - P_{\text{kp|H}})^N \tag{5.21a}$$

$$P_{\text{sf}}\,(\text{after } N \text{ hits}) = (1 - P_{\text{kf|H}})^N \tag{5.21b}$$

$$P_{\text{se1}}\,(\text{after } N \text{ hits}) = (1 - P_{\text{ke1|H}})^N \tag{5.21c}$$

$$P_{\text{se2}}\,(\text{after } N \text{ hits}) = (1 - P_{\text{ke2|H}})^N \tag{5.21d}$$

Thus, the probability the aircraft survives the N hits is

$$P_S \text{ (after } N \text{ hits)} = (1 - P_{kp|H})^N (1 - P_{kf|H})^N [(1 - P_{keI|H})^N + (1 - P_{ke2|H})^N - (1 - P_{keI|H})^N (1 - P_{ke2|H})^N)] \tag{5.21e}$$

according to the intersection and union of independent events equations given by Eqs. (B.17b) and (B.20).

Using the Poisson approach for E expected hits on the aircraft given by Eqs. (5.12a–5.12e) and assuming the entire aircraft is covered by the spray zone,

$$P_{sp} \text{ (after } \rho A_{vp} \text{ expected hits on } A_{vp}) = e^{-\rho A_{vp}} \tag{5.22a}$$

$$P_{sf} \text{ (after } \rho A_{vf} \text{ expected hits on } A_{vf}) = e^{-\rho A_{vf}} \tag{5.22b}$$

$$P_{seI} \text{ (after } \rho A_{veI} \text{ expected hits on } A_{veI}) = e^{-\rho A_{veI}} \tag{5.22c}$$

$$P_{se2} \text{ (after } \rho A_{ve2} \text{ expected hits on } A_{ve2}) = e^{-\rho A_{ve2}} \tag{5.22d}$$

The probability the aircraft survives the E expected hits on the aircraft is

$$P_s \text{ (after } E \text{ expected hits)} = (e^{-\rho A_{vp}})(e^{-\rho A_{vf}}) \times \left[(e^{-\rho A_{ve1}}) + (e^{-\rho A_{ve2}}) - (e^{-\rho A_{ve1}})(e^{-\rho A_{ve2}})\right] \tag{5.22e}$$

Figure 5.23 presents the results for P_K vs the number of hits (or expected number of hits) from the Markov chain method and the simplified approach using

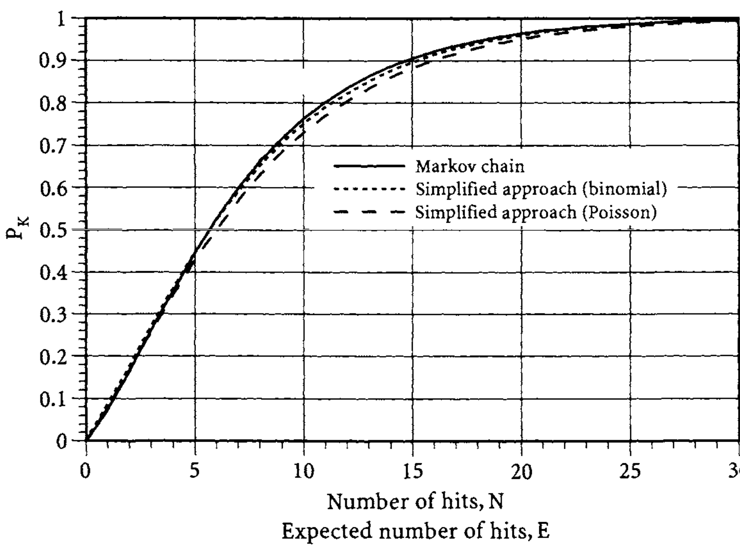


Fig. 5.23 P_K from Markov chain and simplified approach vs number of hits on redundant aircraft model.

the binomial and the Poisson probability functions for the redundant aircraft model described in Table 5.10. (In the Poisson approach $\rho = E/A_P$.) Note that P_K from both of the simplified approaches is close to the Markov chain value, for this example.

Required capabilities. One of the important requirements of any vulnerability assessment is the capability to account for the six VR concepts of component redundancy with separation, component location, passive damage suppression, active damage suppression, component shielding, and component elimination. The methodology for assessing aircraft vulnerability to nonexplosive penetrators and fragments just presented has that capability. Component redundancy is accounted for in the kill expression and the computation of P_K for a number of hits. Component location is accounted for with respect to component overlap, the destruction of adjacent components caused by cascading damage, the component presented area, and the effect of component location behind intervening structure and noncritical components on the component $P_{k|h}$ numerical value. Passive and active damage suppression can be accounted for by reducing the $P_{k|h}$ function. Component shielding is accounted for by reducing the numerical value for $P_{k|h}$ as a result of the reduced velocity of the impacting penetrator. Component elimination is accounted for by removing the component from the kill expression and by replacing a component with a relatively large $P_{k|h}$ with a component with a relatively small $P_{k|h}$. In summary, the four major items that affect an aircraft's vulnerability are the kill expression, the component's location and presented area, and the component's $P_{k|h}$ function.

Presentation of the results. In general, every organization that performs a vulnerability assessment will have a presentation format. In particular, results related to any vulnerability requirements, such as the aircraft must not suffer a B level of attrition kill when hit by a specified penetrator, must be included. The presentation of the vulnerability assessment results, such as the single-hit vulnerable area of the aircraft, varies with the level of detail of the assessment. For a minimum level the six major aspects along the $\pm x$, $\pm y$, and $\pm z$ axes shown in Fig. 4.28 (front, back, left, right, top, and bottom) are usually considered for each kill category and level selected. When a more detailed or a computerized analysis is performed, 26 views (the six major aspects and all 45 deg angles from the major six) are usually assessed, and a number of impact velocities should be considered at each aspect. In addition to the total aircraft A_V tables, the vulnerable area of each critical component should also be listed, and both the true and the incremental vulnerable areas should be presented for overlapping components. Redundant components should be identified, and the number of redundant components that must be killed to cause an aircraft kill should be noted. The single-hit vulnerable area associated with overlapping redundant components should also be identified.

Go to Problems 5.3.11 to 5.3.15.

5.3.4.3 Vulnerability to contact-fuzed HE warheads ($P_{K|H}$ and A_V).

Learning Objective	**5.3.7**	**Use the expanded area approach and the point burst approach to determine the vulnerable area of an aircraft to a contact-fuzed HE warhead.**

Most guided missiles and antiaircraft projectiles 23 mm and larger have an HE warhead with a contact fuze that detonates the warhead either immediately, or shortly after, impacting the aircraft. This results in a detonation on or inside the aircraft, with the accompanying blast and fragment spray in many directions. The assumption of parallel trajectories or shotlines through the aircraft used in the preceding nonexplosive penetrator vulnerability assessment is not valid in this situation. Instead, the fragment shotlines emanate radially from the location of the warhead burst point. The kill of the critical components in the vicinity of the burst point will be dependent upon the relative location of the components and on any masking provided by intervening structure and noncritical components. The probability of kill of each of the critical components as a result of the blast, possible fire or explosion, and the fragment hits on the component must be evaluated and the aircraft probability of kill given a hit and vulnerable area computed for each possible hit location. Two approaches to this problem are presented next. Both approaches are based upon the assumption that the location of the hit is uniformly distributed over the presented area of the aircraft. If the location of the hit is known or assumed, the second approach can also be used to determine the probability the aircraft is killed given the located hit. If the hit distribution is nonuniform, the assessment procedure described in Chapter 6, Sec. 6.2.2.1 can be used.

Expanded area approach. One relatively simple approach, known as the expanded area approach, is to expand the presented area of each of the critical components beyond the actual physical size of the component to account for the fact that the HE warhead does not have to hit the component to kill it. This is illustrated in Fig. 5.24, where a detonation within the expanded area around the engine can kill the engine. In general, the ith component has an expanded presented area around the component of A_{ei}. The component's probability of kill given a hit by the internally detonating HE warhead within the A_{ei} is $P_{ki|hei}$. The component can be killed by the combination of blast, possible fire or explosion, and the fragments from the warhead detonation. Because the component within the expanded area hit by the HE warhead will most likely be hit by more than one fragment from the warhead detonation, either Eq. (5.11b) or Eq. (5.12e) is used to determine the $P_{ki|hei}$ for the component caused by fragments, where the number of fragment hits N or the expected number of hits E is estimated for the component. The probability the component survives the blast and any fire or explosion can be estimated and multiplied by the complement of the probability the component is killed by the fragments (The component must survive the fragments, the blast, and any fire or explosion.) to determine the component's probability of survival given the hit in the

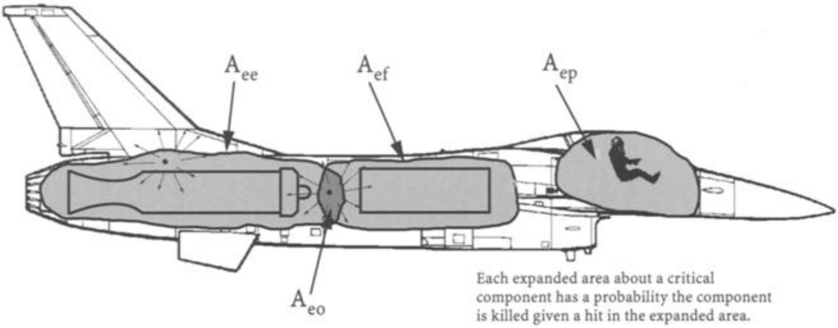


Fig. 5.24 Expanded area approach.

expanded area $P_{si|hei}$. The component's final $P_{ki|hei}$ is the complement of $P_{si|hei}$. Because the hit location is assumed to be uniformly distributed over the presented area of the aircraft, the procedure just described for determining the $P_{K|H}$ and A_V for the nonexplosive penetrator or fragment is also used to determine the $P_{K|H}$ and A_V for the HE warhead, with A_{pi} replaced by A_{ei}. If the expanded areas of two or more components overlap, as illustrated by the hit between the engine and the fuel tank in Fig. 5.24, the procedures described in Sec. 5.3.4.1 in the subsection "An aircraft with nonredundant components that overlap" and in the subsection, "Redundant critical components with overlap" must be used.

Point burst approach. In the point burst approach the warhead detonation is assumed to take place at one or more individual locations within the presented area of the aircraft. When the hit is assumed to be uniformly distributed, a uniform grid is superimposed on the aircraft's presented area, as illustrated in Fig. 5.25. Each grid cell that covers at least part of the aircraft contains one randomly located burst point. Critical components, or parts of critical components, outside of the cell in which the burst occurs are considered when they can be hit and killed by the fragments and blast from the internal detonation. Because several critical components can be killed by the single HE burst, the general approach described

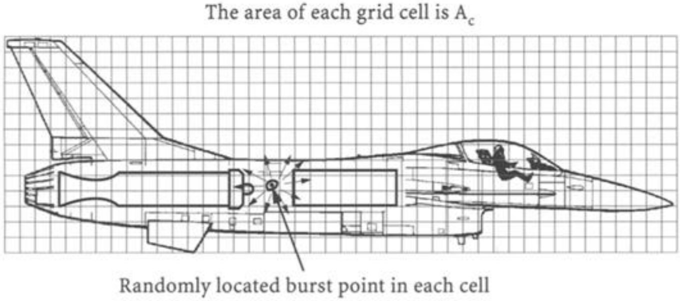


Fig. 5.25 Point burst approach.

above in the subsection "A simplified approach for the P_K" in Sec. 5.4.1.2 is applicable here provided the component kills are independent.

The survival probability equation for the aircraft shown in Fig. 5.25 for a warhead detonation at a given burst point b, $P_{S|Hb}$ is

$$P_{S|Hb} = (1 - P_{kp|Hb})(1 - P_{kf|Hb})(1 - P_{ke|Hb}) \tag{5.23a}$$

where $P_{ki|Hb}$ is the probability the ith component is killed given the detonation at the burst point b. The procedure for determining the $P_{ki|Hb}$ for each of the components on the aircraft caused by the warhead detonation at b is the same as the procedure for determining the component $P_{ki|hei}$ just described for the expanded area approach. Once these probabilities have been determined, they can be substituted into Eq. (5.23a) and $P_{S|Hb}$ computed. The probability the aircraft is killed given the burst at point b is

$$P_{K|Hb} = 1 - P_{S|Hb} \tag{5.23b}$$

The probability that the aircraft is hit in the cell under consideration and is killed by the hit P_{Kb} is the joint probability that that cell is hit P_{Hb} and the probability that the hit kills the aircraft $P_{K|Hb}$. Hence,

$$P_{Kb} = P_{Hb} P_{K|Hb} \tag{5.23c}$$

The probability the cell is hit is given by

$$P_{Hb} = A_c/A_P \tag{5.23d}$$

where A_c is the cell area. (Note that even though critical components outside of the cell are included in $P_{K|Hb}$, just the area of the cell itself is used in the computation for P_{Hb}.).

The probability the aircraft is killed given a random hit on the aircraft is the sum of the probabilities it is hit and killed in each cell, and there are B cells with burst points. Thus,

$$P_{K|H} = \sum_{b=1}^{B} P_{Kb} = \sum_{b=1}^{B} P_{Hb}\, P_{K|Hb} = \frac{1}{A_P} \sum_{b=1}^{B} A_c P_{k|Hb} \tag{5.24a}$$

The product of the cell area and the probability the aircraft is killed given a burst in the cell is the vulnerable area of the cell A_{Vb}, and the aircraft vulnerable area is the sum of the cell vulnerable areas

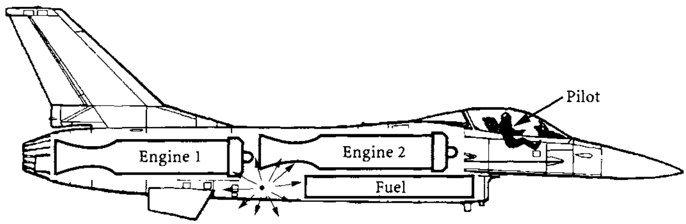
$$A_V = \sum_{b=1}^{B} A_c P_{K|Hb} = \sum_{b=1}^{B} A_{Vb} \tag{5.24b}$$

The vulnerable area for internally detonating HE warheads is usually much larger than the vulnerable area for nonexplosive projectiles and fragments, but it cannot exceed the aircraft presented area.

When the location of the hit is known or assumed rather than random, the measure of vulnerability is $P_{K|Hb}$ given by Eq. (5.23b), where b indicates the hit specified location.

Example 5.9 Vulnerability to the Contact-Fuzed HE Warhead

An aircraft is hit on the lower starboard side by a 23-mm HE-I projectile as shown in the illustration here.



The number of fragment hits on each component is given in the following table. Also shown in the table is the probability each component is killed given a fragment hit on the component. What is the probability the aircraft is killed by this hit $P_{K|Hb}$? Assume the probability of survival of each component to the blast and fire/explosion is 1.0. Use Eq. (5.11a) to determine the component P_s caused by N hits on the component.

Component	Number of hits	$P_{k\|h}$	P_s after the N hits
Pilot	0	1.0	$(1 - 1.0)^0 = 1.0$
Fuel	9	0.1	$(1 - 0.1)^9 = 0.387$
Engine 1	15	0.05	$(1 - 0.05)^{15} = 0.463$
Engine 2	23	0.08	$(1 - 0.08)^{23} = 0.147$

The survival expression for this aircraft is

Aircraft survival = (Pilot) AND. (Fuel) AND. [(Engine 1) OR. (Engine 2)]

according to Eq. (5.20). Thus,

$$P_{S|Hb} = (1.0)(0.387)[0.463 + 0.147 - (0.463)(0.147)] = (1.0)(0.387)(0.542)$$
$$= 0.210$$

according to Eq. (5.21e). Therefore,

$$P_{K|Hb} = 1 - 0.210 = 0.790$$

Suppose the burst occurred in a square cell with $A_c = 2$ ft^2. Also suppose that the $P_{K|Hb}$ in the four cells surrounding this cell had $P_{K|Hb}$ values of 0.732, 0.701, 0.810, and 0.801 respectively. What is the vulnerable area of these five cells?

$$A_V \text{ (5 cells)} = (2 \text{ ft}^2)(0.790 + 0.732 + 0.701 + 0.810 + 0.801) = 7.67 \text{ ft}^2$$

Go to Problem 5.3.16.

5.3.4.4 Vulnerability to proximity-fuzed HE warheads ($P_{K|F}$).

Learning Objective 5.3.8 Determine the probability an aircraft is killed given the fuzing of a proximity HE warhead at a particular location.

The threats that employ externally detonating warheads are the large-caliber AAA and most of the surface-to-air and air-to-air missiles. A large HE warhead detonation is shown in Fig. 3.23 and idealized in Fig. 3.24. The primary damage mechanisms of these threats are usually the blast and the high-velocity fragments or penetrators generated by the detonation. However, missile debris from the detonation and incendiary particles can also be important damage mechanisms. Shortly after the detonation, the blast front precedes the fragments. Eventually, the fragments pass through the front of the blast because the decay of the fragment velocity is less than the blast front velocity decay. The vulnerability of aircraft to the externally detonating warhead is usually analyzed in two separate tasks. The first task is a determination of the aircraft's vulnerability to the blast, and the second examines the aircraft's vulnerability to the fragments and penetrators. Both assessments must consider the conditions that exist between the aircraft and the missile at the time of warhead detonation. These include the missile and aircraft positions, velocity vectors, and the respective attitudes.

Blast. The blast from an HE warhead detonation is described in Chapter 3, Sec. 3.4.2.5. Aircraft vulnerability to external blast is usually expressed as an envelope about the aircraft where the detonation of a specified charge weight of spherical uncased pentolite high explosive will result in a specified level of damage or kill to the aircraft. Detonation outside of such an envelope will result in little or no damage to the aircraft or in a lesser kill level. The damage mechanism is the blast resulting from the detonation of the high explosive charge in the vicinity of the aircraft. A spectrum of charge weights is often specified for which the aircraft vulnerability measures are computed in the vulnerability assessment. The specific charge weights selected are representative of the expected threat warheads that might be encountered. Envelopes are determined for a variety of encounter conditions that account for variations in aircraft speed and altitude, as well as aspect. Aircraft critical components vulnerable to the external blast consist principally of portions of the airframe structure and control surfaces. Threshold

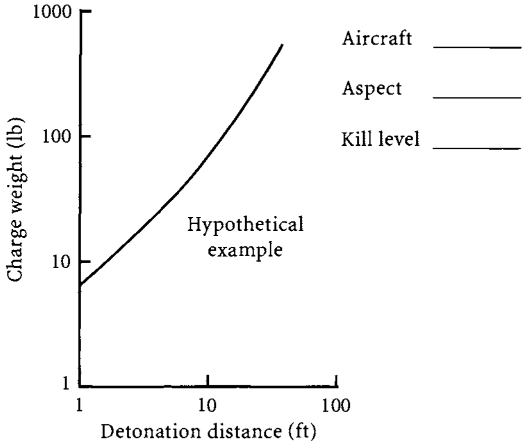


Fig. 5.26a One type of external blast vulnerability presentation.

kill criteria for the critical components are derived from structural and aerodynamic analyses.

Once the blast pressures and impulse levels required for an aircraft kill are determined for several locations on the aircraft surface, a contour can be plotted corresponding to the detonation distance and the weight of pentolite that will provide the required pressure and impulse level. Two different graphical presentations of the data can be used. The first is a plot of charge weight vs distance for a constant kill level. Several curves can be drawn on the same graph, one for each altitude of interest. A similar graph is required at each azimuth and elevation angle of

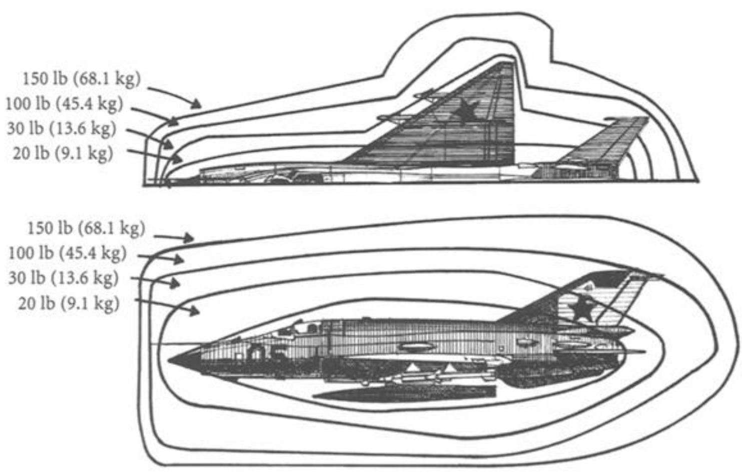


Fig. 5.26b Typical external blast kill contour data for several weights of uncased pentolite at sea level.

interest about the aircraft. Figure 5.26a is an example of this type of presentation. The second graphical method, illustrated in Fig. 5.26b, is to construct isocharge weight contours about the aircraft for a given kill level and altitude in all planes of interest.

Fragments and penetrators. The fragments and penetrators from an HE warhead detonation are described in Chapter 3, Sec. 3.4.2.5. In the idealized static warhead detonation shown in Fig. 3.33, each fragment is located longitudinally between the fragment at the front of the warhead and the fragment at the back of the warhead and radially within a thin fragment spray zone. The fragment spray from the warhead detonation on the moving propagator, relative to a stationary target, is assumed to be spherical as illustrated in Figs. 5.27a and 5.27b. Note that the detonation in Fig. 5.27a is too soon to cause damage to the aircraft. Moving the fragment spray zone radially away from the detonation point reveals that no

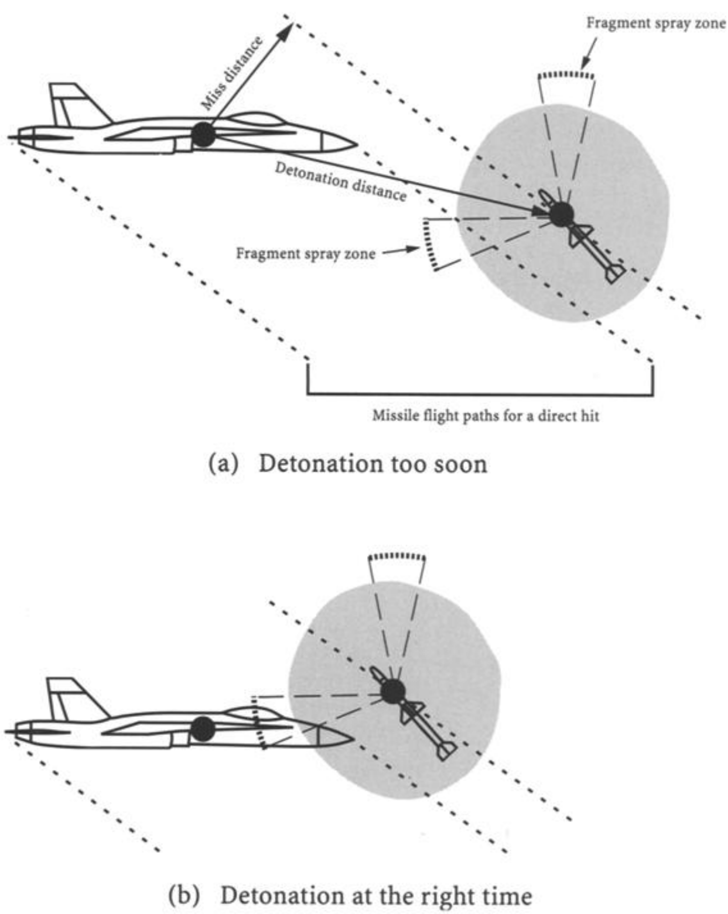


Fig. 5.27 Fragment spray from a moving missile relative to a stationary target.

fragments hit the aircraft. However, the detonation shown in Fig. 5.27b is at the right time (or wrong time depending upon your point of view); the fragment spray zone covers a major portion of the front of the aircraft.

The measure of the vulnerability of an aircraft to the fragments in the fragment spray zone is the probability the aircraft is killed given fuzing $P_{K|F}$. There are two parts to the assessment: first, the determination of the number or expected number of fragments that hit the aircraft, and second, the determination of the probability the aircraft is killed by the fragment hits. The expected number of fragment hits and their location on the aircraft is determined in Chapter 4, Sec. 4.3.7. There, the appropriate zones for warhead detonation are identified, and E, the expected number of fragment hits on the presented area A_P, is given by Eq. (4.49) in terms of the fragment density in the spray (the number of fragments per unit area of spray) ρ, given by Eq. (4.50). Example 4.12 describes the procedure for determining the area presented to the fragment spray zone and the number of fragment hits.

The vulnerability of the aircraft to the fragment hits depends upon the location of the hits. In general, the fragment spray zone either covers the entire aircraft presented area (detonation zone IV in Fig. 4.26) or it covers a part of it (detonation zones I, II, and III in Fig. 4.26). In either event the procedures just described for the vulnerability of an aircraft to multiple hits by nonexplosive penetrators or fragments apply. If the spray zone covers only part of the aircraft's presented area, A_P, A_V, and $P_{K|H}$ must be modified accordingly.

Binomial approximation: Because the fragments are randomly distributed in the fragment spray zone, the number of fragments that hit the aircraft is a random number. Consequently, the binomial approach is an approximation. The binomial approximation for the probability an aircraft composed of only nonredundant critical components is killed by the random fragment hits from an external HE warhead detonation is

$$P_{K|F} = 1 - (1 - P_{K|H})^E \tag{5.25a}$$

according to Eq. (5.11b), where N, the integer number of hits, has been replaced by E, the expected number of hits given by Eq. (4.49). The probability the aircraft is killed given a single fragment hit is given by

$$P_{K|H} = A_V/A_P \tag{5.25b}$$

where A_V is the sum of the vulnerable areas in the fragment spray zone and A_P is the area presented to the spray.

Poisson approach: The Poisson approach for $P_{K|F}$ for the nonredundant aircraft model provides the probability the aircraft survives the fragment hits from the warhead detonation given that it is expected to be killed $EP_{K|H}$ or ρA_V times. Thus,

$$P_{K|F} = 1 - e^{-EP_{K|H}} = 1 - e^{-\rho A_v} \tag{5.26}$$

according to Eq. (5.12e).

Example 5.10 presents the results from the binomial approximation and Poisson approach for the warhead detonation considered in Example 4.12.

Example 5.10 $P_{K|F}$ for the Nonredundant Aircraft Model

In Example 4.12 the fragment spray zone covers the entire bottom of the aircraft, the fragment spray density is 0.0233 fragments/ft^2, the target presented area is 265 ft^2, and the expected number of fragment impacts is 6.2 when the detonation distance is 175 ft.

Assume that $A_V = 5$ ft^2 for the single fragment hit on the aircraft from the attack direction of Example 4.12. Thus, the binomial approximation results in

$$P_{K|F} = 1 - [1 - (5 \text{ ft}^2)/(265 \text{ ft}^2)]^{6.2} = 0.111$$

according to Eqs. (5.25a) and (5.25b).

The Poisson approach given by Eq. (5.26c) yields

$$P_{K|F} = 1 - e^{-0.0233 \cdot 5} = 0.110$$

When the detonation is at 60 ft, the length of the spray arc is 13.8 ft. This is less than the length of the aircraft, and hence the fragment spray covers a portion of the aircraft's bottom. The area presented to the fragment spray is 138 ft^2, the fragment spray density is 0.198 fragments/ft^2, and the number of fragments that hit the bottom is 27.3. Assume the vulnerable area of the components within the fragment spray zone is 3.5 ft^2 (the pilot is outside the spray zone). Thus, the binomial approximation gives

$$P_{K|F} = 1 - [1 - (3.5 \text{ ft}^2)/(138 \text{ ft}^2)]^{27.3} = 0.504$$

and the Poisson approach results in

$$P_{K|F} = 1 - e^{-0.198 \cdot 3.5} = 0.500$$

Markov chain and the simplified approach for both nonredundant and redundant aircraft models: Both the Markov chain and the two simplified approaches can be used to determine the probability an aircraft is killed after getting hit by N fragments or (E expected fragments). Once the curve for P_K as a function of the number of hits has been developed, for example, Fig. 5.23, it can be used to determine the numerical value of $P_{K|F}$ when N fragments from an external HE warhead detonation hit the aircraft. For example, suppose 10 fragments hit the redundant aircraft model from the side. According to the curves in Fig. 5.23, $P_{K|F} = 0.75$ for the binomial simplified approach, and $P_{K|F} = 0.76$ for the Markov chain approach.

Array of $P_{K|F}$ values and the $P_{K|F}$ function: Any of the approaches for determining $P_{K|F}$ can be used to determine an array of numerical $P_{K|F}$ values around the aircraft, such as that shown in Fig. 3.10. These values can be used to determine the optimum-fuzed $P_{K|F}$ as a function of the detonation distance and the warhead lethal radius as shown in Fig. 3.11.

Go to Problems 5.3.17 to 5.3.19.

5.3.4.5 Computer programs for vulnerability assessment.

Learning Objective 5.3.8 Describe the computer programs used for vulnerability assessment.

The determination of an aircraft's vulnerability can be a complex and time-consuming task. When done manually, many simplifications and assumptions are made, the results are subject to interpretation, and the output is usually limited in scope. Consequently, an extensive number of computer programs or models have been developed by the U. S. military and industry for assessing aircraft vulnerability. These programs can be divided into four major categories: shotline generators, vulnerable area routines, internal burst programs, and endgame programs. Programs in the first two categories are used for the penetrator and single fragment damage mechanisms. Those in the third category are used for internally detonating HE warheads, and those in the fourth category are for the proximity-fuzed HE warhead. (The reader is cautioned that just because a computer is used the results are not to be treated as sacrosanct. The output is no more valid than the assumptions that were used to develop the model and the input data.)

Shotline generators. These programs generate shotline descriptions of aircraft targets for use as input data to the codes that calculate vulnerable areas. The programs usually model the aircraft external surface and the individual internal and external components either with a set of geometric shapes or with surface patches. Shotline descriptions are obtained by superimposing a planar grid over the target model and by passing parallel shotlines or rays from the attack direction (normal to the grid) through the individual grid cells, as shown in Fig. 5.28. One shotline is randomly located within each cell. The programs trace the path of a shotline through the aircraft and generate sequential lists of components and fluid and air spaces encountered along the shotline. Specific component data, such as thickness and shotline obliquity, are also recorded. This procedure is repeated for all shotlines originating from the selected attack directions.

Two families of shotline generator routines have been developed. They are the MAGIC/GIFT/BRL-CAD family and the SHOTGEN/FASTGEN family. Both BRL-CAD and FASTGEN are in the SURIVAC Model Guide and are briefly described in Chapter 1, Sec. 1.5.2.

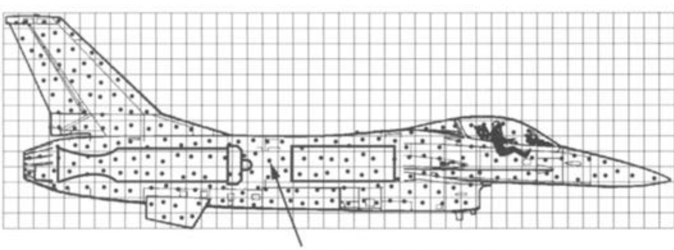


Fig. 5.28 Grid for the shotlines.

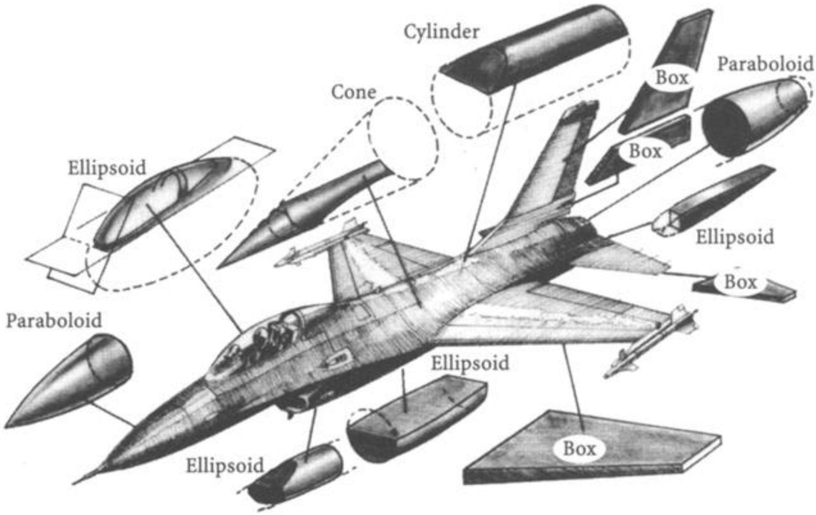


Fig. 5.29 Combinatorial geometry model of an aircraft.

The MAGIC, GIFT, and BRL-CAD codes were developed at the U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland. These codes use the combinatorial geometry approach, with basic body shapes such as spheres, boxes, cylinders, ellipsoids, and cutting or bounding planes, to describe components. GIFT is an improved version of MAGIC, with simpler input requirements, more efficient computation, and computer-generated graphic displays. The BRL-CAD package is the most recent development and is a powerful constructive solid geometry solid modeling system. BRL-CAD includes an interactive geometry editor, ray tracing support for rendering and geometric analysis, network distributed frame buffer support, image processing and signal-processing tools. The entire package is available in source code form. The Web site of BRL-CAD is http://ftp.arl.mil/brlcad/. Figure 5.29 shows the external view of a model built using the combinatorial geometry approach.

The second family, SHOTGEN and the most recent FASTGEN IV, is somewhat similar to the other family, but typically uses the flat triangular patch method to describe the component surfaces. A program called FASTGEN IVAVIEW™ has been developed to interactively display a FASTGEN target model. (SURVICE Engineering Co., Belcamp, MD, http://www.survice.com/SIPages/SI_prod_Ivaview.htm.) Figures 5.30a-c show the external view and the internal components of a flat triangular surface patch model of the Lockheed C-130H.

Vulnerable area routines. These programs generate component and total aircraft vulnerable area tables for a single penetrator or fragment. The vulnerable area routines can be divided into two groups, the 'detailed' or analysis routines, which use the shotline approach to compute the vulnerable area, and the 'simplified' or evaluation routines, which use simplified approaches to determine the vulnerable area. The routines in the analysis group are usually used for problems requiring

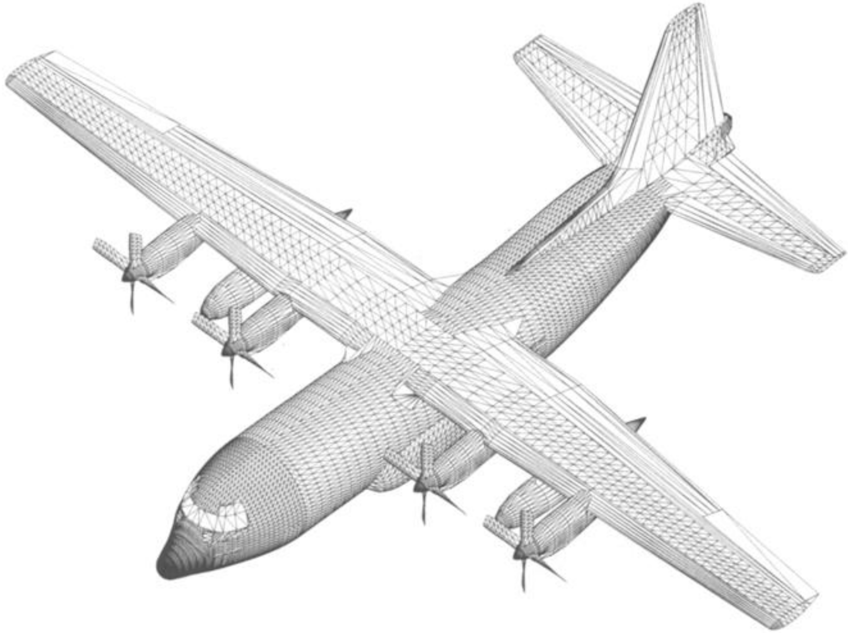


Fig. 5.30a Triangular patch model of the exterior surface of the C-130H (Reproduced with permission of Lockheed Martin Aeronautical Systems).

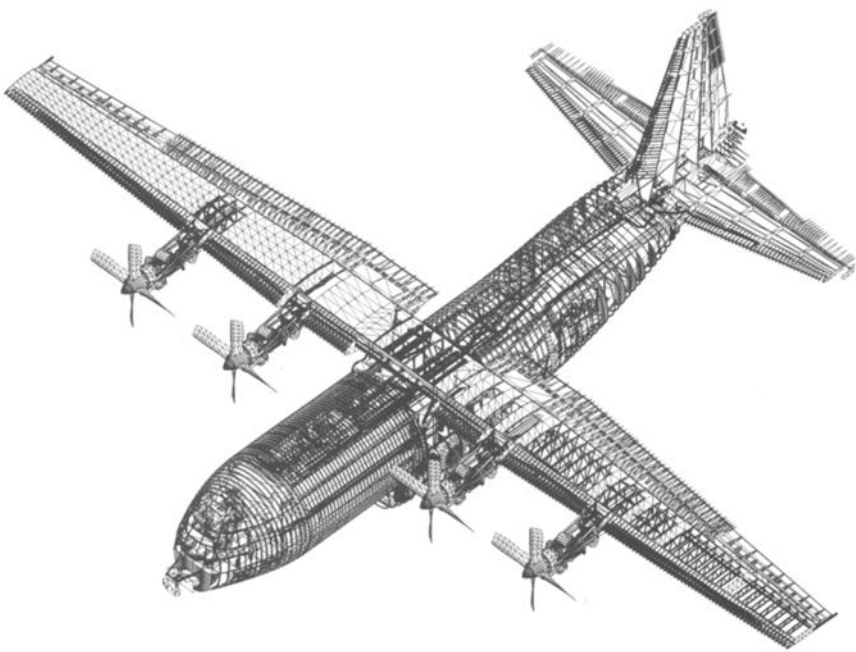


Fig. 5.30b Triangular patch model of the structure and systems of the C-130H (Reproduced with permission of Lockheed Martin Aeronautical Systems).

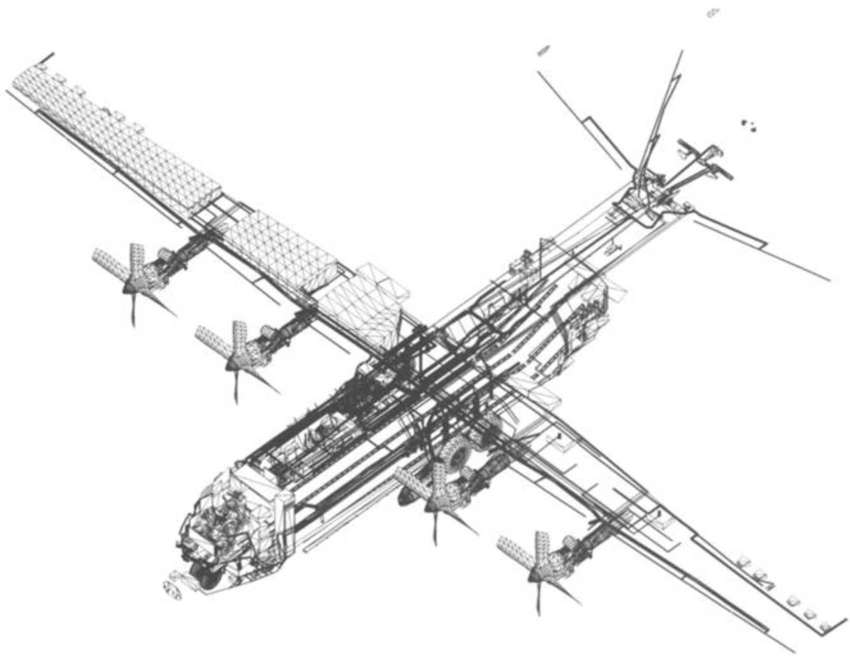


Fig. 5.30c Triangular patch model of the systems of the C-130H (Reproduced with permission of Lockheed Martin Aeronautical Systems).

in-depth studies. However, they have the potential for use in early design studies in which only a limited amount of technical description data are available. The evaluation routines are more appropriate for problems in which a cursory analysis is desired.

Analysis routines: The family of programs VAREA, VAREA02, and COVART belong to the detailed group. COVART (Computation of Vulnerable Area and Repair Time) is in the SURIVAC Model Guide and is briefly described in Chapter 1, Sec. 1.5.2. The latest version is COVART 4. The most recent addition to this category is AJEM (Advanced Joint Effectiveness Model). AJEM is briefly described in Chapter 1, Sec. 1.5.3.

The input data to COVART and AJEM includes the shotline descriptions of the target model generated by the shotline programs FASTGEN and BRL-CAD, probability of kill given a hit data for the individual components, empirical ballistic penetration data, and weapon characteristics data. The procedure used to compute the single-hit vulnerable area is the same as that described in this chapter for a single hit by a nonexplosive penetrator or fragment. In the shotline generator program, a grid is superimposed over the aircraft's presented area and a shotline is randomly located within each grid cell, as illustrated in Fig. 5.28. The extent of a component is defined by the C cells whose shotline intersects the component. Note that two or more overlapping components may lie within a single cell. Each cell within a component has a vulnerable area A_{vi} that is given by the product of the cell presented area A_c and the probability of a component kill for the ith shotline in that cell $P_{k|hi}$. Overlapping components within a common cell will have different cell vulnerable areas when the $P_{k|h}$ values are different. The total vulnerable area of each component is the sum of the component vulnerable areas computed for the C cells whose shotline passes through the component. Thus, each component's vulnerable area is given by

$$A_v = \sum_{i=1}^{C} A_{vi} = \sum^{C} A_c P_{k|hi} \tag{5.27a}$$

When computing the vulnerable area of the aircraft, the probability the aircraft is killed given a hit along the ith shotline $P_{K|Hi}$ is determined for the S shotlines within the aircraft, as shown in Fig. 5.28, using the procedure for a single hit on nonoverlapping and overlapping nonredundant and redundant components described in Sec. 5.3.4.1. Note that $P_{K|Hi}$ will be nonzero only when the ith shotline intersects any nonredundant critical components or when it intersects a sufficient number of redundant critical components to cause an aircraft kill. The product of the cell presented area A_c and the $P_{K|Hi}$ for the ith shotline gives the aircraft vulnerable area for the ith cell A_{Vi}. The total aircraft vulnerable area A_V is the sum of all of the cell aircraft vulnerable areas. Thus,

$$A_V = \sum_{i=1}^{S} A_{Vi} = \sum_{i=1}^{S} A_c P_{K|Hi} \tag{5.27b}$$

Note the similarity between Eq. (5.27b) and Eq. (5.24b) for the A_V for a single hit by a contact-fuzed HE warhead. The difference between the two is that a single hit by a nonexplosive penetrator can only kill components intersected by the shotline (unless the hit component's $P_{k|h}$ has been modified to account for cascading damage), whereas a hit by an HE warhead can kill components that are not intersected.

Evaluation routines: The computer programs COMVAT and QRV (Quick Response Vulnerability) are representative of the routines that belong to the other group, the simplified codes. These routines were developed to fulfill the need for relatively quick methods for computing vulnerable area. They are intended to be used in situations when use of the more sophisticated routines might not be feasible or timely, such as during early conceptual design studies. The simplified routines are not as accurate as the detailed routines, but they should require considerably less effort and computer run time to use.

Internal burst programs. Several programs for computing the vulnerability of aircraft to internally detonating HE warheads have been developed under the direction of the JTCG/AS and the JTCG/ME. These programs are sometimes referred to as point burst or internal burst programs. The two major programs are AJEM and COVART 4. These programs use the second approach described in the preceding section on vulnerability to internally detonating HE warheads.

Endgame programs. The endgame refers to the terminal events in an encounter between an aircraft and an HE warhead with a proximity fuze. Just how the warhead got to the vicinity of the aircraft is irrelevant to the endgame analysis. The endgame events might include target detection by the fuze and usually do include the warhead detonation, blast propagation, and fragment flyout, impact, and penetration through the aircraft. The numerical value for the $P_{K|F}$ is then determined for the given set of encounter conditions and warhead and aircraft characteristics. This procedure is usually repeated for many different sets of encounter conditions and warhead detonation points, and $P_{K|F}$ is established as an array of numbers similar to that shown in Fig. 3.10, or as a function of the detonation distance as shown in Fig. 3.11. The three major endgame programs currently in use are SHAZAM, JSEM (Joint Service Endgame Model), and AJEM. AJEM is briefly described in Chapter 1, Sec. 1.5.3, so only SHAZAM and JSEM will be presented here.

SHAZAM: This code was developed at the U. S. Air Force Research Laboratory Munitions Directorate for the evaluation of air-to-air missile effectiveness. The program sequentially assesses the possibility that the target aircraft is directly impacted by the missile, the effect of blast overpressures upon the target structures, and the cumulative effect of warhead fragment impacts on the target structure and critical components. The size, shape, and position of the target body and internal components are described by discrete surfaces, and each surface can be vulnerable to a direct hit, blast, or fragments. The criteria used to define the kill of each component/surface are supplied by the user. The program utilizes as much of the aircraft descriptions that are prepared for the FASTGEN and COVART programs as is economically feasible. A sufficiently large number of encounter conditions are assessed to generate a single-shot probability of kill that has converged to a user-specified confidence level.

JSEM: The JSEM computer simulation program evaluates the terminal effectiveness of a fragmenting munition against a target (usually airborne). The input consists of the initial conditions of dynamic missile orientations to the target (velocities, angles, and miss distances) and fuzing time. The component probability of kill given a hit ($P_{k/h}$) functions are usually obtained from COVART. In addition to these data, JSEM also requires target contours, blast data, kill trees, component location and damage options, and missile warhead and fuze data.

Go to Problems 5.3.20 to 5.3.23.

5.4 Task III: Design for Low Vulnerability Using Vulnerability Reduction Technology

5.4.1 Vulnerability Reduction Concepts

Learning Objective	**5.4.1**	**Describe the six vulnerability reduction concepts.**

Vulnerability reduction refers to the use of any design technique or piece of equipment that controls or reduces either the amount or the consequence of damage to the aircraft caused by the damage mechanisms. In other words, VR means controlling or reducing the vulnerability measures of the aircraft and its components. The potential kill modes of each system of the aircraft identified in Task I must be examined when considering vulnerability reduction, with particular attention given to those systems that combat data analyses and vulnerability assessments have shown to be the most vulnerable. There are many and varied ways to accomplish this reduction. Some of them involve the design, layout, and location of the various systems; others require special equipment. Some add weight; others are simply the results of good design practice and might actually reduce weight; and many, if not most, also enhance the safety of flight. In general, each of the techniques for reducing vulnerability is a specific application of one of the six vulnerability concepts introduced in Chapter 1, Sec. 1.1.8. These six concepts are 1) component redundancy (with separation), 2) component location, 3) passive damage suppression, 4) active damage suppression, 5) component shielding, and 6) component elimination or replacement. When considering the possible kill modes of each aircraft system, these six VR concepts, described in some detail in the following subsections, should be examined to see how they can effectively be applied to prevent the loss of that system.

5.4.1.1 Component redundancy (with separation). The employment of multiple devices, structural elements, parts, or mechanisms in combination for the purpose of enhancing survivability is known as redundancy. (Redundancy is often specified for safety of flight reasons alone.) Redundancy can be employed at the component, subsystem, or system level, and can be one of two general types; total redundancy, in which each redundant element is fully capable of performing the essential function, and partial redundancy, in which each element independently performs some portion of the function. If the redundancy is achieved through the use of similar sets of components in which each set performs identical functions, the system is said to have actual redundancy. Functional redundancy is achieved through the use of different sets of components to perform the required functions. Examples of total redundancy are dual-power-control hydraulic subsystems, two sump tanks, and multiple engines (with one or more engines out capabilities). Partial redundancy is a copilot who can fly but not land the aircraft and dual electrical generators where a single generator only powers some of the aircraft systems. Functional redundancy is the use of a speed brake as a backup control surface. Inherent in the assumption that redundancy actually exists after damage occurs is the requirement that redundant components be effectively separated such that one hit will not directly or indirectly kill both components. For example, the engines in a twin engine aircraft should be separated so that one hit by a damage mechanism will neither directly kill both engines, such as a penetrator striking and killing both engines, nor indirectly kill them, such as a penetrator causing a fire in one engine that spreads to the adjacent engine, eventually leading to a loss of both engines.

5.4.1.2 Component location. The type of vulnerability reduction that is achieved by positioning critical components in a manner that reduces the probability that a damage mechanism will produce lethal damage is referred to as component location. Component location design techniques include 1) positioning noncritical or tougher components to provide masking for the critical components or burying the critical components deep inside the aircraft; 2) orienting critical components to minimize their presented area in the anticipated threat direction, for example, the bottom; 3) compactly grouping or overlapping *nonredundant* critical components to reduce the aircraft's vulnerable area from a particular direction (Note 32); and 4) locating or isolating components such that the possibility of cascading damage is reduced or eliminated. Examples of component location are the placement of a tail-rotor servoactuator in the tail-rotor gearbox, the location of the hot-air bleed line such that fuel or other combustible mixtures will not leak from punctured lines or containers on to the hot line, and the location of fuel tanks to prevent ingestion of fuel from damaged tanks (Note 33).

5.4.1.3 Passive damage suppression. The term passive damage suppression describes any design technique that reduces vulnerability by incorporating a feature that, after the impingement of a damage mechanism, tends to either contain the damage or reduce its effect. These passive features have no damage-sensing capability. There are several passive damage suppression techniques to consider.

Damage tolerance. Damage-tolerant design techniques provide for the construction of aircraft structure and internal components that will accept a degree of mechanical damage without impairing their functional capability. This is accomplished, for example, by providing redundant load paths in critical structural elements, such as multispar wings, by using high-fracture-toughness materials to limit crack propagation, and by using large-diameter, thin-wall control rods that can function with perforations caused by projectiles and fragments. Dual, tandem hydraulic power actuators can be made with rip-stop construction to prevent cracks in one power cylinder from propagating to the other power cylinder and causing a loss of both power-control hydraulic subsystems.

Ballistic resistance. Ballistic resistance is a design technique involving the use of high-strength materials in components for the purpose of preventing the total penetration of an impacting penetrator or fragment. For example, the casing around a hydraulic actuator or gearbox can be made ballistically resistant.

Delayed failure. The delayed failure technique reduces vulnerability by using elements that continue to function for a prolonged period of time during and after a damage process, such as penetration or fire. For example, helicopter transmissions and gearboxes have been designed to operate long after a loss of lubrication. Another example is the selection of high-temperature-tolerant materials to serve as a fire barrier in areas where critical components might be exposed to fire from burning fuel, hydraulic fluid, or torching from a damaged engine combustor or hot air bleed line.

Leakage suppression. Leakage suppression is a technique that uses self-sealing materials that are designed to accept a degree of ballistic damage and to subsequently allow little or no leakage from the fluid container. Self-sealing materials are beneficial not only because they retain the fluid for continued use, but also because they stop the leakage of the fluid to areas where combustion could occur. Leakage suppression techniques seal off sensitive or ignition-producing areas and also provide for the drainage of combustible fluids. Self-sealing fuel tanks and lines are common examples.

Fire and explosion suppression. Fires and explosions require three basic elements: oxygen, a flammable material or vapor, and an ignition source. Suppression or prevention of fires and explosions requires either the prevention of ignition or the suppression of the flame front propagation once ignition has occurred. For flammable fluids and vapors ignition can be prevented by techniques that do not permit the ratio of fluid vapor and air that will support combustion to occur. For example, forced venting of the internal spaces and voids of an aircraft where a fire might occur, such as the engine compartment, is one method of accomplishing this prevention. Inerting the ullage of fuel tanks with nitrogen or partially filling fuel tanks with a flexible foam that hampers propagation of a flame front are also effective methods.

Fail-safe response. This design technique provides critical systems with components that will revert to a marginally operable condition for a specified or indefinite period of time after damage. Examples include an engine fuel control device that is designed to revert to a predetermined setting if the throttle control signal is severed and control surfaces that become locked in a flyable position in the event of a total loss of hydraulic power to, or control of, the surface actuator.

5.4.1.4 Active damage suppression. Active damage suppression describes any technique that reduces vulnerability by incorporating a sensor or other device that, upon the impingement of a damage mechanism or the occurrence of a damage process, activates a function which either tends to contain the damage or reduces its subsequent effects. The most common example of an active system is a fire detection and extinguishing system that uses a detector to sense an ignition source or high-temperature area. Following detection, the system can automatically dispense an inerting fluid or extinguishing gas, or it can alert the pilot, who can then take appropriate action. Another example is an override switch or shear pin that allows the pilot to disengage a damaged component, such as a jammed control rod which has frozen the control column. An example that was used on the F-105 in the SEA conflict was the vulnerability reduction package that was added to the stabilator hydraulic lines. If a line were damaged, a check valve prevented the fluid in the hydraulic cylinder from draining out and maintained some pressure (passive damage suppression). A warning light came on in the cockpit notifying the pilot that hydraulic power would soon be lost. The pilot quickly leveled the aircraft and threw a switch that activated a mechanical arm that locked the stabilator in place (active damage suppression). Today's self-repairing or reconfigurable flight control systems are another example of active damage suppression. Damage to a flight control surface is detected and identified, and the flight control laws are modified to maintain safe flight. A similar VR feature exists for engine control subsystems.

5.4.1.5 Component shielding. Shielding of components is achieved with the use of coatings or platelike materials that tend to resist or absorb the damage mechanisms. The shielding can be armor material that might or might not be an integral or load-bearing part of the aircraft structure. The armor is called parasitic if it is attached to bulkheads or other structural elements and serves only a shielding function. This is often the only choice available in a retrofit situation. A better technique is to use integral armor that is incorporated early in the design and is a functional part of the structural system. Armor may consist of a solid plate or two or more spaced plates. The plates can be composed of one material, or they can be a composite consisting of two layers of materials, such as a crew seat made of a ceramic front plate attached to a Kevlar® backing material. Shielding may also be provided for the crew members in the form of body armor. However, because the crew member is already encumbered with flight gear, the increased stress and fatigue associated with body armor often makes its use impractical. A blast and fragment shield can be used in the cockpit to effectively separate a pilot and copilot so that an explosion of an HE projectile inside the cockpit does not kill or injure both crew members. The term shielding is used here when additional coatings or plates are added to the design specifically to protect a component. When a critical component is placed behind a another component, the term masking is used, and the associated concept is the location concept.

5.4.1.6 Component elimination or replacement. Vulnerability can be reduced by completely eliminating a particular critical component or by replacing the component with a less vulnerable component that accomplishes the same function. For example, replacing a fuel-feed boost pump with a fuel-feed suction device can reduce vulnerability by eliminating the possibility of pumping fuel through damage-caused holes in fuel transfer and feed lines and into void spaces where a fire can start. Vulnerability also is reduced when a large component (large A_p) is replaced with a small component (small A_p) with a similar value for the $P_{k|h}$. Replacing mechanical flight control rods and linkages with redundant and separated electrical wires or optical fibers can also reduce vulnerability. One major revolution in today's air combat operations that takes advantage of this particular VR feature is the use of UAVs or UCAVs rather than piloted aircraft to reduce the consequences of a downed air vehicle (aircraft). In the unmanned aircraft the onboard human pilot has been replaced with a less vulnerable electro-optic sensor/electronic controller.

5.4.1.7 Damage-tolerant design techniques vs damage-resistant techniques. Damage or ballistically tolerant design techniques are those techniques that are intended to 'bend' with the damage or hit, whereas the damage or ballistically resistant techniques are designed to 'repel' the damage mechanism. Examples of damage-tolerant techniques are helicopter gearboxes that can operate for 30 min without lubrication and engine accessory drives that are located behind noncritical components. The corresponding damage-resistant designs would be the use of armour shielding in front of the gearbox and the accessory drive. When the effectiveness of each of the various reduction concepts described here is evaluated for application to a particular aircraft, the damage-tolerant techniques usually reduce the vulnerability with significantly less weight penalty than that associated with the damage-resistant techniques.

Go to Problems 5.4.1 to 5.4.10.

5.4.2 ABCDEs of Vulnerability Reduction

A convenient acronym was created nearly a half-century ago to assist the reader in remembering the ways vulnerability can be reduced—the ABCDEs.[6] The definition for each letter is given here with the corresponding VR concept in parentheses:

A = add protection to the critical components (passive and active damage suppression and shielding).

B = bury the critical components (location).

C = concentrate the nonredundant critical components (where it makes sense to reduce the presented area) (location).

D = duplicate and separate (redundancy with separation).

E = eliminate unnecessary critical components (elimination/replacement).

5.4.3 Aircraft Design Guidelines for Reduced Vulnerability

The major systems on an aircraft have been described in Chapter 2. These include the fuel system, the propulsion system, the flight control system, the structural system, and the crew system. The kill modes associated with these systems (as well as those for several other systems) are listed in Table 5.5. A brief description of the VR techniques and technology for each of these systems is presented next. The components of the system are defined, and the kill modes listed in Table 5.5 and described in the subsection "*Some important kill modes of critical components and systems*" in Sec. 5.2.2.7 are listed. General design guidance and some specific VR techniques are then presented for each possible kill mode. A template is provided at the end of this section that can be used to list the VR features which are used in any particular design to either prevent or reduce the severity of the system kill modes. The reader who is interested in delving deeper into this subject should refer to the survivability handbooks described in Chapter 1 and Ref. 7 in this chapter.

5.4.3.1 Fuel system.

Learning Objective 5.4.2 List the fuel system kill modes, and describe the VR techniques.

The fuel system is defined as those components that store and deliver fuel to the engine. The system includes, but is not limited to, the following subsystems and components: storage tanks (internal and external), distribution (lines, pumps, valves, controls, and filters), refueling/dumping, and indicating. The fuel tankage and distribution subsystems usually represent the largest subsystems of the aircraft and are vulnerable to almost all of the damage mechanisms. If unprotected, the fuel system is likely to be the primary contributor to aircraft vulnerability. However, proper design of the fuel system can provide a significant degree of system protection. A high priority assigned to the design of the fuel system to reduce vulnerability will therefore be extremely effective in increasing the survivability of the aircraft.

Kill modes. Fuel system damage-caused failure modes are fuel supply depletion, fire/explosion (in-tank/ullage and in the void spaces), and hydrodynamic ram.

Design guidance and VR techniques. The fuel system should be designed to withstand the specific threats identified in the aeronautical system performance specification and in the implementing documentation while providing a specified quantity of protected 'get home' fuel. For carrier-based aircraft the fuel systems should be designed to contain the fuel when the aircraft is engulfed in a fire for the time specified in the aircraft performance specification and in the implementing documentation. Development of aircraft fuel systems with protection against the higher levels of nonnuclear weapon effects can only be achieved if the most effective survivability enhancement techniques are incorporated into the basic design concept. Inherent VR features are relatively easy to incorporate in conceptual or preliminary design when the location and geometry of the fuel system are established, but are very difficult to add to an existing design when tank locations, sizes, and other basic airframe configurations are frozen. This is why it is so important to consider survivability in conceptual and preliminary design. Weight gain and fuel volume loss penalties for modifications of existing designs usually result in reduced payloads and reduced combat range. Nevertheless, although the penalties and installation problems might be significant, improvements to the fuel systems of current production aircraft and to those already delivered should be seriously considered.

General principles: The fuel tanks should be located to minimize presented areas in primary threat directions. The fuel tanks, fuel lines, and other fuel system components should be located in such a way that damage to one element does not cascade into other systems. The tanks should be located so as to take advantage of structural masking and to minimize fuel line runs and exposures. All fuel system components containing fuel should be located so that potential leakage or vapors from combat damage neither flows nor is drawn into engine inlet ducts or into contact with possible ignition sources, such as hot engine components, armament, oxygen systems, engine hot-air bleed lines, and electrical and electronic equipment. Conversely, fuel containers and lines should not be located where they might be exposed to sparking from severed electrical lines or to hot gases from such sources as torching from perforated engine combustors and hot-air bleed lines. Fuel management systems should minimize aircraft center-of-gravity displacement problems if fuel transfer capability is lost.

Prevention of fuel supply depletion: Preventing or minimizing fuel leakage is essential for the prevention of fuel supply depletion. It also significantly reduces the probability of fires, explosions, and engine fuel ingestion as a result of ballistic and hydrodynamic ram damage. Design techniques to minimize fuel leakage include the use of self-sealing fuel tanks and lines in conjunction with the use of a low ullage pressure when the aircraft is in combat areas to promote good sealing and to lower the weight requirements of the self-sealing materials. The system should also be designed for tolerance to hydrodynamic ram. The fuel flow configuration and management sequence should be designed in such a way that the maximum amount of fuel is available to the propulsion system by gravity feed. Multiple, separated sump tanks should be used with feed redundancy provided by crossovers in the fuel transfer lines to each engine, and redundant or damage-tolerant supports for the fuel lines should be used. A suction fuel feed system should be considered in lieu of a boost system, and the length of lines outside of tanks should be minimized. The entering and exiting lines, connectors, and closures should be located in the ullage portion of the tanks to minimize the possibility of leakage outside of the tanks, and pumps and other transfer components should be located so they are shielded by the fuel or major structure. Fuel gauging systems should provide quantity difference indications sufficiently sensitive to permit detection of fuel loss from specific tanks. Fuel flow management should have the capability of bypassing damaged components using crossfeed lines and shielded shut-off valves to conserve the fuel supply and minimize leakage. Compartmentalized fuel tanks should be used to minimize fuel loss resulting from ballistic damage. Leakage drain holes should be located to avoid long leakage paths to the exit from the aircraft and leakage of liquid fuel and fuel vapors to hazardous compartments.

Most fuel tankage is either metal or bladder. The metal or wet tanks obviously leak when punctured. In general, the bladders do not seal any punctures and might or might not be tear resistant. Tear-resistant bladders do reduce the rate of fuel leakage caused by penetration below that of non-tear-resistant bladders. Self-sealing a metal or bladder tank consists of the application of one or more sealant layers possibly reinforced with coated fabrics of various configurations. Exposure of the sealant, such as uncured rubber, to the fuel as a result of a puncture results in a swelling of the sealant and closure of the wound. Self-sealing tanks are often used in conjunction with a backing board, which provides additional support to the tank walls. The backing board suspends the tank away from the aircraft structure and minimizes metal petaling into the tank, which would degrade the self-sealing effectiveness. Fuel tanks designed to be crashworthy are relatively easy to seal because of their resistance to cracking and petaling. There are limitations to the protection provided by the self-sealing technique, such as the inability to seal against large HE threats and very high-velocity penetrators and fragments, and leakage after penetration of fittings, doors, and corners. There can also be increased maintenance problems. The weight penalty incurred by the use of self-sealing construction can range from 0.4 to 2.5 lb/ft^2, depending upon the level of protection. If the fuel is not in contact with the upper portions of a tank during combat, weight can be saved by using a tear-resistant bladder construction without a sealant in this area. Reduced sealant thickness can also be used where ullage and fuel pressures are low.

Liquid pressures in fuel lines and hoses caused by hydrodynamic ram or penetration by a projectile or fragment can cause cracking, tearing, shattering, or petaling of the walls. A liquid pressure pulse can increase the size of perforations, and subsequent leakage in the line can interfere with the sealing function of any self-sealing material. Leakage from pressurized lines can be minimized by proper selection and application of self-sealing hoses and line covers. Self-sealing coverings should also be applied to suction feed fuel lines to maintain the vacuum in the event of a penetration and to improve performance.

Suppression of fires and explosions:[8,9] For many years protection of an aircraft against fire meant engine fire walls, engine compartment venting, fire detection (and possibly extinguishing) in the engine compartments and crew stations, and the elimination of ignition sources in and around fuel tanks. These protection measures were primarily installed to solve the peacetime fire safety problems that occur in engine compartments. However, studies of combat data have revealed that fires and explosions can occur in other areas, such as fuel tank ullages and the void spaces around the tanks, and that these fires are a major contributor to aircraft attrition rates. Consequently, a mature technology for the suppression of fires and explosions has been developed over the past 30 years or so (Note 34). (More data are available online at http://www.army-technology.com/contractors/protection/tss/index.html and http://www.walterkidde.com/Technical%20Paper.pdf.)

Fires and explosions can occur in 1) fuel tank ullages, 2) in the void spaces or dry bays around fuel tanks or lines, 3) in engine bays or nacelles, 4) in crew and cargo spaces, 5) in weapon bays, and 6) on the exterior of the aircraft. They are manifestations of the combustion damage process. Combustion is described in Chapter 3, Sec. 3.5.2.1, and Fig. 5.10 illustrates several possible combustion conditions for different penetrator or fragment shotlines into a fuel tank or line. Techniques for the suppression of in-tank and void space fires and explosions are based upon the following procedures: 1) removal of the energy supporting the combustion process by the absorption of heat, 2) interference with the combustion mixing process, 3) dilution of the oxygen concentration (too rich), 4) removal of the fuel vapors (too lean), and 5) breakdown of the long combustion chain reaction.

There are many suppression techniques available that use one or more of these procedures. One technique is the installation of either flexible or rigid lightweight safety foam in spaces where flammable mixtures could occur. (See Ref. 10 and data online at http://www.fire.tc.faa.gov/pdf/T64.pdf, http://www.crestfoam.com/intro.html, and http://www.foamex.com/technical/safetyfoam.asp.) For example, flexible, reticulated (porous) polyurethane foam can easily be installed in the ullage inside a fuel tank. When the tank is full of fuel, the foam is submerged. As the fuel is drawn from the full tank, some of it will adhere to the foam. When ignition occurs in the ullage, the wetted foam significantly reduces the combustion overpressure by rapidly absorbing and transferring heat away from the ignition point. The foam is also a locally rich zone, and the small pores interfere with the normal turbulence and mixing action that is characteristic of a flame front. The flexible polyurethane foam has been available in five types: the orange, yellow, and red polyester types (I, II, and III); and the dark-blue and light-blue polyether types (IV and V). Each color has a particular density and porosity. The foams typically displace 3% of the fuel by volume, and approximately 2% of the fuel volume will adhere to the foam skeleton.

The primary reason for installing the reticulated foam in the fuel tanks is to prevent large ullage overpressures following ignition of the flammable vapor. The entire tank does not need to be filled with the foam to accomplish this reduction. Optimization of internal foam installations can be achieved by installing only the volume of foam required to keep the combustion overpressure below the strength of the surrounding structure. It is possible to prevent excessive overpressures with much less than 50% of the ullage volume filled with the finer pore foam. Somewhat more of the larger pore foam would be required. This procedure is referred to as gross voiding.

Associated with the use of the polyester polyurethane foams is a problem called hydrolytic instability. When used in fuel tanks under conditions of high temperature and humidity, the early orange polyester foams lost strength, became brittle, and eventually deteriorated to the point that they deposited debris in the fuel system. This problem was extensively researched, and improvements in foam compositions, in particular the introduction of the blue polyether polyurethane foam, appear to have virtually eliminated this problem. Another problem discovered with foam was the ignition of fuel vapors by static electricity. Rapid filling of a fuel tank would result in the buildup of an electrical charge on the dielectric foam. A spark from the foam to an adjacent piece of metal would ignite the ullage gas, but the foam suppressed the combustion overpressure with only minor burning or scorching of the foam—not good. The development of the conductive beige, black (VI), and gray (VII) foams eliminated this problem (http://www.foamex.com/technical/safetyfoam.asp).

The foam provides excellent suppression at all times and under all conditions, including multiple hits. It is passive, there are no moving parts, no sensing devices, and may require only minimum logistic and maintenance support. It can be cut and fitted into awkward configurations. It mitigates fuel surging and sloshing and can reduce the effects of hydrodynamic ram. However, gross voided foam could be scrambled by the fuel during hard maneuvers.

A rigid, closed-cell (nonporous) ballistic foam can be installed in the void spaces or dry bays adjacent to fuel tanks and in other locations where flammable mixtures could accumulate. The rigid foam is an effective system that works for all threats. Typical weights are 1.5 to 2.5 lb/ft^3. It can be installed in individual molded blocks, or it can be sprayed in place. If lines or other equipment are located in the dry bays, cutouts must be provided, and areas where cooling or ventilating airflow is required cannot be totally filled. The main function of the rigid foam is to prevent the ignition source and the flammable mixture from coming in contact. It works best if the voids are completely filled, but thicknesses greater than several inches can provide some protection. The foam usually is covered with a metallic or fabric material. The flexible foam is more advantageous in those dry bays where the rigid foam is difficult to install, but it might be of limited effectiveness against the stronger ignition sources because it normally is dry in this application.

Lightweight fibrous flame suppressors (similar to angel hair) and expanded aluminum foil mesh (known as EXPLOSAFE™) have also been developed for installation in ullages and voids to suppress fires and explosions[11] (http://www.fire.tc.faa.gov/pdf/T64.pdf). These void fillers suppress the combustion overpressure in much the same way as the polyurethane foam. They are chemically stable in hot fuel and can have a fuel displacement and retention of about 3%. They can be used to completely fill the ullage, or they can be installed in a voided pattern, depending on the allowable combustion overpressure. The expanded aluminum foil mesh might be hard to remove from an ullage if internal tank inspection is required.

An alternative to the installation of foam, fibers, or expanded aluminum mesh is the introduction of an inert gas, such as nitrogen, in the ullages and closed void spaces during flight. Inerting systems prevent the initiation of combustion by reducing the oxygen concentration of the gaseous mixture to below the flammable limit; they make the fuel-air mixture too rich to support combustion. There are three different types of inerting techniques that have been designed for fuel tanks using nitrogen as the inerting agent: the dilution or closed-vent technique, the purging or open-vent technique, and the scrubbing technique. The dilution technique feeds nitrogen into the closed tanks as fuel is consumed or as decreases in altitude require a flow of air into the tanks to balance the increasing external atmospheric pressure. The purging technique sweeps out the fuel-air mixture in the ullage and replaces it with nitrogen. The scrubbing technique introduces fine bubbles of nitrogen into the fuel near the tank bottom. As the bubbles rise to the top, they scrub the fuel of dissolved oxygen. The tank ullage and vents are then purged. Three supply systems for the nitrogen exist. They are bottled cryogenic liquid, bottled high-pressure gas, and onboard nitrogen generation, known as the onboard inert gas generating system (OBIGGS). These systems typically require a supply reservoir, pressure regulators, relief valves, a pressure demand feed control, and the necessary plumbing required for distribution to the fuel tanks and void spaces.

The parameters of mission profile, volume of void space, and tank ullage condition and volume in the combat environment play an important role in sizing a nitrogen inerting system. The mission profile dictates the number of excursions to altitude, and thus the quantity of nitrogen lost through the pressure and vent sequences. The tank ullage volume during combat is also defined by the mission profile. Another factor that must be considered when rendering a fuel tank system inert by nitrogen is the fuel itself. If oxygen is introduced into the tank ullage through the pressure and vent system during aircraft flight, the fuel will absorb an amount of air that is dependent upon the total ullage pressure. As the aircraft gains altitude, some of the dissolved air will be expelled from the fuel into the ullage. When this occurs without nitrogen dilution of the expelled gases, the oxygen concentration might exceed the safe level.

The nitrogen inerting system can provide excellent fire and explosion protection at moderate weight, with no fuel loss, and in crowded ullages and voids dispersed throughout the aircraft, as long as the oxygen concentration can be maintained below the flammability limit. However, with very large ignition sources combustion can occur, and the overpressure will vary depending on the ignition level, mixture volume, and oxygen concentration. Furthermore, multihit capabilities might be limited because of leakage of the nitrogen through battle damage holes.

Logistics and maintenance requirements are relatively high for the liquid and gaseous systems because facilities for the supply of the nitrogen are required at each air base, and periodic checks of the equipment are necessary to ensure operational capability. Also, nitrogen inerting cannot be used in habitable compartments. The initial and life-cycle costs are usually relatively high, and the liquid system can require periodic filling when the aircraft is in an alert status. The full-time OBIGGS appears to eliminate many of the disadvantages of the stored liquid and gaseous nitrogen systems. Nitrogen can be obtained from an air supply, such as pressure and temperature conditioned engine bleed air, by absorption or diffusion processes. The absorption or sorbent-bed fuel tank inerting technique uses the phenomenon of oxygen absorption from air by synthetic zeolite. The diffusion type consists of a module composed of many hollow fiber membranes (Note 35). (http://www.airliquide.com/en/business/industry/space_aero/equipment/obiggs.asp and http://www.airproducts.com/membranes/page02.asp.)

Introduction of a HALON gas, such as HALON 1301 (Bromotrifluoromethane or CF_3Br), into ullages and voids during periods of potential combat is another suppression technique that is similar to nitrogen inerting, except that it does not replace the oxygen. Instead, the HALON is there to react with the transient, intermediate combustion products to break down the combustion process. The HALON is stored in liquid form in high-pressure bottles and is introduced as a noncorrosive, low-toxicity gas into the void spaces and ullages by the crew just prior to entering the combat area. A short burst fills the ullages and voids, and this is followed by a steady, low flow rate to replace the HALON that becomes dissolved in the fuel and lost in the voids. One potential problem is the possible stratification of the HALON in deep ullages. The use of HALON has been affected by the 1987 Montreal Protocol, which contained a schedule for the phase out of the production and consumption of ozone-depleting substances, which includes the HALONs (e.g., CFCs and HBFCs). A search for cost-effective and environmentally safe replacements for the HALONs is underway[12]. Three candidates for unoccupied areas, such as fuel tank ullages, dry bays, and engine nacelles, are trifluoromethyl iodide

(CF_3I), HFC-125 (CF_2H_2/CF_3-CHF_2, FE-25), and FC-218 (CF_3-CF_2-CF_3)[12,13] (http://www.afrlhorizons.com/Briefs/0012/ML0008.html).

Other suppression concepts for dry bays are the powder pack, panel, or sleeve and the purge mat. Both the pack and the mat are located within the voids on the wet wall. When they are perforated by a penetrator or fragment, they spill their contents, which suppress any possible combustion from taking place. The powder panel contains a dry fire suppression material, whereas the purge mat contains a high-pressure inerting gas, such as nitrogen.

Another technique for ridding the void spaces of flammable vapors is to provide a continuous flow of air through the space. The air can be obtained from the inlet duct air or from ram-air ducts on the exterior surface of the aircraft. Flowing air is often used in engine compartments to both cool the engine and vent any flammable vapors.

The use of a special 'antimisting' fuel is another technique for preventing combustion. Antimisting fuel is aviation fuel that contains an additive, such as a polymer powder called FM-9, that prevents the development of fuel mists. Although the additive might be very effective in preventing combustion, both in flight and during a crash, it can have some disadvantages. For example, jet engines can only burn fuel that is injected into the combustor as a mist, which is precisely what the additive is supposed to prevent. Consequently, the fuel must be treated by shearing or chopping the polymer chains prior to injection into the combustor. This fuel can also cause problems in the pumps, filters, and other distribution components where a gel could form under certain conditions, causing a blockage of the fuel flow. Furthermore, the properties seem to change with the environmental conditions, and the additive might have to be blended with the fuel at the aircraft fueling station caused by storage stability problems. Nevertheless, the antimisting fuel is a potential survivability enhancement technique. The most effective use of the antimisting fuel will probably require the development of propulsion systems that have been specifically designed to use this type of fuel[14].

The preceeding passive techniques are full time or part time and are referred to as fire and explosion suppression or prevention systems. The other option is to actively detect and extinguish combustion either shortly after ignition occurs (to prevent an explosion) or after a fire has started. The former can be referred to as a suppression system; the latter is a fire detection and extinguishing system. Small volume, lightweight, fire and explosion suppression systems have been developed for fuel tank ullages and dry bays. These systems operate by first detecting the presence of an ignition source or flame front and then rapidly dispersing a fire-suppressing agent or an inert gas from small containers before the combustion process can build up. Two systems that use a compressed gas or vaporizing liquid agent are the linear and the radial fire extinguishers. In these systems the agent is expelled under high pressure through a pattern of holes in the bottle or container. The radial fire extinguisher has the advantage of a zero net force when expelling the agent. The gas generators usually contain a solid propellant that quickly combusts, providing a large volume of inert gas that displaces the air in the ullage or dry bay, similar to the air bag in your automobile.[15]

The ignition/combustion detectors in both types of systems are radiation detectors and can utilize an infrared sensitive lead sulfide photoelectric cell or an ultraviolet sensitive tube. Because radiation sensors are line-of-sight type detectors, complex voids and multicell tanks might require more than one detector and possibly multiple dispensers. The radiation detectors must also be shielded from all stray light to ensure that the system is not inadvertently triggered. Detectors that sense the hydrodynamic ram pressure on the wall of a penetrated tank have also been developed.

The traditional fire detection and extinguishing systems used in engine nacelles and other void spaces where a fire can occur have a temperature sensor that registers an overheat condition and an extinguishing agent is dispensed into the compartment with the fire in one or more shots. This type of system is always used in engine bays and nacelles for multiple-engine aircraft, when sufficient thrust is available with one engine shutdown as a result of a fire. It also might be appropriate to use it on single-engine aircraft when it is possible to isolate any fuel leaks without shutting the engine down.

The active type of fire and explosion suppression systems might be ineffective if the peak combustion overpressure is reached before the chemical agent or inert gas is dispensed. Also, large, damage-caused holes in the protected bay could allow the agent or gas to escape before completely suppressing the combustion. The logistics support for the bottle storage systems might be high because the bottles must be replaced after each activation. Periodic inspection of the bottles might also be required to ensure that inadvertent activation has not occurred, and a deactivation circuit is required for routine maintenance. Toxicity and corrosive properties of the gaseous and the dry chemical suppression agents used must also be considered.

A new, simple passive extinguisher (SPEX) system for protecting dry bays has recently been proposed that eliminates the elements and subsystems required for fire detection and agent dispensing in the active systems. The concept places small containers filled with a reactive agent directly within the dry bay to be protected. An example agent could be the heat-sensitive powder or molded brick propellant called BTATZ that decomposes into a nitrogen gas without flame at ambient pressure. The characteristics of a fire, such as heat, initiates activation of the agent so that it rapidly fills the dry bay and extinguishes the fire.[16]

Fire containment within aircraft dry bays is a major requirement when it is neither possible to prevent the fire from occurring nor possible to extinguish it. Fire migration throughout an aircraft can create many problems that were unforeseen in the early development stages. Exposure of components and structure to high thermal environments can circumvent many excellent survivability features. Recent developments have resulted in various insulating foams, ablators, and intumescent coatings to provide improved fire containment.

A summary listing of some of the current techniques for preventing fires and explosions in aircraft is given in Table 5.11. Also shown in the table are aircraft that use one or more of these techniques. Several examples of fuel tanks designed for fire and explosion suppression and self-sealing are given online at http://www.army-technology.com/contractors/protection/tss/index.html.

Prevention of structural failure caused by hydrodynamic ram: The prevention of structural failure as a result of the overpressure caused by hydrodynamic ram is described in the vulnerability reduction of the structural system.

Go to Problems 5.4.11 to 5.4.14.

Table 5.11b Listing of some current techniques for preventing fires and explosions

Techniques	Location	Aircraft
Passive		
Flexible, reticulated polyurethane foam	Ullage	A-10, F-15, F/A-18, C-130, P-3
Rigid, closed-cell ballistic foam	Dry bay	A-10, F/A-18
Fibrous filler	Ullage and dry bay	——
Expanded aluminum mesh	Ullage	——
Nitrogen inerting (liquid, gas, or OBIGGS)	Ullage	C-5 (L), C-17 (O) F/A-22(O) AH-64 (O) AH-1W (O), V-22 (O)
HALON (or its replacement, e.g., CF_3I, HFC-125, and FC-218)	Ullage	F-16
Antimisting fuel		
Powder pack/panel/sleeve	Dry bay	V-22
Purge mat	Dry bay	——
Void space venting with air	Ullage, dry bay, and engine bay/nacelle	Most aircraft
Fire wall	Dry bay and engine bay/nacelle	All aircraft
Active		
Ignition detection and combustion suppression	Ullage, dry bay, and engine bay/nacelle	F/A-18E/F, V-22
Fire detection and fire extinguishing	Dry bay and engine bay/nacelle	Aircraft with multiple engines

5.4.3.2 Propulsion system.

Learning Objective 5.4.3 List the propulsion system kill modes, and describe the VR techniques.

The propulsion system is usually considered to be made up of the engine(s), the inlet(s) and exhaust(s), the lubrication subsystem, and the controls, accessory drives, and gearboxes. The vulnerability of the propulsion system is highly sensitive to the specific system design and the damage mechanisms. Consequently, gas turbine design requirements have become increasingly more demanding in recent years, not only in terms of performance, but also in terms of survivability requirements. Such items as the engine cycle selection, engine configuration, component design, and component vulnerability should be examined with respect to their contribution to the vulnerability of the propulsion system itself as well as to the survivability of the aircraft. In general, the latest engines under development have higher rotating speeds and higher peak gas temperatures and pressures, which make them appear to be more vulnerable. However, they are also smaller, with fewer stages, and lighter, with cooler casing temperatures and lower specific fuel consumption. These improvements in size, weight, and efficiency contribute to making the aircraft a smaller target with reduced fuel requirements and, consequently, more survivable.

Kill modes. The possible damage-caused failure modes of the propulsion system are air inlet flow distortion; engine failure (fuel ingestion, foreign object damage, fan/compressor damage, combustor damage, turbine damage, and exhaust duct or afterburner damage); engine fire; and engine subsystem or control failure (loss of lubrication and engine controls and accessories failure).

Design guidance and VR techniques. The engine installation should be designed to be protected from the weapon effects required by the aeronautical system performance specification and the implementing documentation. The design of the propulsion system is a highly specialized effort performed by only a few organizations. As a consequence, only a few of the more general VR techniques are described here.

General principles: The propulsion system should be configured to minimize the probability of a complete loss of thrust caused by a single hit from a specified projectile or fragment. Protection of critical engine components should be provided against the damage mechanisms using the masking provided by structural members and other equipment. If masking is not possible, consider shielding the components with armor. The engine mounting system should be redundant and not fail because of a single hit. Redundancy of components should be considered, and the engine should be located out of the expected line of fire and isolated from the fuel tanks as much as possible. Secondary hazards from damaged engines, such as hot gas torching and broken blades, should be contained. Measures should be taken to prevent engine fires from spreading beyond engine compartments or nacelles. The engine compartments or nacelles should be drained and vented, and means should be provided for shutting off the flow of flammable fluids into or through the compartments. A highly reliable and survivable fire detection device and fast-acting fire extinguishers with more than one dispensing shots should be installed in each engine compartment.

A major system redundancy can be provided by the use of multiple engines. For multiple-engine aircraft the engines should be physically separated or protected, including thermal insulation if required, to prevent complete loss of thrust caused by a hit from a single propagator. Design techniques should be incorporated to prevent or minimize the probability of cascading damage, such as fire propagating from one engine to another engine and causing a total loss of thrust or severely degraded performance. The engines should be completely independent, with separate fuel and oil tankage, feed lines (with crossovers), pumps, and controls, and the controls should have a fail-safe response if damaged.

Prevention of inlet flow distortion: Air inlet distortion can be the result of the large petaling of the inlet duct walls caused by hydrodynamic ram or by a detonation of an HE projectile near the duct wall. Construction techniques that mitigate hydrodynamic ram damage should reduce the probability this failure mode will occur.

Prevention of engine failure: The cracking and petaling of common fuel tank and inlet duct walls as a result of penetration and hydrodynamic ram can allow chunks of metal and large quantities of fuel to be ingested into the engine. Elimination of fuel and foreign object ingestion by eliminating the fuel tank/inlet duct interface completely, or by reducing the inlet duct damage caused by hydrodynamic ram, are the most important design techniques for reducing the probability of engine failure caused by ingestion. Techniques for reducing the damage caused by hydrodynamic ram include special construction, the use of duct materials that are ballistically tolerant and yield very little debris when either impacted by penetrators or subjected to hydrodynamic ram, and a fuel management schedule that ensures that fuel in the tanks adjacent to the inlet ducts is used prior to entering hostile areas. When engines are damaged by ingested metal, secondary damage mechanisms can be created, which are more lethal to the aircraft than the primary damage mechanisms. Generation of penetrators as a result of damage to high-speed rotating components, such as broken turbine blades, can be reduced by the incorporation of engine fan, compressor, and turbine blade containment or shielding measures.

Prevention of engine fire: The techniques for preventing or quickly extinguishing a fire associated with the fuel system just described are applicable to the prevention of an engine fire. Fire walls, ventilation, and fire detection and extinguishing systems are essential to the survivability of aircraft, both military and civilian.

Prevention of engine subsystem or control failure: One of the most important techniques for the reduction of propulsion system vulnerability is a fail-safe lubrication subsystem. The relatively large presented areas of the components, their ease of perforation by relatively small damage mechanisms, and the short time the pilot has to act after loss of lubrication make protection of this subsystem vital. The probability of continued operation can be enhanced by the proper location of the components, by redundancy, and by damage-tolerant and fail-safe design. Oil sumps and lines should be self-sealing, shielded, or armored. Bypass lines that isolate damage or leaking lines should be considered, and provision for the manual override of an automatic shutdown of the engine after loss of oil should be available to allow escape from the immediate hostile area. Redundancy (with separation) in the engine controls maintains controlled thrust when control components are killed, and a survivability-biased engine control (SuBEC) system can provide resilient engine response to moderate damage to the engine.[17]

GE T700 engine VR features: Reference 18 contains a description of many of the VR features used on the GE T700 engine. (http://www.geae.com/engines/military/t700/index.html.) The T700 engine was designed to 1) take a 7.62-mm hit and keep running, 2) take a 12.7-mm hit and stay together, and 3) operate 6 min with no usable oil.

The features that enable it to withstand a 7.62-mm hit are 1) emergency lube (safety feature too); 2) suction fuel transfer; 3) inlet particle separator for hit-released debris (sand and dust too); 4) top-mounted accessories out of the line of fire (fuel control nestled between starter and separator blower with no loss of accessibility); 5) compressor blisks (integral blades and disks) eliminate connections that could break; 6) number of stages is minimized, lowering presented area (lowers parts count and costs too); 7) mechanical actuation of three variable vane stages (fluid pressure power source is contained in the fuel control for reduced presented area); 8) small combustor means small presented area; 9) secondary air exposed parts are not critical; and 10) electrical power not required for operation. The engine installation VR features are as follows: 1) a hit on one engine will probably not pass through and kill the second engine; 2) risk of debris from a hit engine damaging the other engine or other critical parts is small; 3) engine bay airflow, fire wall fuel shutoff valves, fire detection and extinguishing, and wide engine spacing isolate and control a hit-caused fire; 4) safe transition from twin-engine to single-engine flight; and 5) good one engine-out performance.

Go to Problems 5.4.15 to 5.4.17.

5.4.3.3 *Flight control system.*

Learning Objective 5.4.4 List the flight control system kill modes, and describe the VR techniques.

The flight control system consists of the controls, the control surfaces, and the hydraulic subsystems. Because maintaining aircraft stability and control is one of the most critical factors affecting safety of flight as well as the combat survival of the aircraft and crew, much attention is given to the design of the control system to ensure that there is no unacceptable degradation of functional capabilities caused by one or more component failures. Many of the safety of flight features, such as independent hydraulic subsystems and backup controls, can also cause a reduction in vulnerability, provided they are properly designed into the aircraft considering the effects of combat damage. Two independent hydraulic subsystems that have lines running side by side through the aircraft can increase the safety of flight but not the combat survivability because of the likelihood that a single hit by a damage mechanism can kill both subsystems, leading to a loss of the aircraft. Reference 19 is a Standard published by the Society of Automotive Engineers for the design of survivable hydraulic and control systems for military aircraft.

Kill modes. The possible damage-caused failure modes of the control system are the disruption of the control signal path (loss of pilot, loss of control lines, computer failure, and sensor damage); the loss of control power (hydraulic failure, electrical failure, and actuator damage); damage to the control surfaces and hinges, and hydraulic fluid fire.

Design guidance and VR techniques. The flight control system, including the control power subsystem, should be designed to minimize failure or malfunction from the nonnuclear weapon effects specified in the implementing documentation.

General principles: The flight control system should be designed to prevent the loss of flight control caused by a single hit by a damage mechanism anywhere on the system, that is, there should be no single-point failure possibilities. To accomplish this, techniques such as multiple, independent, and widely separated control signal paths, motion sensors, control surfaces, and control power systems should be used; and no component failure should result in a hard-over signal to a control surface actuator. Jam protection or override capability should be included in the design, and heat-resistant materials and/or fire suppression techniques should be used to protect those control components located in areas where fires or hot gas impingement could occur.

For highly complex flight control systems, such as fly-by-wire, the implementation of redundancy after damage can be difficult. The flight control components that have been damaged or killed must be identified and the undamaged components reconfigured according to the control law selected. A thorough analysis of the multiple combinations of possible combat damage effects must be evaluated in order to select the most effective component arrangement. Surface management is a recently developed functional redundancy technique in which the surviving control surfaces on an aircraft are reconfigured to fly the aircraft after damage to one of the surfaces. The aircraft automatic flight control system (AFCS) contains a hierarchy of control laws consisting of a primary control mode, which utilizes all of the control surfaces, and various reversion control modes, which utilize all flyable subsets of the control surfaces. The AFCS should be structured such that if any one of the control surfaces on the aircraft is disabled, thereby defeating the primary control mode, the aircraft can remain controllable by reconfiguring to one of the remaining reversion modes.

Prevention of control signal path disruption: Two major procedures used to maintain continuity of the control signal path are to reduce the vulnerability of the individual components and to add additional components for redundancy. The vulnerability of the individual components can be reduced by locating the components behind noncritical components, by reducing their size (miniaturization) and/or by increasing their damage tolerance, or $P_{k|h}$. Small components are less likely to be hit (a smaller A_p) and have the added advantage of usually being lighter. One example of the application of both procedures is the addition of a copilot to the aircrew accompanied by the lowering of the maximum allowable height of pilots and copilots. Another example is the use of a quadruply redundant and separated fly-by-wire electrical signal transmission subsystem to replace a doubly redundant mechanical signal transmission subsystem. The reduction in component $P_{k|h}$ is accomplished by good design and by proper location. For example, mounting the servovalve assembly of a servoactuator on the top of the barrel of the power cylinder reduces the probability of a severed feedback link from the cylinder to the valve because of the shorter length and the protected position of the link. Servoactuators can also jam when penetrated by a metallic damage mechanism. These jams can be freed by several design techniques, such as the use of a frangible piston or malleable internal steel barrel. Jamming of the cockpit controls caused by a jam along one of the mechanical signal paths can be prevented by the use of cartridge springs between the mechanical linkages and by self-aligning bearings for torque tubes. Ballistically tolerant mechanical linkages, such as bell cranks and quadrants, that can accept multiple hits and remain functional have been designed. These components can be constructed of low-density, nonmetallic composite materials with redundant load paths that allow projectiles to core out material with minimum structural damage to the component. Locating the control components out of the line of fire, behind major structure, and out of potential fire areas also helps to ensure their continued operation.

One of the most basic and obvious ways to enhance the survivability of a flight control system is to provide either a backup system providing a 'limp-home' capability or one or more additional subsystems providing flight control functions identical to those provided by the primary subsystems. Adequate separation of the redundant control signal paths is required, and redundant fly-by-wire systems should consider the use of more than one flight control computer, separated of course. Separation of the redundant control paths should be accomplished in such a way that masking is provided by intervening structure and equipment. Statically unstable aircraft using stability augmentation to maintain control require that the backup systems also have stability augmentation in addition to the control power necessary for survivability.

Loss of the air motion data can result in the loss of an unstable aircraft. Continuity of aircraft motion data can be provided to the AFCS in the event of the loss of either a motion sensor or the connecting signal path by using redundant, effectively separated sensors. The concept of analytic redundancy (the use of analytical relationships to determine certain parameters given a set of other parameters) utilizing a digital filter has been developed to maximize the amount of redundancy for a given set of sensors. Alternatively, this concept can also be used to reduce the number of sensors required to meet survivability and reliability specifications, offering a savings in cost and weight. In addition, some indirect improvements in survivability might be possible through the use of analytic redundancy to automatically detect failures of other electronic equipment, a job usually delegated to the pilot.

A simple example of the total redundancy concept is the replacement of a single component with a configuration consisting of two components of the same kind connected in parallel, such that a malfunction of one component will not disable the other component. An example of this type of application is the use of two sets of cables and rods to transmit control signals from the stick to the actuators, with one set running along each side of the fuselage. Functional control redundancy consists of providing a backup capability to the system by using a second, functionally equivalent but physically different system. Nearly all backup flight control systems (BUFCS) fall into this category. A specific example is the use of a fly-by-wire control augmentation system to back up the primary mechanical control signal transmission system.

Prevention of the loss of control power: The major concern here is the prevention or suppression of hydraulic fluid leaks from the reservoirs, plumbing, and servoactuators. One way this can be accomplished is by the addition of logic elements to the hydraulic subsystem. These logic elements detect the leaks and then isolate the damaged portion before a sizable loss of fluid occurs. Fluid in the other branches of the subsystem is preserved, permitting the operation of actuators outside of the damaged portion. The two most common types of hydraulic logic elements are hydraulic fuzes and reservoir level sensors (RLS). Hydraulic fuzes, also known as flow difference sensors, operate on the principle that the return flow must vary in direct proportion to the supply flow in a properly functioning hydraulic subsystem. A difference from the normal ratio between the return flow and the supply flow is interpreted as a leak, and that part of the system monitored by the fuze is disconnected from the rest of the system. The reservoir level sensor is used in subsystems that have two or more independent circuits supplied by one reservoir. The sensor detects a reduction in the level of hydraulic fluid in the reservoir and alternately disconnects the individual circuits from the reservoir, one at a time, until the reservoir level ceases to drop. The damaged circuit has now been disconnected from the rest of the system, thereby conserving the remaining hydraulic fluid for the undamaged circuits.

Another power component that requires attention is the servoactuator. The actuator can be made ballistically resistant to the damage mechanisms using either dual-hardness steel or electroslag remelt steel for the power barrel. The design of the servoactuator with respect to the location of important features, such as the control valve and sensitive linkages, is also important. Dual, tandem actuators can use rip-stop body construction. This technique employs separate sections of the cylinder body that are fastened together at the junction between each power system in such a manner as to prevent the propagation of a rip or crack from one power chamber of the actuator to a location where the hydraulic fluid would be lost from both chambers of the unit, leading to a total loss of power. A major change to this subsystem would be the use of power-by-wire, where the power is obtained from either an electrohydraulic actuator or an electromechanical actuator. This change could eliminate the need for much of the hydraulic plumbing used in contemporary aircraft. However, the requirement for electrical power to the actuators would increase.

When the total loss of either control power to, or control of, a control surface is a possibility, provisions should be made to allow the surface to transition or fail to a safe position. For example, aircraft that incorporate either unit or differential horizontal tails should have some way of capturing the tail and preventing it from going hard-over when the power or control is lost, so that controlled flight can be maintained as long as possible.

Control surface and hinge vulnerability reduction: All components in the flight control system should be fail-safe. Consequently, the hinges and control surfaces should be made damage-tolerant, and redundant load paths, such as multiple hinges, should be used.

Prevention of hydraulic fluid fires: The standard military aircraft hydraulic fluid many years ago, MIL-H-5606, was highly flammable and could be ignited upon exposure to hot surfaces and gun fire, particularly the incendiary projectiles. Consequently, a less flammable hydraulic fluid, MIL-H-83282, was developed. The fluid has been flight tested and found to be suitable for aircraft operational environments and interchangeability with the existing standard fluid and parts. It has met or exceeded the high-temperature range for MIL-H-5606 and is compatible down to −40°F. The fluid is now incorporated in some operational aircraft. Navy tests have indicated that MIL-H-83282 is acceptable (at least to −40°F) in hydraulic devices such as landing gear shock struts and control surface dampers, even though these devices are not connected into the aircraft hydraulic systems and do not benefit from the warming effects associated with hydraulic circulation.

Go to Problems 5.4.18 to 5.4.19.

5.4.3.4 Power train and rotor blade/propeller system.

Learning Objective	**5.4.5**	**List the power train and rotor blade/propeller system kill modes, and describe the VR techniques.**

The power train system consists of a series of transmissions, gearboxes, and connecting drive shafts that transmit power from the engine(s) to the rotor blades, propellers, or fans.

Kill modes. The kill modes of the power train and blade system are loss of lubrication and mechanical or structural failure.

Design guidance and vulnerability reduction techniques. Power train systems, such as those employed by turboprop aircraft, helicopters, or V/STOL aircraft, should be designed to be damage tolerant against the level of threats required by the mission specified in the performance specification, the operational requirements, and the implementing documentation.

Prevention of the loss of lubrication effects: The loss of lubrication in transmissions and gearboxes can be prevented by incorporating a backup or emergency lubrication subsystem or by making these components damage tolerant. Damage-tolerance techniques to delay or prevent failure caused by lubrication subsystem damage can provide significant benefits for little or no penalties if incorporated into the initial design. There are many different types of power train lubrication subsystems, such as the rotor shaft cooler and the integral oil-air system, and the specific damage-tolerant design selected will be dependent upon the type of primary subsystem used. Less vulnerable lubricating techniques include the use of solid lubricants, high-temperature grease, and oil additives and formulations. High-temperature steel bearings and cages and improved bearing geometry allow prolonged operation at elevated temperatures.

Prevention of mechanical or structural failure: For those portions of the transmission and gearbox housing where penetration by a damage mechanism cannot be tolerated, masking should be used if possible; otherwise ballistic-resistant construction or armor shielding must be employed. Rotor blade and drive shaft designs must provide for safe operation after damage. The use of large, thin-wall shafts can prevent total severance and are less prone to low-cycle fatigue failure caused by ballistic damage than small, thick-wall shafts. Shaft couplings and intermediate shaft supports or hangers must also be damage tolerant. The main rotor shaft should be designed to allow autorotation of the main rotor in the event the shaft is severed or the transmission or engine seizes. The prime consideration in the survivability of the rotor blades is to keep them intact. The secondary consideration is to maintain sufficient blade stiffness after damage. Redundant and separated load paths, in conjunction with damage-tolerant materials, are required to accomplish these two goals. Considerable progress has been made in the development of helicopter rotor blades that can withstand hits by HE projectiles. Associated with the design of the moving parts in the power train system is the requirement that they not become secondary damage mechanisms that cause cascading damage, for example, a hit propeller that breaks and ends up inside the fuselage.

Go to Problems 5.4.20 to 5.4.21.

5.4.3.5 Crew system.

Learning Objective **5.4.6 List the crew system kill modes, and describe the VR techniques.**

The crew system consists of the onboard personnel engaged in the operation of the aircraft. Although passengers are not consider a part of the crew system, their survivability must also be considered.

Kill modes. The kill modes of the crew system are injury/death and life support failure.

Design guidance and VR techniques. Many types of combat damage effects can be harmful to aircraft crew members, either directly by penetration or indirectly by smoke, fire, loss of oxygen, or other effects that make the aircraft inhospitable. Vulnerability reduction techniques in the crew and passenger stations are mostly a function of masking or shielding, using either nonessential components or armor. The installation of armor falls into three categories: airframe, seat, and body.

When practical, airframe armor should be integral with the structure. Testing of spaced armor systems has shown that HE projectiles can be defeated by a spaced two-plate (trigger and backup) system. Protection against AP projectiles can be attained by the use of monolithic metal or ceramic armors with a woven fiberglass or Kevlar® backing. An acceptable level of protection can be provided by certain canopy materials against small arms projectiles. The use of spall curtains in the crew compartments can prevent secondary damage, and a transparent blast shield between the pilot and copilot can prevent the loss of both crew members to one internal detonation of an HE warhead. Aircrew seat armor should provide protection from both penetrators and crashes. In some aircraft, attack helicopters for example, body armor might be required for the crew's survival.

The environmental control system should be designed to minimize creation of hazardous conditions for the aircrew and essential components from the specified weapon effects. This includes conditions such as explosive decompression, shattering of liquid-oxygen containers, and hot gas line rupture. Protection should be provided when high-temperature bleed gases or engine exhaust are routed through or adjacent to compartments containing combustibles or temperature-sensitive structure. Protection of the crew from the secondary damage effects of smoke and fire consists mainly of minimizing the amount of combustible or toxic materials in the crew compartments and preventing smoke and toxic fumes from entering the compartments.

Go to Problems 5.4.22 to 5.4.23.

5.4.3.6 Structural system.

Learning Objective	**5.4.7**	**List the structural system kill modes, and describe the VR techniques.**

The structural system consists of all of the components or members used to establish the configuration of the aircraft and to transmit and react to all inertial and aerodynamic loads. The structure consists of the fuselage, the wing, and the empennage subsystems.

Kill modes. The structural damage-caused failure modes are fracture/removal, pressure overload, thermal weakening, delamination/fiber bucking, and connection failure.

Design guidance and VR techniques. The aeronautical system structure should be of a fail-safe design achieved through the use of multiple load paths and crack stoppers to reduce the probability of catastrophic structural failure as a result of battle damage with the aircraft in full-g maneuvering flight. There should be no flight critical structural components or load paths vulnerable to a single detonation, impact, or other damage mechanisms of the threats specified in the implementing documentation that would preclude a safe return and landing (arrested landing in the case of aircraft equipped with an arresting hook). Additional requirements can be listed under Damage Tolerance or Crashworthiness in the performance specification.

The vulnerability reduction of the structural system is largely dependent upon the construction type and material selection, factors that are also critical to modern aircraft from weight and cost considerations. Fiber-reinforced composites, such as graphite fibers bonded within epoxy resins in both sandwich- and solid-layered configurations, are now being used as major load-carrying structures on several aircraft currently in operation and in design. As a consequence of the increase in the structural applications of composites, in particular the fiber-reinforced composites, and the fact that the behavior of these new materials is significantly different in many aspects from the more conventional aluminum structures, investigation of the vulnerability of composite structures is mandatory.

Of prime importance when selecting aircraft structural materials is the selection of materials with qualities that prevent or minimize the propagation of damage. The aircraft structure itself should be designed to be as damage tolerant as practical to minimize the vulnerability of the system to the damage mechanisms. Sufficient strength and redundancy to permit evasive maneuvers to the limit load following the occurrence of damage should be provided, if practical.

Secondary thermal effects should be minimized throughout the entire airframe. These thermal effects include the burning of fuel, hydraulic fluid, oil, or other combustible material, and the torching from a damaged engine or hot-air bleed line. The design of the structure should also minimize the secondary effects from exploding ordnance.

One of the major considerations in the design of fluid-containing structures, such as fuel tanks, is the design for hydrodynamic ram. The hydrodynamic ram damage process is described in Chapter 3, Sec. 3.5.1.2. There are a number of design techniques that have been developed to provide varying degrees of protection against hydrodynamic ram. For example, the volume of fuel in each tank should be maximized because the liquid pressure pulse attenuation is dependent upon the fuel mass available to absorb it. Small (low-volume) tanks, if unavoidable, can be made more survivable provided they are shallow and are not totally filled when hit. Smooth, simple tank contours with shapes and structures designed to resist the internal pressure should be used, and narrow, complex tank shapes, and abrupt section cutouts should be avoided. Crash-resistant tank and structural designs using energy-absorbing and tear-resistant construction can significantly reduce the effects of hydrodynamic ram. Particular attention should be given to any engine inlet duct/fuel tank and engine compartment/fuel tank interfaces. Techniques for minimizing the damage of the tank wall include the use of tear-resistant and energy-absorbing materials and the use of concentric dual-walled tanks next to the inlet duct and engine compartment, with depletion of the interstitial fuel before entering the combat area. The fuel distribution components should also be designed to withstand any internal and external hydrodynamic ram pressures, and external drop tanks should maintain their structural integrity when penetrated.

The hydrodynamic ram overpressure can put enormous stress on the connections between structural members. This stress can cause the connection to fail, particularly when composites are involved. Many members, such as wing skins, are designed to carry the primary load in the plane of the member as a tension or compression load. The connections between the skins and the spars and stringers are typically metal fasteners designed to transfer the in-plane load to the substructure spars and ribs through in-plane shear. However, when the lower skin of a fuel tank containing fuel is penetrated by a metallic penetrator or fragment, the hydrodynamic ram pressure acts normal to the skin. This results in bending of the skin and transverse shear loads at the connections. If the connection is not designed to resist this load, the fastener will pull through the skin, leaving the skin detached. The problem is particularly acute in connections involving composites because of their nonisotropic behavior. A number of design approaches for composites have been proposed to withstand hydrodynamic ram. Reference 20 presents several of these approaches, such as large-head fasteners and radius blocks to prevent fastener pull-through and stitching or pinning to reinforce adhesive bonds against the transverse loads.

Go to Problem 5.4.24.

5.4.3.7 Other aircraft systems. The other systems on combat aircraft, such as the avionics system, the armament system, the launch and recovery systems, and the electrical system, must also be considered when designing for survivability. In general, the VR techniques for these systems are similar in concept to those already described. These include the six major concepts of component redundancy

Table 5.12 VR features on the A-10A,[21] F/A-18A,[22] and UH-60A[23]

A-10A	F/A-18A	UH-60A
	Fuel system kill mode: fuel supply depletion	
Two self-sealing feed tanks located away from ignition sources	Two self-sealing feed tanks located away from ignition sources	Two self-sealing and crashworthy tanks located away from ignition sources
Short, self-sealing feed lines	Short, self-sealing feed lines	Engine-mounted suction pumps
Wing fuel used first	Wing fuel used first	Short, self-sealing feed lines
Most fuel lines located inside tanks	Most fuel lines located inside tanks	Cross-feed capability
Cross-feed capability located within tanks	Cross-feed capability	
Redundant feed flow	Backup pump	
	Redundant feed flow	
	Fuel system kill mode: fire /explosion	
Two self-sealing feed tanks located away from ignition sources	Two self-sealing feed tanks located away from engines and other ignition sources	Two self-sealing and crashworthy tanks located away from ignition sources
Short, self-sealing feed lines	Short, self-sealing feed lines	Engine-mounted suction pumps
Most fuel lines located inside tanks	Most fuel lines located inside tanks	Short, self-sealing feed lines
Open cell foam in all tanks	Open cell foam in wing tanks	Closed cell foam around all tanks
Closed cell foam in dry bays around tanks	Closed cell foam under two fuselage tanks	
Draining and ventilation in vapor areas		
	Fuel system kill mode: hydrodynamic ram (see the structural system)	
	Propulsion system kill mode: loss of thrust	
Two widely separated engines	Two engines	Two widely separated engines
Dual fire walls	Fire walls between engine, AMAD, and APU	Titanium fire walls

Table 5.12 VR features on the A-10A,[21] F/A-18A,[22] and UH-60A[23]; (Continued)

A-10A	F/A-18A	UH-60A
	Propulsion system kill mode: loss of thrust (continued)	
Fail-active fire detection with two shot fire extinguishing	Fire detection and extinguishing system	Fire detection with two-shot fire extinguishing
Engine case armor	Blade containment for fan, compressor, and turbine	Widely separated engine to transmission input modules
Separation between fuel tanks and air inlets	Short inlet duct/fuel tank interface with hyd ram damage control	No fuel ingestion
One engine-out capability	One engine-out capability	Good one engine-out capability
	Flight control system kill modes: disruption of control signal path and loss of control surfaces	
Two independent, separated mechanical flight controls with mechanical disconnects	Two flight control computers with four separated control lines Backup mechanical controls to tail	Two independent, separated mechanical flight controls with mechanical disconnects
Two rudders and elevators	—	Controls are ballistically tolerant
Armor around control stick where redundant controls converge		Spring drives tail rotor blades to fixed pitch setting if control signal is lost
		Tail rotor is stable if pitch control rod is severed
	Flight control system kill modes: loss of control power and hyd fluid fire	
Two independent, separated hyd power subsystems	Two independent, separated hyd power subsystems with four circuits (two/subsystem)	Two independent, separated, and shielded hyd power subsystems

(continued)

Table 5.12 VR features on the A-10A,[21] F/A-18A,[22] and UH-60A[23]; (Continued)

A-10A	F/A-18A	UH-60A
	Flight control system kill modes: loss of control power and hydraulic fluid fire (continued)	
A/C can be controlled without hyd power with mechanical controls and dual, electrically powered trim actuation	Rip-stop actuators	Third electrically driven backup can power either or both primary systems with quick disconnects and leak isolation valves
MIL-H-83282 can be used	Reservoir level sensing	MIL-H-83282 can be used
	MIL-H-83282 can be used	
	Structural system kill mode: hydrodynamic ram	
Minimum fuel in wings during combat	Minimum fuel in wings during combat	Crashworthy tanks also hyd ram tolerant
——	Short inlet duct/fuel tank interface with hyd ram damage control	——
	Crew system kill mode: injury/death	
Titanium/alum armor bathtub surrounds pilot	——	Crashworthy armored seats and retention system
Spall shields between armor and pilot	——	Shatterproof cockpit window
Bullet resistant windscreen	——	Minimum-spall materials used in cockpit
Spall resistant canopy side panels		Kevlar® armor to stop HE fragments

(with separation), component location, passive and active damage suppression, shielding, and component elimination/replacement.

5.4.4 Lessons Learned

All three military services have established a Lessons Learned database. (http:// library.nps.navy.mil/home/lessons.htm.) Some of the lessons apply to the vulnerability of military aircraft. A few of the lessons learned are listed here:

1) Fire-hardening hydraulic lines and the total separation of primary and emergency system components can significantly increase the survivability of the power control subsystem from in-flight fires.

2) Do not route all redundant flight control components together;

3) The design of the flight controls must consider the possibility of foreign object intrusion causing a jam.

4) Backup systems for redundancy in flight control must activate immediately when needed, must have complete control of flight, and must be totally independent from the primary system.

5) Inerting of fuel tanks prevents explosions and is cost effective.

6) Crashworthy fuel systems save lives.

5.4.5 Vulnerability Reduction Features on Some Operational Aircraft

5.4.5.1 VR features on the A-10A, F/A-18A, and UH-60A. Some of the vulnerability reduction features on the A-10A, F/A-18A, and UH-60A are presented in Chapter 1, Sec.1.4.3. Tables 5.12 and 5.13 present in more detail the VR features incorporated in these three aircraft to stop the kill modes.

Table 5.13 UH-60A drive train and rotor blade system kill mode: loss of lubrication and structural damage

Main transmission	Main rotor	Tail rotor drive system
Modular transmission eliminates exposed high-speed shafts and multiple lube subsystems with exposed components	Rotor blades tolerant to HE projectiles	Tail rotor ballistically tolerant
Operates more than one hour after loss of all oil	Elastomeric hub with no lube and tolerant to HE projectiles	Shaft supports provide damping for damaged shaft
Noncatastrophic failure allows autorotation		No bearings or lube in cross-beam rotor
		Large vertical tail with long boom provides antitorque in forward flight
		Damaged parts thrown away from the helicopter

Table 5.14 VR checklist

System	Kill mode	Function lost	VR feature
Fuel	Fuel supply depletion	Thrust	
	Ullage fire/explosion	Lift, thrust, control, structural integrity	
	Dry bay fire/explosion	Lift, thrust, control, structural integrity	
	Hydrodynamic ram	Lift, thrust, control, structural integrity	
Propulsion	Inlet flow distortion	Thrust	
	Engine failure	Thrust	
	Engine fire	Lift, thrust, control, structural integrity	
	Engine subsystem or control failure	Thrust	
Flight control	Disruption of control signal path	Control	
	Loss of control power	Control	
	Damage to control surfaces and hinges	Control	
	Hydraulic fluid fire	Lift, thrust, control, structural integrity	
Power train and rotor blade/propeller	Loss of lubrication	Lift, thrust, control	
	Mechanical damage	Lift, thrust, control	
Crew	Injury/death	Control	
	Life support failure	Control	
Structural	Fracture/removal	Structural integrity	
	Pressure overload	Structural integrity	
	Thermal weakening	Structural integrity	
	Delamination/fiber buckling	Structural integrity	
	Connection failure	Structural integrity	
Electrical power	Severing/grounding	Thrust and control	
	Mechanical damage	Thrust and control	
	Overheating	Thrust and control	
Avionics	Mechanical damage	Thrust and control	
	Fire/overheat	Lift, thrust, control, structural integrity	
Armament	Fire/explosion	Lift, thrust, control, structural integrity	

5.4.5.2 Ballistic protection design of two modern attack helicopters. Reference 24 presents "an overview of the present design and construction philosophies, Swedish computer simulation models for aircraft vulnerability evaluation, and a comparative vulnerability study on the AH-64A Apache and the Mi-28 Havoc designs."

5.4.6 Vulnerability Reduction Checklist

To assist the vulnerability engineer in his/her reduction of the vulnerability of a future aircraft design, a VR checklist or template is presented in Table 5.14. This checklist can be used by the vulnerability engineer and the design team to ensure that the vulnerabilities of an aircraft have been examined and reduced, if appropriate. The template is not inclusive; there most likely will be kill modes that are not presented here that should be added.

Endnotes

1. A review of the terminology for damage mechanisms, damage processes, terminal effects, kill modes, and the aircraft response topical field provided in Chapter 3, Sec. 3.3 might be helpful prior to reading the following material.
2. Designing for low vulnerability can begin early in the design process because much is already known about aircraft vulnerability and how to reduce it. For example, fuel tanks can explode, therefore add an onboard inert gas generator to prevent the explosion; engines can lose thrust, therefore design for two separated engines; and flight control links can break, therefore include redundant and separated links in the design.
3. See Ref. 25 for nine historical perspectives on vulnerability/lethality analysis of land, sea, and air vehicles.
4. The vulnerability, system safety, and reliability communities within the military aircraft world are dedicated to the reduction of risk at an affordable cost. The general area of risk assessment and management is an area that is of major interest to both the military and the civilian world. Many textbooks that describe the general process of probabilistic risk assessment and the tools that are also used by the vulnerability community to identify the critical components and quantify their contribution to vulnerability are available. References 26 and 27 are two such books.
5. Note that most of these loss–cause categories are equivalent to the loss of one or more of the four essential functions for flight (structural integrity, lift, thrust, and control) identified in Chapter 2, Sec. 2.1. For example, fire intensity and explosion can cause the loss of structural integrity. The loss of stable flight can be equivalent to either the loss of structural integrity or loss of lift. The loss of control and pilot incapacitation categories are equivalent to the loss of control, and the loss–cause category of loss of thrust is equivalent to the loss of the essential function of thrust.
6. The single-hit vulnerability requirement for the UTTAS is described in Chapter 1, Sec. 1.4.3, and the requirement for the AAH is described in Note 57 in Chapter 1.
7. Note in Fig. 5.4 that the flight essential functions of lift and thrust have been combined. This is because the helicopter has a main rotor that provides the required

force vector on the aircraft of lift (upward) and thrust (forward) and a tail rotor that provides the sidewise force vector for directional control. For fixed-wing aircraft the lift, thrust, and control functions are somewhat independent and are primarily associated with the wings and fuselage, the engines, and the stabilizers and control surfaces, respectively.

8. Loss-of-function effects propagate to other components; damage effects cascade to other components.
9. The coolant can be a critical component for a mission abort kill when the loss-of-function kill mode occurs because the pilot most likely will abort the mission as a result of the loss of the radar.
10. Nonredundant critical components have been referred to elsewhere as singly vulnerable components. This terminology will not be used here because it is misleading.
11. Redundant critical components have been referred to elsewhere as multiply vulnerable components. This terminology will not be used here because it is misleading.
12. Just because an aircraft has two engines does not always mean it can fly on one engine. The Junkers Ju 88 bomber of the WWII era was such an aircraft. According to Ref. 28, "Under actual operating conditions the plane was unable to maintain level flight with only one engine running. According to computation and tests, it ought to have been able to climb 3 ft/s with bombs dropped and fuel half used up. In combat flight, however, altitude was usually lost, primarily because the hydraulic pitch control of the dead propeller failed to feather the blades into a low drag setting."
13. The assumption has been made here that the fuel leaking from the wing tank will not cause any subsequent problems elsewhere. However, this assumption might not be valid in all situations. For example, the leaking fuel could be ingested by an engine mounted on the rear part of the fuselage. The ingested fuel could result in significant engine damage, another example of cascading damage. Also, the leaking fuel could ignite. The pilot, observing the fire, could decide to eject.
14. Even if there were no subsequent problems associated with the fuel leak, the pilot may decide to abort the mission because of the damage to the wing. In this situation the wing fuel tank is a nonredundant critical component for a mission abort kill.
15. Note the similarity between the FMEA and the system safety hazard analysis and between the CA and the hazard classification described in Chapter 1, Sec. 1.1.15.1.
16. MIL-STD-1629A was cancelled 4 August 1998 and was replaced with industry or international documents that describe the FMECA process. The following standards are applicable: ISO 9000, QS 9000, SAE J1739, SAE ARP5580, and many others. The interested reader can find a very large number of sites on the Internet devoted to the standards, performance, education, training, and software of the FMEA and the FMECA.
17. Figure 5.10 was originally developed by Levelle Mahood.
18. On 31 October 1999, EgyptAir Flight 990, a Boeing 767, crashed into the Atlantic Ocean about 60 miles south of Nantucket Island, Massachusetts. The analysis by Boeing of the possible causes of the loss of the aircraft found that "a single control cable failure combined with a jam of the same cable could produce a (trailing edge) down motion on both elevators ... The manufacturer also found that a valve stuck in a certain position could interact with a pogo spring to force the elevators to deflect downward."[29]

19. The loss of structural integrity usually results in the immediate loss of lift, thrust, and control. It is included here as an essential function to provide the vulnerability engineer the opportunity to identify those components and their kill modes that result in the breakup of major elements of an aircraft.
20. The branching of a fault tree is not unique. In Fig. 5.12b the loss of thrust tree is divided into two major branches: the loss of thrust as a result of engine-related damage events, such as the loss of an engine-mounted fuel pump or damage to the combustor case, and the loss of thrust as a result of the loss of fuel supply to the engine, making the engine nonfunctional. Another fault tree could have located the loss of fuel supply under the fuel system failure event. However, this arrangement could have obscured the fact that the fuel feed tank is a nonredundant critical component. Also, the AND gate link directly to the OR gate under the loss of thrust as a result of loss of fuel supply event is not good practice.[5] The intermediate event of loss of fuel from both the left and the right supply tanks should be inserted between the AND gate and the OR gate for completeness, as is done for all of the other gates in the figure.
21. An explosion in any of the three tanks could also kill the aircraft, but this kill mode is considered in the analysis for the loss of structural integrity.
22. The ability to control the aircraft's pitch and heading by adjusting the thrust from each engine, as was done by Lieutenant Randall 'Duke' Cunningham as described in Chapter 1, Note 25, is not possible here.
23. In some aircraft vulnerability organizations the kill tree is referred to as the fault tree or as a failure analysis logic tree (FALT). In the surface ship vulnerability assessment community the tree is referred to as a deactivation diagram. In reliability studies the kill tree is referred to as a reliability block diagram, and in system safety it is referred to as a dependency diagram.
24. Nonredundant critical components can be considered to be components operating in series, and redundant critical components can be considered to be components operating in parallel.
25. To assist the U. S. vulnerability engineer in obtaining realistic estimates for the $P_{k|h}$ of the critical components on an aircraft, the JTCG/ME and the JTCG/AS jointly initiated the Joint Component Vulnerability Program (JCVP). The primary missions of the JCVP are 1) to coordinate development/documentation of the methodologies for making consistent engineering-level estimates of component dysfunction given a hit $P_{cd|h}$, 2) to standardize $P_{cd|h}$ analysis generation and documentation practices, and 3) to archive supporting data and methodologies. As part of this effort, the Component Vulnerability Analysis Archive (CVAA) has been developed as the repository for methodologies and component vulnerability and test data. The CVAA has been developed, documented, and is being populated with component vulnerability analysis methodologies and the supporting vulnerability, ballistic test, and combat data. Note that the JCVP and CVAA focus on component dysfunction, not component kill, given a hit. This measure represents the level of damage required so that the component can no longer perform its design function. The $P_{cd|h}$ is strictly a function of the component design, and therefore can be determined independently of how it is installed or integrated into a particular weapon system. To determine if a component is no longer functional, that is, killed, the level of damage must be correlated with required capability. This correlation is accomplished through the probability of

component kill given damage $P_{k|d}$. Thus, the component probability of kill given a hit $P_{k|h}$ is the product of $P_{cd|h}$ and $P_{k|d}$. For example, a $P_{cd|h}$ function might describe the probability of achieving a certain leak rate given a puncture of an actuator. The corresponding $P_{k|d}$ would vary from system to system, depending on the size of the hydraulic reservoirs, reservoir sensing/shutoff valves, kill level being assessed, etc. The interested reader is referred to SURVIAC (Sec. 1.3.6) for more informaation on the JCVP and CVAA.

26. In general, the hits on an aircraft in any given scenario will not be uniformly distributed. Perhaps one gunner leads the aircraft too much and the hit is in the nose, whereas another gunner underestimates the lead-angle requirement and the hit is in the tail. However, considering all possible scenarios, the uniform distribution is a reasonable assumption. Furthermore, the assumption of a uniform hit distribution on the aircraft eliminates the requirement to consider in detail the susceptibility of the critical components on the aircraft for any given scenario, that is, where did the aircraft get hit and what is the probability a particular component is hit given that the aircraft was hit there? This means that the measures of aircraft vulnerability, $P_{K|H}$ and A_V, can stand alone as comparable metrics between aircraft. Recall that the vulnerability requirement for the UTTAS program was an ability to take a hit by a 7.62-mm API anywhere on the helicopter and continue to fly for 30 min. If the uniform distribution is not appropriate in certain scenarios, such as an IR missile that homes in on the tail of an aircraft, the susceptibility of the individual components on the aircraft must be considered, that is, components near the tail of the aircraft are more likely to get hit than those in the nose. The assessment procedure for the nonuniform hit distribution is described in Chapter 6, Sec. 6.2.2.1.
27. Although this assumption is usually made in a vulnerability assessment, it is necessary.
28. Equation (5.6a) for the $P_{K|H}$ for the nonredundant aircraft model with no component overlap is written as $P_{K|H} = P_{k1|H} + P_{k2|H} + \cdots + P_{kN|H}$. For completeness it should be written as $P_{K|H} = P_{K|k1}P_{k1|H} + P_{K|k2}P_{k2|H} + \cdots + P_{K|kN}P_{kN|H}$, where $P_{K|ki}$ is the probability the aircraft is killed given component i is killed. Usually, $P_{K|ki} = 1$ for the nonredundant critical components on the kill tree, and hence it normally is not included in the kill expression. However, there are some situations where it is not unity, as described before in the development of the kill tree and kill expression, and therefore should be included.
29. The kills of the two redundant components are independent when the kill of one component has no effect upon the kill of the other component. This assumption of independence eliminates the consideration that a hit on one redundant component can result in a kill of that component and cascading damage that kills the other redundant component. The assumption of independence is not necessary when the joint probability that both components are killed is conditional, as in Eq. (B. 16).
30. The concept of killing the aircraft $NP_{K|H}$ times is examined in Appendix B, Sec. B.6.3.
31. All five branches off of engine 1 are shown because each branch represents a possible outcome of the second hit after a kill of engine 1. The kill of engine 1 branch simply means that the second hit was on engine 1 and it would have killed it if it were not already killed. The *nk* branch means that the second hit did not hit and kill any of the components. Refer to Appendix B, Sec. B.6.3 for more details.

32. Only the nonredundant critical components should overlap. Redundant critical components must be separated; otherwise, a single hit could kill more than one of the redundant components. Refer to Example 5.7.
33. The separation of redundant components is not part of the location concept; it is integral with the component redundancy concept.
34. Protection of fuel tanks is not a new idea. In World War II the Russians pumped the engine exhaust gas into the fuel tanks in the IL-2, and the F-4U used fuel tank inerting in the wing tanks of the early models.
35. Generating the nitrogen-enriched air (NEA) in the OBIGGS also produces oxygen. If the oxygen is in sufficient volume, it can be used as the onboard oxygen supply. The resulting system is a combination onboard inert gas generating system/onboard oxygen generating system (OBIGGS/OBOGS).

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Problems

5.1.1 What does an aircraft's vulnerability depend upon?

5.1.2 What are the critical components on an aircraft?

5.1.3 What is the name of the analysis that identifies the critical components.

5.1.4 What task answers the question "How vulnerable is the aircraft"?

5.1.5 Vulnerability reduction is most effectively accomplished early in the design of the aircraft: True or False.

5.2.1 Give three examples of nonlethal damage by small arms fire and high-explosive AAA shells.

5.2.2 Give three examples of lethal damage incidents. Relate the cause of the loss to the loss of an essential function.

5.2.3 Describe a loss–cause network and its purpose.

5.2.4 What major conclusions do you make from the loss-of-control losses diagrams shown in Figs. 5.2 and 5.3?

5.2.5 List (in order) the five critical systems that led to the loss of aircraft in WWII.

5.2.6 List (in order) the four critical systems that led to the loss of fixed-wing aircraft in Southeast Asia.

5.2.7 List (in order) the four critical systems that led to a helicopter crash aircraft in Southeast Asia.

5.2.8 What is the difference between the attrition kill category and the mission abort kill category?

5.2.9 Give an example of a component kill that results in each of the four levels of attrition kill.

5.2.10 Match the following attrition levels to the elapsed time from hit to out of control:

______A level	1. 30 s
______AB level	2. 3 min
______KK level	3. Immediate
______Z level	4. 30 min
______B level	5. 1 min
______K level	6. 5 min
	7. 1 hr
	8. 2 min

5.2.11 The single pilot on an aircraft is a nonredundant critical component for an A level attrition kill. Thus, the pilot is also a nonredundant critical component for a B level attrition kill: True or False.

5.2.12 The single pilot on an aircraft is a critical component for both the attrition kill category and the mission abort category: True or False.

5.2.13 An aircraft is hit on ingress to the target area. The damage is such that the pilot decides to return to base. This is a mission abort kill: True or False.

5.2.14 An aircraft is hit on ingress to the target area. The damage is such that the pilot decides to return to base. This is a mission denial kill: True or False.

5.2.15 List the four essential functions for controlled flight.

5.2.16 List five terms that are used to describe the inability of a component to provide the function(s) it was designed to provide.

5.2.17 Describe a kill mode.

5.2.18 What is the difference between a failure mode and a damage mode?

5.2.19 When is the term failure mode used in a critical component analysis?

5.2.20 The engine-mounted fuel pump on the single engine on an aircraft is hit and stops providing fuel to the engine. Consequently, the engine stops providing thrust. This is an example of a cascading damage kill mode: True or False.

5.2.21 The fuel tank next to the air inlet is punctured, and leaking fuel is ingested by the single engine. Consequently, the engine stops providing thrust. This is an example of a cascading damage kill: True or False.

5.2.22 The pilot's stick is hit and breaks. Consequently, the pilot can not control the aircraft. Nevertheless, the pilot is said to be functional: True or False.

5.2.23 Give three examples of redundant critical components on an aircraft.

5.2.24 Describe how the engines on a twin-engine aircraft can be redundant critical components and how they can be nonredundant critical components.

5.2.25 Redundant critical components are also known as___________critical components.

5.2.26 Describe the FMEA procedure.

5.2.27 What is the primary difference between an FMEA and a DMEA?

5.2.28 List the three primary fuel system kill modes.

5.2.29 Describe the possible combustion incidents in and around a fuel tank.

5.2.30 List the four primary flight control system kill modes.

5.2.31 Describe the connection failure kill mode for fluid containers made of composite materials, such as the fuel tanks in graphite epoxy wings.

5.2.32 Briefly describe the FTA and the differences between it and the FMEA.

5.2.33 List some potential critical components in the rotor blade/power train system for a helicopter.

5.2.34 What is the kill tree, and how is an aircraft kill determined using the tree?

5.2.35 What is a kill expression?

5.2.36 Refer to Figure 5.13 for the following questions:

The APU is a nonredundant critical component: True or False.

A kill of the pilot's controls and the copilot will cause an aircraft kill: True or False.

The LH supply is a nonredundant critical component for the fuel supply depletion kill mode: True or False.

The LH fuel is a nonredundant critical component for the fire/explosion kill mode: True or False.

The kill expression for the pilot, pilot's controls, copilot, and copilot's controls is (Pilot .AND. Copilot) .OR. (Pilot's controls .AND. Copilot's controls): True or False.

5.2.37 Draw the fault tree and the kill tree for a loss of control kill of an aircraft as the top (undesired) event. Control of the aircraft is required around all three axes (pitch, roll, and yaw). An aerodynamic force is developed at each control surface by moving the surface into the airflow over the surface. Because of the large forces required to move the surfaces, an irreversible hydraulic power control subsystem is required. Your aircraft has only one control surface component for each coordinate (P, R, and Y). You have two engines (E1 and E2). Each engine drives one hydraulic subsystem (E1 drives H1, E2 drives H2). H1 powers all three surfaces. H2 only powers P and Y. Neglect all other components when developing the fault tree. Assume control around all three axes is required for stable flight and a kill of either hydraulic subsystem at any location is a kill of that subsystem at all locations. Identify the damage process(es) or kill mode(s) that causes the kill of each of the components.

5.3.1 What is a vulnerability assessment?

5.3.2 List the three general levels of detail used in these assessments.

5.3.3 The computational methodology used in the assessment should have the capability to account for__________.

5.3.4 The AP projectile is an example of typical threat considered in a vulnerability assessment: True or False.

5.3.5 List three measures of vulnerability.

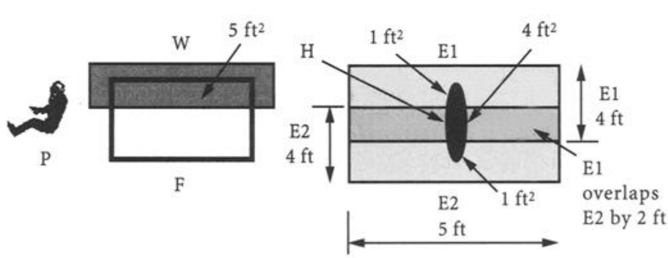
5.3.6 Define vulnerable area.

5.3.7 The result of Task 2 is?

5.3.8 List the three kill criteria used for impacting damage mechanisms and the type of applicable components.

5.3.9 The location of a component inside the aircraft will affect the component's $P_{k|h}$ function: True or False.

5.3.10 Determine the single-hit vulnerability of the target aircraft shown here (not to scale):



The nonredundant critical components are the pilot (P), the fuel tank (F), the whizzer (W), and the hydraulic package (H). Note that 5 ft^2 of the whizzer overlaps the fuel tank. The engines (E1 and E2) are redundant critical components, and 2 ft of E1 overlaps E2 as shown in the figure. The 6 ft^2-hydraulic package overlaps each engine by 1 ft^2 and overlaps the overlapping engines by 4 ft^2. The vulnerability data for each of these components are given in the following table.

Component	A_p, ft^2	$P_{k\|h}$
P	4	1.0
F	40	0.4
H	6	0.5
W	10	0.1
E1	20	0.3
E2	20	0.2

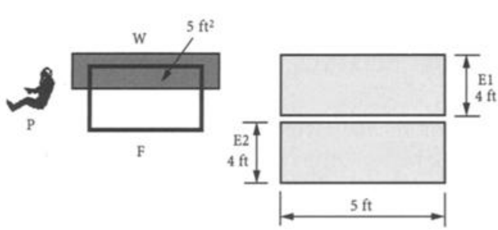
(a) Draw the kill tree, and write the kill expression.
(b) Compute the vulnerable area for each component A_v. Assume the component $P_{k|h}$ values are the same in both the overlap and the nonoverlap areas for each component.
(c) Compute the single-hit vulnerable area and $P_{K|H}$ for the aircraft with $A_P =$ 300 ft^2. Assume independent events in the overlap areas. Hint: What are the unique areas on this aircraft which if hit would cause a kill, and what is the contribution of each of these areas to the total aircraft vulnerable area A_V?

5.3.11 An aircraft composed of only nonredundant critical components is hit by nine fragments. The $P_{K|H}$ for each fragment hit is 0.02. What is the probability the aircraft is killed by the nine fragment hits?

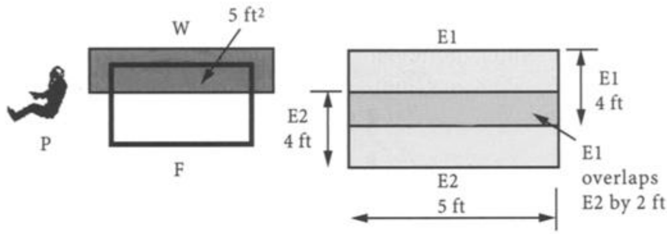
5.3.12 An aircraft composed of only nonredundant critical components has a presented area of 300 ft^2. A fragment spray with the density of 0.03 fragments per ft^2 covers the aircraft. The $P_{K|H}$ for each fragment hit is 0.02. What is the probability the aircraft is killed by the fragment spray?

5.3.13 Multiple hits on an aircraft with redundant critical components do not change the aircraft's A_V and $P_{K|H}$: True or False.

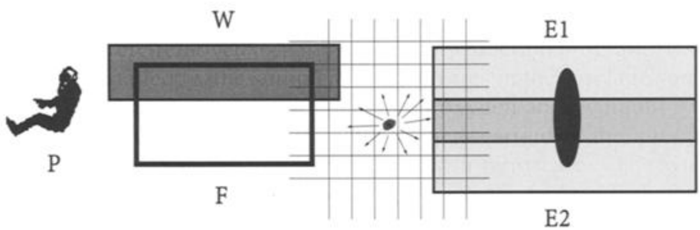
5.3.14 Develop the State Transition Matrix for the 300 ft^2 aircraft shown here (not to scale). Use the vulnerability data given in Problem 5.3.10.



5.3.15 Develop the State Transition Matrix for the 300-ft^2 aircraft with overlapping redundant critical components shown here (not to scale). Use the vulnerability data given in Problem 5.3.10.



5.3.16 Consider the aircraft shown in Problem 5.3.10. A square grid is superimposed over the aircraft, and the area of each grid cell is 2 ft^2. A hit by an internally detonating HE warhead is assumed to occur in one of the cells as illustrated in the following figure. The table after the figure presents the number of fragments from the warhead detonation that hit each component and the component $P_{k|h}$ as a result of each hit. What is the probability the aircraft is killed by this hit $P_{K|Hb}$, and what is the contribution of this cell to the aircraft's vulnerable area? Assume that the $P_{k|h}$ for each component is the same for all hits on the component, even in the overlap areas. Also assume the probability of survival of each component to the blast and fire/explosion is 1.0.



Component	Number of hits	$P_{k\|h}$
P	0	1.0
F	3	0.3
H	0	0.5
W	4	0.1
E1	7	0.2
E2	9	0.2

5.3.17 What are the two steps in analyzing the vulnerability of an aircraft to the effects of an externally detonating HE warhead?

5.3.18 How is an aircraft's vulnerability to blast expressed?

5.3.19 An HE warhead detonates below an aircraft. The fragment spray zone covers the entire bottom of the aircraft, the fragment spray density at the aircraft is 0.04 fragments/ft^2, and the target presented area is 400 ft^2. Assume that $A_V = 2$ ft^2 for each fragment hit on the aircraft. Determine $P_{K|F}$ using both the binomial approach and the Poisson approach.

5.3.20 What are the four categories of programs used to assess aircraft vulnerability, and what types of warheads or damage mechanisms are they used for?

5.3.21 BRL-CAD and SHOTGEN are two shotline generator programs that use surface patches to model the aircraft: True or False.

5.3.22 COVART is the acronym for____________.

5.3.23 The major endgame programs are?

5.4.1 What does vulnerability reduction refer to?

5.4.2 List the six vulnerability reduction concepts.

5.4.3 The pilot and copilot provide total redundancy: True or False.

5.4.4 The pilot and copilot provide partial redundancy: True or False.

5.4.5 The use of the rudder for roll control in the event of aileron failure is an example of functional redundancy: True or False.

5.4.6 Orienting critical components to minimize their presented area in the anticipated threat direction is an example of VR using component location: True or False.

5.4.7 Separation of redundant critical components is an example of VR using component location: True or False.

5.4.8 List and give an example of each of the six passive damage suppression techniques.

5.4.9 Explosion suppression foam in the ullage of a fuel tank is an example of active damage suppression: True or False.

5.4.10 Locating a nonredundant critical component behind one or more noncritical components is an example of VR using component shielding: True or False.

5.4.11 List the three fuel system kill modes.

5.4.12 List three examples of the prevention of fuel supply depletion.

5.4.13 List the five general techniques for the suppression of ullage and dry bay fires and explosions.

5.4.14 List two passive and two active techniques for preventing fires and explosions in ullages and dry bays.

5.4.15 How should the propulsion system be configured?

5.4.16 One of the most important techniques for the reduction of propulsion system vulnerability is a____________.

5.4.17 The T700 engine was designed to take a 12.7-mm hit and keep running: True or False.

5.4.18 How should the flight control system be designed?

5.4.19 List the four control system damage-caused failure modes, and give an example of a VR technique for each mode.

5.4.20 List the two kill modes of the power train and rotor blade/propeller system.

5.4.21 The prime consideration in the survivability of the rotor blades is to keep them intact: True or False.

5.4.22 List the two kill modes of the crew system.

5.4.23 The installation of armor falls into two categories: airframe and body: True or False.

5.4.24 The use of composites has eliminated the vulnerability of the structural system to hydrodynamic ram: True or False.

Chapter 6
Survivability (P_S and P_K)

6.1 Survivability Program

Learning Objective	**6.1.1**	**Describe the two remaining tasks in a survivability program for U. S. military aircraft.**

The survivability program for U. S. military aircraft is described in Chapter 1, Sec. 1.3. The guidelines for the general program are contained in DoD MIL-HDBK-2069A (Sec. 1.3.4), and the program tasks specifically identified in that document include (4) mission-threat encounter analysis, (5) flight and mission critical function analysis, (6) failure mode, effects, and criticality analysis, (7) damage mode and effects analysis, (8) computerized target description, (9) aircraft vulnerability analysis, (10) susceptibility analysis, (11) survivability analysis, (12) survivability enhancement trade studies, and (13) combat damage repair analysis. Tasks (4) through (10) and (13) have been described in Chapters 1 (task 13), 3 (task 4), 4 (task 10), and 5 (tasks 5 through 9). This final chapter contains descriptions of the two remaining tasks; (11) the assessment of the aircraft's survivability in the predicted threat environment to determine the survivability measures and (12) the conduct of effectiveness analyses and enhancement trade studies to determine those survivability enhancement features that increase the effectiveness of the aircraft as a weapon system. The survivability assessment is the culmination of the quantification of the measures of survivability. It combines the results from the mission-threat analysis with the studies of the aircraft's susceptibility and vulnerability and provides measures that can be used in the effectiveness analyses and trade studies. Because the design process normally involves competition between the various aircraft design disciplines for the limited allowable space, weight, and dollar cost, the selection of the particular survivability features to be included generally involves survivability enhancement trade studies that are based upon the survivability measures and their relationship to effectiveness. These trade studies determine the benefits or payoffs associated with one or more survivability enhancement features and the impact of the feature(s) on the dollar cost and all of the attributes of the aircraft, such as weight, flight performance, safety, payload, and maintenance.

Go to Problem 6.1.1.

6.2 Survivability Assessment

Learning Objectives	**6.2.1**	**Describe the survivability assessment process.**
	6.2.2	**Compute $P_{K\|SS}$, one-on-one survivability, mission survivability, and campaign survivability.**

The survivability assessment consists of the systematic description, delineation, quantification, and statistical characterization of the survivability of an aircraft in encounters with hostile forces. It combines 1) the results of the mission-threat analysis, which include the identification of the specific threats to the aircraft and the scenarios describing the encounter conditions between the aircraft and the threats; 2) the results of the susceptibility assessment, such as the aircraft signatures, propagator miss distances, and the number of fragment hits; and 3) the results of the vulnerability assessment for the threat propagators, such as the vulnerable area tables and probability of kill given a detonation arrays and curves. Figure 6.1 illustrates the overall survivability assessment process and some of the computer programs that can be used for each task. The three levels of survivability assessment are the one-on-one or engagement level survivability assessment, the many-on-many or mission-level survivability assessment, and the campaign-level survivability assessment. Assessment of survivability at these three levels is introduced in Chapter1, Sec.1.1. There are several measures of survivability available that depend upon the scenario and the goal of the assessment. The measures most often used in survivability assessments and trade studies are the probability an aircraft is killed given a single shot $P_{K|SS}$, the probability an aircraft is killed in

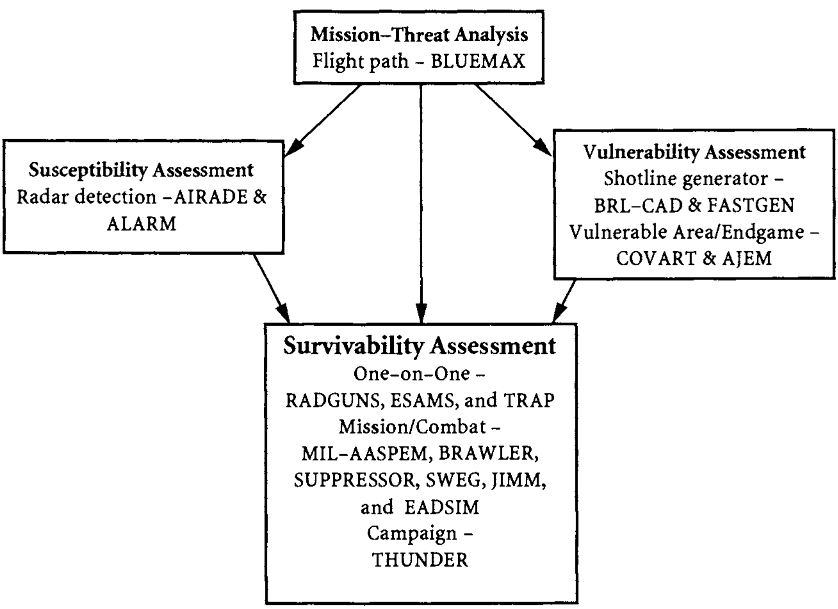


Fig. 6.1 Survivability assessment process and some applicable computer programs.

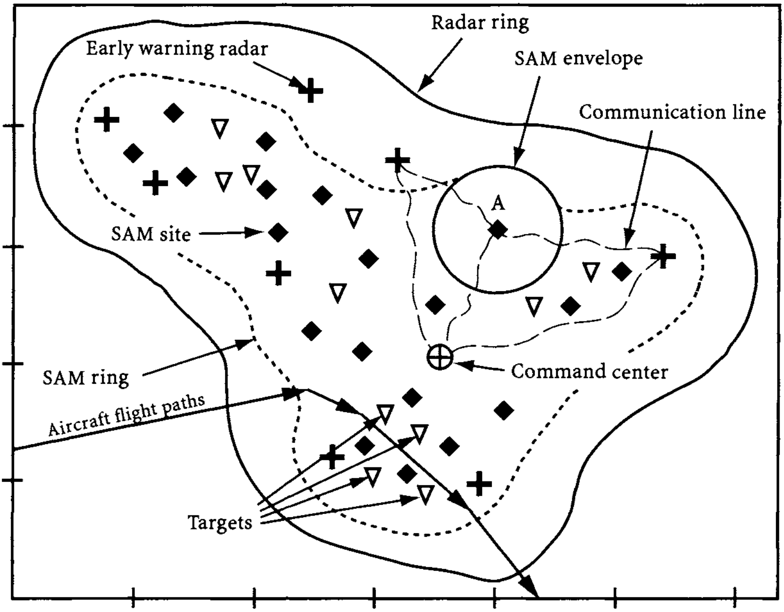


Fig. 6.2 General air interdiction scenario (adapted from Ref. 1, reprinted with permission).

a multiple shot one-on-one encounter with a single weapon $P_{K|E}$, the mission or sortie loss rate (LR), and the number of aircraft remaining at the end of a campaign. These measures can be used in trade studies to determine the effectiveness of the aircraft for a given campaign or aircraft lifetime.

Go to Problem 6.2.1.

6.2.1 Scenario

The scenario is a specific description of the many factors that characterize an encounter between one or more aircraft and the hostile air defense forces. Among these factors are the aircraft flight path(s); the type, number, and locations of the threat weapons; the threat doctrine and tactics; and the environmental conditions. An example of a scenario consisting of a flight of four aircraft on an air interdiction mission against four targets is illustrated in Fig. 6.2. Each target is protected by one SAM. The aircraft can carry dumb bombs, or smart (guided) bombs, or guided missiles, self-defense air-to-air missiles, and an ECM pod. The attack aircraft could be accompanied all of the way by an escort, or part of the way by a stand-off, electronic jamming aircraft, whose primary function is to jam or disrupt the communications links, air search radars, and target tracking radars (Note 1).

6.2.2 Survivability Measures and Equations

The assessment of aircraft survivability involves the computation of some measure of aircraft probability of survival (or kill) in a particular scenario. Aircraft probability of kill is a summary measure for the scenario that combines the aircraft's susceptibility (from initial aircraft detection and tracking through propagator launch to intercept and propagator impact or proximity warhead fuzing) with its vulnerability to the threat propagator warhead. Survivability can be expressed indirectly as the probability of kill per single shot $P_{K|SS}$, as given by Eq. (1.5i), as the probability of kill per encounter or weapon site P_K as given by Eq. (1.6a), or as the mission or sortie loss rate (LR), or directly as the probability of survival per sortie or the mission survival rate (SR), as given by Eq. (1.7a). Once the probability of mission survival or kill has been determined, other measures can be used, such as the losses per 1000 sorties, or the losses in a campaign, or the losses over the expected combat lifetime of the aircraft. In general, the assessment can be accomplished 'by hand,' or it can use small-scale digital computer programs for an evaluation or large-scale programs for an analysis.

6.2.2.1 Probability of kill given a single shot. The probability of an aircraft kill given a single shot $P_{K|SS}$ is computed using the assumption that the aircraft has been detected and that a threat propagator has been launched or fired. Thus, the $P_{K|SS}$ depends on the ability of the fire control/guidance system to direct the propagator to the vicinity of the aircraft, on the fuzing employed, if any, and on the aircraft vulnerability to the damage mechanisms generated by the warhead. The ability of the fire control/guidance system to direct the propagator to the vicinity of the aircraft can be represented by the two dimensional miss distance probability density function $\eta(\xi, \zeta)$ in the miss distance plane. If the warhead has an high-explosive charge, fuzing can be modeled by $P_F(\xi, \zeta)$, which is the probability of fuzing of an HE warhead on a propagator whose trajectory would intersect the miss distance plane at (ξ, ζ). The vulnerability of the aircraft to the damage mechanisms generated by the warhead can be defined by a kill function $V(\xi, \zeta)$, which provides the probability the target is killed as a result of a propagator whose trajectory intersects the miss distance plane at (ξ, ζ). The $P_{K|SS}$ for both gun projectiles and guided missiles with either contact or proximity warheads is determined by integrating the joint probability that the propagator miss distance is within the incremental interval $d\xi d\zeta$ located at (ξ, ζ) and the probability that fuzing occurs somewhere along the propagator flight path that intersects the miss distance plane at (ξ, ζ), and the probability that the aircraft is killed given that the propagator miss distance is located at (ξ, ζ) over the (ξ, ζ) plane. Thus,

$$P_{K|SS} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \eta(\xi, \zeta)\, P_F(\xi, \zeta)\, V(\xi, \zeta)\, d\xi\, d\zeta \tag{6.1}$$

For contact warheads, such as small arms and HE warheads with contact fuzes, a hit on the aircraft must occur to cause damage. High-explosive warheads with proximity fuzes only need to come close.

Contact warheads. Figure 6.3 illustrates the miss distance distribution $\eta(\xi, \zeta)$ and the shoe-box approximation of the aircraft for the contact warhead. The miss distance distribution, fuzing considerations, and the aircraft's vulnerability are examined next.

Miss distance: The assumption is made that the ability of the threat system to fire or guide a propagator to the vicinity of the aircraft can be modeled by the bivariate

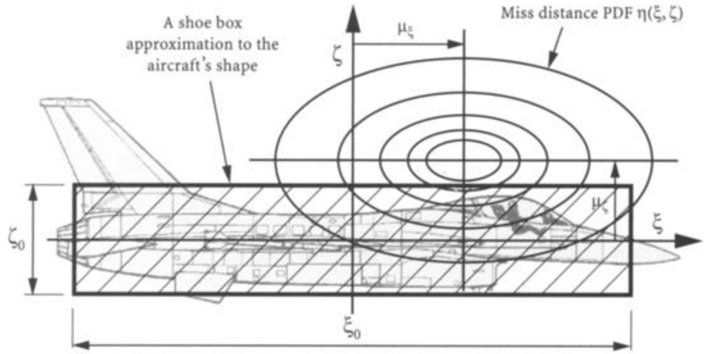


Fig. 6.3 Miss distance and kill functions.

normal miss distance PDF in the miss distance plane given by Eq. (4.29a). Thus,

$$\eta(\xi, \zeta) = \frac{1}{2\pi\sigma_\xi\sigma_\zeta} \exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2} - \frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2}\right] \tag{6.2a}$$

When the miss distance is circularly symmetric about the aircraft center,

$$\eta(\rho) = \frac{1}{2\pi\sigma_\rho^2} \exp\left(-\frac{\rho^2}{2\sigma_\rho^2}\right) \tag{6.2b}$$

according to Eq. (4.30a).

Fuzing: For nonexplosive propagators $P_F = 1$. For contact-fuzed HE warheads P_F is a value between 0 and 1 that accounts for the reliability of the fuze.

Aircraft vulnerability and the $P_{K|SS}$: There are two approaches to the evaluation of $P_{K|SS}$ for the contact warhead using the aircraft vulnerability measures $P_{K|H}$ and A_V that are based upon a uniform hit distribution as described in Chapter 5, Sec. 5.3. In one approach the probability the aircraft is hit by the propagator P_H is multiplied by the probability the aircraft is killed given a random hit on the aircraft $P_{K|H}$, which is equal to $P_F A_V / A_P$. Thus, in this approach $P_F(\xi, \zeta)V(\xi, \zeta)$ in Eq.(6.1) is replaced with $P_F(A_V/A_P)$, and Eq. (6.1) becomes

$$P_{K|SS} = \left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \eta(\xi, \zeta)\, H(\xi, \zeta)\, \mathrm{d}\xi\, \mathrm{d}\zeta\right] P_{K|H} = P_H P_{K|H} = P_H P_F(A_V/A_P) \tag{6.2c}$$

where $H(\xi, \zeta)$ is the hit function defined by Eq. (4.37b). The results for P_H are presented in Sec. 4.3.7.1 in Chapter 4 for the shoe-box approximation to the aircraft shown in Fig. 6.3 and the circularly symmetric aircraft shown in Fig. 4.24. The corresponding results for $P_{K|SS}$ are presented in the second paragraph next for both the cookie-cutter and the Carlton hit functions for the bivariate normal miss distance PDF, $\eta(\xi, \zeta)$, and when circular symmetry exists or is assumed, $\eta(\rho)$. The aircraft's A_V is developed in Chapter 5, Sec. 5.3.4.1 for the nonexplosive penetrator and Sec. 5.3.4.3 for the contact-fuzed HE warhead (Note 2).

In the second approach the aircraft's vulnerability is represented by its vulnerable area A_V, centered at the aim point. Any hit on the vulnerable area causes an aircraft kill, and any hit outside A_V does not kill the aircraft. Thus, $P_F(\xi, \zeta)V(\xi, \zeta) = H(\xi, \zeta)$, and A_P is replaced with A_V. The shoe box in Fig. 6.3 now represents the vulnerable area. Accordingly, the equations presented in Chapter 4 in Sec. 4.3.7.1 for the probability of hitting the aircraft presented area A_P can be used with A_P replaced by A_V. The results for $P_{K|SS}$ using this approach are also presented next as the alternate (or) equations:

Contact warheads: cookie-cutter hit function:
for (ξ, ζ),

$$P_{K|SS} = \frac{A_V}{A_P} P_F \int_{-\zeta_0/2}^{\zeta_0/2} \int_{-\xi_0/2}^{\xi_0/2} \frac{1}{2\pi\sigma_\xi\sigma_\zeta} \exp\left[-\frac{(\xi-\mu_\xi)^2}{2\sigma_\xi^2} - \frac{(\zeta-\mu_\zeta)^2}{2\sigma_\zeta^2}\right] \mathrm{d}\xi\,\mathrm{d}\zeta \tag{6.3a}$$

for (ρ),

$$P_{K|SS} = \left[1 - \exp\left(\frac{-A_P}{2\pi\sigma_\rho^2}\right)\right] P_F \left(\frac{A_V}{A_P}\right) \quad \text{or} \quad P_F\left[1 - \exp\left(\frac{-A_V}{2\pi\sigma_\rho^2}\right)\right] \tag{6.3b}$$

Contact warheads: Carlton hit function:
for (ξ, ζ),

$$P_{K|SS} = \frac{A_V P_F}{\sqrt{2\pi\sigma_\xi^2 + \xi_0^2}\sqrt{2\pi\sigma_\zeta^2 + \zeta_0^2}} \exp\left(-\frac{\pi\mu_\xi^2}{2\pi\sigma_\xi^2 + \xi_0^2} - \frac{\pi\mu_\zeta^2}{2\pi\sigma_\zeta^2 + \zeta_0^2}\right) \tag{6.3c}$$

$$\xi_0\zeta_0 = A_P \quad \text{or} \quad \xi_0\zeta_0 = A_V$$

for (ρ),

$$P_{K|SS} = \frac{A_V P_F}{2\pi\sigma_\rho^2 + A_P} \quad \text{or} \quad \frac{A_V P_F}{2\pi\sigma_\rho^2 + A_V} \tag{6.3d}$$

Example 6.1 Determination of $P_{K|SS}$ for a Contact Warhead

A particular helicopter has a presented area of 150 ft^2 and a vulnerable area for the 23-mm contact-fuzed HE-I round of 50 ft^2. A particular gun fires 23-mm rounds at the hovering helicopter with $\mu_\xi = \mu_\zeta = 0$ and $\sigma_\xi = \sigma_\zeta = 16$ ft. Assume $P_F = 1$ and a circular aircraft. Compute the $P_{K|SS}$ using both the cookie-cutter and the Carlton hit functions and both approaches.

For the circularly symmetric cookie-cutter hit function and miss distance with the first approach

$$P_{K|SS} = \left\{1 - \exp\left[\frac{-150\,\text{ft}^2}{2\pi(16\,\text{ft})^2}\right]\right\}\left(\frac{50\,\text{ft}}{150\,\text{ft}}\right) = 0.0297$$

according to Eq. (6.3b). For the cookie-cutter hit function and the second approach

$$P_{K|SS} = 1 - \exp\left[\frac{-50\,\text{ft}}{2\pi(16\,\text{ft})^2}\right] = 0.0306$$

Using Eq. (6.3d) for the circularly symmetric Carlton hit function and miss distance

$$P_{K|SS} = \frac{50\,\text{ft}^2}{2\pi(16\,\text{ft})^2 + 150\,\text{ft}^2} = 0.0284$$

$$P_{K|SS} = \frac{50\,\text{ft}}{2\pi(16\,\text{ft})^2 + 50\,\text{ft}^2} = 0.0301$$

for the first and second approaches, respectively.

$P_{K|SS}$ based upon component kills: The results given in the preceding equations are based upon the assumption in the vulnerability assessment for $P_{K|H}$ and A_V that the hits are uniformly distributed over the aircraft's presented area. Using this assumption, the vulnerability of all of the individual critical components is replaced by the vulnerability of the aircraft as measured by $P_{K|H}$ and A_V. Because the bivariate normal miss distance distribution is not uniform, the assumption of a uniform hit distribution when determining vulnerability is incorrect. In this section the assumption that the hit distribution is uniform is not made. Instead, the probability of kill of the individual components, and hence the kill of the aircraft, is determined for the bivariate normal miss distance distribution given by Eq. (6.2a).

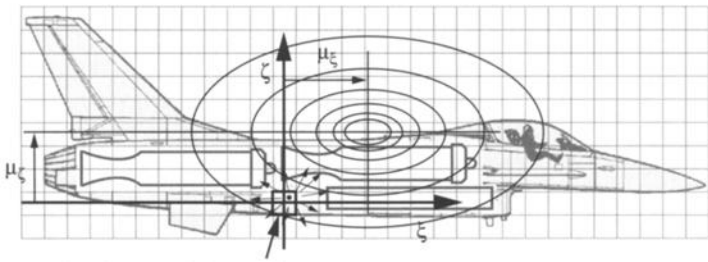
First, consider the nonexplosive penetrator or fragment. The probability of a kill of any individual component on the aircraft with a presented area A_p and probability of component kill given a hit on the component $P_{k|h}$ can be computed using Eqs. (6.3a–d) with $\xi_0\zeta_0 = A_P$ for the first approach and $\xi_0\zeta_0 = A_V$ for the second approach, provided the miss distance means μ_ξ and μ_ζ are measured with respect to the location of the component center rather than the aircraft center. Thus, if the locations and vulnerability data on all of the critical components are known, the probability each of the critical components is killed by the single shot can be determined for the miss distance distribution given by Eq. (6.2a). These component kill probabilities can be substitued into the appropriate kill or survival expression, resulting in a more realistic value for $P_{K|SS}$. However, if the miss distance distribution variation over the extent of the aircraft is essentially uniform, then the $P_{K|SS}$ based upon the individual components will be essentially the same as the $P_{K|SS}$ given by Eqs. (6.3) (refer to Note 2).

Next, consider the contact-fuzed HE warhead. The $P_{K|SS}$ for this threat can be determined using the point burst approach, which is presented in Chapter 5, Sec. 5.3.4.3. There, a uniform grid is superimposed over the aircraft, and the probability the aircraft is killed by a randomly located burst in the bth cell $P_{K|Hb}$ is determined for $b = 1, 2, \ldots B$. The procedure for determining $P_{K|H}$ and A_V described there assumes a uniform hit distribution, and consequently the area of each cell within the uniform grid superimposed over the aircraft A_c, as illustrated in Fig. 5.25, is equally likely hit with the value P_{Hb} expressed by Eq. (5.23d). Here, the bivariate normal distribution given by Eq. (6.2a) is assumed. The probability the area of the bth cell within the grid is hit P_{Hb} can be computed using the equations given in

Sec. 4.3.7.1 in Chapter 4, with A_p replaced by A_c and with μ_ξ and μ_ζ measured with respect to the location of the bth cell center rather than the aircraft center. The values for P_{Hb} and $P_{K|Hb}$ for the cells $b = 1, 2, \ldots B$ are then used in Eq. (5.24a) to compute the $P_{K|SS}$. If the fuze has a probability less than one of functioning, the $P_{K|SS}$ is multiplied by the fuze P_F.

Example 6.2 Determination of $P_{K|SS}$ for a Contact HE Warhead Based upon the Kill of the Individual Components

Consider the aircraft in Example 5.9. There, a 23-mm HE-I projectile hits an aircraft on the lower right side, as illustrated here. The $P_{K|Hb}$ for this particular burst = 0.790, and the probability of fuzing is one. Of interest here is the $P_{K|SS}$ for this projectile based upon a kill of the individual components. In the point burst approach a uniform square grid is superimposed on the aircraft as shown here. The area of each grid cell $A_c = 4\,\text{ft}^2$ in this example. The projectile miss distance is the bivariate normal PDF shown in the following illustration.



Cell with randomly located burst point

The miss distance means (with respect to the center of the cell with the burst point b) and the standard deviations are

$$\mu_\xi = 7\,\text{ft}, \quad \mu_\zeta = 6\,\text{ft}, \quad \sigma_\xi = 10\,\text{ft}, \quad \sigma_\zeta = 5\,\text{ft}$$

The probability the projectile will hit the cell containing the burst point can be determined using either P_{Hb} based upon the cookie-cutter hit function, Eq. (4.36a), or P_{Hb} based upon the Carlton hit function, Eq. (4.40a). The procedure for calculating P_{Hb} based upon the cookie cutter is described in Example 4.9. Using the P_{Hb} based upon the Carlton hit function, Eq. (4.40a) for the square cell, results in

$$P_{Hb} = \frac{4\,\text{ft}^2}{\sqrt{2\pi(10\,\text{ft})^2 + 4\,\text{ft}^2}\sqrt{2\pi(5\,\text{ft})^2 + 4\,\text{ft}^2}} \exp\left[-\frac{\pi(7\,\text{ft})^2}{2\pi(10\,\text{ft})^2 + 4\,\text{ft}^2} - \frac{\pi(6\,\text{ft})^2}{2\pi(5\,\text{ft})^2 + 4\,\text{ft}^2}\right]$$
$$= 0.00487$$

Thus, the contribution to the $P_{K|SS}$ of this particular burst point is

$$P_{K|SS}(\text{due to the single burst point}\, b) = P_{Hb} \cdot P_{K|Hb} = 0.00487 \cdot 0.790$$
$$= 0.00385$$

according to Eq. (5.24a). Performing similar calculations for the P_{Hb} for all of the other grid cells where a hit can occur, determining the $P_{K|Hb}$ for the random burst in each of these cells, and summing the results as indicated in Eq. (5.24a) results in the total $P_{K|SS}$ for this aircraft and threat weapon based upon the kill of the individual critical components.

$P_{K|SS}$ reduction: Note in the preceding equations for contact and proximity-fuzed warheads that in the first approach $P_{K|SS}$ is linearly proportional to A_V. Thus, any reduction in A_V will cause a linear reduction in $P_{K|SS}$. In the second approach $P_{K|SS}$ is not directly proportional to A_V, and any reduction will not result in a linear reduction in $P_{K|SS}$. Also note in the first approach that $P_{K|SS}$ is reduced by increasing A_P; larger aircraft with the same vulnerable area are less likely to be killed given a hit. The pilot on the F-16 is more likely to be killed given a random hit on the F-16 than the pilot on the C-130 given a random hit on the C-130.

The reduction in $P_{K|SS}$ caused by a reduction in susceptibility is not as obvious. Figure 6.4 shows plots of the $P_{K|SS}$, using the Carlton hit function and the first approach, for a square aircraft as a function of the miss distance means, μ_ξ and μ_ζ, and three values of the standard deviations, with $\sigma_\xi = \sigma_\zeta$. Also shown in the figure is the target and the CEP for $(\sigma_\xi)^2/A_P = 1$ with $(\mu_\xi)^2/A_P = 0$ and 4. Note that the distribution with the smallest miss distance variance is not as effective as the two distributions with the larger variances when the means are relatively large. That is why guns, with relative large means, are more effective when the variances (ballistic dispersion) are also relatively large (Note 3).

Go to Problems 6.2.2 to 6.2.5.

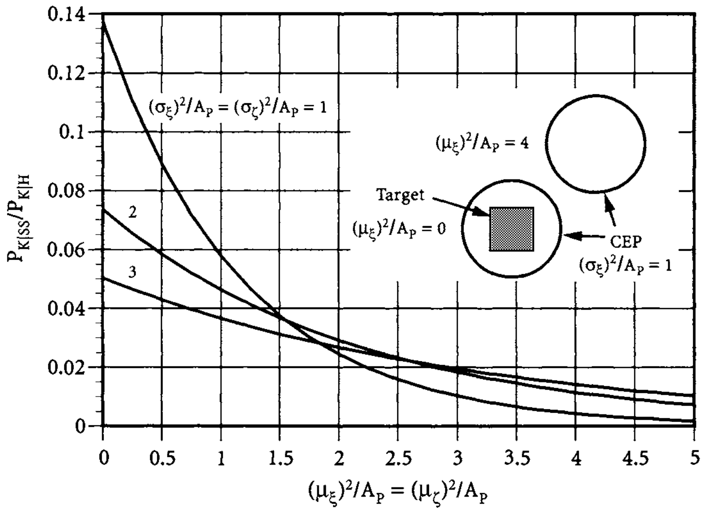


Fig. 6.4 $P_{K|SS}$ vs the miss distance means and standard deviations.

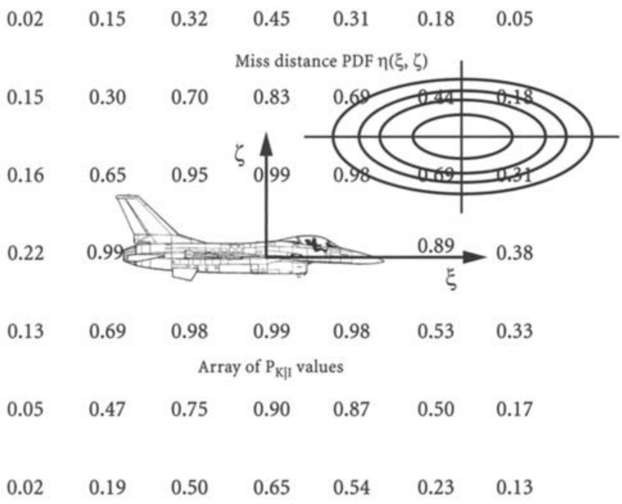


Fig. 6.5 Miss distance and values of $P_{K|I}$.

Proximity-fuzed warheads. Figure 6.5 illustrates the proximity warhead situation. A propagator with a proximity-fuzed HE warhead is moving normal to the page relative to the target aircraft. (Your eyes are the missile's seeker.) The page is in the miss distance plane. The ellipses in the upper right corner of the figure represent the miss distance distribution, and the array of numbers is the joint probability $P_{F|I}P_{K|F}$ or $P_{K|I}$ at specific locations of (ξ, ζ). Thus, each number represents the probability the aircraft is killed by a warhead detonation on a propagator traveling normal to the page whose flight path with respect to the aircraft intersects the page at the location of the number. In Eq. (6.1), $P_F(\xi, \zeta)V(\xi, \zeta)$ is the product $P_{F|I}P_{K|F}$ for a given (ξ, ζ).

Miss distance: The assumption is made that the ability of the threat system to fire or guide a propagator with a proximity warhead to the vicinity of the aircraft also can be expressed by the bivariate normal PDF illustrated in Fig. 6.5. Thus, the miss distance PDF is (Note 4)

$$\eta(\xi, \zeta) = \frac{1}{2\pi\sigma_\xi\sigma_\zeta}\exp\left[-\frac{(\xi - \mu_\xi)^2}{2\sigma_\xi^2} - \frac{(\zeta - \mu_\zeta)^2}{2\sigma_\zeta^2}\right] \tag{6.4a}$$

according to Eq. (4.29a). When the miss distance is circularly symmetric about the aircraft center,

$$\eta(\rho) = \frac{1}{2\pi\sigma_\rho^2}\exp\left(-\frac{\rho^2}{2\sigma_\rho^2}\right) \tag{6.4b}$$

according to Eq. (4.30a).

Fuzing: The probability of fuzing for proximity warheads is examined in Chapter 4, Sec. 4.3.7.2. Three options for fuzing along the missile flight path are shown in Fig. 4.27. Note that the use of a two-dimensional analysis for $P_{K|SS}$ does not require a proximity-fuzed warhead to detonate in the miss distance plane. A three-dimensional effect (warhead detonation before the propagator reaches the CPA) is accounted for in the two-dimensional analysis described next.

Aircraft vulnerability and the $P_{K|SS}$: The array of numbers around the aircraft shown in Fig. 6.5 are the numerical values for $P_{F|I}P_{K|F}$ for specific locations (ξ, ζ). These numbers are obtained using any one of the three options for fuzing along the propagator flight path and any one of several equations for $P_{K|F}$. The procedure for determining $P_{F|I}P_{K|F}$ at each (ξ, ζ) is as follows. A flight path with the miss distance (ξ, ζ) is chosen. A fuzing location along the flight path is selected. For example, the assumption could be made that fuzing occurs on the optimum fuzing line shown in Fig. 4.27. The probability the aircraft is killed given fuzing at that location $P_{K|F}$ is determined by first computing the number of fragment hits on the aircraft caused by fuzing at that location N, using the procedure presented in Chapter 4, Sec. 4.3.7.2. The probability the aircraft is killed by those N hits is then determined by conducting a vulnerability assessment as described in Chapter 5, Sec. 5.3.4.4. If the uniform or normal PDF is selected for the fuzing option rather than a single location then $P_{K|F}$ is determined for a number of fuzing locations along the flight path. For example, $P_{K|F}$ is determined at five equally spaced locations along the fight path shown in Fig. 6.6a; three in zone I and two in zone II. The value of $P_{F|I}$ for the fuzing option selected is then plotted along the flight path. The normal distribution is shown in Fig. 6.6b. The continuous integration over the flight path of the product of $P_{K|F}$ and $P_{F|I}$ determines the probability the aircraft is killed as a result of an intercept along the given flight path, which is one of the numbers in the array shown in Fig. 6.5. Because of the variability of $P_{K|F}$ along the flight path, the integration is usually accomplished numerically by dividing the path length into a number of intervals, for example, six in Figs. 6.6a and 6.6b. The value of $P_{K|F}$ in the center of the interval is multiplied by the

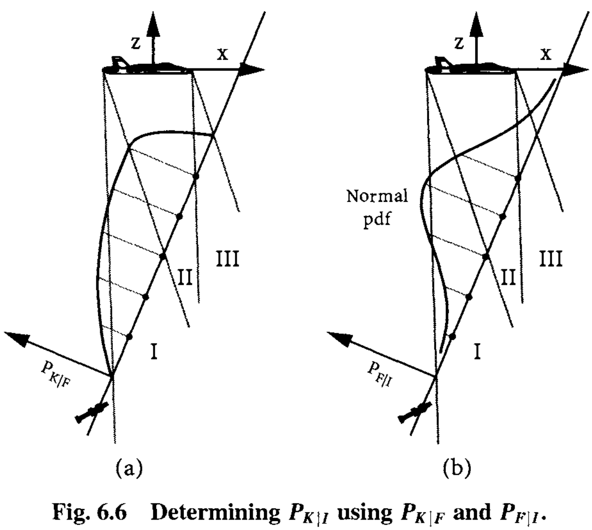


Fig. 6.6 Determining $P_{K|I}$ using $P_{K|F}$ and $P_{F|I}$.

probability fuzing occurs within the interval, which is the area under $P_{F|I}$ for the interval. The product is computed for all intervals, and the integration for $P_{K|I}$ is the sum of the products. Note that P_F has been assumed to be one, that is, the integral of the fuzing PDF is unity. If a smaller value is desired, then the numerical value computed for $P_{K|I}$ using the PDF is multiplied by that P_F.

Given the array of numbers for $P_{K|I}$ or $P_F(\xi, \zeta)V(\xi, \zeta)$ and the miss distance distribution $\eta(\xi, \zeta)$, the integrand in Eq. (6.1) for $P_{K|SS}$ can be evaluated numerically by dividing the miss distance plane into small square cells $\Delta\xi\,\Delta\zeta$ similar to the grid shown in Fig. 5.28. In each cell the probability that the propagator is within the incremental interval $\Delta\xi\,\Delta\zeta$ located at (ξ, ζ), $\eta(\xi, \zeta)\Delta\xi\,\Delta\zeta$, is multiplied by the numerical value of $P_{K|I}$ in that cell. This process is carried out for all cells in the miss distance plane, and $P_{K|SS}$ is the sum of the products in all of the cells.

It should be apparent that none of the expressions for $P_{K|F}$ given in Chapter 5, when combined with the fuzing PDF and either the bivariate or the circular normal miss distance function, lead to a simple analytical solution of Eq. (6.1) for $P_{K|SS}$ in closed form. Consequently, the product $P_F(\xi, \zeta)V(\xi, \zeta)$ is often approximated by a simpler expression in the radial miss distance ρ, with the parameters of the reliability probability of fuzing P_F, and a lethal radius r_L or lethal area A_L. To accomplish this simplification, the array of numerical values for $P_{K|I}$ given in Fig. 6.5 must be converted into a circularly symmetric function. Figure 6.7 shows the values of $P_{K|I}$ given in Fig. 6.5. Circles are drawn around the center of the aircraft indicating a constant miss distance, and the average of the $P_{K|I}$ values on each circle is indicated in the figure. The circularly symmetric $P_{K|I}$ curve based upon the average values on the rings is shown in the lower diagram in terms of the radial miss distance ρ. This curve is analogous to the $P_{K|F}$ warhead lethality function shown in Fig. 3.11 in terms of the detonation distance. The lethal miss distance where $P_{K|I} = 0.5$ is indicated in the figure, and the lethal area A_L is equal to the area under the $P_{K|I}$ curve.

If the kill function shown in Fig. 6.7 is approximated by the circularly symmetric Carlton kill function centered at the aircraft

$$P_F(\xi, \zeta)V(\xi, \zeta) = P_{K|I} = P_F \exp\left(-\rho^2/\rho_0^2\right) = P_F \exp\left(-\xi^2/\rho_0^2\right) \exp\left(-\zeta^2/\rho_0^2\right) \tag{6.5a}$$

where ρ_0 is a scaling parameter. Using Eq. (6.5a) for $P_F(\xi, \zeta)V(\xi, \zeta)$, $P_{K|SS}$ is given by

$$P_{K|SS} = \frac{\rho_0^2 P_F}{\sqrt{2\sigma_\xi^2 + \rho_0^2}\sqrt{2\sigma_\zeta^2 + \rho_0^2}} \exp\left(-\frac{\mu_\xi^2}{2\sigma_\xi^2 + \rho_0^2} - \frac{\mu_\zeta^2}{2\sigma_\zeta^2 + \rho_0^2} \right) \tag{6.5b}$$

according to Eq. (6.1). One option for ρ_0 is to require $P_{K|I}$ be equal to 0.5 when $\rho = r_L$. This leads to

$$\rho_0 = 1.2 r_L \tag{6.6a}$$

Another option is to equate the area under the Carlton kill function to the lethal

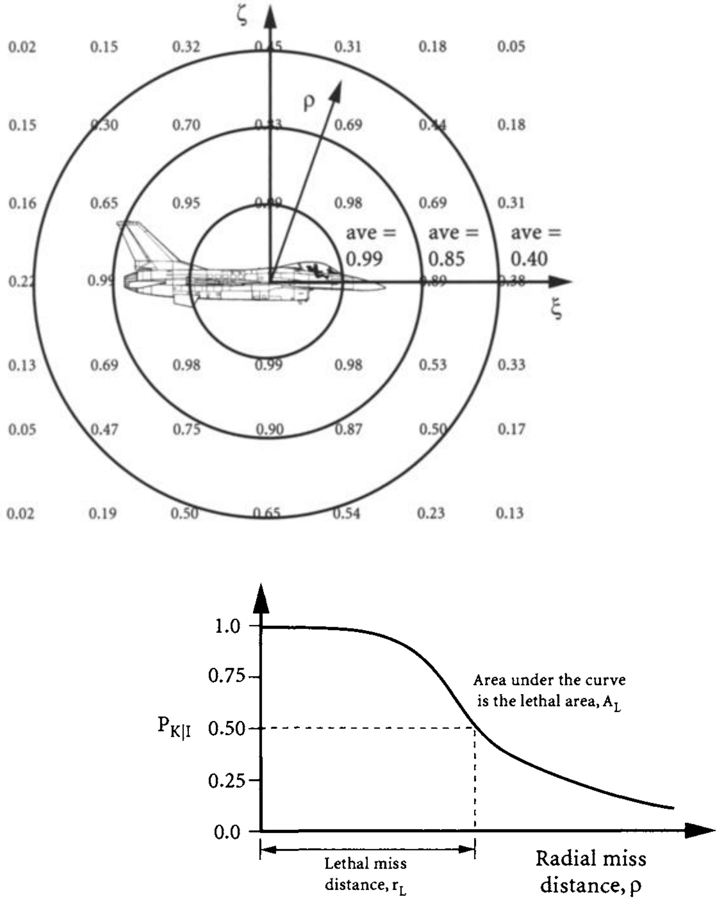


Fig. 6.7 Circularly symmetric $P_{K|I}$.

area A_L under the actual $P_{K|I}$ distribution. This leads to

$$\rho_0 = \sqrt{\frac{A_L}{\pi}} \tag{6.6b}$$

according to Eq. (4.42b).

For a circularly symmetric normal miss distance distribution about the aim point given by Eq. (6.4b), a fuze cutoff range r_c beyond ρ_0, and the cookie-cutter kill function, where $P_{K|I} = 1$ when $\rho \leq \rho_0$ and $P_{K|I} = 0$ when $\rho > \rho_0$, Eq. (6.1) results in

$$P_{K|SS} = P_F \left[1 - \exp\left(-\frac{\rho_0^2}{2\sigma_\rho^2} \right) \right] \tag{6.7a}$$

which can be shown to be equivalent to (Note 5)

$$P_{K|SS} = P_F\left[1 - 0.5^{(\rho_0/\mathrm{CEP})^2}\right] \tag{6.7b}$$

One option for ρ_0 is

$$\rho_0 = r_L \tag{6.7c}$$

The extent of the cookie-cutter kill function also can be defined by the lethal area under the $P_{K|I}$. Using A_L as the yardstick (rather than the radius where $P_{K|I} = 0.5$) results in a new definition for ρ_0 such that

$$\rho_0 = \sqrt{\frac{A_L}{\pi}} \tag{6.7d}$$

Under the same circularly symmetric conditions for the aircraft and the miss distance, the Carlton kill function given by Eq. (6.5a) leads to

$$P_{K|SS} = \frac{\rho_0^2}{2\sigma_\rho^2 + \rho_0^2} P_F\left[1 - \exp\left(-\frac{2\sigma^2 + \rho_0^2}{2\sigma_\rho^2\rho_0^2} r_c^2\right)\right] \tag{6.7e}$$

where ρ_0 is defined by either Eq. (6.6a) or (6.6b).

A summary of the $P_{K|SS}$ equations for the proximity warhead for both the cookie-cutter and the Carlton kill functions for the two-dimensional miss distance and when circular symmetry exists or is assumed are given next.

Proximity-fuzed warheads: cookie-cutter kill function:
for (ρ),

$$P_{K|SS} = P_F\left[1 - \exp\left(-\frac{\rho_0^2}{2\sigma_\rho^2}\right)\right] = P_F\left[1 - 0.5^{(\rho_0/\mathrm{CEP})}\right] \tag{6.8a}$$

$$\rho_0 = r_L \quad \text{or} \quad \rho_0 = (A_L/\pi)^{1/2}$$

Proximity-fuzed warheads: Carlton (circularly symmetric) kill function:
for (ξ, ζ),

$$P_{K|SS} = \frac{\rho_0^2 P_F}{\sqrt{2\sigma_\xi^2 + \rho_0^2}\sqrt{2\sigma_\zeta^2 + \rho_0^2}} \exp\left(-\frac{\mu_\xi^2}{2\sigma_\xi^2 + \rho_0^2} - \frac{\mu_\zeta^2}{2\sigma_\zeta^2 + \rho_0^2}\right) \tag{6.8b}$$

$$\rho_0 = 1.2 r_L \quad \text{or} \quad \rho_0 = (A_L/\pi)^{1/2}$$

for (ρ),

$$P_{K|SS} = \frac{\rho_0^2}{2\sigma_\rho^2 + \rho_0^2} P_F\left[1 - \exp\left(-\frac{2\sigma_\rho^2 + \rho_0^2}{2\sigma_\rho^2\rho_0^2} r_c^2\right)\right] \tag{6.8c}$$

$$\rho_0 = 1.2 r_L \quad \text{or} \quad \rho_0 = (A_L/\pi)^{1/2}$$

Figure 6.8 presents $P_{K|SS}$ as a function of r_L/CEP for the circularly symmetric miss distance and $P_F = 1$. Plots of both the cookie-cutter results, Eq. (6.7b), and

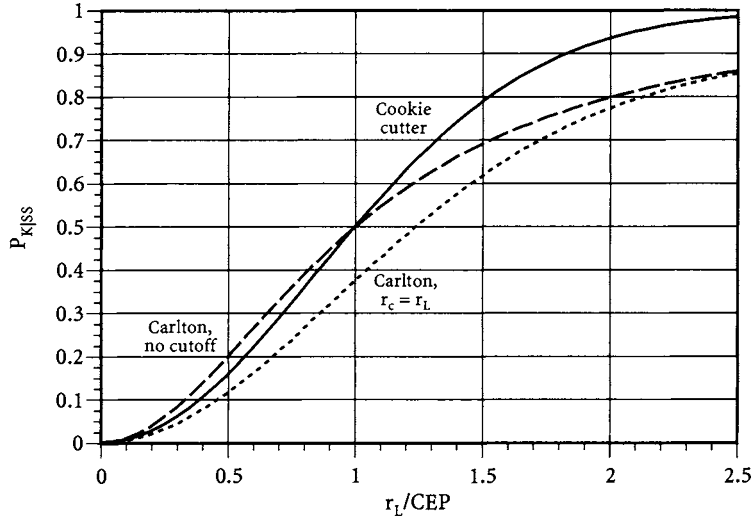


Fig. 6.8 $P_{K|SS}$ **vs** r_L**/CEP for the circularly symmetric condition.**

the Carlton results, Eq. (6.8), with ρ_0 given by Eq. (6.6a) and with no fuze cutoff and with $r_c = r_L$, are shown.

Reducing $P_{K|SS}$: Reducing the vulnerability of the aircraft to the proximity warhead reduces the aircraft's $P_{K|F}$, which reduces the values for $P_{K|I}$ in the array shown in Fig. 6.5, and the lethal radius r_L and lethal area A_L. Reducing the aircraft's susceptibility to the propagator increases the miss distance bivariate means and the CEP. For example, suppose $r_L/\text{CEP} = 2$ for a particular shot. Hence, $P_{K|SS} = 0.8$ for the Carlton kill function with no fuze cutoff according to Fig. 6.8. Reducing r_L to one-half of its original value reduces r_L/CEP to one, where $P_{K|SS} = 0.5$. On the other hand, if r_L remains the same, but the CEP is doubled, r_L/CEP is again reduced to one, where $P_{K|SS} = 0.5$. If both vulnerability and susceptibility are reduced the same amount, r_L/CEP becomes 0.5, and $P_{K|SS}$ is 0.2, a 75% reduction from the original 0.8 value.

Example 6.3 Determination of $P_{K|SS}$ With and Without Onboard ECM Equipment

Of significant interest to the program manager of the Firefly bomber is the increase in survivability of the bomber against a particular SAM system because of the use of an onboard electronic jammer. The signals generated by the jammer can prevent or delay the launch of a missile, reduce the number of missiles launched, increase the miss distance of any launched missiles, and they might prevent fuzing. Of particular interest here is the effect of the jammer on the miss distance of a launched missile and the corresponding reduction in the $P_{K|SS}$.

To determine the effect of the jammer on the miss distance, a test program was conducted where a number of missiles were launched at an aircraft from various ranges within a range interval, and the minimum separation or radial miss distance

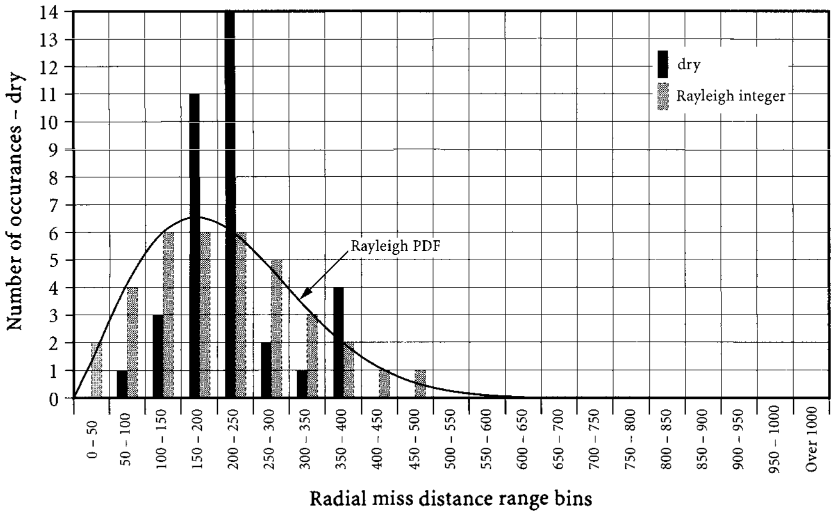


Fig. 6.9a Dry miss distance distribution.

for each launch was measured. (The assumption was made that the miss distances would be circularly symmetric; hence, only the radial distance is required.) Thirty-six launches were made in the dry (no ECM) environment, and 25 were launched in the wet (with ECM) environment. The miss distance histograms from the dry tests (black columns) and the wet tests (cross-hatched columns) are shown in Figs.6.9a and 6.9b, respectively.

Using Eq. (4.22d) to determine the standard deviation of the dry miss distances results in $\sigma = 163$ ft, and consequently CEP $= 192$ ft according to Eq. (B.53). Determining the CEP based upon the 18th and 19th largest miss distance (one-half of the miss distances are smaller and one-half are larger) results in a CEP in the 200- to 250-ft bin, which is reasonably close to 192 ft. In the wet tests Eq. (4.22d) resulted in $\sigma = 680$ ft, and hence CEP $= 800$ ft. The CEP estimated from the miss distance of the 13th launch, which is in the 550- to 600-ft bin, is CEP $= 575$ ft. An average CEP of 675 ft and σ of 575 ft will be used in the following assessment

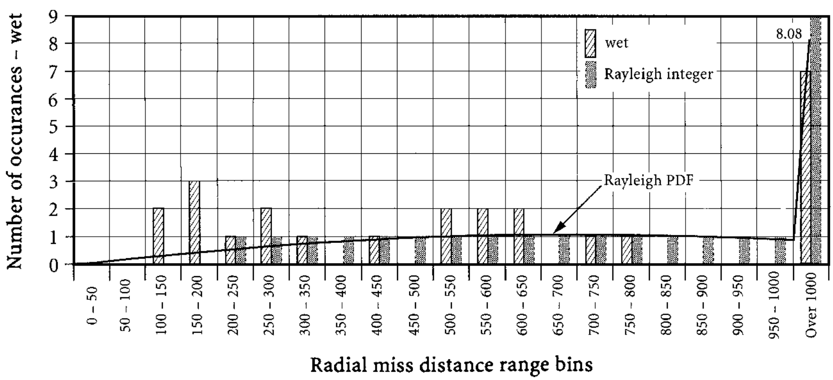


Fig. 6.9b Wet miss distance distribution.

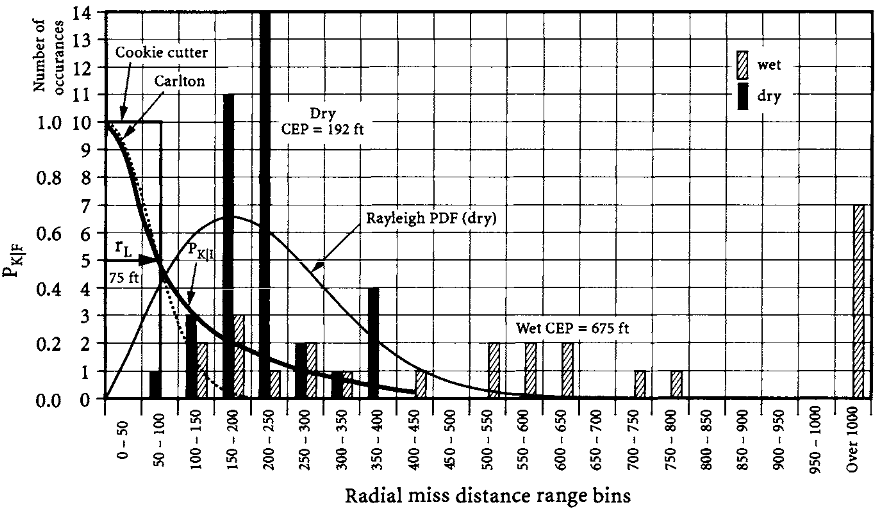


Fig. 6.9c Miss distance distributions and the $P_{K|I}$ kill functions based upon r_L.

for $P_{K|SS}$ for the wet condition. The smooth line in the two figures is the Rayleigh PDF (Fig. B. 28a) based upon the standard deviation computed from the test results converted to the number of occurrences, and the gray bars are the nearest integer of the Rayleigh distribution within each range bin (Note 6). Note that the Rayleigh distribution is a good representation of the dry and a reasonable representation of the wet miss distance distributions.

Figure 6.9c contains both the dry and the wet miss distance experimental distributions and the dry Rayleigh PDF. The $P_{K|I}$ function for the bomber, determined, using the methods presented in Chapter 6, is the solid black line shown in Fig. 6.9c. The lethal miss distance is 75 ft. Also shown in the figure are the cookie-cutter and the Carlton (dashed line) approximations to the function based upon the lethal miss distance. Miss distances inside the cookie are sometimes referred to as hits, where $P_{K|I} = 1$, and those outside of the cookie are misses, where $P_{K|I} = 0$. Note that, in this example, both of these approximations decay with range much faster than does the $P_{K|I}$ function.

The $P_{K|SS}$ based upon the histogram miss distance results and the $P_{K|I}$ are obtained in three ways; numerically using the experimental miss distance results, using Eq. (6.7b), and using Eq. (6.7e). Numerically, $P_{K|SS}$ is obtained by multiplying the probability the missile is in a miss distance range bin times the probability the bomber is killed given the intercept in the center of the bin and summing the results for all miss distance range bins. The assumption is made that $P_F = 1$ and there is no fuze cutoff ($r_c = \infty$). Both the experimental miss distance distribution and the corresponding Rayleigh distribution shown in Figs. 6.9a and 6.9b are used.

$$P_{K|SS}(\text{dry}, P_{K|I}, \text{exp}) = (1 \cdot 0.50 + 3 \cdot 0.30 + 11 \cdot 0.20 + 14 \cdot 0.14 + 2 \cdot 0.10 \\ +1 \cdot 08 + 4 \cdot 0.04)/36 = 0.17$$

$$P_{K|SS}(\text{dry}, P_{K|I}, \text{normal}) = (2 \cdot 0.90 + 4 \cdot 0.50 + 6 \cdot 0.30 + 6 \cdot 0.20 + 6 \cdot 0.14 \\ +5 \cdot 0.10 + 3 \cdot 08 + 2 \cdot 0.04 + 1 \cdot 0.01)/36 = 0.24$$

When using the cookie-cutter kill function with the experimental data, because the lethal miss distance is in the middle of the 50–100 ft bin, only one-half of the occurrences will be included in that bin. Thus,

$$P_{K|SS}(\text{dry, cookie cutter, exp}) = 1.0 \cdot (0.5 \cdot 1)/36 = 0.01$$

Using the Carlton kill function and the experimental data gives

$$P_{K|SS}(\text{dry, Carlton, exp}) = (1 \cdot 0.50 + 3 \cdot 0.15 + 11 \cdot 0.02)/36 = 0.03$$

Using the cookie-cutter kill function and Eq. (6.7b) results in

$$P_{K|SS}(\text{dry, cookie cutter}) = 1 - 0.5^{(75\,\text{ft}/192\,\text{ft})^2} = 0.10$$

Using the Carlton kill function and Eq. (6.7e) leads to

$$P_{K|SS}(\text{dry, Carlton}) = \frac{[1.2 \cdot (75\ \text{ft})]^2}{2 \cdot (163\ \text{ft})^2 + [1.2 \cdot (75\ \text{ft})]^2} = 0.13$$

For the wet condition, numerically

$$P_{K|SS}\,(\text{wet}, P_{K|I}, \text{exp}) = (2 \cdot 0.30 + 3 \cdot 0.20 + 1 \cdot 0.14 + 2 \cdot 0.10 + 1 \cdot 0.08$$
$$+1 \cdot 0.02)/25 = 0.07$$

$$P_{K|SS}\,(\text{wet}, P_{K|I}, \text{normal}) = (1 \cdot 0.14 + 1 \cdot 0.10 + 1 \cdot 08 + 1 \cdot 0.04$$
$$+1 \cdot 0.01)/25 = 0.01$$

$$P_{K|SS}\,(\text{wet, cookie cutter, exp}) = 0$$

$$P_{K|SS}\,(\text{wet, Carlton, exp}) = (2 \cdot 0.15 + 3 \cdot 0.02)/25 = 0.01$$

Using the cookie cutter and Eq. (6.7b),

$$P_{K|SS}(\text{wet, cookie cutter}) = 1 - 0.5^{(75\,\text{ft}/675\,\text{ft})^2} = 0.01$$

and using the Carlton and Eq. (6.7e)

$$P_{K|SS}\,(\text{wet, Carlton}) = \frac{[1.2 \cdot (75\ \text{ft})]^2}{2 \cdot (575\ \text{ft})^2 + [1.2 \cdot (75\ \text{ft})]^2} = 0.01$$

Note that for this example both the cookie-cutter and the Carlton kill functions underestimate the value of $P_{K|SS}$ for both the dry and the wet conditions. Because the $P_{K|I}$ function decays relatively slowly with miss distance, better agreement can be obtained by basing the cookie-cutter and Carlton functions on the lethal area under the $P_{K|I}$ curve rather than on the lethal miss distance.

A numerical integration of the area under the $P_{K|I}$ curve in Fig. 6.9c can be obtained by summing the product of the area within each range bin and the value of $P_{K|I}$ at the center of the bin over all bins. The area within each bin is equal to π times the difference between the bin's outer radius squared and its inner radius

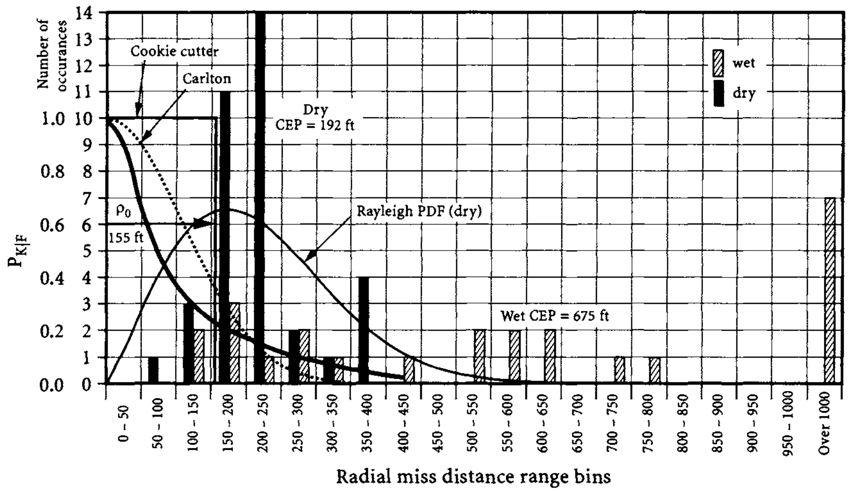


Fig. 6.9d Miss distance distributions and the $P_{K|I}$ kill functions based upon A_L.

squared. Thus

$$\begin{aligned} A_L &= \pi[(2500\,\text{ft}^2)\cdot 0.9 + (7500\,\text{ft}^2)\cdot 0.5 + (12{,}500\,\text{ft}^2)\cdot 0.3 \\ &\quad +(17{,}500\,\text{ft}^2)\cdot 0.2 + (22{,}500\,\text{ft}^2)\cdot 0.14 + (27{,}500\,\text{ft}^2)\cdot 0.1 \\ &\quad +(32{,}500\,\text{ft}^2)\cdot 0.08 + (37{,}500\,\text{ft}^2)\cdot 0.04 + (42{,}500\,\text{ft}^2)\cdot 0.02] \\ &= 75{,}712\,\text{ft}^2 \end{aligned}$$

Therefore, ρ_0 for both the cookie-cutter and the Carlton kill functions is

$$\rho_0 = [(75{,}712\ \text{ft}^2)/\pi]^{0.5} = 155\ \text{ft}$$

according to Eqs. (6.6b) and (6.7d). The new $P_{K|I}$ functions are shown in Fig. 6.9d.

The corresponding values for the $P_{K|SS}$ are

$$P_{K|SS}(\text{dry}, P_{K|I}, \text{exp}) = 0.17$$

$$P_{K|SS}(\text{dry}, P_{K|I}, \text{normal}) = 0.24$$

$$P_{K|SS}(\text{dry, cookie cutter, exp}) = 1.0\cdot(1+3+0.1\cdot 11)/36 = 0.14$$

$$\begin{aligned} P_{K|SS}(\text{dry, Carlton, exp}) &= (1\cdot 0.80 + 3\cdot 0.50 + 11\cdot 0.30 + 14\cdot 0.10 \\ &\quad +2\cdot 0.05)/36 = 0.20 \end{aligned}$$

$$P_{K|SS}(\text{dry, cookie cutter}) = 1 - 0.5^{(155\,\text{ft}/192\,\text{ft})^2} = 0.36$$

$$P_{K|SS}(\text{dry, Carlton}) = \frac{(155\,\text{ft})^2}{2\cdot(163\,\text{ft})^2 + (155\,\text{ft})^2} = 0.31$$

and

$$P_{K|SS}(\text{wet}, P_{\mathrm{K|I}}, \text{exp}) = 0.07$$

$$P_{K|SS}(\text{wet}, P_{\mathrm{K|I}}, \text{normal}) = 0.01$$

$$P_{K|SS}(\text{wet, cookie cutter, exp}) = 1.0 \cdot (2 + 0.1 \cdot 3)/25 = 0.09$$

$$P_{K|SS}(\text{wet, Carlton, exp}) = (2 \cdot 0.50 + 3 \cdot 0.30 + 1 \cdot 0.10 + 2 \cdot 0.05)/25 = 0.08$$

$$P_{K|SS}(\text{wet, cookie cutter}) = 1 - 0.5^{(155\,\text{ft}/675\,\text{ft})^2} = 0.04$$

$$P_{K|SS}(\text{wet, Carlton}) = \frac{(155\,\text{ft})^2}{2 \cdot (575\,\text{ft})^2 + (155\,\text{ft})^2} = 0.04$$

Note that, in general, the new dry and wet values for both the cookie-cutter and Carlton kill functions are closer together. Thus, for this example, using the lethal area rather than the lethal radius appears to yield the best agreement.

Presentation of the results: The $P_{K|SS}$ can be used in one-on-one engagement studies and in mission and campaign analyses, and it can be used to define the effectiveness envelope of a weapon. To define the weapon envelope, a series of trials for the specified flight path, at a given offset, can be conducted using several different target altitudes. In each trial, when the required conditions for a successful launch are satisfied, such as successful target detection and continuous tracking, a missile is fired at the aircraft when the aircraft is located at a series of specific horizontal distances in front of, and behind, the location of the firing unit. The numerical result for the $P_{K|SS}$ obtained from the shots can be presented in the two-dimensional array form shown in Fig. 3.12a for each offset for approaching aircraft. Note in Fig. 3.12a that P_K is equivalent to $P_{K|SS}$ because only one shot is fired. Each number in the array is the P_K (or $P_{K|SS}$) obtained for a missile launch when the aircraft was at the location indicated by the position of the number in the array. If a missile cannot be launched when the aircraft is at a particular location because the aircraft has not been successfully detected and tracked, then $P_K = 0$ for that location because $P_E = 0$. When a missile can be fired, $P_E = 1.0$, and the subsequent P_K is equal to $P_{K|E}$. Repeating the simulation for other offsets provides the total, three-dimensional array of P_K values for the selected scenario. A definition of weapon effectiveness, such as $P_K \geq 0.5$, is made, and the $P_K = 0.5$ contour is drawn in the figure, as shown in Fig. 3.12a for the zero offset. The envelope, known as the lethal (launch) envelope, can be determined for both dry and wet countermeasure environments, as well as other reactions, such as aircraft manuevers. If the miss distance for each shot is used as the lethality measure, instead of the $P_{K|SS}$, as in Fig. 3.13, the weapon envelope is known as the intercept or engagement envelope, and the extent of the envelope is defined by the lethal miss distance.

Go to Problem 6.2.6.

6.2.2.2 One-on-one survivability. According to Eq. (1.6a), the probability an aircraft is killed in an encounter with a single threat weapon is

$$P_K = P_E P_{K|E} \tag{6.9a}$$

where P_E is the probability the aircraft is engaged by the weapon and $P_{K|E}$ is the probability the aircraft is killed given the engagement. The engagement probability is given by

$$P_E = P_A P_{E|A} = P_A(P_{D|A} P_{L|D}) \tag{6.9b}$$

according to Eq. (1.5f), where P_A is the probability the threat weapon is active, $P_{D|A}$ is the probability the aircraft is detected by the active weapon, and $P_{L|D}$ is the probability one or more shots are fired, or missiles launched, at the detected aircraft. When the engagement consists of N independent shots, the probability the aircraft survives all of these shots is given by (Note 7)

$$\begin{aligned} P_{S|E} &= P_{S1} P_{S2} \ldots P_{SN} = (1 - P_{K1})(1 - P_{K2}) \ldots (1 - P_{KN}) \\ &= 1 - \left[P_K^{(1)} + P_K^{(2)} \ldots + P_K^{(N)}\right] = 1 - P_{K|E} \end{aligned} \tag{6.9c}$$

according to Eq. (1.6f), where P_{Si} and P_{Ki} denote probability of survival and of kill for the ith shot, respectively. (The probability P_{Ki} is also referred to as the probability the aircraft is killed given the ith single shot $P_{K|SSi}$.) Finally, $P_K^{(i)}$ denotes the probability the aircraft survives the previous i-1 shots and is killed by the ith shot. The probability the aircraft is killed given the engagement is

$$P_{K|E} = 1 - P_{S|E} \tag{6.9d}$$

according to Eq. (1.6i).

The specific encounter conditions between the aircraft and the threat are defined by the scenario. In most scenarios, in order for an active threat to have an opportunity to kill the aircraft it must first detect the aircraft (Note 8). The measure of detection by the active weapon is $P_{D|A}$, the probability that the aircraft has been detected (at least once) from the start of a search up to the present time t. In most situations this probability is directly proportional to the probability there is a clear line-of-sight from the detecting element to the aircraft. Given that the aircraft has been detected, the probability that one or more propagators will be fired or launched at the aircraft $P_{L|D}$ can be assigned. Once the ith propagator leaves the firing platform, the probability it kills the aircraft is denoted by $P_{K|SSi}$ [denoted in Eq. (6.9c) by P_{Ki} for the ith shot].

If the threat is a gun system, several to quite a few shots at the aircraft are to be expected after detection, and each shot has a $P_{K|SS}$. If the threat is a missile system, more than one missile could be launched at the aircraft, depending upon the circumstances, and each missile has a $P_{K|SS}$. The probability that the aircraft is killed by the sequence of N gun shots or missile launches is given by Eq. (6.9d), where $P_{S|E}$ is given by Eq. (6.9c). Thus, $P_{K|E}$ can be given in the form

$$P_{K|E} = 1 - \prod_{i=1}^{N} \left(1 - P_{K|SSi}\right) \tag{6.10a}$$

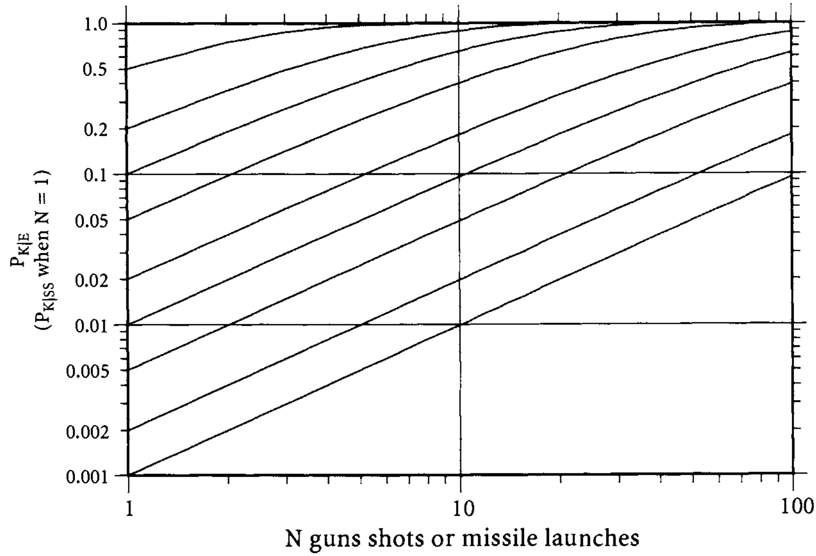


Fig. 6.10 $P_{K|E}$ **vs** N **for several values of** $P_{K|SS}$.

If $P_{K|SSi}$ is constant for all i, Eq. (6.10a) becomes

$$P_{K|E} = 1 - \left(1 - P_{K|SS}\right)^N \tag{6.10b}$$

Figure 6.10 presents $P_{K|E}$ as a function of N for several values of $P_{K|SS}$ denoted by the value where $N = 1$.

Example 6.4 One-on-One Survivability

You are flying into an area defended by two guns. You have the choice of flying over a 23-mm rapid firing gun or a larger 85-mm gun. The following probabilities apply:

23-mm gun:

$$P_A = 1, \quad P_{D|A} = 0.7, \quad P_{L|D} = 0.8$$
$$\text{number of rounds fired} = 20, \quad P_{K|SS} = 0.05$$

85-mm gun

$$P_A = 1, \quad P_{D|A} = 0.9, \quad P_{L|D} = 0.9$$
$$\text{number of rounds fired} = 5, \quad P_{K|SS} = 0.2$$

Which path would you choose?

The effectiveness of the 23-mm gun is

$$P_K = 1 \cdot 0.7 \cdot 0.8 \cdot [1 - (1 - 0.05)^{20}] = 0.56 \cdot 0.64 = 0.36$$

and the effectiveness of the 85-mm gun is

$$P_K = 1 \cdot 0.9 \cdot 0.9 \cdot [1 - (1 - 0.2)^5] = 0.81 \cdot 0.67 = 0.54$$

Therefore, you have a higher probability of surviving the 23-mm gun.

Go to Problem 6.2.7.

6.2.2.3 Mission survivability. Mission survivability was first examined in Chapter 1, Sec. 1.1.5. There, A aircraft enter into an area defended by W weapons. The expected number of aircraft killed by the W weapons is determined for $W < A$ and $W \geq A$. Here, one or more aircraft on a mission to attack a surface target fly through a defended zone to the defended target area, and then fly back through the defended zone, as illustrated in Fig. 6.11. The threats in the defended zone are uniformly distributed. The aircraft can have multiple encounters with several different weapon types as they fly through the zones and at the target. The probability each aircraft survives the mission depends upon the number of expected threat encounters as it flies through the zone and target defenses and the probability it survives each encounter (Note 9).

In this general mission survivability assessment the zone air defense is assumed to be composed of a number of weapons of several types randomly distributed over the area to be defended, as illustrated in Fig. 6.11 for weapon types 1 and 2. If W_{Zi} weapons or weapon sites of type i, where $i = 1, I$, are randomly located within a rectangular defense zone of length L and width H, the weapon density ω_i,the number of weapons of type i per unit zone area, is given by

$$\omega_i = W_{Zi}/(L \times H) \tag{6.11a}$$

The ith weapon type is assumed to have an effective diameter D_i within which it can engage aircraft, as illustrated in Fig. 6.11. A single aircraft flying through the defended zone will pass through the coverage of E_{Zi} weapons of type i. Because the weapons are assumed to be uniformly distributed, the expected number of

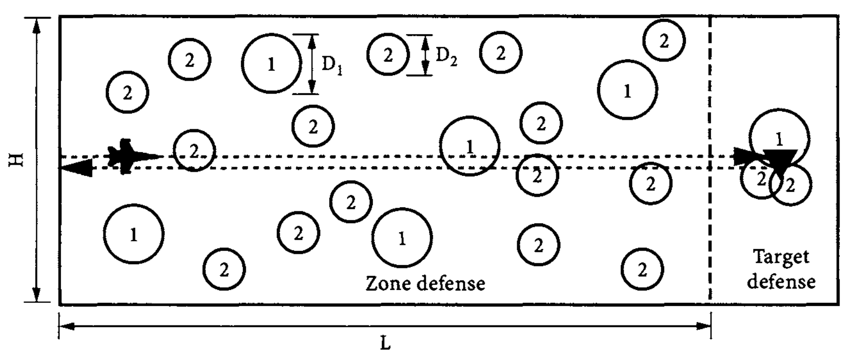


Fig. 6.11 Threat encounters while on a mission.

weapon encounters for an aircraft that flies straight through the zone is given by

$$E_{Zi} = D_i L\omega_i = (D_i/H)W_{Zi} \tag{6.11b}$$

that is, the probability the aircraft will encounter a weapon in the zone depends upon the ratio of the weapon's diameter D_i to the width of the zone H. If there is a total of A aircraft on the mission, the expected number of encounters between any one of the aircraft flying through the zone and the threat weapons is given by

$$E_{Zi} = D_i L\omega_i/A = (D_i/H)(W/A) \tag{6.11c}$$

when the weapons can only encounter and engage one aircraft.

Assume that all A aircraft survive the flight through the defended zone (Note 10). Therefore, at the target defended by W_{Ti} weapons of type i, $i = 1, I$, each of the A aircraft encounters E_{Ti} weapons, where

$$E_{Ti} = W_{Ti}/A \tag{6.12}$$

Again, assume that all A aircraft survive the defenses at the target. Thus, A aircraft fly back through the defended zone on the return to home base, and each aircraft will again have E_{zi} encounters.

While on the mission, each aircraft is expected to have a total of E_i encounters with the ith threat weapon. The E_i encounters include the encounters that occur as the aircraft flies through the zone defenses to get the target, the encounters that occur at the defended target, and those that occur as the aircraft returns through the same defended zone. Thus,

$$E_i = 2E_{Zi} + E_{Ti} \tag{6.13}$$

The probability the aircraft is killed in each encounter with the ith weapon type is assumed to be the constant value P_{Ki}. When the E_i expected encounters are approximated as a binomial experiment with the outcomes P_{Ki} and P_{Si} and a specified noninteger number of trials, the probability the aircraft survives the expected E_i encounters with the ith weapon type is given by

$$P_S\,(i\text{th weapon type}) = (1 - P_{Ki})^{E_i} \tag{6.14a}$$

according to Eq. (B.45)

When the mission is properly treated as a Poisson process, the aircraft is expected to be killed $E_i P_{Ki}$ times by the ith weapon type. The probability the aircraft survives given that it is expected to be killed $E_i P_{Ki}$ times is given by

$$P_S\,(i\text{th weapon type}) = \exp(-E_i P_{Ki}) \tag{6.14b}$$

according to Eq. (B.44).

To survive the mission, the aircraft must survive all encounters with all weapon types. Hence, the probability the aircraft survives the mission, denoted as the survival rate (SR) in Chapter 1, is given by

$$P_S(\text{mission}) = P_S(\text{weapon type 1})P_S(\text{weapon type 2})\ldots P_S(\text{weapon type } I) \tag{6.15}$$

where the P_S for each weapon type is computed using Eq. (6.14a) or (6.14b).

The expected number of aircraft killed out of the A aircraft on the mission is given by

$$\text{Expected number of mission aircraft killed} = E_K = A[1 - P_S\,(\text{mission})] \tag{6.16a}$$

where P_S (mission) is given by Eq. (6.15), and the loss rate (LR) is

$$LR = \frac{\text{expected number of mission aircraft killed}}{\text{number of aircraft on the mission}} = 1 - P_S\,(\text{mission}) \tag{6.16b}$$

according to Eqs. (1.7f) and (6.16a).

Example 6.5 Mission Survivability

Four aircraft are sent on an air interdiction mission. The defended area is a rectangle 100 km long and 50 km wide. There are five type 1 weapons in the zone defense and one at the target. The D_1 is 16 km and the P_{KI} is 0.30. There are 15 type 2 weapons in the zone and two at the target. The D_2 is 4 km, and the P_{K2} is 0.05. What is the probability each aircraft survives the mission? What is the expected mission loss rate?

The weapon density is

$$\omega_1 = 5/(100\,\text{km} \times 50\,\text{km}) = 0.001 \text{ weapons per km}^2$$
$$\omega_2 = 15/(100\,\text{km} \times 50\,\text{km}) = 0.003 \text{ weapons per km}^2$$

according to Eq. (6.11a). The number of expected encounters within the defended zone is

$$\begin{aligned} E_{ZI} &= (16\text{ km}) \cdot (100\,\text{km}) \cdot (0.001 \text{ weapons per km}^2)/(4\,\text{aircraft}) \\ &= 0.4\,\text{encounters per aircraft} \\ E_{Z2} &= (4\,\text{km}) \cdot (100\,\text{km}) \cdot (0.003 \text{ weapons per km}^2)/(4\,\text{aircraft}) \\ &= 0.3\,\text{encounters per aircraft} \end{aligned}$$

according to Eq. (6.11c). The number of encounters at the target is

$$E_{TI} = 1/4, \qquad E_{T2} = 2/4$$

Thus, the total number of encounters per weapon type is

$$E_1 = 2 \cdot 0.4 + 0.25 = 1.05, \qquad E_2 = 2 \cdot 0.3 + 0.5 = 1.1$$

according to Eq. (6.13).

The probability each aircraft survives the mission is

$$P_S(\text{mission}) = (1-0.3)^{1.05}(1-0.05)^{1.1} = 0.688 \cdot 0.945 = 0.65$$

using Eq. (6.15) and the binomial approximation given by Eq. (6.14a), and is

$$P_S(\text{mission}) = [\exp(-(1.05)\cdot(0.3)][\exp(-(1.1)\cdot(0.05))] = 0.69$$

using Eq. (6.15) and the Poisson approach given by Eq. (6.14b).

The expected number of mission aircraft killed is

$$E_K = 4\cdot(1-0.65) = 1.40 \quad \text{or} \quad E_K = 4\cdot(1-0.69) = 1.24$$

according to Eq. (6.16a). Therefore, the expected *LR* is

$$LR = 1.40/4 = 35\% \quad \text{or} \quad 350 \text{ per } 1000 \text{ sorties}$$

or

$$LR = 1.24/4 = 31\% \quad \text{or} \quad 310 \text{ per } 1000 \text{ sorties}$$

according to Eq. (6.16b).

Go to Problem 6.2.8.

6.2.2.4 Campaign survivability. Campaign-level survivability assessment is described in Chapter 1, Sec. 1.1.6. The probability an aircraft survives a campaign consisting of *N* missions is

$$CS = P_{S1}P_{S2}\ldots P_{SN} = (1-P_{K1})(1-P_{K2})\ldots(1-P_{KN}) \tag{6.17a}$$

according to Eq. (1.8a), where P_{Si} and P_{Ki} refer to the aircraft's mission survivability or SR and killability or LR on the *i*th mission, respectively. When the mission survivability is constant and identical for each mission, $P_{Si} = P_S$ and $P_{Ki} = P_K$, and Eq. (6.17a) becomes

$$CS = P_S^N = SR^N = (1-P_K)^N = (1-LR)^N \tag{6.17b}$$

according to Eq. (1.8b).

Go to Problem 6.2.9.

6.2.3 Computer Programs for Survivability

Some of the computer programs used in survivability assessment are shown in Fig. 6.1. The survivability programs currently accepted as standards by the JTCG/AS for engagement-level assessment are RADGUNS for survivability against antiaircraft guns; ESAMS for survivability against surface-to-air missiles;

and TRAP for survivability against air-to-air missiles. BLUEMAX is used to generate the flight path data for RADGUNS and ESAMS. The programs for air combat mission survivability are MIL-AASPEM and BRAWLER. The more general mission/combat models that can be used for survivability studies are SUPPRESSOR, SWEG, JIMM, and EADSIM; and THUNDER is a campaign computer model. These programs, and several others, are briefly described in Chapter 1, Secs. 1.5.2 and 1.5.3. For information on how to contact SURVIAC for more detail on the models, refer to Chapter 1, Sec. 1.3.6.

6.3 Survivability Enhancement Trade Studies

Learning Objective	6.3.1	**Conduct a survivability trade study.**

Survivability trade studies are conducted to determine both the benefits and the performance and cost impacts (burdens) that are associated with each survivability feature considered. Of major importance here is the selection of the measures of effectiveness for the weapon system and for its contribution to the force.

6.3.1 System Effectiveness

The relationship between airborne weapon system effectiveness and aircraft survivability was examined in Chapter 1, Sec. 1.1.10. Two simple, conceptual measures of effectiveness, the offensive mission attainment measure (MAM) and the defensive mission survival rate (SR), are defined there. Their product, SR · MAM, equals the measure of mission success. Adding aircraft availability results in an overall measure of mission effectiveness (MOME) given by Eq. (1.9b). Values for these and other similar effectiveness measures can be determined by using mission and campaign analyses and conducting effectiveness studies. Because no effectiveness study is complete without the consideration of costs, a system cost-effectiveness analysis is usually a required part of the survivability program.

6.3.1.1 Mission analysis. The mission analysis typically consists of the mathematical generalization of the multiple encounters and outcomes between friendly aircraft and the hostile air defense. The scenario illustrated in Fig. 6.2 is an example of the scenario for an interdiction mission. Some of the outcomes usually of interest in this scenario are the number of aircraft that survive the sortie, the number of aircraft that are damaged, and the number of bombs dropped on the target and targets killed. Two mission/combat computer programs for air-to-air combat are currently in the SURVIAC model repository, MIL-AASPEM and BRAWLER. Four more general mission models are SUPPRESSOR, SWEG, JIMM, and EADSIM. These models are briefly described in Chapter 1, Sec. 1.5.2 and 1.5.3.

6.3.1.2 Campaign analysis. The campaign analysis typically consists of the mathematical generalization of the offensive and defensive outcomes for a specified number of missions. The campaign analysis can become extremely detailed in the simulation and can include such events as the return of damage-repaired aircraft to operational status and the attrition of the air defense elements. The campaign model THUNDER is briefly described in Chapter 1, Sec. 1.5.3.

6.3.2 Survivability Design and the Trade Study

The survivability design of an aircraft is that process in which those design features that have the potential to enhance the survivability of the aircraft are considered and are either incorporated into the design, proposed as a future modification, or rejected. If the enhancement feature does not negatively impact weight, cost, maintenance, performance, or any of the other aircraft attributes, it should be included as part of the design. If a feature does affect one or more of these attributes, its inclusion is questioned. The decision to include, postpone, or reject a particular feature should not be based upon whim or expediency, but instead should be based upon the results of the effectiveness studies. The flow of the methodology for the selection of those susceptibility reduction features described in Chapter 4 and vulnerability reduction features described in Chapter 5 that contribute to the effectiveness of the aircraft is illustrated in Figs. 1.10 and 6.1.

The task of interest here is the trade study. The trade study is the determination and examination of the various peacetime and wartime effectiveness measures and attributes for each candidate survivability enhancement feature considered. Of particular interest are the payoffs and the costs in dollars, attribute degradation, and schedule delay. The impact of each survivability enhancement feature on the system weight, safety, maintenance, reliability, logistics, flight performance, and development, acquisition, and operations dollar costs; as well as on the aircraft's survivability and operational effectiveness must also be determined.

6.3.2.1 Other disciplines.

System safety. Probable changes in system safety rates must be evaluated for the candidate survivability enhancement features. In most cases they (especially the vulnerability reduction features) would be expected to lead to improvements in safety. For example, a lubrication bypass design that permits continued flight after damage to an oil cooler provides a greater probability of safe recovery of the aircraft and aircrew because of a material failure or maintenance error associated with the lubrication subsystem. However, some features can degrade the safety rates. A piece of ECM gear that unnecessarily distracts the pilot can increase the probability of a crash, and an IR flare is a source of fire. The system safety rates that should be examined include 1) mishaps per flying time and 2) aircrew survival per mishap.

Maintenance. The addition of survivability enhancement features as a modification to an existing aircraft can result in an increase of maintenance man-hours (scheduled and unscheduled) for the total system. For new designs the penalties can be minimized and, in some cases, might result in benefits. However, there might be exceptions, such as the coatings and materials used to reduce signatures. They might require more care and attention than the usual nonstealthy coatings and materials. Concentration and integration of a number of components in a subsystem to minimize its vulnerability might also require less maintenance effort and time to troubleshoot and repair. The maintenance factors are 1) maintenance man-hours per flight hour, 2) downtime per flight hour, and 3) mean task times (accessibility).

Reliability. System reliability values also can be affected by survivability enhancement features. The addition of redundant subsystem circuits might affect the reliability requirements upon individual components within each of the redundant systems in order to attain the overall system reliability allocations. The reliability factors are 1) component reliability, 2) component redundancies, 3) aircraft availability, and 4) mission success reliability.

Logistics. The operation of military aircraft requires logistic support in order to perform the designated missions. The major items that can be affected by survivability enhancement features include fuel consumed, spares required, and payload (munitions) expended to achieve a given level of combat effectiveness. For example, the addition of weight to a design for survivability enhancement might require the expenditure of more fuel to achieve a given level of performance, and an increase in system complexity might affect the number of aircraft required for specific missions over a given time period.

Flight performance. Aircraft flight performance penalties are generally expressed in terms of mission range or radius loss or of a reduction in payload. For major subsystem additions to aircraft in design, the penalties can be expressed in terms of required aircraft weight and cost growth, with performance factors remaining constant. The combined effect of the survivability features can also affect the limitations on aircraft speed and maneuverability. For example, features that require the use of an external store station, such as an ECM pod, can affect aircraft performance, depending on the particular aircraft and store configuration. Aircrew performance factors refer to the effects that the survivability features have on the ability of the aircraft aircrew to perform their assigned tasks, such as flying the aircraft, navigating, locating the target, accurately delivering the weapon or payload, and observing the terrain flown over. This parameter also includes the effect on personnel mobility during emergency egress.

6.3.2.2 Dollar costs. The cost in dollars of the airborne weapon system might be the one factor on which all trade study outcomes are ultimately based. It provides a basis upon which management can decide what combinations of survivability enhancement features will be the most effective for a specific design configuration, hostile threat spectrum, and length and intensity of the assumed conflict. Cost factors that can be influenced by survivability features include 1) development costs, including aircraft design, tests, and research; 2) acquisition costs, such as production aircraft and spares; and 3) life-cycle costs (LCC), including development costs, aircraft and crew acquisition costs (including peacetime and wartime replacement as a result of accidental attrition and wartime replacement caused by combat attrition), peacetime operations and logistics costs, wartime operations and logistics costs, and disposal costs.

The inclusion of survivability enhancement features might increase the development and acquisition costs on a per aircraft basis. However, because the aircraft is more survivable fewer aircraft need to be purchased to accomplish a specific operational goal because fewer aircraft will be lost in combat. This can lead to a smaller total cost over the lifetime of the system. For any assumed conflict more of the more survivable aircraft will be left at the end of the conflict, and hence less aircraft will be required for replacement of the killed aircraft. The more intense or prolonged the conflict, the more important survivability becomes. For every aircraft that returns to base after a mission because of its enhanced survivability, one less aircraft has to be purchased, and one less aircrew has to be recruited and trained. The cost of survivability enhancement can be greatly exceeded by the cost of replacing killed aircraft and their crews in the next conflict. The loss of the U. S. Government's investment in acquiring and training the crew, and the cost penalties for search and rescue operations, administrative costs, dependency costs, and death costs associated with a lost aircraft can be a significant fraction of the hardware cost of the aircraft and, consequently, should be included in the cost of losing an aircraft in combat. And then there is the political factor associated with lost aircrews and prisoners of war.

6.3.2.3 Example trade study. For an example of a trade study, consider the survivability design of an attack aircraft whose primary mission is the delivery of 10,000 lb of ordnance at medium to low level within a combat radius of 600 miles. The mission-threat analysis has identified a ground-based AAA and a SAM as the two major threats to the aircraft. The AAA detects and tracks the aircraft using either radar or electro-optics and fires an HE warhead with a contact fuze at 1200 rounds per minute. The SAM threat also detects and tracks the aircraft using radar, and the missile is command guided and carries an HE controlled-fragmentation warhead with a proximity fuze with a cutoff range of 50 m.

The susceptibility study has determined that the typical AAA platform will be able to detect the aircraft and fire 20 shots, with a mean miss distance of 6 m in both the ξ and ζ directions and a standard deviation of 3 m in both directions. The typical SAM site also will be able to detect and track the aircraft, with enough time to launch two missiles, both with a CEP of 20 m. The fuze is assumed to function on all shots.

The vulnerability study has identified the critical components for an A level attrition kill. Among the nonredundant critical components are the wing and fuselage fuel tanks. The baseline design of the aircraft has no provision for suppressing the occurrence of a fire or explosion in the ullage of the tanks. The survivability enhancement design feature to be examined in the trade study is the use of a particular technique to suppress any fires and explosions within the wing tanks. The weighted average single-hit vulnerable area of the baseline design with respect to the AAA threat A_V is 6 m^2. (Only the single-hit vulnerability will be used in this example.) The lethal radius with respect to the SAM r_L is 10 m. Suppression of fires and explosions within the wing fuel tanks reduces the single-hit vulnerable area and lethal radius to 5 m^2 and 9 m, respectively.

The $P_{K|SS}$ for the contact-fuzed AAA HE warhead is computed using the Carlton hit function, Eq. (6.3c), with $P_F = 1$, $\xi_0 = \zeta_0$, and $\xi_0\zeta_0 = A_V$; and the $P_{K|SS}$ for the proximity-fuzed SAM warhead is computed using Eq. (6.8c), with $P_F = 1$, $\rho_0 = 1.2r_L$, $\sigma = \text{CEP}/1.177$, and $r_c = 50$ m. The probability of kill of the aircraft in a one-on-one engagment with the AAA and the SAM $P_{K|E}$ can be computed using

Eq. (6.10b), with $N = 20$ for the AAA and $N = 2$ for the SAM. The weapons are assumed to be active, and the probability of detection $P_{D|A}$ and probability of engagement $P_{L|D}$ are taken as unity for this study. Thus, $P_E = 1$ and $P_K = P_{K|E}$ according to Eqs. (6.9b) and (6.9a), respectively. The one-on-one results for both designs and both threats are given in Table 6.1.

For the mission survivability assessment the assumption is made that 40 aircraft on an interdiction mission will ingress a defended zone 50 km wide. No weapons are located at the target, and the egress is through an undefended zone. There are 20 AAA sites and two SAM sites in the defended zone. The diameter of the weapon envelope for the AAA and SAM sites is 5 and 20 km, respectively. The expected number of encounters with each weapon type is computed using Eq. (6.11c), and the mission survivability for each weapon type is determined using Eq. (6.14a). The mission SR is obtained using Eq. (6.15). The results are presented in Table 6.2 for both aircraft designs. Note in Table 6.2 that the loss rates are approximately 1% or 10 per 1000 sorties, which is comparable to the long-term loss rate for US/RAF fighters in WWII and to some short-term loss rates of more recent conflicts (see Fig. 1.16). The number of threat weapons for the two threat types were specifically chosen to give this result. More encounters would lead to a higher loss rate, and fewer encounters would lead to a smaller loss rate. A loss rate this high can only be sustained today in a relatively short conflict. After 50 missions only 24 of the original 40 aircraft would be left according to Fig. 1.5.

The weapon system effectiveness measure used in this trade study is the sum of the peace-time 15-year LCC of the total fleet of aircraft and the cost of replacing aircraft lost in combat. The flyaway or replacement cost of one baseline aircraft is \$30M. (This does not include the cost of replacing the crew, which can be significant, and should be considered in the trade study.) The peacetime LCC for 300 production aircraft and 10 operational squadrons with 200 aircraft is \$18.00B. The more survivable aircraft flyaway cost is \$30.08 million. The increase over the baseline flyaway cost is due to the cost of incorporating the fire/explosion suppression feature. The more survivable aircraft LCC is \$18.04B. The additional LCC is due to the increase in the flyaway cost, the increase in the empty weight of the aircraft, the increase in maintenance requirements, and any decrease in reliability caused by the incorporation of the suppression feature.

The total mission effectiveness measure selected for the study is the delivery of 50,000,000 lb of ordnance on the target. The weight of bombs dropped on the target per aircraft launch (normalized with respect to 10,000 lb) is selected as the sortie effectiveness measure. The optimistic assumption is made that the MAM for the aircraft is unity, that is, every aircraft that is not killed delivers its 10,000 lb of bombs on the target. Thus, if no baseline aircraft are killed, 5000 sorties are required to deliver the total ordnance load. However, according to Table 6.2, the sortie survival rate of the baseline aircraft is 0.9885. Thus, the MOMS of the baseline aircraft is $(0.9885) \cdot (1)$, or 0.9885, according to Eq. (1.9a). Assuming that all aircraft lost in combat are killed on their way to the target, the bombs delivered per aircraft launch by the baseline aircraft are 9885 lb. Thus, 50,000,000/9885, or 5058.2, aircraft launches are required to get 5000 baseline aircraft over the target, and 58.2 aircraft are lost in combat. The total replacement cost of these 58.2 aircraft is \$1.746B.

The payload carried by the more survivable aircraft is reduced to 9850 lb because of the increase in the aircraft empty weight of 150 lb caused by the addition of

Table 6.1 One-on-one survivability

	AAA					SAM			
Parameter	A_V, m^2	$\mu_\xi = \mu_\zeta$, m	$\sigma_\xi = \sigma_\zeta$, m	$P_{K\|SS}$	$P_K(N=20)$	r_L	CEP	$P_{K\|SS}$	$P_K(N=2)$
Baseline aircraft	6	6	3	0.002579	0.05034	10	20	0.1996	0.3594
More survivable	5	6	3	0.002059	0.04038	9	20	0.1680	0.3078

Table 6.2 Mission survivability

	AAA						SAM						Mission	
Parameter	W	D, km	H, km	A	E	P_S	W	D, km	H, km	A	E	P_S	SR	LR/1000
Baseline aircraft	20	5	50	40	0.05	0.9974	2	20	50	40	0.02	0.9911	0.9885	11.5
More survivable	20	5	50	40	0.05	0.9979	2	20	50	40	0.02	0.9927	0.9906	9.4

Table 6.3 Trade study results

Parameter	Δ weight, lb	Payload, lb	Aircraft launches required	Loss rate	Replacement aircraft required	Cost of one aircraft, $M	Combat replacement costs, $B	Peacetime 15-yr LCC, $B	Peacetime+ replacement costs, $B	Δ cost, $M
Baseline aircraft	0	10,000	5058.2	11.5	58.2	30.00	1.75	18	19.75	0
More survivable	150	9,850	5124.5	9.4	48.4	30.08	1.46	18.04	19.50	–250

the survivability enhancement feature (Note 11). Thus, the MAM is 0.9850 for the modified aircraft, compared to unity for the baseline, and 50,000,000/9850, or 5076.1, sorties are required when no modified aircraft are killed. The sortie survival rate for the modified aircraft is 0.9906. Thus, the measure of mission success is 0.9906 × 0.9850, or 0.9757; that is, 9757 lb of bombs are delivered per aircraft launch. Hence, 50,000,000/9757, or 5124.5, aircraft launches are required, and 5124.5 − 5076.1, or 48.4, aircraft are lost in combat. The total replacement cost of these 48.4 modified aircraft is $1.457B.

The major results of the trade study are presented in Table 6.3. The more survivable aircraft requires more aircraft launches and has a smaller MOMS (fewer bombs on the target per aircraft launch), but the significant savings in the replacement cost of $290 million more than offsets the additional LCC caused by the fuel tank protection feature. The total savings in cost of $290 million − $40 million = $250 million, and in the lives of the 58.2 − 48.4 = 9.8 aircrews, will increase for more intense or longer duration conflicts and will decrease for less intense or shorter conflicts. In a trade study meeting someone will remark that if no battles are fought over the life of the aircraft, an extra $40 million has been spent for nothing. Survivability is somewhat like fire insurance on your house. If you do not have a fire, you are out the insurance premiums over all those years; but if you ever do have a fire, the cost of the premiums is insignificant, and you might wish you had taken out more insurance. The same philosophy applies to survivability. And do not forget that this particular feature also makes the aircraft safer; there are no wing fuel tank fires and explosions to contend with.

6.4 Conclusions

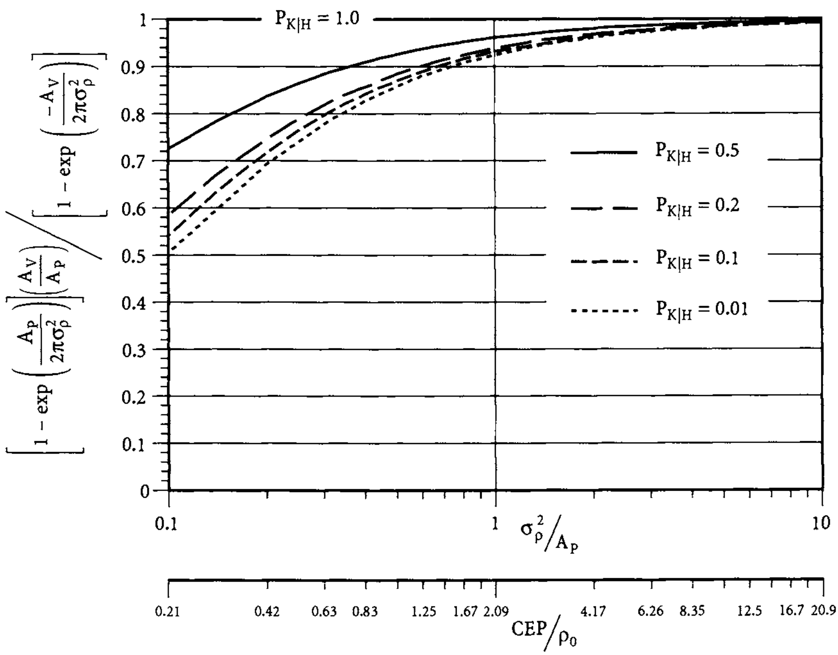
Learning Objective 6.4.1 Explain why it is important to design an aircraft to be survivable.

The consideration of survivability in the design and utilization of aircraft has been important in past conflicts and will be more so in future conflicts. The cost of procuring and operating modern aircraft makes imperative a thorough study of each system and feature to ensure that no Achilles' heel is lurking there, just waiting to be discovered in combat. If there is a next war, the battles will be fought with the aircraft on hand. There will not be time to build new aircraft and to train new crews to fly them. What we have has to survive.

Endnotes

1. More detail is in Ref. 2 regarding the scenario for the air interdiction mission as well as other air-to-air and air-to-surface missions.
2. The $P_{K|H}$ developed in Chapter 5 is based upon the assumption that the hit is uniformly distributed over the aircraft presented area. On the other hand, the $P_{K|SS}$ given by Eqs. (6.3a–d) is based upon the assumption the miss distance (or hit) is normally distributed in ξ and ζ. If the variation of the miss distance's bivariate normal distribution over the extent of the aircraft is small (nearly uniform), because of relatively large means or standard deviations compared to A_P, then the results for $P_{K|SS}$ are

valid. However, if the variation in η is relatively large (very nonuniform), then the results are inaccurate. For example, increasing A_P in Eq. (6.3b) will reduce $P_{K|H}$ more than it will increase P_H, and hence the $P_{K|SS}$ will decrease. In the limit as $A_P \to \infty$, $P_H \to 1$, $P_{K|H} \to 0$, *and* $P_{K|SS} \to 0$, which of course is wrong. Making an aircraft larger should not increase its survivability, everything else being the same. Thus, the first approach for $P_{K|SS}$ requires a nearly uniform miss distance over A_P. The following figure provides a guideline for determining the accuracy of Eq. (6.3b) for a given A_P, A_V, and σ_ρ. Both the aircraft and the miss distance distribution are circularly symmetric, and the hit function is the cookie cutter, as illustrated in Fig. 4.24. The aircraft has a variable presented area A_P with a radius ρ_0 and a constant vulnerable area A_V, which is centered at the aim point (0,0). In general, $A_P \geq A_V$. Shown in the figure is the ratio of $P_{K|SS}$ for the first approach, which depends upon A_P, to $P_{K|SS}$ for the second approach, which does not depend upon A_P and hence is the correct value (when A_V is centered at the aim point). The ratio is given for several values of $P_{K|H}$ (increasing A_P). One abscissa is the circularly symmetric miss distance standard deviation σ_ρ normalized with respect to A_P. The second abscissa is the CEP normalized with respect to ρ_0. Note that the error in $P_{K|SS}$ for the first approach is largest for small values of σ_ρ (or CEP) because the miss distance variation over A_P is large for small CEP. The error reduces when σ_ρ (or CEP) increases because the variation over A_P decreases. Examination of the figure reveals that $P_{K|SS}$ for the first approach is within 10% of the correct value when σ_ρ^2/A_P is unity or larger, or the CEP is more than twice the target radius ρ_0.



3. Refer to Fig. 3.81 for an example of the dispersion built into the Trinity gun fire control system.

4. If a different miss distance probability density function $\eta(\xi, \zeta)$ is available from test results or more detailed analyses, this more representative distribution should be used in place of the bivariate PDF in the numerical integration for $P_{K|SS}$.
5. Recall that CEP = 1.177σ from Eq. (B.53).
6. Refer to Chapter 4, Sec. 4.3.4.2 for a description of the histogram and of the procedure to convert the Rayleigh PDF to the number of occurrences in each range bin.
7. Aircraft survival does not mean that no damage has been suffered, only that the aircraft was not killed according to the specified kill level.
8. Barrage fire in anticipation of the appearance of an aircraft and a missile that is launched during a search are examples of scenarios where detection prior to firing or launch does not take place.
9. Refer to Sec. B.6.3 in Appendix B for more detail on the one-on-many scenario.
10. Assuming all aircraft survive the zone defenses allows the common divisor A when determining the number of encounters per aircraft. The expected number of aircraft killed by the zone defense during ingress to the target area could be determined and subtracted from A to determine the number of encounters at the target. However, because the number of killed aircraft is expected to be relatively small, the increase in the number of encounters per aircraft should be small. Furthermore, this simple estimate does not consider any weapons eliminated by SEAD aircraft, which would reduce the number of encounters.
11. Traditionally, the ordnance weight would remain the same, for example, 20 Mk 82 500-lb bombs, and the takeoff gross weight (TOGW) would grow to accommodate the extra weight. However, in today's design constraints there might be a cap on the TOGW (and the cost), and so 150-lb might have to be taken away from another attribute. This exchange, known as a zero sum game, was not made here in order to keep the example relatively simple.

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Problems

6.1.1 Describe the two program tasks presented in this chapter.

6.2.1 List the measures most often used in survivability assessments and trade studies.

6.2.2 Given $A_V = 20\,\text{ft}^2$, $A_P = 200\,\text{ft}^2$, and $P_{K|SS} = 0.01$, what is the miss distance CEP? Assume circular symmetry, and use the cookie-cutter hit function with the first approach.

6.2.3 A smaller miss distance variance always results in a larger $P_{K|SS}$: True or False.

6.2.4 The vulnerability requirements for a new attack helicopter are being developed. The design threat is the 30-mm HEI round. One member of the requirements team believes the vulnerability requirement should be a limit on the aircraft's vulnerable area to the 30-mm round. Another member believes the limit should be on $P_{K|H}$. What do you think?

6.2.5 Consider the $P_{K|SS}$ for the aircraft described in Example 6.2. The enemy changed some of the fire control components so that the new means and standard deviations for cell b are $\mu_\xi = 4$ ft, $\mu_\zeta = 3$ ft, $\sigma_\xi = 4$ ft, and $\sigma_\zeta = 2$ ft. What is the contribution of this cell to the $P_{K|SS}$ if $P_{K|Hb} = 0.790$?

6.2.6 The lethal miss distance r_L in Example 6.3 has been extended from 75 to 175 ft because of a heavier warhead. What is the new $P_{K|SS}$ for both the dry and the wet conditions. Use the cookie-cutter kill function, and assume $P_F = 1$.

6.2.7 The aircraft in Example 6.4 has its survivability enhanced so that $P_{K|SS} =$ 0.03 for the 23-mm gun and 0.14 for the 85-mm gun. What path would you choose?

6.2.8 The aircraft in Example 6.5 has its radar signature reduced so that the envelope of both weapon types is reduced by 50%. What is the probability each aircraft survives the mission, and what is the mission loss rate?

6.2.9 The theater commander has 100 aircraft and 40 pilots available at the start of Operation 'How Many.' If 40 of the missions described in Problem 6.2.8 are flown and each mission has four aircraft, how many aircraft are remaining at the end of the campaign? Assume none of the downed aircraft are replaced, and use the Poisson approach results in Problem 6.2.8. If you fly on 10 of those 40 missions, what is the probability you will not be shot down? Any volunteers?

Appendix A
Survivability Features of Several Aircraft Used in World War II

This appendix presents the development of the survivability features of several of the most famous aircraft from World War II. Included are the Boeing B-17 Flying Fortress, the Lockheed P-38 Lightning, the Republic P-47 Thunderbolt, the North American P-51 Mustang, the Brewster F2A Buffalo, the Grumman F4F Wildcat and F6F Hellcat, the Vought F4U Corsair, the German Messerschmitt Bf-109, the Russian Ilyushin IL-2, and the Japanese Mitsubishi Zero.

A.1 Most Famous Bomber of Them All: The Boeing B-17 Flying Fortress

The Boeing B-17 Flying Fortress is perhaps the most famous bomber of the Second World War. Over 12,000 of these heavy bombers were accepted by the U. S. Army Air Corps/Force between July 1940 and August 1945. However, as a result of considerable combat experience the last production version, the B-17G, was a far cry from the early models. Survivability considerations played a major role in the evolution of the B-17 into one of the classic bomber designs of all time.

The first B-17s were produced in the mid-1930s for the Army Air Corps. The early models were the YIB-17A, the B-17B, and the B-17C. The original mission of the B-17 was that of coastal defense of the United States against hostile ships, and the airplane was designed from the beginning to deliver a bomb load with great accuracy from high altitude under daylight conditions. The development of an improved bombsight, aircrew oxygen supply, and engine supercharger eventually boosted the high-altitude performance to a service ceiling of 37,000 ft. The B-17C had a maximum loaded weight of 50,000 lb, a top speed of 320 mph, a cruising speed in formation of 160 mph, and range of 1100 miles with a normal internal bomb load of 6000 lb.

The all-metal fuselage of the Fortress was a circular, semimonocoque structure with its strength evenly distributed throughout the entire length in order to maintain integrity after combat damage. The circular cross section of the fuselage was selected because of its efficient strength-to-weight ratio and ease of manufacture. The flight controls were manually operated with no power assist, except when automatic flight control equipment was used. The flaps and landing gear were moved by electrical actuators with a mechanical backup capability. Most of the other systems were also electrically actuated. However, the engine cowl flaps, the wheel brakes, and the emergency brake were hydraulically actuated.

There were four 1200-hp Wright Cyclone air-cooled radial engines with a fire wall in each engine nacelle, and the aircraft was capable of flying on just two engines. Yaw with one engine out was not a severe problem. The low-mounted wing had two main spars with one auxiliary midspar between the engines. The internal bomb bay fit between the front and rear spar locations. The wing loading was relatively low. All of the fuel tanks were located in the wings; no fuel was carried in the fuselage.

The pilot and copilot were protected by armor plate at the back of their seats and by armor placed on the No. 3 bulkhead (just forward of the windshield) and on the No. 4 bulkhead (leading into the bomb bay behind them). All other crew stations were similarly shielded by armor. Fire extinguishers were carried in the cockpit. The window glass throughout the aircraft was laminated and strengthened, but it was not bulletproof.

The self-protection armament carried by the B-17 went through a succession of increases. It consisted of either five .50 caliber or five .30 caliber machine guns on the YIB-17A, two .30 caliber and three .50 caliber machine guns on the B-17B, and one .30 caliber and six .50 caliber machine guns on the B-17C, all manually aimed.

The first B-17s to engage in combat were those sent to the Royal Air Force under provisions of the Lend-Lease Act. Twenty B-17Cs, modified to British standards and called Fortress I by the RAF, were delivered to England in May 1941. These modifications included replacing the small side blisters with flat, paneled gun positions and installing a bathtub-type gun position under the fuselage with its single machine gun oriented to the rear. More protective armor was added around the crew stations, and the fuel system was retrofitted with self-sealing fuel tanks. (The self-sealing compound was not particularly effective against the 20-mm cannon projectiles used by the enemy fighters.)

Misled by the airplane's nickname of 'Flying Fortress' (a registered trademark), the British employed the B-17C during July 1941 in offensive, daylight raids over France, Germany, and Norway with only three to four aircraft per raid. Because the B-17Cs operated beyond the escorting range of Spitfire and Hurricane fighters and during the daylight hours, they were highly susceptible to concentrated fighter attacks and consequently suffered heavy damage and loss. Eight of the original 20 B-17s were either lost or destroyed between May and September 1941, and after 22 missions, 18 planes out of 39 planes dispatched aborted because of mechanical problems. As the British quickly discovered, the B-17C was lacking in firepower and unable to defend itself under heavy daylight attack. The British pilots renamed the B-17 the 'Flying Target,' and the German Luftwaffe called it the 'Flying Coffin.' As a result of the poor initial performance, the British canceled the daylight raids, withdrew the aircraft from British squadrons, and sent them on coastal reconnaissance missions.

Boeing was aware of the potential survival problems of the B-17C prior to its use in combat by the British and was already making modifications to the C model in 1940. The B-17D, which was designed for the U. S. Army Air Corps, became operational in February 1941. The B-17D was equipped with a better bladder-type self-sealing fuel cell system and additional crew armor. However, no changes were made to the defensive armament package.

The B-17D exhibited many of the same weaknesses as the B-17C, and it became obvious that an extensive redesign, including increased defensive armament, was vital. Consequently, Boeing greatly modified its earlier designs and introduced the B-17E in October 1941, two years after the start of the war in Europe and two months before the Japanese attack on Pearl Harbor. Boeing considered the B-17E to be the first 'Flying Fortress' designed for offensive operations. The airplane had been lengthened by 6 ft to incorporate twin .50 caliber machine guns in a manually operated turret in the tail. The empennage was significantly increased in size to make room for the turret and to improve the directional handling. This change was particularly helpful during the bombing run and when the tail guns were fired. Twin .50 caliber machine guns were also installed in a Bendix electrically powered turret located in the top of the fuselage just behind the cockpit, and a Sperry electrically powered ball turret with twin .50 caliber guns was installed under the fuselage. Provision was made for .50 caliber guns to be fired upward from the radio compartment on the top of the aircraft and from a removable window on each side aft of the wing. In the nose of the aircraft, hand-operated .30 caliber guns were placed on flexible socket mounts on both sides of the aircraft for use by the bombardier and navigator when they were not engaged in their primary duty. (The flexible-mounted guns in the nose and waist, referred to as wobble guns, were rumored to be ineffective because of the difficulties in aiming.)

The B-17F, introduced in May 1942, was an improved E model with more than 400 design modifications. It had additional protective armor, self-sealing oil tanks, and additional electrical power sources. Extra fuel cells in the wings, known as 'Tokyo' tanks, were also added. These tanks added to the vulnerability of the aircraft because fumes tended to collect in the outer wing sections (these tanks were not vented), and an incendiary strike could cause an explosion that was capable of ripping off an entire wing. Only in the latter part of the war was a successful venting system incorporated to reduce the vapor hazard. Approximately 3400 B-17Fs were produced by Boeing, Vega, and Douglas.

Subsequent battle experience vividly illustrated the need for further improvement in survivability. The B-17E and F models were still susceptible to head-on fighter attacks. These attacks were nerve shattering to the bomber crews because of the possibility of a crash with a fighter containing a dead or crazed pilot. Consequently, numerous B-17Fs were modified with a Bendix powered chin turret containing twin .50 caliber machine guns. The subsequent B-17G model, the final version introduced in September 1943, incorporated the chin turret and .50 caliber guns in place of the .30 caliber 'cheek' guns. The G model was heavier (65,600 lb) and somewhat slower (290 mph) than the C model and typically carried 6000 lb of bombs. Over 8600 B-17Gs were built by Boeing, Vertol, and Douglas.

An interesting variation of the B-17 was the YB-40, a 'Flying Destroyer.' The idea was to use a B-17 as a fighter escort to provide protection to the B-17 bombers on the longer missions. The program began in August 1942 with modified B-17Fs, and the first model was completed in four months. The Bendix chin turret was added, as well as a second upper turret at the rear of the cockpit fairing, which was modified to give better coverage. This version had seven pairs of .50 caliber machine guns with over 12,000 rounds of ammunition available. Additional armor was also added. Unfortunately, the idea did not work out as planned. The plane, heavily loaded, could not keep up with the formation of B-17 bombers, even before the bombs were dropped. The idea was dropped, and the YB-40s were either reconverted to bombers or used as trainers.

The development of the B-17 into an effective daylight, strategic bomber was fraught with controversy. The British, as a result of their bad experiences with daylight bombing early in the war, confined their strategic bombing to nighttime in order to avoid what they considered an unacceptably high level of attrition. The Americans, on the other hand, were convinced that daylight precision bombing, flying at high altitude to reduce the effectiveness of antiaircraft artillery and in very tight formations for mutual protection and massed firepower against enemy fighters, was the most effective strategy in the European theater.

In early 1942, before the American bombing in Europe began, the British, including Prime Minister Churchill, were convinced that the accuracy gained by precision bombing using the Norden bombsight would be outweighed by the heavy losses that would take place as the unescorted bombers literally fought their way to the Ruhr and back home. Even if the bombers were escorted by long-range fighters, it was unreasonable to expect the fuel-ladened long-range fighter to cope with the short-range enemy defensive fighters operating over their homeland. They wanted the Americans to join them on their area bombing raids at night. Furthermore, they believed the United States should stop building the B-17 and start building the Lancaster, which they considered the world's best bomber because it could carry the heaviest load. (The Lancaster carried only .30 caliber machine guns, was not as tough as the B-17, and did not have a precision bombsight.) In their view the B-17 was too dependent upon clear weather, was easy to detect because of extensive contrails, and carried an uneconomical bomb load in relation to the crews and maintenance required. The Americans did not want to use the B-17 at night because the crews were not trained for nighttime operations, the simultaneous flights with the British could pose horrendous coordination problems, the Norden bombsight would be wasted, the engine exhausts would clearly be visible, and the entire design philosophy of the B-17 as a daylight bomber would become superfluous.

The Americans prevailed in their fight for daylight bombing, and consequently much of the bomb-carrying ability of the B-17 was used up by the addition of heavy armor plate, self-sealing fuel tanks, and all of the manpower and equipment required to support as many as 13 heavy machine guns. Out of a typical crew of 10, eight men (four gunners and four part-time gunners) manned the machine guns during attack, often wearing heavy flak jackets and helmets for protection. The other two men were the pilot and the copilot, both capable of flying the aircraft, and thus providing an important redundancy.

Flying at 26,000 ft in the B-17 was not exactly the same as flying in today's intercontinental passenger jet. It was terribly cold; only the cockpit was heated. The temperature often dropped to 60 deg below zero. The equipment was difficult to work with, the guns often jammed, and hands and feet froze. Gathering into formation for a major strike could take over an hour and was dangerous. The planes bunched into such tight boxes that sometimes the wings would nearly touch. It was a long trip, traveling at 170 mph, and a complete mission usually took over 6 hours. The flak (a word that denotes both bursting shells and the AAA itself) was heavy, the fighters many, and the straight-and-level bomb run took forever. There was always the fear that your airplane would be hit by a bomb dropped from an airplane overhead. The remaining bombers would be hassled again by the fighters on the way out. A standard tour for a B-17 crew was 25 missions.

Avoidance of early detection and confusion of intent were important to the survivability of the B-17. This was made difficult by the fact that the contrails from the hundreds of bombers in formation could be seen for hundreds of miles. The flight path to a European target was usually circuitous, avoiding known locations of AAA, and often one or more groups of bombers would depart on diversionary operations to draw the enemy fighters away from the main group or to delay their takeoff. Many different formations were tried. A staggered formation that was good for avoiding flak was bad for fighter defense, and vice versa.

The bombers were originally painted in a camouflage pattern to prevent them from being seen from the air when they were parked. Later in the war, when the danger of an airfield attack was reduced the paint was removed to save weight and reduce drag. Fighter escort, which was not available on the longer missions until late 1943, had a dramatic effect on the survivability of the B-17. The losses were typically seven times higher on unescorted missions. The P-47 Thunderbolt was used on the shorter trips. The P-38 Lightning, which had a longer range, was in short supply in the European theater. Only the P-51 Mustang had the range to accompany the bombers on the longer missions without auxiliary tanks.

Electronic countermeasures were also used to enhance survivability. To reduce the effectiveness of radar-directed search lights and AAA, a few B-17s in each bomber group carried a pretuned spot noise jammer known as Carpet. Carpet was first used in October 1943, and over 7000 were built. The British experimented with several types of countermeasures, and an elaborate device that sent back amplified and extended radar echoes was used in August 1943 to divert nearly 150 German fighters from a B-17 attack on Rouen. Chaff, known by the code name Window, was also used, starting in 1943, to confuse the radar operators. When it was first introduced, it was very effective in reducing B-17 losses. However, within a few months enemy counter-countermeasures began to reduce the benefits of the countermeasures. The British Bomber Command used several lend-lease B-17Es, Fs, and Gs as support aircraft whose role was radio and radar countermeasures in support of the main force. Painted black, they escorted the Lancasters and Halifaxes, or they made Window spoofs simulating bomber streams. This was the beginning of electronic warfare.

The B-17 was credited with the ability to absorb an amazing amount of battle damage throughout the war. Many of these rugged bombers limped back to base with engines destroyed and control surfaces shot away and were still able to make either safe landings or controlled crash landings. Early in the war in the Pacific, one B-17 was attacked by Japanese fighters and had all of its guns either shot out of action or jammed. Its radio was destroyed, the oxygen system put out of action, and one fuel tank was shot up. It eventually crash landed near its home base and was found to have over 1000 bullet holes. Another B-17 had the misfortune of colliding with a German Bf-109. The Bf-109 sliced into the aft section of the fuselage of the B-17, nearly cutting the fuselage in half and destroying the left elevator. In a similar example a Bf-109 collided with the aft end of a B-17, gouging out big chunks of the B-17's fuselage where the propeller sliced through. The bomber continued on its bombing mission. The tail gunner was not even aware of the collision until the plane had landed. The B-17 was also able to absorb large numbers of fragments from the high-explosive projectiles used by the German AAA batteries.

The combat data gathered from World War II indicate the intensity of the conflict. In the three and a half years of the war, 4700 B-17s were lost on combat missions out of a total of 12,700 built. More B-17s were lost than any other aircraft. Very few airplanes lasted a hundred missions. Those that did usually required many engine changes and major repairs. Loss rates on a raid were often as high as 10%

and sometimes went as high as 25%. One such event was the infamous October 1943 raid on Schweinfurt, when 60 out of 280 aircraft failed to return and 17 were damaged beyond repair.

In the nearly three years of operations by the 384th Bombardment Group of the 8th Air Force over Europe, B-17s flew 9348 sorties on 386 missions. On these missions 159 aircraft were lost for an average loss rate of approximately 1.5%. However, in the first six months of operations (June to November 1943), the loss rate for over 600 sorties on 38 missions was 8.7%. A crewman's chance of completing his required 25 missions was not good in those first months.

The British also suffered heavy losses during their nighttime bombing. Losses in the Bomber Command in late 1943 were nearly 4%, rising to 6% in January 1944, and 7% in February. On bad nights it could go as high as 10%, and on 30 March, 1944, 96 out of 795 aircraft failed to return from a raid on Nuremberg. A crewman's tour consisted of 30 missions, and his chance of surviving a complete tour in 1943 was about one in six.

In the European Theater most of the B-17 losses were caused by powerplant trouble, the inability to feather propellers, fires, and explosions. Fifty percent of the losses suffered engine damage serious enough to prevent the aircraft's return to home base. Also, any engine trouble that forced the aircraft to drop out of formation led to a much higher probability of loss as a result of the susceptibility of the lone aircraft to enemy fighter attack. The B-17 could maintain formation with one engine out if the propeller were feathered. Any other combination of engine problems caused the aircraft to drop out of formation. The B-17 had no backup feathering system; the B-24 Liberator did.

Fires were the major cause of about one-third of the bomber losses. The major areas for fire were the engine nacelles, the fuselage, and the wings. The early B-17s were equipped with nacelle fire extinguishers, but in the spring of 1943 the extinguishers were removed as part of a weight reduction program. The extinguishers were reinstalled by the summer of 1944. Fires in the fuselage sometimes resulted from hits that simultaneously punctured oxygen and hydraulic systems. Crew members using the portable fire extinguishers carried in the aircraft were unable to control the hydraulic fluid-oxygen fires in most cases. The wing fires usually resulted from hits on fuel lines or from holes in the fuel tanks that were too severe for the self-sealing compound to close. Fuel leaking from the wing tanks would flow the length of the wing and into the engine nacelles and the fuselage bomb bay.

The story of the B-17 is a heroic story of an airplane that evolved from an early reject because of its lack of survivability into a respected bomber that carried 40% of the bombs dropped on European targets. However, fighting its way to the target and back home took a heavy toll, and for every B-17 lost 10 crew members were potential victims. Nevertheless, the plane won international renown and was one of the few aircraft that saw continuous service throughout the war, despite having first flown in 1935.

A.2 Some Famous U. S. Army Air Corps Fighters of World War II

A.2.1 Lockheed P-38 Lightning

The Lockheed P-38 Lightning, originally designed as a pursuit or bomber interceptor, developed into a noteworthy fighter during the Second World War and is credited with destroying more Japanese aircraft than any other Allied fighter. The 1938 Lockheed twin-boom design was quite unorthodox for a pursuit, but resulted in a handsome, streamlined aircraft. The booms were used to carry the liquid-cooled Allison engines with their turbosuperchargers, radiators, and fuel tanks, as well as the main undercarriage. The relatively small center fuselage made an excellent gun platform. A pressurized cockpit was tested, but full-scale development was abandoned. The Lightning carried more and heavier armament than its contemporaries: one 20-mm automatic cannon and four .50 caliber electrically heated machine guns were installed in the nose of the center fuselage. At about 15,000 lb it was heavier than a combat-loaded Bristol Blenheim I, Britain's standard medium bomber at that time, and its wing loading was nearly twice as high as that of other current fighters.

The early models of the P-38 saw initial combat with the British Royal Air Force. The design shortcomings (no self-sealing fuel tanks, lack of climb power, and poor protective armor) quickly became obvious to the RAF, and priority messages were sent to Lockheed requesting a redesign. The result was the P-38D, introduced in August 1941. The P-38D was the first model Lockheed considered close to being a true combat fighter. Self-sealing fuel tanks were added, a new propeller was installed, and heavier armor plating was installed in the cockpit area. This armor, placed directly behind the pilot's seat, protected the head and torso from the rear only. There was no armor on the sides or front of the cockpit. Consequently, many units produced their own armor plates and attached them to the sides of the cockpit.

The P-38 owed its combat ruggedness to the structural design. Its ability to absorb damage is exemplified in an incident where a P-38 and a Messerschmitt Bf-109, engaged in head-on firing passes, collided. The Bf-109 lost its wings and crashed immediately. The P-38, also a wreck, continued to fly. It had a prop torn away from one engine, its horizontal tail was severed, and one of its fuselage booms was reduced to rubble. The pilot was able to return the aircraft for a successful crash landing. In another case a pilot flew his P-38 into a telephone pole. The wing sliced the pole in two and sustained severe leading-edge damage, but the aircraft returned to base safely. Another P-38 returned to base with one engine dead and riddled with over 100 bullet holes and five cannon strikes. In another extreme example an overzealous pilot on a strafing run against a Japanese destroyer pulled up too late, and his wing tip sheared off the ship's foremast. A 3-ft section of the P-38's wing was missing, yet it continued to fly and eventually landed safely at its home base.

Even with its ruggedness the P-38 had several shortcomings in combat. The turbosuperchargers produced a thick contrail at high altitudes that was visible to enemy fighters at great distances. The distinctive body design led to long-range recognition by the enemy fighter pilots and allowed them to prepare for engagement before the P-38 pilots spotted them. The contrail problem was eventually solved by using a water trap and enlarging the intake duct scoops. The P-38 was also extremely cold when used at altitudes above 30,000 ft, leading to pilot fatigue and many cases of frostbite during long bomber escort missions. The aircraft was difficult to maneuver at high altitudes, and the cold, damp European weather caused problems with the carburetor and the supercharger.

The twin-engine design of the P-38 would seem to be a survivability enhancement feature. However, combat data from the European Theater of Operations on damaged P-38's returning to base indicated that only 10% returned after one engine was disabled. In most cases the disablement of one engine led to a loss of the aircraft. This could be because damage to the liquid coolant subsystem would put the engine out of action and often would cause a fire, eventually resulting in the loss of the aircraft. Thus, the second engine probably increased the vulnerability of the aircraft rather than reduced it. The P-38 also had its dive speed limited as a result of compressibility effects near Mach 1. These shortcomings led many senior officials, including General Doolittle, the 8th Air Force Commander, to question the use of the P-38 in the European Theater.

Later production P-38J models had the curved windshield replaced with a bulletproof glass canopy, and the P-38L had an AB/APS-13 tail-warning radar installed. The radar warning system detected the presence of an aircraft in a cone-shaped area behind the P-38 and signaled the pilot with a warning light and ringing bell. The P-38J-25-Lo and subsequent variants were fitted with a hydraulic power boost system for the ailerons to increase maneuverability. This was one of the first applications of power-assisted controls to any fighter.

Although only 9923 P-38s were produced, the smallest number of the major USAAF combat fighters, it served on every battlefront in a wide variety of roles, including fighter escort, bombing with the Norden bombsight and with radar, photo-reconnaissance, casualty evacuation, smoke laying, and night fighting.

A.2.2 Republic P-47 Thunderbolt

The largest, heaviest (15,000 to 21,000 lb), and one of the most rugged single-engine, single-seat aircraft to be produced during World War II was the Republic P-47 Thunderbolt. The Thunderbolt's ability to absorb punishment was undisputed. With its two self-sealing fuselage fuel tanks, air-cooled Pratt and Whitney Double Wasp engine, cockpit armor, laminated-glass canopy, and rugged structure, the P-47 often survived the most damaging blows from 20-mm cannon fire, returning to base riddled with holes and with the majority of its control surfaces damaged or missing.

When the Thunderbolt was first introduced to the war in Europe in 1943, it was the only Allied radial engine, single-seat fighter, and there was concern that it would be confused with the blunt-nosed German Focke-Wulfe 190 fighter. Consequently, to prevent Thunderbolts from being shot at by other Allied fighters the engine cowlings were painted either white or a checkerboard white and black, and white bands were painted around the vertical and horizontal tail surfaces. Another survivability feature of the Thunderbolt, first introduced in the P-47D, was the use of emergency water injection into the intake manifold to increase the engine performance temporarily. In addition, conversion to a bubble canopy on some versions of the D model eliminated a 20-deg blind spot to the rear of the aircraft. Canopies that could be jettisoned were also added to the D model to help the pilot quickly get out of a damaged aircraft.

The major criticism of the P-47 was not its survivability, but its lack of range. The P-47 had been specifically designed to escort U. S. daylight bombers over Europe. Although it was sluggish at low altitudes, its high-altitude performance was superior to that of the P-38, and consequently it was better suited to the escort role. However, even with external fuel tanks it could only escort B-17 formations to the German border when operating from bases in England. As a consequence, the 8th Air Force suffered its greatest B-17 losses when attacking targets inside the German border. The Luftwaffe's favorite tactic was to wait until the P-47 escort was forced to return to England because of low fuel and then engage the bomber formations with overwhelming numbers of fighters. Sometimes they would make a feint at the fighters just as they crossed the English Channel, forcing them to drop their external fuel tanks in order to maneuver, thus limiting their range. Perhaps this sturdy fighter was too rugged for the escort role, its heavily weighted components too limiting to its operational range.

After forward bases were secured on the Continent, the P-47 was able to range over Germany and take advantage of its rugged construction, destroying both air and ground targets with its eight .50 caliber guns, bombs, and rockets. It became a very successful ground attacker and dive bomber. It was even used in formation on medium-altitude, bad weather, level bombing missions, dropping over half of a normal B-17 bomb load on command from a ground-based radar.

Over 15,600 P-47s were built, and 12,600 of these were P-47Ds, the largest U. S. production quantity of any one model fighter. It was operational in all active theaters except Alaska and was used by the RAF, the Free French, and the Russian forces. Perhaps the most significant statistic regarding the survivability of the Thunderbolt is the fact that all 10 of the leading Thunderbolt aces survived the war.

A.2.3 North American P-51 Mustang

The Mustang, considered by most authorities to be the best fighter aircraft of World War II, was originally ordered into production in 1940 by the British as an improvement over the Curtiss P-40 Hawk. The Mustang Mark I aircraft built for the RAF had a laminar flow wing, a low-drag fuselage, and an Allison liquid-cooled inline engine. The distinctive air scoop for the radiator was located under the wing and behind the cockpit. With the Allison engine the Mustang did not come near meeting the RAF's specifications for speed or rate of climb at altitudes above 20,000 ft. Although it had good performance qualities at 15,000 ft, it was outclassed by both the RAF Spitfire V and the Bf-109G at the higher altitudes. As a consequence, it was used as a close support/reconnaissance aircraft by the RAF in the early years of the war.

In the spring of 1942, a U. S. test pilot suggested that a Rolls-Royce Merlin 61 supercharged, liquid-cooled engine be fitted to the Mustang. The first converted Mustang was flown by the RAF in October 1942; while in the United States, two RAF Mustangs were converted to Packard-built Merlin engines and were flown in November 1942. Because most of the U. S. aircraft used air-cooled radial engines, there was a debate on the wisdom of using a liquid-cooled engine, with its increased vulnerability caused by the radiator and the long coolant lines being located aft of the cockpit, over an air-cooled engine. Just when the limitations of the P-38 and P-47 as long-range, high-altitude escort aircraft were becoming apparent, the decision to mass produce the P-51 was delayed. The United States wanted to wait for a more powerful air-cooled engine that was being rushed into production. Eventually, the critical need for an improved escort fighter overcame the reluctance to use the liquid-cooled engine, and the P-51B with the Packard-Merlin engine was rushed into production. The first P-51B production aircraft were delivered in June 1943, and the first P-51 group joined the 8th Air Force in November 1943.

The aircraft had a pressurized cockpit, weighed 6840 lb empty, and had a top speed of 453 mph at 28,000 ft. Its armament consisted of four or six 0.50-in. Browning machine guns.

The P-51 was equipped with two self-sealing wing tanks and one self-sealing fuselage tank behind the pilot. It had armor plating on the fire wall and on the pilot's seat back and had a laminated-glass canopy. As with most fighter aircraft, the P-51 had no onboard fire-extinguishing system. The early P-51s did have vulnerable coolant lines, but one of the last models had the oil cooling core in the aft radiator replaced by a heat exchanger located in the engine compartment. This eliminated the long oil lines back to the rear cooler.

In early 1944, when the German attacks on air bases in England diminished, the olive drab finish was abandoned in favor of a polished base metal finish to increase the top speed. To accommodate taller pilots and to improve rearward vision, a full bubble canopy was introduced on the P-51D, and some pilots got their ground crews to fit rear-view mirrors in the cockpit to help keep a watch out behind. (The physical resemblance of the early P-51s without the bubble canopy to the Bf-109 caused the loss of quite a few aircraft to U. S. guns.) A tail-warning radar system was also installed, and the 8th Air Force P-51 pilots were among the first to wear the new anti-'G' suits.

A specialized dive-bomber version of the P-51 with the Allison engine was designated the A-36; and an interesting variant of the P-51 was the P-82 Twin Mustang, which had two P-51Hs joined together at midwing. This twin fuselage design was prompted by the desire to use two pilots, thus reducing pilot fatigue on very long flights in the Pacific Theater.

Over 15,500 P-51s were built, and they were credited with nearly 5000 of the 10,200 air combat victories claimed by USAAF pilots in the European Theater.

A.2.4 Conclusion

The successful development of these three long-range fighters was totally unexpected by the German and Japanese forces. They did not imagine that such large and rugged aircraft could fly over long ranges for protracted periods of time and then effectively engage their short-range, maneuverable, defensive fighters on an even basis. They were versatile, handsome, loved, and sometimes cursed, and they will be remembered for a long time to come for their significant contribution to the Allied victory.

A.3 U. S. Navy and Marine Fighters of World War II

The U. S. Navy had a more difficult job than the Army Air Force in developing aircraft that could outclimb, outmaneuver, outshoot, overtake, and, if necessary, outrun both land- and carrier-based enemy fighters such as the Japanese Zero. For example, carrier-based aircraft must have very good slow-speed landing and touchdown characteristics and an ample fuel supply to ensure a return to the carrier from the combat area. The wings have to fold, a tail hook is required, and the structure and landing gear have to be rugged in order to absorb the shock at touchdown. These requirements usually add considerable weight to the aircraft and can degrade performance. As a consequence, the radial air-cooled engine was generally used on carrier aircraft because it was lighter, more tolerant to abuse and to landing shock, easier to maintain, change, and store, and less vulnerable than a liquid-cooled engine of equivalent power.

The two prewar Navy carrier fighters were the Brewster Buffalo and the Grumman Wildcat. When the war started, these two aircraft were almost totally outclassed by the Zero, particularly in range, climb, and maneuverability, and the need for better fighters became painfully obvious. The result was the appearance in 1943 of the Grumman Hellcat and the Chance Vought Corsair.

A.3.1 Brewster F2A Buffalo

In 1935 the Navy issued a design competition for the next-generation fighter. The most promising designs were Seversky's NF-1, a Grumman biplane, the XF4F-l, and a monoplane design from the newly formed Brewster Corporation, the XF2A-1. The Navy canceled the Grumman biplane design in 1936, believing the biplane had passed its prime, and issued a contract for a midwing monoplane, the XF4F-2. The Brewster design continued, with many modifications, and had its maiden flight in late 1937. Officially known as the Buffalo (a fighter named Buffalo?), other names for this stubby, all-metal, stressed-skin, flush-rivet aircraft were Peanut Special and Flying Barrel. It had many new features for a Navy fighter, including an enclosed cockpit, split flaps, and hydraulically operated, retractable landing gear that unfortunately exhibited a propensity for collapsing during a hard landing. Its armament consisted of one 0.30-in. and one 0.50-in. machine gun located in the top of the cowling, with provision for one 0.50-in. machine gun in each wing outside of the propeller arc.

The Buffalo was considered by the Navy to have better potential than the Grumman XF4F-2 and the much slower Seversky design and, consequently, won the competition in 1938. The design of the F2A-2 Buffalo continued to change through 1939 and 1940 as the lessons of combat came in from Europe, where heavier armament, faster speed, and more armor were believed to be essential in a fighter. Consequently, the Buffalo got a new Wright Cyclone engine, a new variable-pitch propeller, increased fuel capacity, improved flotation gear, and an increase in armament to two 0.50-in. cowling machine guns and one 0.50-in. machine gun in each wing. Armor was added to the cockpit and around the fuel tanks. The additional weight totaled 900 lb, bringing the aircraft to over 7000 lb loaded, and causing a very high wing loading. The penalty for the increased weight was a decrease in service ceiling, maneuverability, and maximum speed, which was slightly better than 300 mph. This decrease in performance changed a marginally acceptable fighter into an unacceptable one. The F2A-3 model had increased armor protection for the pilot, self-sealing fuel tanks, a bulletproof windscreen, and a more powerful engine. In service the Buffalo suffered from much faulty equipment that either performed badly or simply failed to work. About 160 Buffalos were eventually built.

The Navy eventually decided the Buffalo was unsuitable for carrier operation and relegated it to the Marines. Typically, inexperienced Marine pilots flying the Buffalo against experienced Japanese pilots flying the Zero had little hope for survival, let alone winning. In the Battle of Midway, on 4 June, 1942, Marine squadron VMF-221 sent 19 Buffalos and 16 F4Fs to oppose 108 Japanese aircraft.

After a brief engagement the score was a kill of six Japanese aircraft for a loss of 13 Buffalos and two missing F4Fs. The Marines were bitter, and one of the survivors said that any commander who ordered a pilot up in combat in an F2A should consider the pilot lost before he left the ground. As a result of this experience, the Navy withdrew the Buffalo from combat.

Although outclassed by almost all opposing fighters, the Buffalo saw service on a surprisingly wide scale from the far north of Finland to the Dutch East Indies. It is worth noting that it was Finland's most successful fighter. Kapt Hans Wind was credited with 38.5 victories against Russian aircraft, and the total Russian and German kills by Finns flying Buffalos was 477.

A.3.2 Grumman F4F Wildcat

Although the Grumman XF4F-2 lost in the Navy's design competition in 1938, it was regarded as a strong second, and, consequently, Grumman was given a contract for 54 F4F-3 aircraft in August 1939. The F4F-3 was rotund and rugged like the Buffalo; not sleek and feline like the Bf-109, RAF Spitfire, and Zero. It had a strong, retractable undercarriage, the Wright Twin Wasp two-stage supercharged engine, and two 0.50-in. machine guns in each wing. The French ordered 81 aircraft basically similar to the F4F-3, with the Wright Cyclone engine and six wing-mounted 7.5-mm guns. When France fell, the British took over the contract, changed the armament back to four 0.50-in. wing guns, and called them Martlet Is.

The F4F-4, which arrived in November 1941, was the first model to be produced in large numbers. This model was officially designated the Wildcat. A hydraulic wing folding system was initially installed, but the added weight and complexity were not felt to justify it, and so the wings were folded manually. It had the Pratt and Whitney Twin Wasp 14-cylinder radial air-cooled engine and a variable-pitch propeller. Three 0.50-in. machine guns were installed in each wing, and the pilot was protected by a stainless-steel fire wall, 25 lb of armored windscreen, and 94 lb of armor aft of his seat. A 45-lb armor plate was located directly in front of the oil tank. The empty weight of the aircraft was nearly 6000 lb, and it had a maximum speed of 320 mph and a range of 1300 miles with two drop tanks. By the end of 1942, all Navy carrier-based fighter squadrons were equipped with the Wildcat.

Against the Zero the Wildcat was inferior in range, ceiling, speed, and climb above 1000 ft. It had equal or better dive speed, but the Zero had a much smaller turn radius. Only through tactics (a two-plane weave for mutual protection and diving down on the enemy from above), superior firepower, and the ability to withstand damage was an experienced Wildcat pilot (and there were not many in the beginning) able to survive a fight with a Zero.

Early in 1942, production of the F4F-4 was transferred to the Eastern Aircraft Division of General Motors, and the aircraft was called the FM-I. A lightweight version of the GM-produced Wildcat, the FM-2, was developed in late 1942 for operation from the short flight decks of the smaller carriers. This aircraft had a new, lighter Wright Cyclone engine, some models of which had a water injection feature for temporary boosted performance. The armament was reduced to four 0.50-in. machine guns in the wings.

A total of over 7200 Wildcats were produced: 1060 FM-ls, 4777 FM-2s, 280 F4F-3s, and 1169 F4F-4s. The Wildcat was credited with the destruction of over

900 enemy aircraft in aerial combat, with the loss of only 178, during the period 1941–43. For the entire war the victory-to-loss ratio was 6.7 to 1. The memory of the heavy losses early in the war tends to overshadow the excellent record of this portly little fighter that held the line in the Pacific until the arrival of the Hellcat and Corsair.

A.3.3 Grumman F6F Hellcat

The Navy ordered Grumman to develop the F6F Hellcat in June 1941, and the first production F6F-3 flew in October 1942. It had a low-mounted three-spar wing and a single Pratt and Whitney R-2800 Double Wasp 18-cylinder air-cooled radial engine with water injection for an emergency boost of power. The Hamilton Standard hydromatic propeller replaced the original Curtiss electric fully feathering propeller. It weighed 9000 lb empty and had a maximum range of 1600 miles with a centerline drop tank and a maximum speed of about 380 mph. It was armed with six 0.50-in. Browning machine guns and could carry two 1000-lb bombs.

The design of the Hellcat somewhat resembled that of the Wildcat, but it was considerably larger. The pilot was located at the highest position amidships, giving good all-around visibility. The design lacked elegance, but like that of the Wildcat it allowed for a very rugged structure.

Because the Hellcat design was proceeding during the early days of the war, there was some thought that perhaps the rugged, heavily weighted structure and armor plating should be sacrificed for more maneuverability and range, as was done with the Zero. However, the capability to absorb damage and to protect the pilot was eventually considered to be too important to sacrifice; improved performance had to come from a more powerful engine and good aeronautical design, rather than from a lighter-weight airframe. (In contemporary terms vulnerability was not to be increased in order to gain a reduction in susceptibility.) Consequently, the Hellcat was designed to be tough. It had 212 lb of armor to protect the pilot, the oil tank, and the oil cooler. Initially, the armor plate located behind the pilot's head was shaped and sized for the head, but was not thick enough to stop the shrapnel from the Zero's 20-mm cannon shells from penetrating it. Its fuel tanks were located in the center wing section and were self-sealing, and it had an armored glass screen behind a curved Plexiglas® windscreen. Two variants of the F6F-3, the -3E and -3N, were developed for night fighting by installing a radar set in a pod attached to the starboard wing. To improve the poor night vision from the cockpit, red instrument lights were installed to cut down on cockpit glare, and the curved windscreen was replaced by a flat-faced screen.

The F6F-5 model appeared in 1944 and had a flat-faced windshield, red instrument panel lighting, a strengthened tail assembly, 242 lb of armor, racks for six 5-in. rockets, and a special smooth finish. The armor plate behind the pilot's head was expanded to provide protection over a greater area, and the thickness was increased to stop the 20-mm shrapnel. Its empty weight was 9238 lb and its maximum speed was 380 mph. Some late −5 models had a pair of wing-mounted 20-mm cannons in addition to four .50 caliber machine guns.

The Hellcat was famous for its ability to absorb damage and continue to fly. Retired Navy Captain David McCampbell (with 34 air victories, nine of them on one mission), in an interview for *Wings* magazine, stated that on one mission in his

Hellcat he was shot up badly by antiaircraft fire over Marcus Island. His Hellcat had a belly tank on fire, a hydraulic fire in the fuselage, partial loss of aileron control, loss of left rudder control, and loss of hydraulic power to lower the wheels and flaps. Nevertheless, the Hellcat brought McCampbell back to the carrier 135 miles away. McCampbell said that he never saw a Hellcat go down in flames or explode when hit. He attributed this to the superbly designed self-sealing fuel tanks.

The Hellcat was considered to be superior to the Zero in speed, dive, and altitude capabilities, but maneuverability and low-level climb rate were inferior. Thus, the Hellcat tactics were essentially the same as those of the Wildcat; pilots would generally avoid dogfighting, with its tight turns and loops in which the Zero excelled, and would attack from above, diving down on the enemy. Once on the tail of a Zero, the Hellcat could usually stay with it in a turn long enough to get off a short burst from the six 0.50-in. guns, which was sufficient to destroy the highly vulnerable Japanese fighter.

The total number of Hellcats produced was over 12,000: 4402 –3s and 7870 –5s, 3578 of which were produced from January to November 1945, when production was stopped. The Japanese pilots that encountered the Hellcat considered it to be the best U. S. aircraft in fighter-vs-fighter combat, and at the end of the war the Hellcat accounted for 4947 of the 6477 enemy aircraft destroyed in the air by U. S. Navy pilots. Shore-based U. S. Marine squadrons brought the total up to 5156 Hellcat victories. During the war, the Hellcat enjoyed a 19 to 1 kill-to-loss ratio.

A.3.4 Chance Vought F4U Corsair

The Chance Vought F4U Corsair was the eventual result of a Navy design contest of 1 Feb., 1938 for a single-seat shipboard fighter with a particularly good service ceiling and speed. The F4U design was the most impressive of four designs and was built around the Pratt and Whitney Double Wasp engine, the largest and most powerful air-cooled radial, which drove the largest propeller ever considered for a fighter, the Hamilton Standard three-bladed, constant-speed, fully feathering hydromatic. The unusual inverted nonfolding gull-wing configuration solved the problems of accommodating the large propeller, while keeping the landing gear length and ground angle acceptable and providing a good angle at the wing root for minimum drag. The airframe consisted of relatively heavy frames and stringers and a thick skin, thus reducing the number of longitudinal members. A new spot-welding technique was used, resulting in an exceptionally smooth finish. The prototype had one 0.30-in. and one 0.50-in. gun in the upper decking of the forward fuselage and a single 0.50-in. gun in each wing. The F4U-1 first flew in May 1940 and was indirectly responsible for the U. S. Army Air Corps allowing Pratt and Whitney to abandon their liquid-cooled engine program.

Extensive modifications were made to the F4U-1 prior to production based upon the British combat experience in Europe. The need for better armament was met by installing two, and later three, 0.50-in. machine guns with greatly increased ammunition capacity in each outer wing panel outside of the propeller arc and removing the fuselage guns. The integral fuel tanks in the wing leading edges, which initially incorporated a carbon dioxide vapor dilution system for inerting the ullage, were removed, and a large self-sealing fuselage tank was installed near the aircraft center of gravity. This required the cockpit to be moved 3 ft aft, resulting in an extremely long length of fuselage in front of the pilot, obscuring his forward view, particularly during landing. One-hundred-and-fifty pounds of armor were added around the cockpit and oil tank, rearward vision was improved, the canopy was made jettisonable, and IFF was installed. All Corsairs had a provision for automatically pressurizing the main fuel tank at altitudes above 12,000 ft. The pressure could be manually released in the event of a fuel tank puncture or prior to a crash landing, and all F4U models were equipped with an emergency landing gear extension system activated by a carbon dioxide bottle.

The early design of the Corsair did not prove to be suitable for carrier operations. The principal trouble was the restricted vision during deck landing caused by the long forward fuselage. The aircraft also tended to bounce and swing badly on touchdown. The cockpit was raised, and a frameless clear-view canopy was employed to improve the forward view. Several other changes improved the touchdown behavior, such as changing from a solid to a pneumatic tail-wheel tire. It was not until the end of 1944 that the Corsair was used operationally from a carrier.

In 1943 the water injection engine was added. At least one particular Navy lieutenant owed his life to the temporary boost in power provided by the water. According to the Navy, the 25-year-old pilot found himself in a position that is a nightmare to every combat pilot. He was only 50 ft over the water, and three Zeros were close on the tail of his plane, two on the right, astern, and one on the left. If he pulled up, he would be at the mercy of the Zeros, and he was in the same predicament if he turned right or left. It was then that the young lieutenant flicked the water injection switch. The resulting burst of speed took him out of the range of the enemy guns.

Some Corsairs were given a new armament consisting of four wing-mounted 20-mm cannons in place of the six 0.50-in. machine guns. However, only 200 Corsairs with the 20-mm cannons were produced because most pilots preferred the machine guns. Several radar-equipped Corsair models were also developed.

The Corsair first saw action at Guadalcanal in early 1943. Like all U. S. carrier fighters of World War II, the Corsair was found to be very rugged. U. S. Marine 1st Lt. Kenneth Walsh, a Corsair ace, was flying his Corsair over Guadalcanal on 15 August, 1943, when he encountered an overwhelming number of Japanese Val dive bombers and Zero fighters. He succeeded in destroying two Vals and one Zero before his aircraft was riddled by 20-mm cannon fire. His right wing was full of holes, his hydraulic lines were severed, the vertical stabilizer was shredded, and the right tire was blown. Lt. Walsh managed to elude his attackers and return home for a successful crash landing. Walsh was uninjured, but the Corsair was so badly damaged that it was declared a total loss.

The F4U-l weighed nearly 9000 lb empty, had a maximum speed of nearly 400 mph, and had a maximum range of 2200 miles with a drop tank. In comparison with the Hellcat, a Navy evaluation board in May of 1944 concluded that the F4U is "... a better fighter, a better bomber, and an equally suitable carrier aircraft compared with the F6F." Over 12,500 Corsairs were produced by Chance Vought, Goodyear (FG), and Brewster (F3A). The U. S. Corsair destroyed 2140 Japanese aircraft with a corresponding loss of 189 aircraft in aerial combat. Further F4U losses included 349 from antiaircraft fire, 230 from other causes, 692 losses on nonoperational flights, and 164 in crashes on carriers or airfields. There were approximately 64,000 operational sorties; 54,500 from land; and 9600 from carriers.

The life of this spectacular aircraft, the last piston-engined fighter to be produced in the United States, was not to end at the conclusion of World War II.

A.3.5 Summary

At the beginning of the war, the Navy Wildcat and Buffalo fighters, at the hands of inexperienced pilots, were generally not survivable when matched against the experienced Japanese Zero pilot. The two new fighters, the Hellcat and Corsair, gave the United States a capability to match or exceed the performance of the Zero, without the vulnerability of the Zero. The Japanese did not intend to fight a prolonged war and consequently did not make sufficient plans for improving their aircraft. The U. S. Navy pilot received more and better training (three to five times more flight hours before assignment to an operational unit) and had the opportunity for rotation for R & R, a luxury the Japanese pilot did not have. Consequently, as more U. S. pilots survived and gained valuable experience, the ratio of experienced U. S. pilots to experienced Japanese pilots began to grow heavily in favor of the U. S. pilot. Thus, the combination of rugged aircraft with comparable or better performance, better crew training, experienced leaders, and improved communications and control gave the U. S. Navy pilot a very good chance of surviving an encounter with his enemy.

A.4 World War II Aircraft from Other Countries

A.4.1 Messerschmitt Bf-109

The primary opponent of the Allies in the European Theater was the Bf-109, flown by the Germans, the Italians, and the Hungarians. (Several were also flown by the Swiss for neutrality defense only.) The Bf-109 was designed in 1934 by Professor Willy Messerschmitt for the Bayerische Flugzeugwerke to be an all-metal, lightweight, maneuverable, single-seat, low-wing, cantilever monoplane fighter with a liquid-cooled engine. It had its teething troubles, but it was a highly successful combat aircraft in the early years of the war. In spite of its problems, the final version, the Bf-109K, was still in production at the end of the war. The K model weighed nearly 7500 lb fully loaded and had a top speed of 377 mph at sea level and 450 mph at 20,000 ft. It had a range of 350 miles at 20,000 ft and 6800 lb. It had a relatively thin wing and small wing area, resulting in a high wing loading compared to its contemporaries.

The armament on the Bf-109 underwent many changes. Originally designed to carry two 7.9-mm machine guns in the upper decking of the nose, the 1939 E model, the first true mass production version, also carried two wing-mounted 20-mm cannons. A third 20-mm cannon was installed in the nose of the 109E-3 to be fired through the airscrew boss, but the engine-mounted cannon was unreliable and consequently was seldom used. Later models carried a 15-mm cannon in the nose, and some had a 20-mm cannon mounted in a gondola under each wing. One heavily armed antibomber version of the G model carried a 30-mm cannon that fired high-explosive projectiles through the airscrew boss, two 13-mm machine guns above the engine, and two 20-mm cannons in the underwing gondolas. There were conflicting opinions among the German pilots concerning the armament. Some favored more of the lighter-caliber machine guns whereas others preferred the more destructive cannon. However, the cannon pod, required because of the extreme thinness of the wing, adversely affected maneuverability.

There were many variants of the aircraft. For example, one of the E model versions was modified for low-flying, attack roles in North Africa. These aircraft had armor bolted beneath the engine and the coolant radiators. Many aircraft carried bombs weighing up to 551 lb and were the first land-based fighter bombers.

The Bf-109 Daimler-Benz engine was especially noted for its fuel injection system that prevented fuel starvation during negative g maneuvers, and the engine in the G-5 model incorporated a methanol and water injection system. The two agents were carried in a jettisonable tank under the fuselage and were fed to the engine in times of emergency to temporarily boost the power output. The G model was also the first to have a pressurized cockpit, a feature that had become necessary because of the increasing amount of combat at the higher altitudes. The Galland hood on the G model gave better visibility.

Even though constructed with weight savings in mind, the Bf-109 still had a rugged structure. (An isolated incident in 1937 in Spain in which a Bf-109 lost its tail in a high-speed dive led to the rumor that the aircraft would fall apart during high-stress maneuvers.) The aircraft typically broke into three parts when crash landed. The cockpit area was one of these parts, and its tendency to maintain structural integrity saved the life of many pilots, as did the armor plating located behind the pilot's seat. The wings were of single-spar construction, and all of the internal fuel was carried below and behind the pilot. The windscreen was made of armorglass and was surrounded by an armored frame.

Although the Bf-109 was a popular fighter, the pilots were very uncomfortable in the cramped cockpit, and flying the aircraft was an exhausting occupation. It could hardly be maneuvered at speeds over 400 mph, and it was notoriously difficult to handle during takeoff and landing. Its narrow-tracked landing gear, high angle of incidence, and tendency to swing on takeoff and landing caused the loss of some 1500 fighters between the beginning of the war in September 1939 and the autumn of 1941.

From 1939 through 1943, the Bf-109 ranked as a superior fighter. Several fighter wings had 1000 victories before 1942, and some eventually exceeded 7000. However, toward the end of the war, the Bf-109, faced with P-51 Mustang and P-47 Thunderbolt opponents, the Luftwaffe's lack of trained pilots, the use of wood in place of aluminum as a result of material shortages, and construction by conscripted foreign laborers, suffered severe losses. No exact records are available on the total number of aircraft produced, but it has been estimated that more than 33,000 were built between 1935 and 1945, representing more than 60% of the total number of single-engine fighters produced by Germany. Czechoslovakia and Spain continued to manufacture the Bf-109 after the end of the war.

A.4.2 Ilyushin IL-2

The Russian-built Ilyushin IL-2 Sturmovik was possibly the most heavily used aircraft in World War II. Over 36,000 IL-2s and 6000 follow-on IL-10s were built between 1941 and 1945. It was designed in 1938 specifically for the purpose of destroying tanks, and in time would come to be known as the 'Flying Tank' and the 'Black Death.' Its empty weight was somewhat over 7100 lb, and its maximum speed ranged from 260 to 310 mph. It carried underwing racks for rockets and bombs and internal wing cells for bombs. One 20-, 23-, or 37-mm antitank cannon was installed in each wing.

The Ilyushin design incorporated many features for reducing vulnerability. A single, compact, welded-steel armor cell weighing over 1500 lb encompassed the entire lower portion of the nose and center of the fuselage and provided protection for the pilot, the liquid-cooled engine and radiator, the fuel tanks, and other critical components of the aircraft. The armored cell was not parasitic, but was part of the stressed airframe. The rear section of the aircraft fuselage was wooden, but the wings and empennage were made from hard duraluminum. It had self-sealing fuel tanks that were made from hard aluminum sheets covered with a rubberized fabric. The engine exhaust gases were cooled and piped into the fuel tanks to inert the tank ullage, thus reducing the possibility of a fire or explosion.

The early versions of the IL-2 were single seat and, although well protected from forward ground fire, were highly susceptible to air attack from above and from the rear. They were also vulnerable from these aspects. This problem was solved by adding a rear seat that was equipped with a rearward-facing 12.7-mm machine gun. When the first IL-2s carrying rear-seat gunners appeared, a number of German fighters were shot down when they made their usual attack on the IL-2s previously susceptible and vulnerable tail. This modification led to dramatically reduced losses, and the IL-2 became almost indestructable. Yakolev, the famous Russian airplane designer, in his book on 50 years of Soviet aircraft production states that neither the Allies nor the Soviet Union's enemies had anything similar to the IL-2.

Erich Hartmann, the Luftwaffe's leading ace with 352 victories in World War II, said that the Sturmovik was the hardest aircraft to destroy once hit. He saw machine gun and cannon rounds bounce off the Flying Tank on countless occasions. Hitting the IL-2 was not very easy either. About the only tactic that was successful was to approach from behind and below and attempt to fire into the wooden fuselage.

The Flying Tank was also very effective in its mission of destroying tanks. When the German offensive at Kursk took place on 5 July, 1943, IL-2s, armed with 37-mm cannons, destroyed 70 German tanks in 20 min. The aircraft played a central role in the Soviet effort in World War II and was described by Stalin to be as necessary to the Red Army as air and bread.

A.4.3 Mitsubishi A6M (Zeke) Zero

A contrast to the rugged designs of fighters from most of the other countries was that of the Japanese A6M Zeke, more popularly known as the Zero. The Zero was introduced in 1940 and quickly showed its superiority over its early opponents: the Chinese fighters, the Curtiss P-40, the Curtiss Hawk, and the Brewster Buffalo. The Zero was even flying combat sorties of over 1400 miles in China, a feat considered impossible by all other aircraft producers. The Zero maintained its superiority until 1943, when the United States started introducing P-38 Lightnings, F4U Corsairs, and F6F Hellcats to the Pacific Theater.

The model A6M6, produced in 1944, weighed nearly 4000 lb empty and 6500 lb fully loaded. It had a maximum speed of 290 mph at sea level and 345 mph at 20,000 ft. Its maximum range with a normal fuel load was 1130 miles at 150 mph. It carried two 20-mm cannons and two 13.2-mm machine guns in the wings and one 13.7-mm machine gun and one 7.7-mm machine gun in the upper decking of the engine cowling.

The Zero was famous for its range and maneuverability and was notorious for its vulnerability. Jiro Horikoshi, the lead aeronautical engineer for Mitsubishi during the development and manufacture of the Zero, said

> The Zero was a product of a given set of circumstances. The design answered specifically the unique requirements of Japanese pilots, who stressed the factor of unexcelled maneuverability. Much has been said of the Zero fighter's lack of pilot protection devices, such as armor plate and self-sealing fuel tanks. These items were omitted from the Zero at the insistence of our pilots. To them, fighting in the air meant only one thing: attack. They would not tolerate the encumbering weight solely for protective purposes. They felt that the gain in performance resulting from minimum weight more than compensated for a lack of safety features, which, to them, represented unnecessary luxury (Ref. 1).

A specific example of the Japanese philosophy is the fact that many Japanese pilots flew without parachutes because they found the harness irksome, and it prevented them from becoming an integral part of their aircraft.

In the initial stages of the war, the Japanese philosophy proved to be valid, based upon the loss ratios of Zero's opponents. However, many of the best Japanese pilots were killed in the early years, and when eventually opposed by Allied aircraft possessing greater firepower, less vulnerable design, and increased maneuverability, the Zero lost its superiority. As happened to Germany, the lack of capable pilots and the material shortages contributed to severe loss rates as the war progressed.

Demand for a new and better aircraft led to the development by Mitsubishi of the A7M Reppu or Hurricane. However, production of the Hurricane was delayed, and the Japanese Navy was forced to make do with modifications to the Zero. After the Philippine Sea disaster the specifications for the A6M5C included (for the very first time) protection for the pilot. Several survivability features were to be put in the A6M5C and the A6M6C models, including bullet-resistant glass for the cockpit windshield, a toughened-steel plate under the pilot's seat, automatic carbon-dioxide fire extinguishers for the fuel tanks, water-methanol injection for a temporary boost in engine power, and self-sealing fuselage and wing tanks. However, the new and more powerful engines required to support the additional weight without loss of performance were not fully tested and ready for installation. They were also drastically overrated, as well as unreliable.

The Zero was still in production at the end of the war, and in spite of technical problems, a natural disaster in the form of an earthquake, and the devastation caused by the Allied bombing, the last version produced by Mitsubishi in 1945, the A6M8, was a very good aircraft. The airframe had been strengthened, a new engine manufacturer had been selected, and the survivability features of the A6M5 and A6M6 models were retained and improved upon. However, it still weighed less than half that of a Grumman Hellcat. It is questionable whether this new aircraft, improved as it was, could compete against the more massive, rugged, capable, and numerous American aircraft flown by skilled and experienced pilots.

Nearly 11,000 Zeros were eventually produced, more than any other wartime Japanese aircraft. The last version was first flown in May 1945, but no production aircraft had been completed by the end of the war. Had the war been short, as originally planned by the Japanese, the Zero would have reigned supreme. Instead, it suffered horrendous losses in the last two years of the war, and one of its final roles was that of a suicide aircraft.

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Appendix B
Probability Theory and Its Application to Survivability Assessment

B.1 Concepts and Definitions

B.1.1 Statistics and Probabilities

Learning Objective	**B.1.1**	**Describe the terms statistics and probability, and relate these terms to a combat operation, action, or incident.**

According to Ref. 1, statistics is "the science of collecting, analyzing, and interpreting numerical data relating to an aggregate of individuals." The data on the properties of interest can be collected from the population or from a sample drawn from the population. Statistical properties of interest in the civilian world include 1) the attitudes of U. S. voters regarding certain laws or politicians, 2) the effectiveness of a particular drug for curing bone cancer, 3) the correlation between cigarette smoking and lung cancer, and 4) the number of lives saved by automobile air bags.

Items of statistical interest in survivability include 1) the loss rates of past conflicts; 2) the number of combat sorties flown in Desert Storm; 3) the number of Desert Storm aircraft that were hit; 4) the number that were hit on the lower surface; 5) the V_{50} ballistic limit of an aluminum alloy 2024-T3 plate; and 6) the cost and effectiveness associated with the survivability enhancement features on a particular type of modern aircraft, such as the cost and effectiveness of the onboard electronic attack equipment and of the fuel system protection features on a particular U. S. fighter aircraft. In these examples the numerical data are related to the occurrence of a particular event, such as an aircraft is hit, or to the magnitude of a parameter, such as the V_{50}.

Processes over time, such as the machining of a particular aircraft part or an encounter between an aircraft and an antiaircraft weapon, also have statistical properties of interest, such as 1) the time required to complete the machining task, 2) the magnitude of the radar echo from an aircraft over a time interval, 3) the minimum time required for a SAM system to launch a missile after detecting an aircraft, and 4) the thrust of the booster motor on the missile as a function of time.

If statistics is the method of determining what is true of the sample and what is estimated to be true of the population, then probability theory could be described as the method of determining what might happen in the future. To determine the probability of a particular outcome occurring in a future scenario, such as an aircraft hit or kill in a future encounter, numerical data on the properties or parameters of interest are collected from samples, and inferences are made regarding these parameters for the population using inferential statistical methods (Note 1). These statistical parameters, such as the mean, variance or standard deviation, and probability distribution, are then used in probability theory to predict the likelihood, frequency of occurrence, or probability that certain outcomes of interest would occur in the population in the future—the what might happen.

For example, suppose data on the number of USAF fixed-wing aircraft killed and the number of combat sorties flown in North Vietnam were collected from a few operational units for the period from 1 January 1965 to 31 December 1967. Further, suppose the statistic 'the number of aircraft killed per sortie,' that is, the combat loss rate, was computed using these data. Suppose a loss rate for all of the USAF operational units in Southeast Asia during this same period is inferred from the loss rate for the sampled units. This is statistics.

Now, suppose this 1965–1967 loss rate is then used in December of 1990 to predict the expected number of aircraft that would be killed in 100,000 combat sorties in 1991 in Operation Desert Storm. This is probability theory. The value of the prediction is inherently related to the relavance of the statistical parameters to the future scenario. If valid statistical data are not available to make the predictions, then the numerical values for the statistical parameters must be estimated.

Go to Problems B.1.1 to B.1.2.

B.1.2 Outcomes, Parameters, Variables, and Probability Functions and Distributions

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Learning Objective B.1.2 **Describe the terms outcome, deterministic, random, parameter, variable, independent, dependent, discrete random variable, continuous random variable, probability mass function, and probability density function, and relate these terms to a combat operation, action, or incident.**

All combat operations, actions, and incidents have one or more possible observables, results, or outcomes. Some of the possible outcomes associated with an encounter between an aircraft and a radar-directed gun are as follows: 1) the aircraft is detected or not detected by the radar, 2) the gun is fired or is not fired at the aircraft, 3) the projectile travels more than 1 km, 4) the aircraft is hit or not hit by the projectile, and 5) the aircraft is killed or not killed by the projectile hit. In general, outcomes are either deterministic or random. Deterministic outcomes can be predicted with certainty. If a voltage of V volts is applied to a wire with an electrical resistance of R ohms, then a current of V/R amps is predicted to flow in the wire. If a force F in newtons is applied to a ballistic projectile of mass M in kilograms, the projectile is predicted to accelerate in a vacuum with an acceleration F/M m/s^2. Experiments conducted on the wire and the projectile reveal that these predictions are accurate, and the experimental results are repeatable.

On the other hand, fire a ballistic projectile from a gun toward an approaching aircraft and the projectile might or might not hit the aircraft; the outcome is uncertain. Any outcome that cannot be predicted with certainty is referred to as a random outcome. A roll of a fair die might or might not result in a six; a fuel tank might or might not explode when hit by a ballistic projectile; and 10 air defense guns defending an area against a 20 plane strike might kill zero aircraft, or perhaps one aircraft, or perhaps all 20 aircraft.

B.1.2.1 Deterministic outcomes. Outcomes are deterministic when the physical laws and the associated parameters and variables of the incident are deterministic. In incidents with deterministic outcomes, all parameters are known quantities. Examples of parameters involved in a gun-firing incident are the muzzle velocity of the ballistic projectile V_0, the elevation angle of the gun when fired θ, and the gravitational force on the projectile g (Note 2). A variable is a quantity that can change during the incident. Variables associated with deterministic incidents are referred to as independent or dependent. Time t and the three space coordinates or axes x, y, z are typical independent variables in an encounter between an aircraft and an air defense gun. Dependent variables are functions of independent variables. An example of a dependent variable is h, the height of a ballistic projectile fired from a gun, which is a function of the independent variable time t, that is, $h = f(t)$. If gravity is the only force on the projectile after it leaves the gun barrel,

$$h = f(t) = (V_0 \sin\theta)t - 0.5gt^2 \tag{B.1}$$

Thus, the height of the projectile above the gun h (a dependent variable) can be predicted as a function f of time t (the independent variable) V_0, θ, and g (the deterministic parameters). Figure B.1a shows the deterministic outcome h as a function of t for specific values of θ and V_0.

B.1.2.2 Random outcomes. Outcomes are random when the nature of the incident is random or the incident involves parameters and variables with uncertain values, for example, parameters and variables that do not always occur at the same time or location or have the same value or function in every incident. These nondeterministic outcomes, parameters, and variables are referred to as random variables or variates.[1] There are several random variables involved in the gun-firing

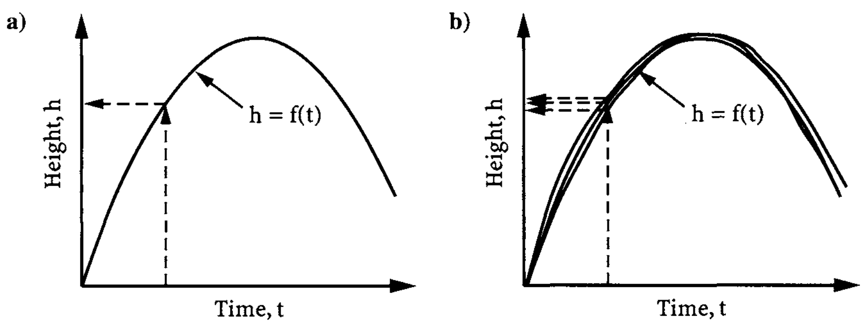

Fig. B.1 Height of a ballistic projectile vs time: a) a deterministic variable and b) a random variable.

incident just described that were either treated as deterministic or neglected. For example, the muzzle velocity of the projectile can change from shot to shot. If it is not precisely known prior to firing, it is a random variable. Likewise, the elevation angle of the gun can be a random variable. In the deterministic treatment of the gun-firing incident, wind forces on the projectile were neglected. However, fire a projectile on a windy day, and the projectile's vertical position will deviate from the value predicted based upon no wind. If the magnitude of V_0, θ, and any wind forces are uncertain or random, the height of the projectile cannot be predicted with certainty, and the outcome h (at any particular time) is a random variable. Figure B.1b shows the random projectile trajectories from three gun shots (Note 3).

Most of the parameters and variables of combat are random; consequently, most of the outcomes are random. The exact moment a gunner decides to fire at an aircraft is a random variable, and the occurrence of an explosion in an aircraft's fuel tank as a result of a hit by an armor-piercing incendiary (AP-I) round is a random outcome because it depends upon the location of the hit, the amount and location of any sloshing fuel in the tank, the temperature in the tank, the oxygen concentration in the ullage, and the functioning and location of the incendiary material, all of which are random variables. The number of aircraft killed by 10 guns during a 20 plane strike also is a random variable.

B.1.2.3 Probability functions and distributions. Any specific outcome of a random variable can be related to a relative frequency of occurrence, or likelihood, or probability that the outcome will occur by a probability function (an equation) or probability distribution (a graph) (Note 4). Random variables have outcomes that are either discrete or continuous. Discrete random variables have discrete outcomes. The number of aircraft killed in 10 one-on-one encounters during a 20 plane strike is a discrete random variable because only a nonnegative integer number of aircraft (0, 1, 2, ... 10) can be killed. A discrete probability function or probability mass function (PMF) relates each discrete outcome to a probability. Examples of a probability mass function are the binomial and Poisson PMFs. Figure B.1c is an example of a discrete probability distribution obtained from the binomial PMF. This distribution is based upon the assumption that the probability an aircraft is killed in a one-on-one encounter with a threat weapon, the encounter P_K, is 0.3. Associated with each possible outcome (0 aircraft killed, 1 aircraft killed, 2 aircraft killed, ... 10 aircraft killed) is a probability that the outcome will occur. For example, according to Fig. B.1c, the probability that two aircraft are killed in the 10 encounters is 0.234.

Continuous random variables have outcomes that are not discrete. The muzzle velocity and the height of the projectile 3 s after firing are continuous random variables because they can have any real value within some interval. For example, the muzzle velocity can range from 2500 to 2700 fps, and the projectile height can range from 2000 to 3000 ft at $t = 3$ s, as shown in Fig. B.1b. A probability density function (PDF) is used to relate the outcome of interest to the probability that outcome occurs. Examples of a probability density function are the uniform, the normal or Gaussian, and the Weibull. Figure B.1d is an example of the normal probability distribution for the height of a projectile at a particular time. The outcomes of interest for continuous random variables are associated with random variable intervals. For example, suppose the outcome of interest is a projectile

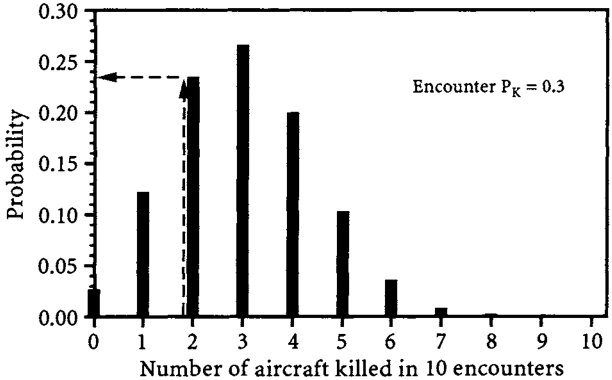

Fig. B.1c Probability mass function for the number of aircraft killed (a discrete random variable).

height between 2550 and 2575 fps at $t = 3$ s. The probability that the projectile will be located within that height interval is equal to the area under the probability density distribution, as shown in Fig. B.1d.

Incidents that contain random parameters and variables require the application of probability theory to determine the specific probabilities associated with the parameters and variables. Because most outcomes of combat are random, the determination of the relative frequency of occurrence or likelihood or probability that any particular outcome will occur in combat is essential in survivability assessment.

Go to Problems B.1.3 to B.1.12.

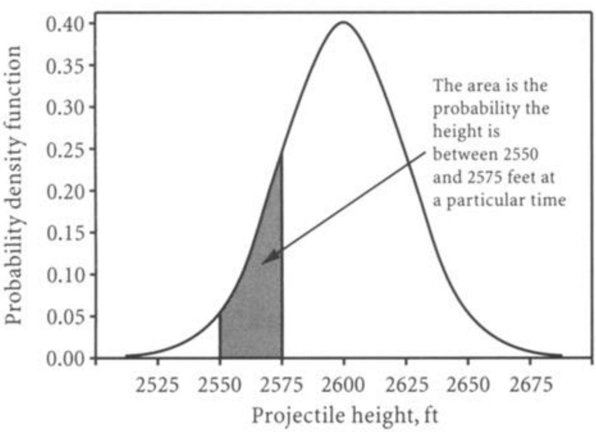

Fig. B.1d Probability density function for the projectile height at a given time (a continuous random variable).

B.1.3 Processes, Experiments, Events, and Event Probabilities

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Learning Objective	**B.1.3**	**Describe the terms process, stochastic, experiment, trial, event, probability, exhaustive, and mutually exclusive, and relate these terms to a combat operation, action, or incident.**

In probability theory any combat operation, action, or incident that consists of a timewise sequence or combination of interrelated actions involving one or more parameters and variables associated with a system is referred to as a process. If the system contains one or more random variables, the process is a random or stochastic process. An example of a stochastic process is the sequence of actions in an encounter between a weapon and an aircraft, such as aircraft detection, missile launch, and aircraft hit and kill. Another stochastic process is the 10 weapon vs 20 aircraft strike scenario.

A process typically has two or more outcomes of interest, and an event is the occurrence of one or more of the process outcomes. For example, one event in air defense is the detection of a hostile aircraft (an outcome) and the subsequent launch of a missile at the aircraft (another outcome). Another event is the detonation of the proximity-fuzed high-explosive (HE) warhead on the missile and the subsequent kill of the aircraft.

An experiment in probability theory is the observation of a process, noting the outcomes, and each repetition of the experiment is a trial.

Consider the stochastic process consisting of one or more sequential rolls of a fair die. In an experiment consisting of one roll of the die, there are six possible outcomes of the roll: a 1, 2, 3, 4, 5, and 6. One event for this process is one particular outcome of the roll, for example, a 2. Another event is the roll of a 2 or a 6. The six possible outcomes of this experiment are said to be exhaustive, that is, there are no other possible outcomes of the roll. The six outcomes are also said to be mutually exclusive, that is, only one of the six possible outcomes can occur on any one roll.

A similar process in combat is the encounter between one aircraft and one weapon in a particular scenario (Note 5). Two possible discrete outcomes of this one-on-one encounter are 1) the weapon kills the aircraft, based upon the specific definition of kill used, such as attrition or mission abort, and 2) the aircraft survives the encounter. These two outcomes are exhaustive, that is, there are no other possible outcomes that are not included in either of these two outcomes (Note 6). They also are mutually exclusive, that is, the aircraft cannot be killed in the encounter and also survive the encounter. These two outcomes are random outcomes because they depend upon many random parameters and variables. Of interest is their frequency of occurrence in the scenario. If the frequency of occurrence can be determined for each outcome, this number, which lies between zero and one, can be used as an estimate of the probability that the same outcome will occur in future scenarios.

There are three general procedures used to determine the frequency of occurrence, and hence the probability, of a particular event A: classical theory, intuition, and experimentation. In classical probability theory the probability is deduced from logical considerations. For example, in the fair die experiment just described a priori logic leads to the conclusion that the probability that any particular number on the die A will be face up after the roll is $\frac{1}{6}$. The equation for this probability, denoted by $P(A)$ or P_A, is

$$P(A) = \frac{\text{number of possible outcomes of } A \text{ on one roll} = 1}{\text{number of possible outcomes on one roll} = 6} \tag{B.2}$$

This value for the probability can deduced without conducting any experiments. Because the die is fair, there is no physical reason to expect any one number to be more likely to occur than any other number; hence, all six outcomes are said to be equally likely to occur (Note 7).

The situation is much more difficult in the one-on-one combat experiment. The outcomes of kill and survival in an encounter cannot be deduced from logical considerations, and any estimate for the probability based upon intuition might be suspect. Consequently, experimentation is (or should be) used to determine the event probabilities. The combat experiment should be conducted many times to determine an accurate estimate of the probability of each outcome (Note 8). On each trial the occurrence of the outcomes of interest are noted. Thus, if event A occurred M times in N trials the probability that event A will occur in a future experiment is estimated using

$$P(A) = \frac{\text{number of trials in which } A \text{ occurred} = M}{\text{number of trials} = N} \tag{B.3}$$

The assumptions are made in probability theory that the probability $P(A)$ has a true value for a specific process and that $P(A)$ will approach its true value as the number of trials increases.[2,3]

The experiment required to determine $P(A)$ can be conducted using real aircraft and weapons in a realistic scenario, or it can be conducted using a mathematical or engineering model to simulate the scenario, or some combination of reality and simulation can be used. After each trial, real or simulated, the results can be examined to determine the results for the outcomes of interest. For example, after a one-on-one encounter the aircraft can be examined to determine which of the two mutually exclusive outcomes or kill or survival took place: either the aircraft was killed by the weapon, based upon the definition of kill used, or it survived. This process is repeated for N encounters or trials (using a new, identical aircraft on each trial). In the N encounters the aircraft was killed M times, where $0 \leq M \leq N$. An estimate of the probability that the aircraft will be killed in a future encounter P_K is determined using Eq. (B.3). The probability of survival P_S also can be estimated using Eq. (B.3), or, because survival and kill are mutually exclusive and exhaustive outcomes it can be determined using $P_S = 1 - P_K$.

Example B.1 Experiment Consisting of 10 One-on-One Encounters

Assume that 10 strike aircraft went on a mission to an area defended by several radar-directed AAA sites. Assume that all 10 aircraft had a one-on-one encounter

Table B.1 Ten one-on-one encounter outcomes

Encounter	1	2	3	4	5	6	7	8	9	10	Total
A/C killed	—	—	—	x	—	—	—	—	x	x	3
A/C survived	x	x[a]	x	—	x[a]	x	x	x	—	—	7
Target killed	x	—	—	—	x	—	x	x	—	—	7

[a] A/C damaged.

with a gun and that each encounter had the same scenario. The gun's projectiles contained an HE warhead with a contact fuze. Thus, the projectile must hit the aircraft in order to kill it. Two exhaustive and mutually exclusive outcomes of interest for each encounter are the aircraft was killed and the aircraft survived, that is, was not killed. Another possible outcome is a projectile hit and damaged the aircraft but did not kill it. An outcome of interest to the friendly forces is the number of targets killed by the aircraft. The observed outcomes of the 10 encounters are tabulated in Table B.1. An x in the appropriate location in Table B.1 indicates an aircraft kill or survival for the encounter. The additional outcomes of a damaged but surviving aircraft and a kill of the target by the aircraft also are noted. The outcomes of the individual encounters are illustrated in Fig. B.2, where the abscissa consists of the 10 discrete encounters and the ordinate is the outcome. Because the two outcomes of kill and survival are exhaustive, their sum must be 10. The ratio $^3/_{10}$ is the relative frequency of an aircraft kill, the ratio $^7/_{10}$ is the relative frequency of aircraft survival, and the sum of the two ratios is unity. Thus, P_K and P_S, are estimated to be 0.3 and 0.7, respectively, based upon these 10 encounters. The probability the outcome of aircraft hit will occur P_H is estimated to be $^5/_{10}$. The probability that an aircraft will kill a target is $^4/_{10}$.

Go to Problems B.1.13 to B.1.24.

B.1.4 Summary

Table B.2 contains the definitions of the major terms used in probability theory and examples of their application to survivability assessment.

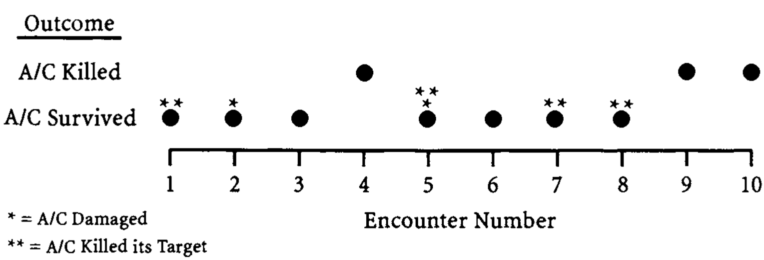


Fig. B.2 Outcomes for 10 one-on-one encounters.

Table B.2 Definitions and examples of some probability terms

Term	Definition	Example
Continuous variable	Any variable that can have any value on the real number axis	Height of the projectile above the gun at a particular time
Deterministic outcome	Result that can be predicted with certainty	Trajectory of the projectile in a vacuum when the muzzle velocity and gun elevation angle are known
Deterministic parameter	Known quantity	Acceleration of the projectile caused by the force of gravity is 32.2 ft/s^2.
Deterministic variable	Quantity that changes in a predictable manner during the experiment	Height of the projectile above the gun as a function of the independent variable time
Discrete variable	Any variable with discrete outcomes	Number of aircraft killed by a gun in 10 encounters
Event	Combination of one or more outcomes	One event is the combination of a hit on the aircraft by the projectile (an outcome) and the subsequent kill of the aircraft as a result of the hit (another outcome).
Exhaustive outcomes	Collection of all outcomes of a process	Kill of the aircraft and the survival of the aircraft
Experiment	Observation of a process	Results of the gun-firing incident are observed.
Mutually exclusive outcomes	Outcomes that cannot occur together	Projectile hits the aircraft, and the projectile misses the aircraft.
Outcome	Result observed in an experiment	Trajectory of the projectile is determined, and the survival or kill of the aircraft is noted.
Probability	Relative frequency of occurrence of an outcome	Gun has a probability of 0.3 of killing the aircraft when it fires.
Probability density function	Function for the probability that a continuous random variable lies within specific limits	Normal PDF is used to determine that the probability of the absolute value of the miss distance of a projectile is less than a certain value.
Probability mass function	Function for the probability that a discrete random outcome occurs	Binomial PMF is used to determine the probability five aircraft are killed in a strike.
Process	Time-wise sequence or combination of interrelated actions involving one or more parameters and variables associated with a system	Antiaircraft gun fires a ballistic projectile at an aircraft.

Table B.2 Definitions and examples of some probability terms (continued)

Term	Definition	Example
Random outcome	Result that cannot be predicted with certainty	Survival of the aircraft when fired upon
Random or stochastic process	Process whose outcomes cannot be predicted with certainty	Kill of the aircraft by the projectile cannot be predicted with certainty.
Random variable	Any parameter or variable that cannot be predicted with certainty	Velocity of the projectile at impact.
Trial	One repetition of an experiment	Gun fires three projectiles at the aircraft; each firing is a trial.

B.2 Sets and the Venn Diagram

Learning Objectives	**B.2.1**	**Describe the terms set, element, universal set, sample space, and the Venn diagram, and relate these terms to a combat operation, action, or incident.**
	B.2.2	**Given the outcomes from an experiment, construct the universal set, the sample space, subsets of the universal set, and develop the Venn diagram.**

B.2.1 Sets and the Sample Space

A fundamental concept used in probability theory is the set. A set is a collection of elements or members that have some property in common. The property in common in survivability could be the event that the aircraft survived, or it was killed, or it was hit and survived an encounter with a threat weapon. The 10 encounters given in Table B.1 have the common property that they are elements of a 10 trial experiment, and because there are no elements in the experiment other than these 10 they form the set U, known as the universal set. The universal set of encounters can be written in the form

$$U = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\} \tag{B.4}$$

where each element of the set represents a particular encounter whose outcomes are given in Table B.1.

The universal set of 10 encounters, with the associated outcomes observed in each encounter, form the sample space or event space of the experiment. Each encounter, with its outcomes, is a sample point in the sample space. The sample space for the 10 aircraft-threat weapon encounter experiment is illustrated in Fig. B.3. The encounter outcomes of a projectile hit on the aircraft H, the aircraft is killed in the encounter K, the aircraft survives the encounter S, and the aircraft kills its target T are listed in the sample space for each of the 10 encounters using the information given in Table B.1. Each encounter in Fig. B.3 is given the same

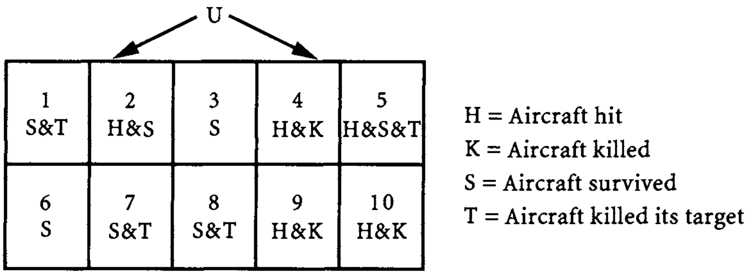


Fig. B.3 Sample space of 10 encounters.

area in the sample space because each encounter is an identical trial or uniform representation of the experiment. Thus, if a random selection of an encounter is made from Fig. B.3 each encounter is equally likely to be selected. This particular type of sample space is known as a finite, equiprobable, or uniform sample space (Note 9).

Any particular outcome or combination of outcomes in the sample space is a subset of the universal set, and each subset is an event. For example, the three encounters with kill outcomes $\{4, 9, 10\}$ can be grouped together to form a set of encounters with kill outcomes K. Similarly, the seven encounters with survival outcomes $\{1, 2, 3, 5, 6, 7, 8\}$ can be grouped together to form the set S. The set H consists of those encounters where the aircraft was hit by the projectile $\{2, 4, 5, 9, 10\}$, and the target killed set T consists of encounters $\{1, 5, 7, 8\}$. Additional sets can be defined using combinations of the four outcomes of kill, hit, survive, and target kill. For example, the members of the set for the event consisting of hit and survive are $\{2, 5\}$.

Each encounter with a kill outcome is an element or member of the set K. This is written as

$$k_i \in K, \qquad i = 1, 2, 3$$

where k_i is the ith element in K. Thus, k_1 is encounter 4, k_2 is encounter 9, and k_3 is encounter 10. The set K is a subset of H because every element of K also belongs to H. Set K is said to be contained in set H. This is expressed in the form

$$K \subset H \quad \text{or} \quad H \supset K$$

Two sets that are subsets of each other are equal. All sets are subsets of the universal set, and a set that contains no elements is the null set Φ, which is a subset of all sets.

Go to Problems B.2.1 to B.2.3.

B.2.2 Venn Diagram

The sample space of the 10 encounter experiment shown in Fig. B.3 contains the four outcomes or events represented by the sets K, H, S, and T. This space and these events can be represented in a different geometrical arrangement by grouping the encounters with the same events together. This diagram is known as the Venn

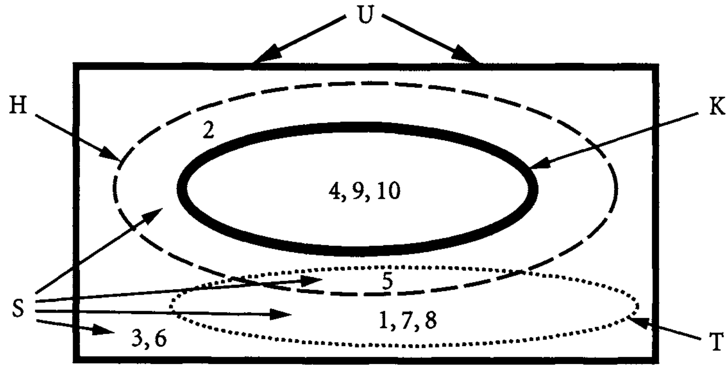


Fig. B.4 Venn diagram for the 10-encounter example.

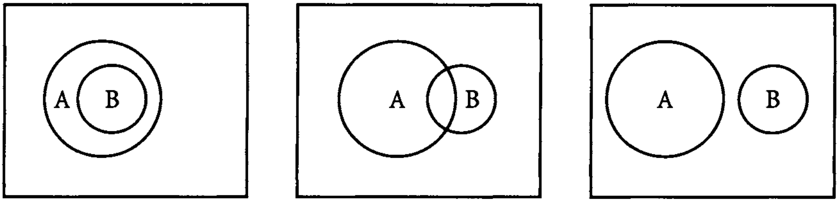
diagram and is shown in Fig. B.4 for the 10 encounter experiment. The area within the rectangular boundary represents the universal set U. The ellipse labeled K contains the three kill outcomes $\{4, 9, 10\}$ and encloses an area that is 30% of the area of the universal set because it contains 3 of the 10 encounters. The entire area outside of K, labeled S, contains the seven survival (or not kill) outcomes $\{1, 2, 3, 5, 6, 7, 8\}$ and is 70% of the area of U. The ellipse labeled H contains the five encounters where the aircraft was hit $\{2, 4, 5, 9, 10\}$ and is 50% of the area of U. The ellipse labeled T contains the four encounters $\{1, 5, 7, 8\}$ where the target was killed and is 40% of the area of U. The Venn diagram shown in Fig. B.4 has the same information content as Fig. B.3, and a random selection of an encounter from Fig. B.4 is equally likely to obtain any one of the 10 encounters. Other events are also represented in the Venn diagram by a particular area. For example, the event consisting of an aircraft hit $\{2, 4, 5, 9, 10\}$ and survival $\{1, 2, 3, 5, 6, 7, 8\}$ and target kill $\{1, 5, 7, 8\}$ is the area associated with encounter 5 because it is the only encounter common to these three outcomes. Similarly, the event of aircraft survival and aircraft not hit and no target kill is the area associated with encounters 3 and 6. Consequently, an examination of the Venn diagram in Fig. B.4 reveals that it can be considered as an exhaustive set of mutually exclusive events represented by the encounters $\{3, 6\}$, $\{2\}$, $\{5\}$, $\{1, 7, 8\}$, and $\{4, 9, 10\}$.

Go to Problems B.2.4 to B.2.7.

B.3 Set Operations

Learning Objective	**B.3.1**	**Perform the intersection, union, exclusive union, complement, difference, and product operations on sets.**

There are five major operations that are performed on sets: the intersection of sets, the union of sets, the complement of sets, the difference of sets, and the product of sets. These operations are described for sets A and B using the three different Venn diagrams shown in Fig. B.5.



(a) B is contained in A

(b) A and B intersect

(c) A and B are mutually exclusive

Fig. B.5 Venn diagrams for two sets A and B.

B.3.1 Intersection of Sets

Consider the two sets A and B shown in Figs. B.5. The intersection of the two sets, written as

$$A \cap B \quad \text{or} \quad A \text{ AND } B \tag{B.5}$$

where AND is a logical variable, is the set of those elements in A and B that are common to both A and B.

In Fig. B.5a, B is a subset of A, and the intersection of the two sets is the area of overlap of the two sets, which is the set B. In Fig. B.4 the intersection of the set of aircraft kills $K\{4, 9, 10\}$ and the set of aircraft hits $H\{2, 4, 5, 9, 10\}$ consists of the set of kills K because K is a subset of H. Also, T AND S is T because T is a subset of S.

A more general intersection is illustrated in Fig. B.5b, where the sets A and B have some, but not all, elements in common. The common elements are contained in the overlap or intersection of the two sets. In Fig. B.4 the intersection of $H\{2, 4, 5, 9, 10\}$ and $T\{1, 5, 7, 8\}$ is $\{5\}$.

Finally, consider the two mutually exclusive sets A and B shown in Fig. B.5c and K AND S and K AND T in Fig. B.4. In mutually exclusive sets there are no elements common to both sets. Thus, their areas in the Venn diagram do not overlap. Sets with no common elements are disjoint sets, and their intersection is the null set Φ, referred to as the impossible event.

B.3.2 Union of Sets

Another important set operation is the union of sets. The union of sets A and B, written as

$$A \cup B \quad \text{or} \quad A \text{ OR } B \tag{B.6}$$

where OR is a logical variable, is the set that contains those elements in A and B that are in A only, or B only, or both A and B. Those elements that are in both A and B are given by the intersection of A and B.

In Fig. B.5a the union of A and B is represented by the area covered by the two sets, which is the area A because $A \supset B$. In Fig. B.4 the union of sets $H\{2, 4, 5, 9, 10\}$ and $K\{4, 9, 10\}$ is the set H because K is a subset of H, and S OR T is S because T is a subset of S.

In Fig. B.5b the union of A and B is the area covered by the two sets, which is less than the area of the two sets individually. In Fig. B.4 the union of H $\{2, 4, 5, 9, 10\}$ and T $\{1, 5, 7, 8\}$ is $\{1, 2, 4, 5, 7, 8, 9, 10\}$, which represents the event of aircraft hit or target killed.

A variation of the OR logical variable is XOR, the exclusive union. The exclusive union of the sets A and B is the set of elements that belong to A only or to B only, but are not common to both A and B. Thus, in Fig. B.4 the exclusive union of sets S $\{1, 2, 3, 5, 6, 7, 8\}$ and H $\{2, 4, 5, 9, 10\}$ is the set containing $\{1, 3, 4, 6, 7, 8, 9, 10\}$, which represents the event of aircraft survival or aircraft hit and killed.

In the mutually exclusive case, illustrated in Fig. B.5c, the union of A and B is the sum of the individual areas of A and B. Thus, in Fig. B.4 the union of the mutually exclusive sets K and S forms the universal set U because the sets K and S contain the two exhaustive sets of outcomes in the experiment. Also, K OR T is $\{1, 4, 5, 7, 8, 9, 10\}$.

The union of the exhaustive set of events is referred to as the certain event.

B.3.3 Complement of a Set

The complement of a set A, written as

$$A^c \quad \text{or} \quad \text{NOT } A \tag{B.7}$$

is the set of elements in the universal set that do not belong to A. In Fig. B.5a, A^c is represented by the white area surrounding A. In Figs. B.5b and B.5c, NOT (A OR B) is the white area surrounding the two sets. In Fig. B.4 the complement of S is K because the union of S and K is U, and those aircraft not hit, NOT H, is $\{1, 3, 6, 7, 8\}$.

B.3.4 Difference of Sets

The difference of set A and set B, written as

$$A \backslash B \quad \text{or} \quad A \text{ AND (NOT } B) \tag{B.8}$$

is the set of elements that belong to A and not to B. In Figs. B.5a and B.5b, $A \backslash B$ is the area in A that is outside of B. In the mutually exclusive situation $A \backslash B$ is A. In Fig. B.4 the difference of H $\{2, 4, 5, 9, 10\}$ and K $\{4, 9, 10\}$ is the set $\{2, 5\}$, the aircraft that were not killed by the hit. Also, $T \backslash H$ is $\{1, 7, 8\}$.

B.3.5 Product of Sets

The product of sets A and B, written as

$$A \times B$$

is equal to a set whose elements are all possible ordered pairs of the elements in A and B. Thus,

$$A \times B = \{(a, b) \text{ where } a \in A \text{ and } b \in B\}$$

For example, if A consists of two members, $a1$ and $a2$, and B consists of three members, $b1$, $b2$, and $b3$, then $A \times B$ is given by

$$\{(a1, b1), (a1, b2), (a1, b3), (a2, b1), (a2, b2), (a2, b3)\}$$

Table B.3 Laws of the algebra of sets[2]

Idempotent laws	$A \cup A = A$, $A \cap A = A$
Associative laws	$(A \cup B) \cup C = A \cup (B \cup C)$, $(A \cap B) \cap C = A \cap (B \cap C)$
Commutative laws	$A \cup B = B \cup A$, $A \cap B = B \cap A$
Distributive laws	$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$, $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$
Identity laws	$A \cup \Phi = A$, $A \cup U = U$, $A \cap U = A$, $A \cap \Phi = \Phi$
Complement laws	$A \cup A^c = U$, $(A^c)^c = A$, $A \cap A^c = \Phi$, $U^c = \Phi$, $\Phi^c = U$
DeMorgan's laws	$(A \cup B)^c = A^c \cap B^c$, $(A \cap B)^c = A^c \cup B^c$

B.3.6 Algebra of Sets

The general laws of the algebra of sets are given in Table B.3 (Ref. 2).

Go to Problems B.3.1 to B.3.5.

B.4 Event Probabilities

Learning Objectives	**B.4.1**	**Determine event probabilities, joint probabilities, and conditional probabilities.**
	B.4.2	**Construct the Venn probability diagram for independent, conditional, and mutually exclusive events for any combat operation, action, or incident.**

B.4.1 Probabilities

The preceding section described the major operations that can be performed on sets or events. Associated with each set operation is a probability. In the equiprobable sample space the probability of occurrence of any event A, denoted by $P(A)$ or P_A, is given by

$$P(A) = P_A = \frac{\text{number of elements in } A}{\text{number of elements in } U} \tag{B.9}$$

according to Eq. (B.3).

The probability associated with the event formed by the intersection of any two or more events is referred to as the joint probability of the events. The joint probability for the two events A and B is given by

$$P(A \text{ AND } B) = P_{A \text{ AND } B} = \frac{\text{number of elements in intersection of } A \text{ and } B}{\text{number of elements in } U} \tag{B.10}$$

The probability associated with the union of events A and B is

$$\begin{aligned} P(A \text{ OR } B) &= P_{A \text{ OR } B} \\ &= \frac{\text{elements in } A}{\text{elements in } U} + \frac{\text{elements in } B}{\text{elements in } U} - \frac{\text{elements in intersection of } A \text{ and } B}{\text{elements in } U} \\ &= P(A) + P(B) - P(A \text{ AND } B) = P_A + P_B - P_{A \text{ AND } B} \end{aligned} \tag{B.11}$$

where P_A and P_B are given by Eq. (B.9) and $P_{A \text{ AND } B}$ is given by Eq. (B.10). Subtracting $P_{A \text{ AND } B}$ from the sum of P_A and P_B prevents those elements in both A and B from being counted twice, as illustrated in Figs. B.5a and B.5b.

The probability associated with the exclusive union of A and B is

$$\begin{aligned} P(A \text{ XOR } B) &= P_{A \text{ XOR } B} = P(A) + P(B) - 2P(A \text{ AND } B) \\ &= P_A + P_B - 2P_{A \text{ AND } B} \end{aligned} \tag{B.12}$$

where P_A and P_B are given by Eq. (B.9) and $P_{A \text{ AND } B}$ is given by Eq. (B.10). Note that the elements in the intersection are removed twice.

The probability associated with the complement of event A is given by

$$P(A^c) = P(\text{NOT } A) = P_A^c = P_{\text{NOT } A} = 1 - P(A) = 1 - P_A \tag{B.13}$$

where P_A is given by Eq. (B.9).

The probability associated with the difference of A and B is

$$P(A \backslash B) = P[A \text{ AND } (\text{NOT } B)] = P_A - P_{A \text{ AND } B} \tag{B.14}$$

where P_A is given by Eq. (B.9) and $P_{A \text{ AND } B}$ is given by Eq. (B.10)

Example B.2 Event Probabilities for the Experiment Consisting of 10 One-on-One Encounters.

The outcomes from the 10 encounters given in Table B.1 and illustrated in Figs. B.3 and B.4 can be used to estimate the probability that any particular event will occur in this encounter. For example, P_K is 3/10, and P_S is 7/10 according to Eq. (B.9) and Fig. B.4. The probability the aircraft will be hit in the encounter P_H, the measure of the aircraft's susceptibility, is 5/10. The probability the aircraft is hit and killed $P(H \text{ AND } K)$ is 3/10 according to Eq. (B.10). The probability the aircraft is killed and survives $P(K \text{ AND } S)$ is 0/10 because the sets are disjoint. The probability the aircraft is hit or killed $P_{H \text{ OR } K}$ is 5/10 according to Eq. (B.1). The probability the aircraft is killed or survives $P_{K \text{ OR } S}$ is $(3 + 7)/10$. Thus, the event K OR S is a certain event because it always happens. The probability the aircraft is not killed $P_{\text{NOT } K}$ is $1 - 3/10$ according to Eq. (B.13), which is the probability the aircraft survives. The probability the aircraft is hit and not killed $P[H \text{ AND } (\text{NOT } K)]$ is $(5 - 3)/10$ according to Eq. (B.14).

B.4.2 Independent and Dependent Events

Some events occur in an experiment with a probability that is not influenced by the occurrence of any other event in the experiment. These events are referred to as independent events. Examples of independent events are the outcomes from multiple rolls of a fair die or tosses of a fair coin. The probability that a 6 will occur on any particular roll is 1/6, regardless of the outcomes on any preceeding rolls; and the probability that a head will occur on any particular toss is 1/2, regardless of the outcomes on any preceeding tosses. These events and associated probabilities are independent (Note 10).

One example of an independent event in survivability is the situation where the outcomes associated with a hit on one part of an aircraft are uninfluenced by the outcomes associated with a hit on another part of the aircraft, and vice versa. Suppose the aircraft takes a hit in the nose, killing the radar antenna. Suppose a second hit occurs in the tail, killing a rudder hinge. If the likelihood of the kill of the rudder hinge on the second hit was uninfluenced by any of the outcomes of the first hit, the two events (the kill of the radar and the kill of the rudder hinge) are independent. For another example of independent events, consider the scenario where one aircraft encounters two weapons sequentially. If the probability the aircraft survives an encounter with the second weapon is uninfluenced by the outcomes associated with the first encounter, the two events (survival of the first encounter and survival of the second encounter) are independent.

On the other hand, some events have a probability of occurrence that is dependent or conditional upon the outcomes from another event. These events are referred to as dependent or conditional events, and they have conditional probabilities. The conditional probability $P_{A|B}$ is the probability that a particular event A occurs, given that another event B has occurred. In essence, the event B is analogous to a smaller universal set, that is, the sample space of interest consists of only those events that contain B (Note 11). A conditional probability in susceptibility is the probability that missile has been launched at an aircraft, given that the aircraft has been detected $P_{L|D}$. A conditional probability in vulnerability is $P_{K|H}$, the conditional probability that the aircraft is killed, given that it is hit. The condition might be simple, such as the aircraft hit is randomly located on the presented area of the aircraft, or it might be complex, such as defining a location where it was hit. Examining the independent situation just described where an aircraft was hit in the nose and the tail, if the two hits had been sufficiently close together, the outcomes of the first hit could have influenced the outcomes of the second hit. For example, the second hit is more likely to kill a particular component because of damage to the component caused by the first hit. If a second weapon encounters an aircraft that was damaged in a previous encounter, or if the aircraft descended to avoid the first weapon, the second weapon might be more likely to kill the aircraft because of the damage or descent. Hence, the outcomes of the second encounter are said to be dependent upon the outcomes of the first encounter.

B.4.3 Conditional Probability of an Event

The conditional probability that A occurs given that B occurs $P_{A|B}$ is determined using the relationship

$$P_{A|B} = \frac{\text{number of elements in } A \text{ AND } B}{\text{number of elements in } B} \tag{B.15a}$$

according to Eq. (B.10), where the universal set has been replaced with the set B. If both the numerator and the denominator in Eq. (B.15a) are divided by the number of elements in the universal set, Eq. (B.15a) can be given in the form

$$P_{A|B} = \frac{(\text{elements in } A \text{ AND } B)/(\text{elements in } U)}{(\text{elements in } B)/(\text{elements in } U)} = \frac{P_{A \text{ AND } B}}{P_B} \tag{B.15b}$$

according to Eqs. (B.9) and (B.10). If B is the set of aircraft hit and A is the set of aircraft killed, then $P_{K|H}$ is given by

$$P_{K|H} = \frac{P_{K \text{ AND } H}}{P_H} = \frac{P_{H \text{ AND } K}}{P_H} \tag{B.15c}$$

according to Eq. (B.15b) and the cummutative law for intersections.

Example B.3 Conditional Probabilities for the Experiment Consisting of 10 One-on-One Encounters

In the 10 encounter example given in Fig. B.4, $P(H \text{ AND } K)$ is 3/10, and P_H is 5/10. Thus, the conditional probability $P_{K|H}$ is 3/5. The probability that any of the 10 aircraft in the strike package will kill the target is 4/10. The conditional probability that the target is killed given the attacking aircraft survives is 4/7.

B.4.4 *Some Important Set Operations*

B.4.4.1 *Intersection of events.*

Two events. The probability associated with the intersection of events A and B, that is, the joint probability $P(A \text{ AND } B)$, is given by Eq. (B.10) in terms of the elements in A, B, and U. It also can be determined using Eq. (B.15b). Solving this equation for the joint probability of A and B results in (Note 12)

$$P_{(A \text{ AND } B)}\,(\text{dependent}) = P_B P_{A|B} = P_A P_{B|A} \tag{B.16}$$

When events A and B are independent,

$$P_{B|A} = P_B \quad \text{and} \quad P_{A|B} = P_A \tag{B.17a}$$

Substituting $P_{B|A}$ and $P_{A|B}$ given by Eq. (B.17a) into Eq. (B.16) gives

$$P_{(A \text{ AND } B)}\,(\text{independent}) = P_B P_A = P_A P_B \tag{B.17b}$$

Thus, the joint probability that two independent events will both occur is the product of the two individual event probabilities.

If the events are mutually exclusive, they are not independent, and there is no intersection. Hence,

$$P_{(A \text{ AND } B)}\,(\text{mutually exclusive}) = 0 \tag{B.18}$$

Example B.4 Joint Probability of Two Events A and B

Consider the experiment whose universal set U consisted of 100 trials, A occurred in 10 trials, and B occurred in 20 trials. Therefore, $P(A) =$

$10/100 = 0.1$ and $P(B) = 20/100 = 0.2$. If the two events are independent, then $P(A \text{ AND } B) = P(A)P(B) = 0.1 \cdot 0.2 = 0.02$, and consequently $0.02 \cdot 100 = 2$ of the trials in which A occurred also had the outcome B. Note that A occurred in U with the frequency 10/100 and occurred in B with the frequency 2/20. Thus, A occurs with the same frequency in the universal set (0.1) as it does when B occurs (0.1). Likewise, B occurred in U with the frequency 20/100 and occurred in A with the frequency 2/10. Thus, B occurs with the same frequency in the universal set as it does when A occurs (Note 13). This is independence between events; an event will occur with the same frequency whether or not another event occurs.

As an example of dependent events, suppose 5 of the 10 trials in which A occurred also had the outcome B. Because A occurred in 5 of the 20 trials in which B occurred whereas A occurred in only 10 of the 100 trials of the universal set, then A and B are not independent because $5/20 \neq 10/100$. Thus, A does not occur with the same frequency when B occurs as it does in U.

More than two events. The expression for the joint probability associated with the intersection of two events A and B given by Eq. (B.10) can be extended to the general case of the joint probability associated with the intersection of N events, A_1, A_2, A_N,

$$P(A_1 \text{ AND } A_2 \text{ AND} \cdots A_N) = P_{A_1} P_{A_2|A_1} P_{A_3|(A_1 \cap A_2)} \cdots P_{A_N|(A_1 \cap A_2 \cap \cdots \cap A_{N-1})} \tag{B.19a}$$

An example of this equation is given in Chapter 1, Eqs. (1.5a) and (1.5c). In Eq. (1.5c) the equation for the probability an aircraft was killed by a weapon while on a mission was given in the form

$$P_K = (P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I}) P_{K|H} = P_H P_{K|H} \tag{B.19b}$$

It was noted in Chapter 1 that the notation for the conditional probabilities used in this equation implied a condition on all preceding events.

For the situation when the N events are independent, Eq. (B.19a) becomes

$$P(A_1 \text{ AND } A_2 \cdots \text{AND } A_N) = P_{A_1} P_{A_2} \cdots P_{A_N} = \prod_{i=1}^{N} P_{Ai}; \tag{B.19c}$$

B.4.4.2 Union and exclusive union of events.

Two events. The probability associated with the union of events A and B, $P(A \text{ OR } B)$, is given by Eq. (B.11) in terms of the elements in A, B, and U. If the events are independent, the probability becomes

$$P_{(A \text{ OR } B)} = P_A + P_B - P_A P_B \tag{B.20}$$

according to Eqs. (B.11) and (B.17b).

The probability associated with the exclusive union of independent events A and B is given by

$$P(A \text{ XOR } B) = P_A + P_B - 2P_A P_B \tag{B.21}$$

according to Eqs. (B.12) and (B.17b).

If the two events A and B are mutually exclusive, the probability associated with both the union and the exclusive union of A and B becomes

$$P(A \,\mathrm{OR}\, B) = P(A \,\mathrm{XOR}\, B) = P_A + P_B \tag{B.22}$$

according to Eqs. (B.12) and (B.18).

More than two events. The probability associated with the union of two independent events can be extended to the union of three independent events A, B, and C using the associative law. Thus,

$$\begin{aligned} P(A \,\mathrm{OR}\, B \,\mathrm{OR}\, C) &= P[(A \,\mathrm{OR}\, B) \,\mathrm{OR}\, C] = P[A \,\mathrm{OR}\, (B \,\mathrm{OR}\, C)] \\ &= (P_A + P_B - P_A P_B) + P_C - (P_A + P_B - P_A P_B) P_C \\ &= P_A + P_B + P_C - P_A P_B - P_A P_C - P_B P_C + P_A P_B P_C \end{aligned} \tag{B.23}$$

Similar expressions can be developed for higher-order combinations.

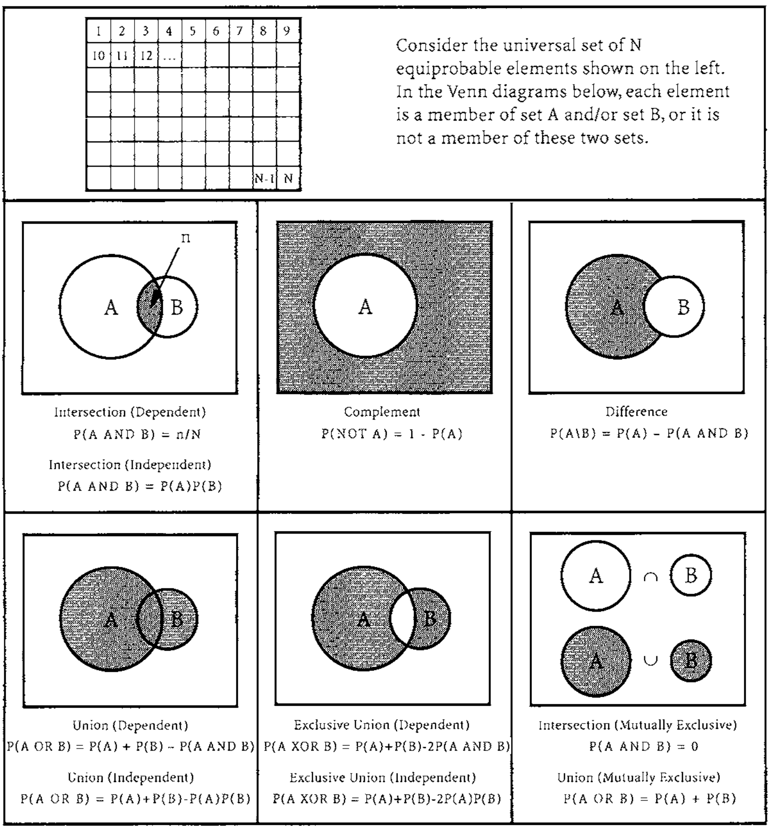


Fig. B.6 Venn diagram and probability equations.

B.4.5 Summary

The Venn diagrams and the corresponding probability equations for combinations of events A and B are summarized in Fig. B.6.

Go to Problems B.4.1 to B.4.5.

B.5 Tree Diagrams

B.5.1 The Experiment

Learning Objective	**B.5.1**	**Describe the experiment for any combat operation, action, or incident.**

The experiment given in Table B.1 consists of 10 separate encounters between one aircraft and one weapon in a particular scenario. The outcomes of aircraft kill and no kill from this experiment were used to determine the encounter probabilities P_K and P_S for the one-on-one scenario. These probabilities for the one-on-one encounter can be used to determine the probabilities of one or more aircraft kills when the air defense consists of more than one weapon.

For example, suppose 20 aircraft are on a strike mission to an area defended by 10 weapons. Assume that the 10 weapons encounter and engage 10 of the 20 aircraft in a one-on-one scenario. No aircraft is engaged more than once, and 10 aircraft are not engaged. In this multiple one-on-one encounter situation, the experiment consists of the total number of one-on-one encounters, 10, and each encounter is a trial. The mutually exclusive outcomes of interest from each trial are aircraft kill and aircraft survival, with encounter outcome probabilities P_K and P_S, respectively. The values for P_K and P_S can be different for the different encounters. The sequence or combination of 10 trials can be treated as a stochastic process when the system is defined to be comprised of the 10 encountered and engaged aircraft. The outcomes of the 10 trials that are of interest are the probabilities that none of the 10 aircraft are killed, that one aircraft is killed, that two aircraft are killed, ... and that all 10 aircraft are killed by the 10 weapons in the 10 encounters.

The number of aircraft killed in the 10 encounters is a discrete random variable because there is a probability associated with the specific numbers of aircraft killed (0, 1, 2, ... 10) in the experiment. The set of probabilities associated with the 11 discrete numbers of killed aircraft in the 10 encounters is referred to as a discrete probability distribution. The function that generates the distribution is known as the discrete probability function or probability mass function. Two discrete probability functions often used in survivability assessment are the binomial probability function and the Poisson probability function. The tree diagram is a very useful tool to illustrate the stochastic process in general and the binomial distribution in particular. Two separate one-on-one encounters will be described first, followed by the general case of N separate one-on-one encounters.

Go to Problem B.5.1.

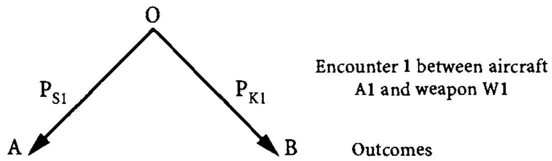


Fig. B.7 Tree diagram for encounter 1.

B.5.2 Tree Diagram and Venn Diagram for Separate One-on-One Encounters

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Learning Objective	**B.5.2**	**Draw the tree diagram and Venn diagram for two or more trials and outcomes of any combat operation, action, or incident.**

Consider the experiment consisting of two aircraft, $A1$ and $A2$ (the system), and two weapons, $W1$ and $W2$. Each aircraft encounters only one weapon, that is, $A1$ encounters $W1$, referred to as encounter 1, and $A2$ encounters $W2$, referred to as encounter 2. The two outcomes of interest for each encounter are the aircraft is killed and the aircraft survives. The three events of interest for the experiment (the two encounters) are neither aircraft is killed, only one aircraft is killed, and both aircraft are killed.

B.5.2.1 Tree diagram. The probabilities that zero, one, and two aircraft are killed in the two encounters can be determined using a tree diagram. The tree diagram illustrates all possible outcomes for a combination or sequence of trials. The tree diagram for encounter 1 of the two encounter experiment is shown in Fig. B.7. The two outcomes of interest are the mutually exclusive outcomes of aircraft survival and aircraft kill. The tree starts at the top at point O. The left branch from point O to point A represents a survival of aircraft $A1$. The probability of an aircraft survival in encounter 1 is denoted by P_{S1}. The right branch from O to B represents an aircraft kill. The probability of aircraft kill in encounter 1 is denoted by P_{K1}. Thus, after one encounter the probability that one aircraft is killed is P_{K1}, the probability that one aircraft is not killed is P_{S1}, and the union of these two mutually exclusive event probabilities is one. The tree diagram of Fig. B.7 is extended in Fig. B.8 to include encounter 2 between $A2$ and $W2$.

The second level of the tree in Fig. B.8 represents all possible outcomes of encounter 1 and encounter 2. Branches down and to the left represent aircraft survival or no kill, and those down and to the right represent an aircraft kill. There are four branches at this level because each branch represents a possible outcome of encounter 2 that occurs in combination with a specific outcome from encounter 1. The four branches represent all possible outcomes of the two encounters. The probability associated with the branch AC, $P_{S2|S1}$, is the conditional probability of the survival of aircraft $A2$ in encounter 2 given that aircraft $A1$ survived in encounter 1. Likewise, the branch AD represents a kill of aircraft $A2$ in encounter 2 given that aircraft $A1$ survived encounter 1. The conditional probability of that event occurring is denoted by $P_{K2|S1}$. Similar conditional probabilities exist for the other two branches in encounter 2 from branch point B.

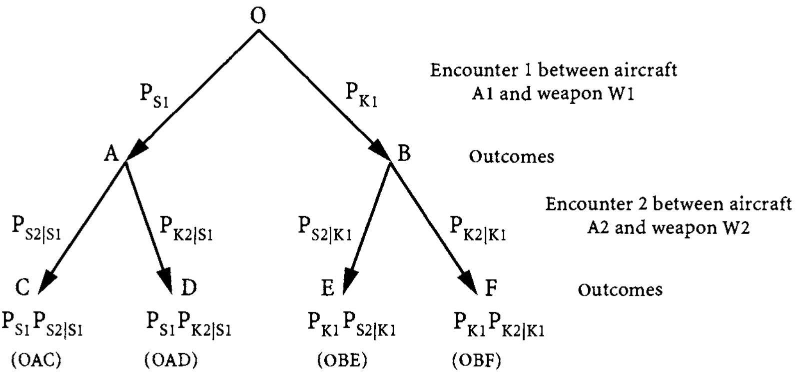

Fig. B.8 Tree diagram for encounters 1 and 2.

There are four unique events in the tree diagram in Fig. B.8: the path *OAC* representing the survival of both aircraft (survival of $A1$ AND $A2$), the path *OAD* representing a kill of only $A2$ [kill of $A2$ AND (NOT $A1$)], the path *OBE* representing a kill of only $A1$ [kill of $A1$ AND (NOT $A2$)], and the path *OBF* representing the kill of both aircraft (kill of $A1$ AND $A2$). The joint probabilities for the occurrence of each of these four mutually exclusive events are given by Eq. (B.16) and are shown below the final four branch points of the tree diagram in Fig. B.8.

B.5.2.2 Independent trials. The conditional probabilities in the second trial, for example, $P_{K2|K1}$, are either independent of the outcomes of the first trial or they are dependent upon them. The concept of independent trials is the same as the concept of independent outcomes in a trial. For two trials to be independent, the probability of any outcome or event occurring in one trial must be uninfluenced by the occurrence of all of the outcomes or events in the other trial. An example of independent trials is the multiple flips of a fair coin. Although the two outcomes of any one flip or trial are mutually exclusive, the outcome of a flip is not influenced by any of the outcomes from previous flips. Thus, the outcomes in any one flip are mutually exclusive, but the flips are independent. If the trials are independent, the equation for the probability associated with the intersection of event A in the ith trial Ai with event B in the jth trial Bj is equal to the equation for the probability associated with the intersection of two independent events A and B in one trial given by Eq. (B.17b). Thus,

$$P(Ai \text{ AND } Bj) = P_{Ai} P_{Bj} \tag{B.24}$$

The union of events A and B in the i and j independent trials is given by

$$P(Ai \text{ OR } Bj) = P_{Ai} + P_{Bj} - P_{Ai} P_{Bj} \tag{B.25}$$

according to Eq. (B.20), and the exclusive union of the two events in the two independent trials is

$$P(Ai \text{ XOR } Bj) = P_{Ai} + P_{Bj} - 2P_{Ai} P_{Bj} \tag{B.26}$$

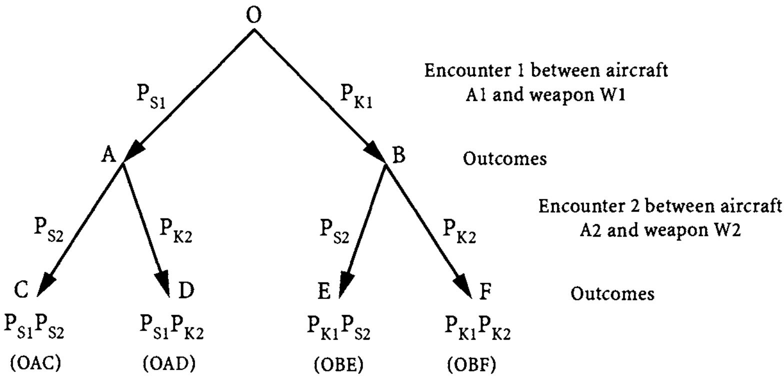

Fig. B.9 Tree diagram for independent encounters 1 and 2.

according to Eq. (B.21). Figure B.9 is the tree diagram for the two encounters when they are independent.

B.5.2.3 Dependent trials. If the probability of occurrence of an event in one trial is dependent upon the occurrence of events in another trial, Eq. (B.15a) must be used to determine the values of the conditional probabilities. An example of sequentially dependent trials is the experiment that consists of two random draws from a deck of playing cards without replacement, that is, the first card drawn is not put back into the deck. The event of interest is the probability of drawing an ace on the second draw. The first draw or trial has a probability of 4/52 of drawing an ace. The probability of drawing an ace from the remaining 51 cards on the second draw is not 4/51. The probability of drawing an ace on the second draw depends upon the outcome of the first draw. If an ace was drawn on the first draw, the probability of drawing an ace on the second draw is 3/51. If it was not, the probability is 4/51. Thus, the outcome probabilities for the second draw depend upon the outcome of the first draw; the draws are not independent. This dependency is illustrated by the tree diagram shown in Fig. B.10. Note that the two branches from A have different probabilities than the two branches from B and that the sum of all four events is unity, indicating that all possible outcomes have been included.

On the other hand, if the card drawn on the first draw was replaced before the second draw, the chance of drawing an ace on the second draw would be 4/52 regardless of the outcome of the first draw, and the draws would be independent. Thus, when the trials are independent the two branches from A have the same probabilities as the two-branches from B. The distinction between draws or trials without replacement and trials with replacement is important.

B.5.2.4 Two independent, identical encounters. If the two encounters are independent, the conditional probabilities become unconditional. If the two encounters are identical, the kill and survival probabilities are the same for both encounters. The tree diagram for this particular two-encounter experiment is given in Fig. B.11 using the encounter probabilities given in Table B.1 of 0.3 for P_K and

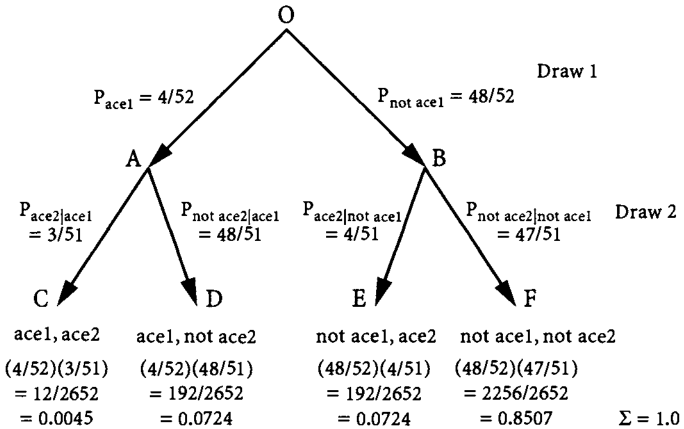

Fig. B.10 Dependent trials.

0.7 for P_S. In the general stochastic process where the probabilities are different for each encounter, the appropriate probability would be used for the branches from the preceding encounter.

Path *OAC* in Fig. B.11 is the joint probability that both aircraft survive (0.49). Path *OAD* is the probability that only aircraft $A2$ is killed (0.21). Path *OBE* is the path on which only aircraft $A1$ is killed (0.21). Path *OBF* is the joint probability that both aircraft are killed (0.09). If the second encounter probabilities were different from those of the first encounter, the appropriate values for P_{K2} and P_{S2} would be used for the four branches in encounter 2.

The events of interest are the probabilities that two, one, and zero aircraft are killed. The probability that both aircraft ($A1$ AND $A2$) are killed is given by the joint probability along path *OBF*

$$P_K(A1 \text{ AND } A2) = 0.3 \cdot 0.3 = 0.09$$

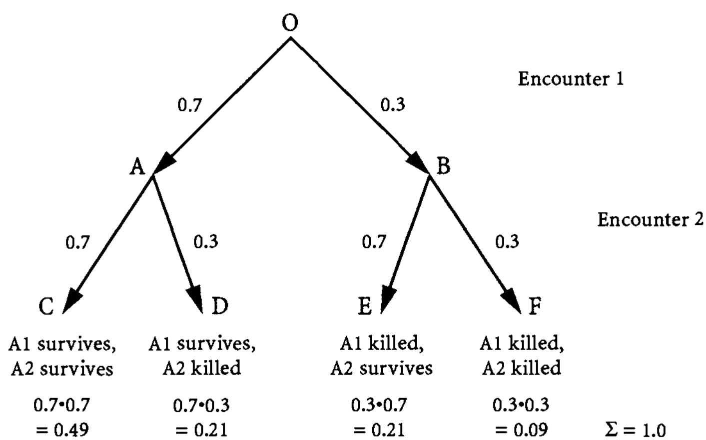

Fig. B.11 Two independent, identical encounters.

according to Eq. (B.17b). The probability that at least one aircraft is killed is given by the union of aircraft kills ($A1$ OR $A2$). According to Eq. (B.20),

$$P_K(A1 \text{ OR } A2) = 0.3 + 0.3 - 0.3 \cdot 0.3 = 0.51$$

which is equivalent to the union of the three exclusive paths *OAD*, *OBE*, and *OBF*. The probability that only one aircraft is killed is given by the exclusive union of aircraft kills, Eq. (B.21), that is, either $A1$ is killed, or $A2$ is killed, but both aircraft are not killed. Thus,

$$P_K(A1 \text{ XOR } A2) = 0.3 + 0.3 - 2 \cdot 0.3 \cdot 0.3 = 0.42$$

which is equivalent to the union of paths *OAD* and *OBE*. The joint probability that neither aircraft is killed is given by

$$P_S(A1 \text{ AND } A2) = 0.7 \cdot 0.7 = 0.49$$

which is the path *OAC*. The sum of the four event probabilities at the bottom of the tree is unity, as it should be.

B.5.2.5 Venn diagram. A Venn diagram can be constructed for the two independent, identical encounter experiment using the results of the tree diagram in Fig. B.11. The diagram is given in Fig. B.12. The two sets, $A1$ kill and $A2$ kill, are independent.

B.5.2.6 Three independent, identical encounters. The probabilities that three aircraft, two aircraft, one aircraft, and zero aircraft are killed in three encounters can be obtained by extending the tree diagram for two encounters, shown in Figs. B.8–B.11, by another encounter, with two branches off of each of the lowest branch points in Fig. B.11. The tree diagram for three independent and identical encounters, with $P_K = 0.3$ and $P_S = 0.7$, is shown in Fig. B.13.

Each path down the tree represents a unique sequence or ordered arrangement of outcomes into a mutually exclusive event. For example, the path *OADJ* represents the unique event that aircraft $A1$ survives and $A2$ and $A3$ are killed. In terms of set operations, this path is NOT $A1$ AND $A2$ AND $A3$. The joint probability this particular event occurs is $0.7 \cdot 0.3 \cdot 0.3 = 0.063$. The path *OBEL*, which is the event consisting of a survival of $A2$ and a kill of $A1$ and $A3$ and has the joint probability of $0.3 \cdot 0.7 \cdot 0.3 = 0.063$, is another event in which two aircraft are

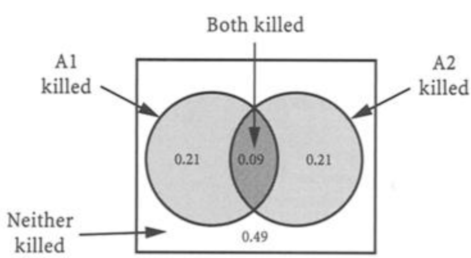

Fig. B.12 Venn diagram for two identical encounters.

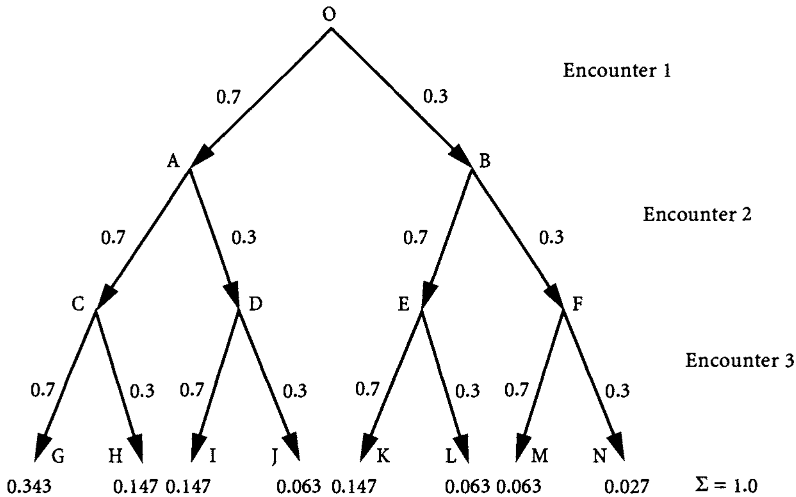

Fig. B.13 Tree diagram for three independent, identical encounters.

killed. The logical equation for this path is $A1$ AND NOT $A2$ AND $A3$. Together, the eight paths down the tree compose the sample space for this experiment, and the outcomes for each path ($A1$ survives and $A2$ and $A3$ are killed) define the event. The eight mutually exclusive events shown in the tree diagram can be presented as eight areas in the Venn diagram as shown in Fig. B.14.

Of interest here is the probability that a specific number of aircraft are killed, such as 0, 1, 2, or 3, in this three-encounter experiment. Note that each path down

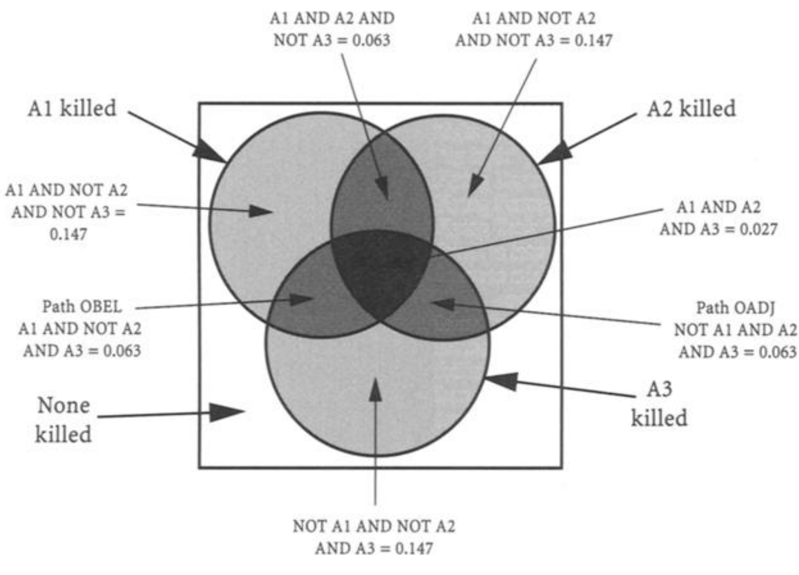

Fig. B.14 Venn diagram for the three-encounter experiment.

the tree in Fig. B.13, and each unique area in Fig. B.14, makes a contribution to the probability that a specific number of aircraft are killed. Consequently, the eight mutually exclusive outcomes can be combined into four mutually exclusive events, each event representing a specific number of aircraft killed. Examining Figs. B.13 and B.14 reveals that the number of paths down the tree diagram (or areas in the Venn diagram) that contribute to the probability that one aircraft is killed is three (*OACH*, *OADI*, and *OBEK*), and the joint probability associated with each of these three paths is $(P_K)^1(P_S)^2$. Thus, the probability that one aircraft is killed is obtained by the union of the three mutually exclusive events in which one aircraft is killed. Because the events are mutually exclusive, the union of events is simply the sum of the events (0.441). Likewise, the joint probability that two aircraft are killed and one survives is the union of the three mutually exclusive paths of *OADJ*, *OBEL*, and *OBFM* with the joint probability $(P_K)^2(P_S)$. Summing the probabilities for each number of aircraft killed given in the tree diagram in Fig. B.13 results in the probabilities $(0.7)^3 = 0.343$, $3 \cdot (0.3)(0.7)^2 = 0.441$, $3 \cdot (0.3)^2(0.7) = 0.189$, and $(0.3)^3 = 0.027$ that 0, 1, 2, and 3 aircraft, respectively, will be killed in the three encounters. The set of the four probabilities is the probability distribution.

Go to Problems B.5.2 to B.5.4.

B.6 Discrete Probability Functions

B.6.1 Binomial Probability Function for Multiple One-on-One Encounters

Learning Objective	**B.6.1**	**Use the binomial probability function to determine the probability of K aircraft kills in N encounters. Describe and compute the expected number of kills, the variance, the standard deviation, and the cumulative distribution.**

The stochastic process just described using the tree diagram can be carried out for any number of one-on-one encounters, regardless of the kill and survival probability values used in each of the encounters; the probabilities do not have to be independent or identical for each encounter. However, for the specific case of N identical, independent one-on-one encounters between an aircraft and a weapon, with the two outcomes of aircraft kill and survival, the binomial theorem can be used to determine the probability of K aircraft kills in the N encounters. The binomial theorem or function applies to a process that consists of N independent trials of an experiment that has only two outcomes whose probability of occurrence is constant for all trials. Each trial in the binomial process is referred to as a Bernoulli trial. According to the binomial theorem, the probability of K kills in N encounters is given by Ref. 3.

$$\text{Probability of } K \text{ kills in } N \text{ encounters} = \binom{N}{K} (P_K)^K (1 - P_K)^{(N-K)} \tag{B.27}$$

Table B.4 Probability distribution for number of A/C Kills

No. of A/C killed	Probability
0	0.0282
1	0.1211
2	0.2335
3	0.2668
4	0.2001
5	0.1029
6	0.0368
7	0.0090
8	0.0014
9	0.0001
10	0.0000

where $\binom{N}{K}$ is the binomial coefficient that provides the number of possible paths down the tree diagram that results in K kills out of N encounters and is given by

$$\binom{N}{K} = \frac{N!}{(N-K)!K!} \tag{B.28}$$

and P_K is the encounter kill outcome probability (Note 14). The function defined in Eq. (B.27) is the binomial probability function. The results from Eq. (B.27) are given in Table B.4 and plotted in Fig. B.15 for 10 independent encounters using 0.3 and 0.7 for P_K and P_S, respectively. The set of the 11 event probabilities is the binomial probability distribution, or simply the binomial distribution.

B.6.1.1 Expected number of aircraft killed. The 11 probabilities given in Table B.4 and plotted in Fig. B.15 might not be a convenient measure to use

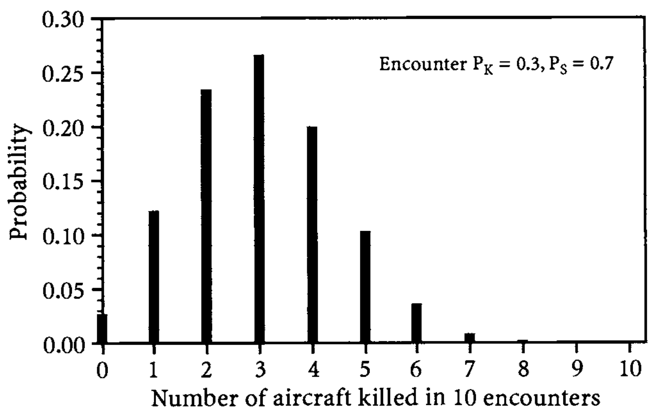

Fig. B.15 Binomial distribution for the number of aircraft killed in 10 encounters.

when evaluating the survivability of the aircraft. One or two summary measures of this probability function that can be used to compare survivabilities or as part of a larger experiment are desirable. Two such measures are the expected value for the number of aircraft killed in the N encounters and the variance or the standard deviation about the expected value.

The expected value, also known as the mean and the expectation, is the first moment of the probabilities about the origin of the axis of the random variable. Thus, for N values of probabilities $P(x_i)$, $i = 1, 2, \ldots N$ for the N discrete values of the random variable x, the expected value of x, $E(x)$, is given by

$$E(x) = P(x_1)x_1 + P(x_2)x_2 + \cdots + P(x_N)x_N = \sum_{i=1}^{N} P(x_i)x_i \tag{B.29}$$

The expected value is a weighted average of the random variable, and the weights are the probabilities. Substituting the numbers given in Table B.4 into Eq. (B.29) for the probabilities $P(x_i)$ and the number of aircraft killed x_i results in

$$\begin{aligned} E(x) &= 0.028 \cdot 0 + 0.121 \cdot 1 + 0.233 \cdot 2 + 0.267 \cdot 3 + 0.200 \cdot 4 \\ &\quad +0.103 \cdot 5 + 0.037 \cdot 6 + 0.009 \cdot 7 + 0.001 \cdot 8 \\ &\quad +0.000 \cdot 9 + 0.000 \cdot 10 = 3.00 \end{aligned}$$

Thus, the expected number of aircraft killed in the 10 encounters is 3.00, which is the same as the number of aircraft killed in Table B.1 and that was used to determine the encounter P_K. This is not a coincidence. The expected value for the binomial distribution of probabilities associated with N identical encounters is given by[3] (Note 15)

$$\text{Expected number of aircraft killed} = N P_K \tag{B.30}$$

The same expectation relationship given by Eq. (B.30) applies to aircraft not killed. If there are 100 aircraft in a strike and the mission survivability of each aircraft P_S is 0.99, then the expected number of surviving aircraft is $100 \cdot 0.99 = 99.0$.

B.6.1.2 Variance and standard deviation. A second measure of the discrete probability distribution shown in Fig. B.15 is the variance. The variance *Var*(x) is the second moment about the expected value of the random variable x and is given by

$$\begin{aligned} Var(x) &= P(x_1)[x_1 - E(x)]^2 + P(x_2)[x_2 - E(x)]^2 + \cdots \\ &\quad + P(x_N)[x_N - E(x)]^2 = \sum_{i=1}^{N} P(x_i)[x_i - E(x)]^2 \end{aligned} \tag{B.31}$$

The standard deviation of the variance σ_x is defined by

$$\sigma_x = \sqrt{Var(x)} \tag{B.32}$$

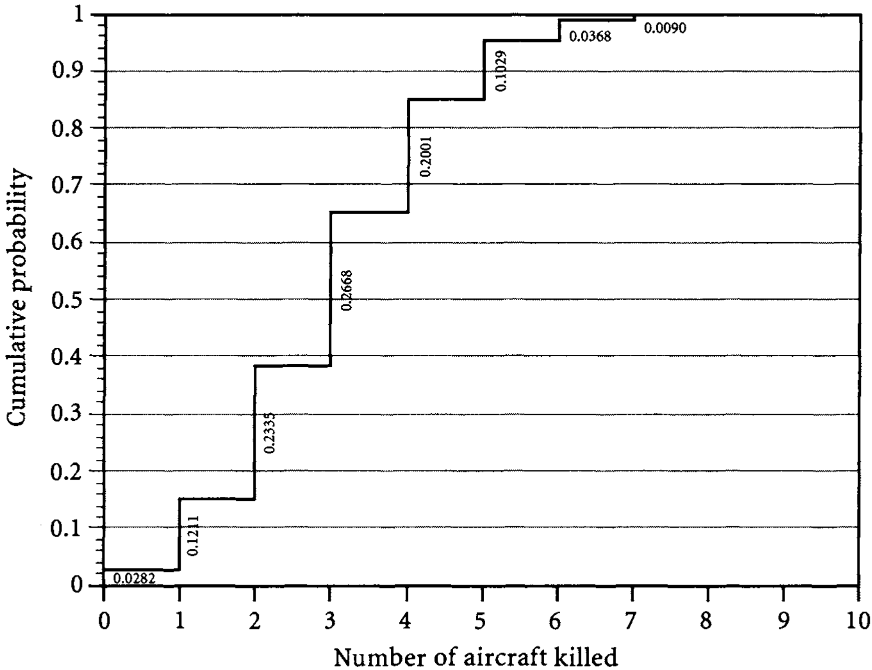

Fig. B.16 Cumulative distribution for the number of aircraft killed in 10 encounters.

The variance and standard deviation of the probability function for the 10 encounters is

$$\begin{aligned} Var(x) &= 0.028 \cdot (0-3)^2 + 0.121 \cdot (1-3)^2 + 0.233 \cdot (2-3)^2 + 0.267 \cdot (3-3)^2 \\ &+0.200 \cdot (4-3)^2 + 0.103 \cdot (5-3)^2 + 0.037 \cdot (6-3)^2 + 0.009 \cdot (7-3)^2 \\ &+0.001 \cdot (8-3)^2 + 0.000 \cdot (9-3)^2 + 0.000 \cdot (10-3)^2 = 2.1 \end{aligned}$$

$$\sigma_x = \sqrt{2.1} = 1.45$$

In general, the variance of the binomial distribution is[3]

$$Var(x) = N P_K P_S \tag{B.33}$$

B.6.1.3 Cumulative distribution. The cumulative distribution defines the probability that the random variable lies in the interval between the lowest value considered and a particular value x. Figure B.16 shows the cumulative distribution for the binomial distribution given in Table B.4 and plotted in Fig. B.15.

Go to Problem B.6.1.

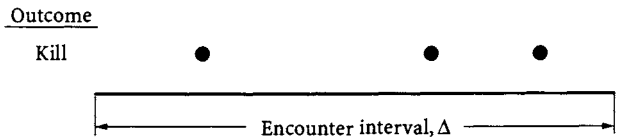

Fig. B.17 Discrete outcomes over an interval.

B.6.2 Poisson Probability Function for Multiple One-on-One Encounters

Learning Objective	**B.6.2**	**Use the Poisson function to determine the probability of K aircraft kills when the expected number of aircraft kills is λ.**

The binomial probability function given by Eq. (B.27) provides the probability that K aircraft are killed in exactly N encounters or trials using the kill outcome probability per encounter P_K. Both K and N are integers. An aircraft kill can occur with the probability P_K for each of the encounters at the N discrete locations along the encounter axis (the independent variable) as shown in Fig. B.2, and the expected number of aircraft killed in the N encounters is N (the number of encounters) $\times$ P_K (the probability an aircraft is killed given an encounter, a rate).

Now consider the experiment where the number of one-on-one encounters or trials approaches infinity and the P_K (per encounter) approaches zero, but the expected number of kill outcomes remains the same, that is, $NP_K = (N \to \infty)\times (P_K \to 0) = \lambda$. Under these conditions the binomial probability function for K kills in N encounters given by Eq. (B.27) converges to the Poisson probability function for K kills when λ kills are expected over the interval Δ shown in Fig. B.17. Note that the discrete encounter axis (1, 2, ... 10) in Fig. B.2 has been replaced in Fig. B.17 by the continuous encounter interval Δ. There are an infinite number of encounters or trials over the encounter interval, and the kill outcome has an infinitesimally small probability of occurrence at each encounter, but the expected number of aircraft killed over the interval is λ. Note that three aircraft kills have occurred over the interval in Fig. B.17, which is analogous to the three aircraft killed in the 10 encounters shown in Fig. B.2. Because the Poisson probability function is the limit of the binomial probability function, it is based upon the same assumptions; the kills are assumed to be independent, a kill can occur with equal likelihood at any location within the interval, and the rate of occurrence is constant over the interval.

The two parameters in the binomial probability function are N and P_K. The single parameter associated with the Poisson probability function is the expected number of kills within the interval λ, where $\lambda = NP_K$. The Poisson probability function for K kills when λ kills are expected can be given in the form

$$\text{Probability of } K \text{ kills when } \lambda \text{ kills are expected}$$
$$= \frac{\lambda^K e^{-\lambda}}{K!} \qquad (K = 0, 1, 2, \ldots \infty) \tag{B.34a}$$

The set of probabilities for $K = 0, 1, 2, \infty$ kills generated by Eq. (B.34a) is the Poisson distribution. The expected value or mean and the variance for the Poisson

Table B.5 Poisson probability distribution for number of A/C kills

No. of A/C killed	Probability
0	0.0498
1	0.1494
2	0.2240
3	0.2240
4	0.1680
5	0.1008
6	0.0504
7	0.0216
8	0.0081
9	0.0027
10	0.0008

distribution are

$$\text{Expected value} = \lambda \tag{B.34b}$$

$$\text{Variance} = \lambda \tag{B.34c}$$

Of special interest is the Poisson probability for zero kills, that is, all aircraft survive when λ kills are expected

$$\text{Probability of 0 kills when } \lambda \text{ kills are expected} = e^{-\lambda} \tag{B.35}$$

The Poisson probability function is derived by letting $N \to \infty$, $P_K \to 0$, and $NP_K = \lambda$. Because P_K (per encounter or trial) is very, very small, the outcome is sometimes referred to as a rare event.[2] However, the Poisson distribution is a close approximation to the binomial distribution provided K is small compared to N and P_K is small compared to unity, for example, for a few occurrences of unlikely outcomes. Table B.5 contains the Poisson probabilities for the 11 possible outcomes of number of aircraft kill in the 10 trial experiment of Table B.1, and Fig. B.18 shows the comparison of the Poisson distribution with the binomial distribution with $N = 10$, $P_K = 0.3$, and $\lambda = 3$. Note that the Poisson distribution, in contrast to the binomial distribution, does not stop at 10 aircraft killed. There is a very, very small probability that 100 aircraft are killed when three aircraft are expected to be killed.

The continuous encounter axis in Fig. B.17 is the limiting approximation to the discrete encounter axis shown in Fig. B.2, and consequently the Poisson probability function is an approximation to the binomial probability function. Continuous axes or independent variables where the Poisson probability function is the correct function are the space and time axes. Example B.5 presents an application of the Poisson function to a time problem.

Example B.5 Poisson Function and Telephone Calls

The Poisson probability function can be used to determine the probability that K telephone calls will be received at a particular telephone within a specified

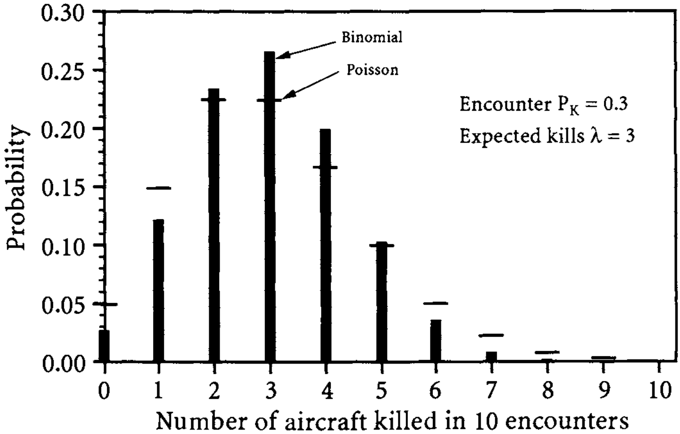

Fig. B.18 Comparison of the binomial and Poisson probability distributions for the 10-encounter experiment.

time interval ΔT. The time interval ΔT is conceptually divided into a very large number of very small increments or trials, for example, 0.01 s per increment, and the probability a call is received in any one increment or trial is very small. Each call is an independent occurrence and can occur with equal likelihood at any time (or in any time increment). The expected number of calls within ΔT, λ, is equal to the rate at which calls are received (analogous to P_K per encounter, a rate) multiplied by the time interval ΔT (analogous to the number of encounters N). Thus, if an average of 80 phone calls are received during the hours from 0800 to 1600, the rate of phone calls is (80 calls)/(8 hrs) = 10 calls per hr. Suppose the time interval of interest is $\Delta T = 15$ min, which is (15 min) · (60 s per minute) · (100 increments per second) = 90,000 increments. The expected number of calls within that interval is (10 calls per hour) · (15 min/60 min per hour) or $\lambda = 2.5$ calls per ΔT. Thus, only 2.5 calls are expected in the 90,000 increments or trials, a rare event. The probability that a specific number of phone calls, such as 5, will be received in any 15-min interval within the 8 hours is given by

$$\text{Probability of 5 calls when 2.5 calls are expected} = \frac{2.5^5 e^{-2.5}}{5!} = 0.067$$

Go to Problems B.6.2 to B.6.3.

B.6.3 One Aircraft Is Encountered by Multiple Weapons

Learning Objective	**B.6.3**	**Compute the probability that one aircraft is killed in two or more encounters with air defense weapons.**

The one aircraft vs multiple weapons, or one-on-many, situation is not the same as the multiple, separate one-on-one encounters situation just presented. Here, one

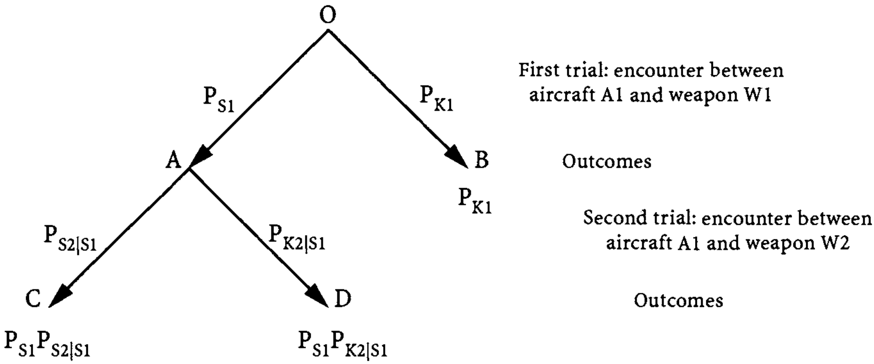

Fig. B.19 Tree diagram for one aircraft encountering two weapons.

aircraft is encountered and engaged by two or more weapons either simultaneously or sequentially. (The assumption is made that the simultaneous encounters can be considered to be sequential.) Furthermore, the explanation for the probability of surviving multiple encounters with threat weapons also applies to surviving multiple firings or launchings from one or more weapons. For example, the procedure for determining the probability of surviving three sequential encounters is the same as the procedure for determining the probability of surviving three rounds from one gun, and surviving a total of six rounds from two guns is conceptually the same as surviving six encounters. The procedure is very general and applies to many different situations.

B.6.3.1 Two sequential encounters. In the two-sequential-encounter experiment weapon $W1$ is the first weapon to encounter and engage the aircraft. This weapon can kill the aircraft with a probability P_{K1}, or the aircraft can survive with a probability P_{S1}. If the aircraft survives the first encounter, it will encounter the second weapon $W2$. This weapon has a conditional probability of killing the surviving aircraft of $P_{K2|SI}$. If the aircraft survives the encounters with the first and second weapons, it might encounter a third weapon, and so on. The tree diagram for two sequential encounters is shown in Fig. B.19.

Note the difference between the two aircraft/two weapons tree of Fig. B.8 and this one aircraft/two weapons tree. There are no branches from point B because weapon $W2$ cannot encounter an aircraft killed by weapon $W1$; it can only encounter an aircraft that is not killed by weapon $W1$ (Note 16) Thus, any kills by the two weapons are mutually exclusive. The two branches from point A represent the probability that a second encounter with a live, but perhaps damaged, aircraft takes place. If the P_K for the second encounter is not affected by the results of the first encounter, $P_{K2|SI}$ is replaced by P_{K2}, the probability $W2$ kills the aircraft in an independent encounter. However, if the first encounter damages the aircraft then $P_{K2|SI}$ most likely will not be the same as P_{K2}, and the conditional probability of kill given by Eq. (B.15a) must be used. Similar statements can be made for the probability that the aircraft survives the second encounter given that it survived the first encounter $P_{S2|SI}$.

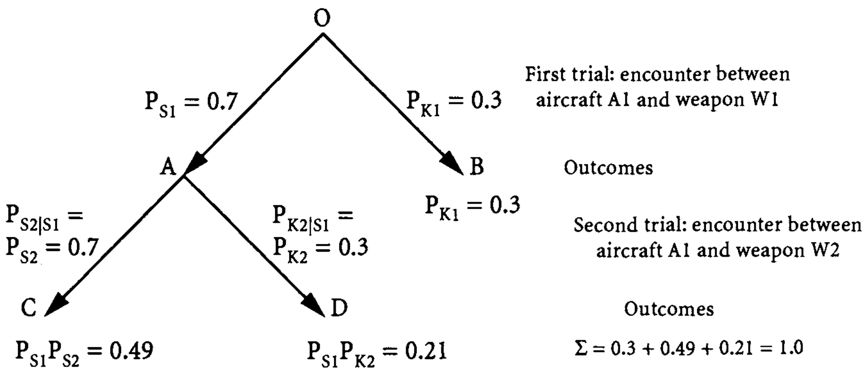

Fig. B.20a Probability tree diagram for one aircraft with two encounters.

If the assumption is made that the aircraft is unaffected by the first encounter (i.e., the second encounter is independent of the outcomes of the first encounter), the tree diagram for the experiment where the two sequential encounters are independent and identical, with $P_K = 0.3$ and $P_S = 0.7$, is shown in Fig. B.20a. The corresponding Venn probability diagram is shown in Fig. B.20b.

Note that weapon *W*1 has a 0.30 probability of killing the aircraft, whereas *W*2 only has a 0.21 probability of killing the aircraft, not the 0.3 associated with the P_K of the weapon. This is because the weapon P_K has the implied condition that there is an aircraft available to be killed, that is, $P_{K2|S1}$. Thus, the branch from *O* to *C* has the joint probability that the aircraft survived the first encounter and survived the second encounter given that it survived the first encounter. The joint probability the aircraft survives both encounters $P_{S2|S1}P_{S1}$ is given by

$$P_S(W1 \text{ AND } W2) = 0.7 \cdot 0.7 = 0.49 \tag{B.36}$$

The probability the aircraft is killed either by *W*1 or by *W*2 in the two encounters $P_K(W1 \text{ OR } W2)$ is given by the union of the two mutually exclusive kill events along path *OB* for *W*1 and path *OAD* for *W*2. Therefore,

$$P_K(W1 \text{ OR } W2) = 0.3 + 0.7 \cdot 0.3 = 0.51 \tag{B.37}$$

which is the complement of the joint probability of survival of the aircraft in the two encounters.

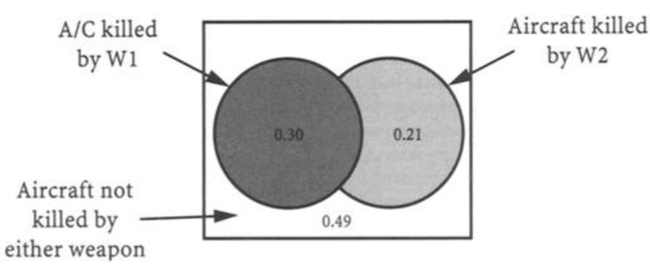

Fig. B.20b Venn diagram for the two encounters.

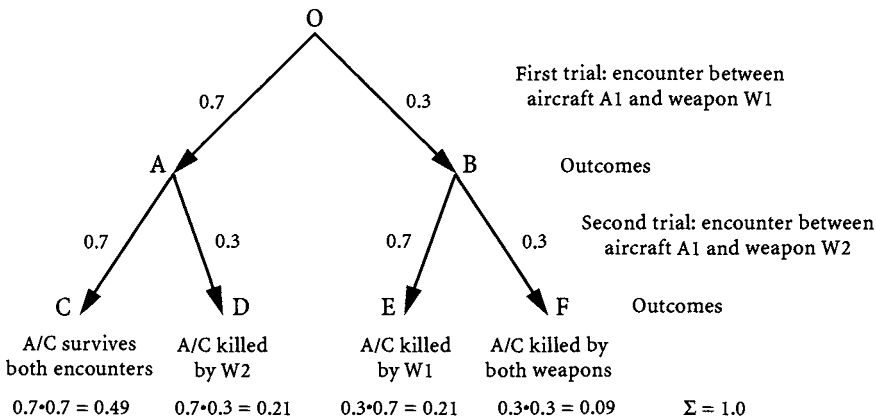

Fig. B.21 One aircraft with two independent encounters.

Note that Eq. (B.37) for the probability that either weapon $W1$ or $W2$ (but not both) kill the aircraft can be written in the form

$$
\begin{aligned}
P_K(W1 \text{ OR } W2) &= 0.3 + 0.7 \cdot 0.3 \\
&= 0.3 + (1 - 0.3) \cdot 0.3 = 0.3 + 0.3 - 0.3 \cdot 0.3 = 0.51 \qquad \text{(B.38)}
\end{aligned}
$$

which is identical to the union of two independent events, that is, the aircraft is killed by $W1$, or by $W2$, or by both $W1$ and $W2$. In this approach, shown by the tree diagram in Fig. B.21, the second weapon encounters the aircraft regardless of the outcome of the first encounter. The two possible outcomes below B (E and F) have a combined probability of 0.3, which is the probability the aircraft was killed prior to the second encounter, and hence no modification to the kill probability is made by including the branch from A because both E and F represent a killed aircraft. Note that use of the *XOR* condition with the two independent encounters, that is, the aircraft is killed by $W1$ or $W2$ but not both, gives $0.3 + 0.3 - 2 \cdot 0.3 \cdot 0.3$ or 0.42 according to Eq. (B.21), which is not the right answer because it leaves out the branch *OBF*.

Figure B.22 illustrates three different ways the kill of an aircraft by two weapons can be treated. They are 1) using the union of two mutually exclusive kills in which the second weapon encounters only the aircraft that survive the first encounter, that is, the two mutually exclusive kills shown in Fig. B.22a; or 2) using the union of two independent weapon encounter kills, that is, allowing an aircraft to be killed twice as shown in Fig. B.22b; or 3) using the complement of the joint probability the aircraft survives the two encounters, that is, the complement of the white area in Figs. B.22a and B.22b.

B.6.3.2 N sequential encounters.

Binomial approach. When N weapons encounter one aircraft sequentially, where N is a known integer, the aircraft will survive only if it survives all of the encounters. The joint probability the aircraft survives all of the encounters is given

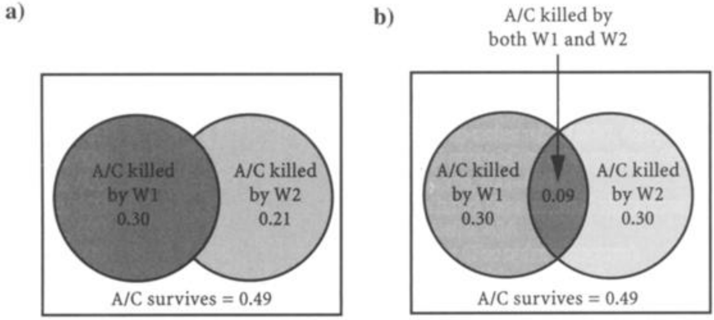

Fig. B.22 Three different approaches to determine the probabilities: a) mutually exclusive and b) independent.

by Eq. (B.19a) in general and by Eq. (B.19c) when the encounter outcomes are independent. When each encounter is independent and identical, with a probability of survival P_S, Eq. (B.19c) becomes

$$P_S(W1 \text{ AND } W2 \text{ AND} \ldots WN) = (P_S)^N = (1 - P_K)^N \tag{B.39}$$

The probability the aircraft is killed in the N identical encounters can be computed using any of the three methods just described; the union of N mutually exclusive encounters, the union of N independent encounters, and the complement of the probability the aircraft survives all N encounters. Thus,

$$P_K(W1 \text{ OR } W2 \text{ OR} \ldots WN) = 1 - (P_S)^N = 1 - (1 - P_K)^N \tag{B.40}$$

Poisson approximation. The Poisson probability function can be used to determine an approximation to the probability an aircraft survives N encounters when it is expected be killed NP_K times. The concept of killing the aircraft NP_K times is analogous to the situation where the aircraft is killed by multiple weapons in the independent encounter approach. The aircraft survives the N encounters when zero kills occur. Thus,

$$\text{Probability of 0 kills of the aircraft when } NP_K \text{ kills are expected} = e^{-NP_K} \tag{B.41}$$

according to Eq. (B.35). Figure B.23 presents a comparison of the survivability results from both the binomial approach and the Poisson approximation, given by Eqs. (B.39) and (B.41), respectively, vs N for several values of P_K.

B.6.3.3 E expected encounters. In the preceding analysis for the one-on-many experiment, the many is a given integer N. However, suppose the number of weapons encountered by an aircraft is a random variable rather than the given integer N. For example, instead of four sequential encounters between an aircraft and an air defense weapon, four encounters are expected to occur, that is, the exact number of encounters is not known a priori. Perhaps there will be one encounter, or two encounters, or 20 encounters. All that is known is that the expectation is four encounters. In this experiment the randomness is in both the number of encounters

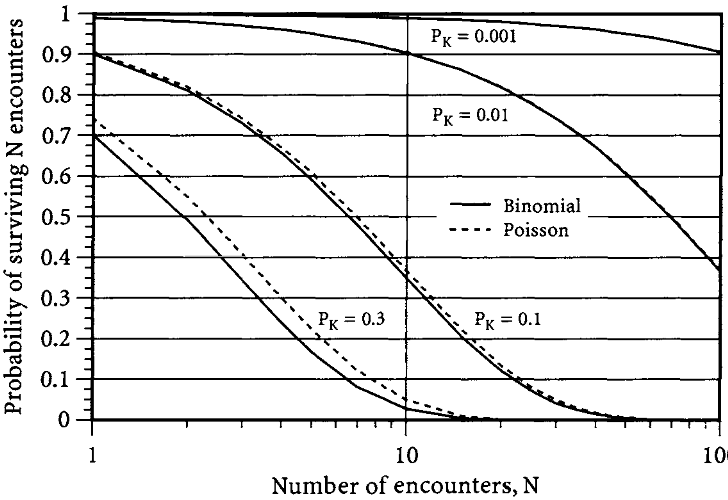

Fig. B.23 Comparison of the binomial results with the Poisson approximation.

as well as in the outcome of any encounter that does take place. In this experiment the Poisson probability function provides the correct answer, and the binomial probability function is an approximation.

Poisson approach. To illustrate this new experiment, consider the aircraft flying straight through through a rectangular area $L \times H$ defended by W randomly (uniformly) distributed weapons of type 1 shown in Fig. B.24 (Note 17). The weapon envelope is the circle of diameter D around the weapon site. The probability the aircraft is killed if its flight path enters this envelope is P_K. Thus, any weapon site center that is located within the band $D \times L$ along the flight path (indicated by the dashed lines) can encounter, engage, and kill the aircraft with the probability P_K. Note in Fig. B.24 that for the illustrated threat laydown, only one weapon site is encountered. Another uniform distribution of the eight weapon sites

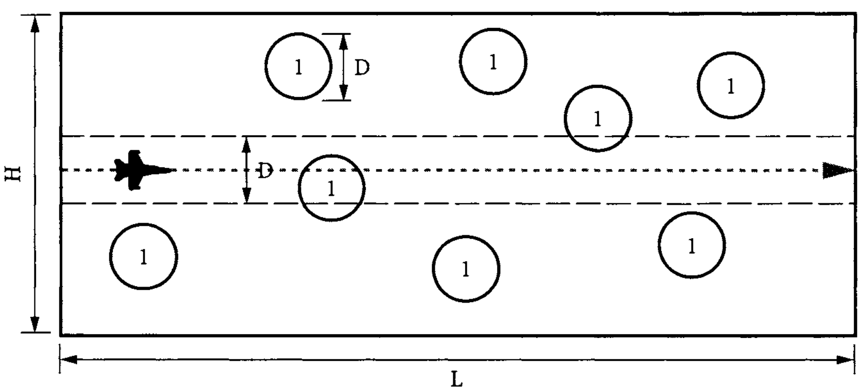

Fig. B.24 One-on-many scenario with eight type 1 weapons uniformly distributed.

could result in zero encounters, or encounters with all eight weapons, depending upon how many site centers are within the encounter band.

Of interest here is the value for E, the expected number of weapon encounters the aircraft will have as it flies through the defended area. Because the weapons are assumed to be uniformly distributed, the weapon density ω, the number of weapons of type 1 per unit defended area, is given by

$$\omega = W/(L \times H) \tag{B.42}$$

The expected number of weapon encounters is equal to the number of weapon site centers that are expected to be within the band $D \times L$, as shown in Fig. B.24. Thus,

$$E = DL\omega = (D/H)W \tag{B.43}$$

that is, the probability the aircraft will encounter a weapon in the area depends upon the ratio of the weapon's envelope diameter D to the width of the zone H. Given the expected number of encounters E, the aircraft is expected to be killed EP_K times. Thus, Eq. (B.35) becomes

$$\text{Probability of 0 kills of the aircraft when } EP_K \text{ kills are expected} = e^{-EP_K} \tag{B.44}$$

This experiment is a Poisson process for the following reasons. The independent variable or axis is the continuous path length or interval L shown in Fig. B.24. This length can be divided into a very large number of very small increments. When the aircraft reaches each of the increments along L, there is a very small probability any one of the W weapons will be encountered. Furthermore, the experiment satisfies the assumptions that the kills are assumed to be independent, a kill can occur with equal likelihood at any location along the path length, and the rate of encounter occurrence is constant over the interval.

Binomial approximation. The binomial probability function can be used to determine an approximation to the probability the aircraft survives when it is expected to be killed EP_K times in E expected encounters. Thus, Eq. (B.39) becomes

$$P_S(E \text{ expected encounters}) = (P_S)^E = (1 - P_K)^E \tag{B.45}$$

Note that E most likely will not be an integer.

Go to Problems B.6.4 to B.6.5.

B.7 Continuous Probability Functions

Learning Objective	**B.7.1**	**Describe the difference between discrete variable probability functions and continuous probability functions.**

The binomial and Poisson probability functions just described are for discrete random variables, they provide the probability that exactly K outcomes or events will occur in N trials (the binomial function) or when λ events are expected to occur (the Poisson function), where K is a positive integer. The discrete random variable is defined at specific integer locations along the axis, and a probability is associated with each location, as shown in Fig. B.18 for the number of aircraft killed in 10 encounters. The number of trials N and the probability the outcome occurs in each trial P_K affect the probability values at each location along the axis. Many other random variables in survivability assessment, such as the muzzle velocity of a ballistic projectile, the tracking error associated with a radar system, the burn time of a missile rocket motor, and the closest point of approach or miss distance between a projectile and an aircraft, are not confined to the set of positive integers. Consequently, they are referred to as continuous random variables, and they require a continuous probability function or probability density function to assign a probability to each of the possible outcomes. The outcome of interest for a continuous random variable is not the probability that a specific value of the variable will occur, for example, the probability the muzzle velocity will be 2581.5 fps, but instead is the probability that the variable will be within a specific interval, for example, the probability the muzzle velocity will be between 2580 and 2585 fps.

Probability density functions have one or more parameters that are used to adjust the location of a particular value of the random variable along the axis, to adjust the scale of the function, and to adjust the shape. The integration of all PDFs from $-\infty$ to $+\infty$ is unity, just as the sum of all outcome probabilities is unity in discrete probability problems. Four probability density functions for continuous random variables that are often used in survivability assessment are the uniform PDF, the one-dimensional normal or Gaussian PDF, the two-dimensional or bivariate normal PDF, and the circular normal or Rayleigh PDF (Note 18).

Go to Problems B.7.1 to B.7.2.

B.7.1 Uniform Probability Density Function

Learning Objective B.7.2 Use the normal distribution to compute the probability that a continuous random variable will be within a specified interval.

The uniform probability density function is the equally likely PDF. The value of the random variable is equally likely to have a particular value in one interval as it is in any other interval of the same size. The value of the probability is related to the size of the interval in relation to the extent of the domain. For example, if the location of a fragment hit on a plate of area A_P is uniformly distributed the fragment is equally likely to hit any location on the plate. Thus, the probability it hits any area A_p within the plate is equal to the ratio of the areas A_p/A_P. The phrase randomly located usually means uniformly distributed.

Go to Problems B.7.3 to B.7.4.

B.7.2 One-Dimensional Normal Probability Density Function

Learning Objective B.7.3 Use the one-dimensional normal distribution to compute the probability that a continuous random variable will be within a specified interval.

B.7.2.1 General and standard forms of the normal PDF. As the number of trials in the binomial process approaches infinity, the number of possible outcomes becomes infinite, and the discontinuous binomial distribution approaches the continuous normal PDF. The general form of the normal PDF in terms of the random variable x is given by

$$\text{Normal pdf (general form)} = f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5\left(\frac{x-\mu}{\sigma}\right)^2} \tag{B.46a}$$

where σ^2 is the variance, σ is the standard deviation or scale parameter, μ is the mean or location parameter, and $x - \mu$ is referred to as the deviation (Note 19). (http://www.itl.nist.gov/div898/software/dataplot/refman2/ch8/homepage.htm.) Equation (B.46a) can be converted to the standard form by defining the nondimensional random variable χ, where

$$\chi = \frac{x - \mu}{\sigma} \tag{B.46b}$$

Replacing x with χ in Eq. (B.46a) results in the standard form of the normal PDF

$$\text{Normal pdf (standard form)} = f(\chi) = \frac{1}{\sqrt{2\pi}} e^{-0.5\chi^2} \tag{B.46c}$$

This form of the PDF is shown in Fig. B.25a. Note that $\chi = 1$ in Fig. B.25a corresponds to $(x - \mu)/\sigma = 1$. Thus, the integers 1, 2, and 3 on the χ axis correspond to integers of σ, that is, $x - \mu = 1\sigma, 2\sigma$, and 3σ.

The normal PDF given by Eqs. (B.46a) for x and (B.46c) for χ and shown in Fig. B.25a does not give the probability that the random variable x (or χ) has any specific value, but instead is used to compute the probability that x (or χ) falls within an interval from x_a to x_b (or from χ_a to χ_b). For example, the probability that χ falls between the interval from $\chi_a = 1$ to $\chi_b = 2$ is given by the integral

$$\text{Probability } (1 \leq \chi \leq 2) = \int_1^2 f(\chi)\,\mathrm{d}\chi \tag{B.47}$$

which is the area under the PDF curve shown in gray in Fig. B.25a.

Evaluating Eq. (B.47) with the limits $-\infty$ to χ yields the cumulative distribution shown in Fig. B.25b that is analogous to the cumulative distribution for the discrete PMF shown in Fig. B.16.

Of considerable interest in probability theory is the probability that the random variable χ falls within the interval $\pm\chi_\alpha$ shown in Fig. B.25a, where χ_α is an arbitrary number. The answer to this question can be determined by applying the limits $-\chi_\alpha$ and $+\chi_\alpha$ to Eq. (B.47) and carrying out the integration for all values

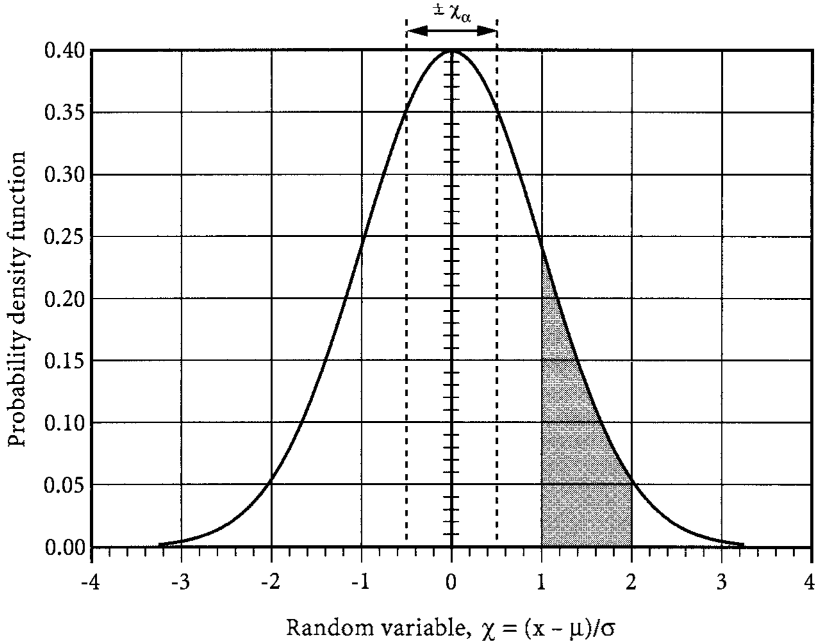

Fig. B.25a Standard form of the normal PDF.

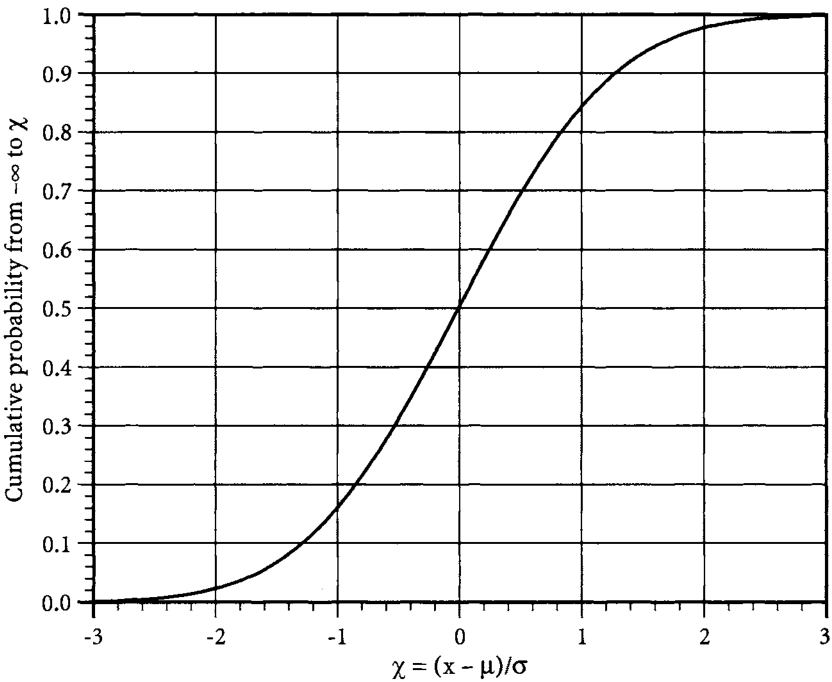

Fig. B.25b Normal cumulative distribution.

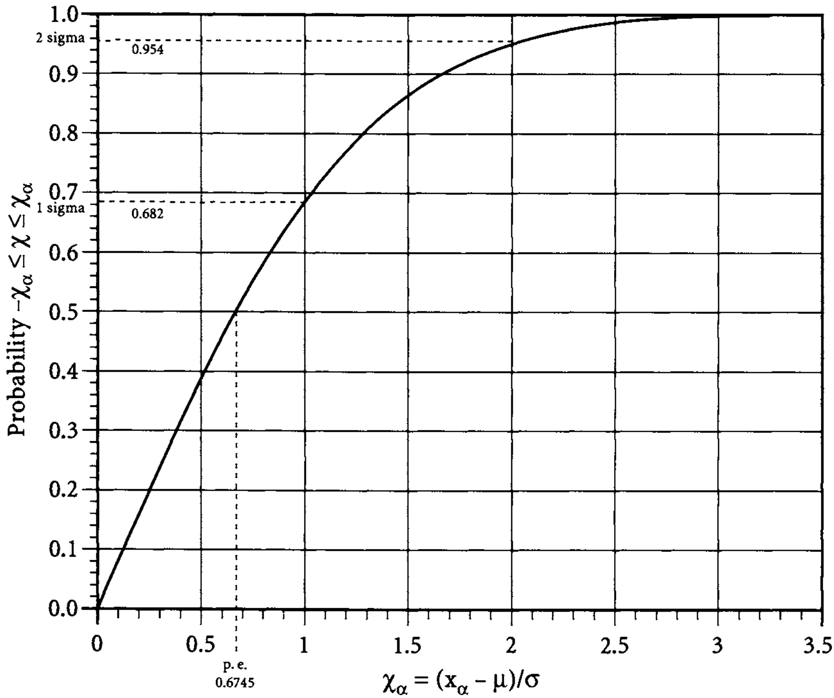

Fig. B.25c Probability χ falls within the interval $\pm\chi_\alpha$.

of χ_α. The results are presented in Fig. B.25c. For example, the probability that χ falls between ± 1 (or $x - \mu$ is between $\pm\sigma$) is 0.682, and the probability is 0.954 for χ between ± 2 (or $x - \mu$ is between $\pm 2\sigma$), according to Fig. B.25c. Another value of $\pm\chi_\alpha$ of interest is the one in which the probability that χ is within the interval is 0.5. This particular limit is known as the error probable (e. p.) or probable error (p. e.) and is

$$\text{e. p.}(\chi) \pm -0.6745 \tag{B.48}$$

according to Fig. B.25c.

B.7.2.2 Comparison of the normal PDF to the binomial PMF. The normal distribution for a random variable is a probability density function, and consequently the probability that the random variable will have a value within an interval is equal to the area under the PDF curve within the interval, as illustrated in Fig. B.25a. On the other hand, the binomial distribution is defined at discrete integer locations along the variable axis, as illustrated in Fig. B.15 for the 10-encounter scenario. If the discrete probability values at the integer locations are expanded into rectangular areas centered at the integers such that the area over the integer is equal to the probability, a discrete PDF is created. For example, the binomial distribution shown in Fig. B.15 is illustrated in Fig. B.26 by the narrow gray bars at each specific number of aircraft killed in the 10 encounters. The binomial distribution indicated by the gray bars can be converted into the discrete binomial PDF shown in

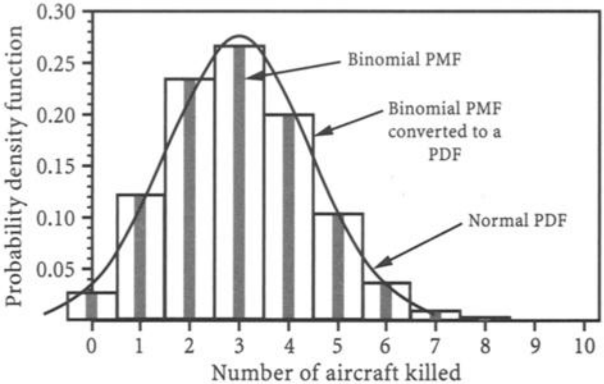

Fig. B.26 Comparison of the binomial and normal distributions for the 10-encounter problem.

Fig. B.26. For example, the binomial value for two aircraft killed is 0.2335 according to Table B.4. Equating this value to the area in the rectangle about the binomial value results in a height (or equivalent PDF value) of 0.2335. Note that the PDF value is equal to the binomial probability because the interval (or width of the rectangle) is unity. The normal PDF given by Eq. (B.46a) with the same mean ($\mu = 3$) and variance ($\sigma^2 = 2.1$) is also shown in Fig. B.26. Note the relatively close agreement. In general, the binomial distribution is closely approximated by the normal distribution provided that neither P_K nor P_S are close to zero and that N is large.[2]

Go to Problem B.7.5.

B.7.3 Two-Dimensional Normal Probability Density Function

Learning Objective B.7.4 Use the bivariate normal distribution to compute the probability that two continuous random variables will be within specified intervals.

The one-dimensional normal PDF given by Eqs. (B.46a) and (B.46c) can be used to develop the normal PDF in a two-dimensional or bivariate space (x_1, x_2) if the random variables x_1 and x_2 are independent. When the variables are independent, the outcome of one variable is unaffected by the outcome of the second variable, and hence the two-dimensional PDF is given by the joint probability or product of the two one-dimensional normal distributions. Thus, the general form of the bivariate normal PDF is

$$f(x_1, x_2) = f(x_1)f(x_2) = \left[\frac{1}{\sigma_1\sqrt{2\pi}} e^{-0.5\left(\frac{x_1-\mu_1}{\sigma_1}\right)^2}\right]\left[\frac{1}{\sigma_2\sqrt{2\pi}} e^{-0.5\left(\frac{x_2-\mu_2}{\sigma_2}\right)^2}\right]$$

$$= \frac{1}{2\pi\sigma_1\sigma_2} e^{\left[-0.5\left(\frac{x_1-\mu_1}{\sigma_1}\right)^2 - 0.5\left(\frac{x_2-\mu_2}{\sigma_2}\right)^2\right]} \tag{B.49a}$$

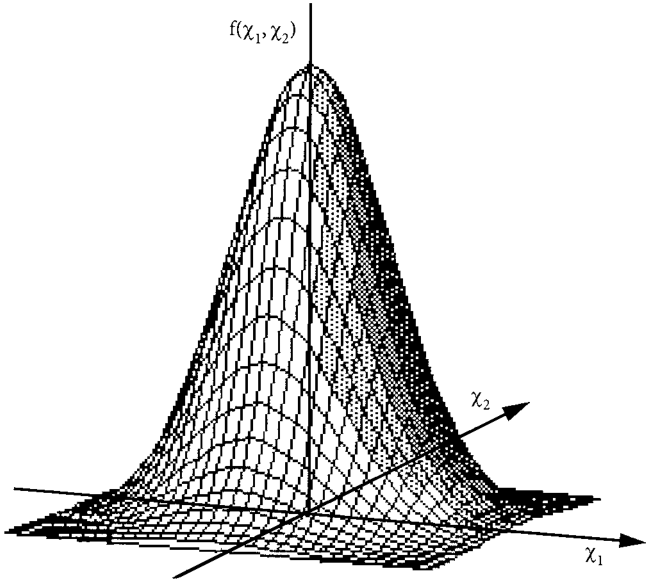

Fig. B.27 Bivariate normal distribution.

where μ_1 and μ_2 are the variable means and σ_1 and σ_2 are the variable standard deviations. The standard form of the bivariate normal in terms of the nondimensional variables χ_1 and χ_2 is given by

$$f(\chi_1, \chi_2) = f(\chi_1)f(\chi_2) = \left(\frac{1}{\sqrt{2\pi}}e^{-0.5\chi_1^2}\right)\left(\frac{1}{\sqrt{2\pi}}e^{-0.5\chi_2^2}\right)$$

$$= \frac{1}{2\pi}e^{(-0.5\chi_1^2-0.5\chi_2^2)} \tag{B.49b}$$

where

$$\chi_1 = \frac{x_1 - \mu_1}{\sigma_1} \quad \text{and} \quad \chi_2 = \frac{x_2 - \mu_2}{\sigma_2} \tag{B.49c}$$

Figure B.27 illustrates the bivariate normal distribution in χ_1 and χ_2.

The bivariate normal PDF is used to calculate the joint probability that each of the variables lies within some specified interval. For example, the probability that the χ_1 lies between 2 and 3 and χ_2 lies between 0.5 and 1.0 is given by

$$\text{Probability}\left\{\begin{matrix} 2 \le \chi_1 \le 3 \\ 0.5 \le \chi_2 \le 1 \end{matrix}\right\} = \frac{1}{2\pi}\int_2^3 \left(e^{-0.5\chi_1^2}\right) d\chi_1 \int_{0.5}^1 \left(e^{-0.5\chi^2}\right) d\chi_2 \tag{B.50}$$

Go to Problem B.7.6.

B.7.4 Circular Normal or Rayleigh Probability Density Function

Learning Objectives	**B.7.5**	**Use the circular normal to determine the probability the random variable will be within a specified range.**
	B.7.6	**Describe and relate the error probable and the circular error probable.**

In certain two-dimensional situations the conditions of circular or axisymmetric symmetry either apply or are assumed. For example, the tracking errors associated with a circular dish antenna might not be a function of the line-of-sight angle, and the miss distance of rounds around an aimpoint might be circularly symmetric. In such situations the two standard deviations σ_1 and σ_2 are, or are assumed to be, equal to σ_r. Furthermore, the means μ_1 and μ_2 can be, or are assumed to be, zero. Under these conditions the bivariate normal function given by Eq. (B.49a) simplifies to the one-dimensional circular normal PDF in the radial variable r and is given by

$$f(r) = \frac{1}{2\pi\sigma_r^2}\exp\left(\frac{-r^2}{2\sigma_r^2}\right) \tag{B.51a}$$

where

$$\begin{aligned}\mu_1 &= \mu_2 = 0\\ \sigma_1 &= \sigma_2 = \sigma_r\\ r^2 &= x_1^2 + x_2^2\end{aligned} \tag{B.51b}$$

The circular normal PDF in the standard form in the nondimensional radial variable ρ is

$$f(\rho) = \frac{1}{2\pi}\exp(-0.5\rho^2) \tag{B.51c}$$

where

$$\begin{aligned}\chi_1 &= \frac{x_1}{\sigma_r}\\ \chi_? &= \frac{x_2}{\sigma_r}\\ \rho^2 &= \frac{r^2}{\sigma_r^2} = \chi_1^2 + \chi_2^2\end{aligned} \tag{B.51d}$$

The probability that ρ (or r/σ_r) lies within a radial interval from ρ_a (or r_a/σ_r) to ρ_b (or r_b/σ_r) is given by

$$\text{Probability } (\rho_a \le \rho \le \rho_b) = \frac{1}{2\pi}\int_{\rho_a}^{\rho_b}\int_0^{2\pi}\exp(-0.5\rho^2)\,\rho\,\mathrm{d}\theta\,\mathrm{d}\rho$$

$$= \int_{\rho_a}^{\rho_b}\rho\exp(-0.5\rho^2)\,\mathrm{d}\rho \tag{B.52}$$

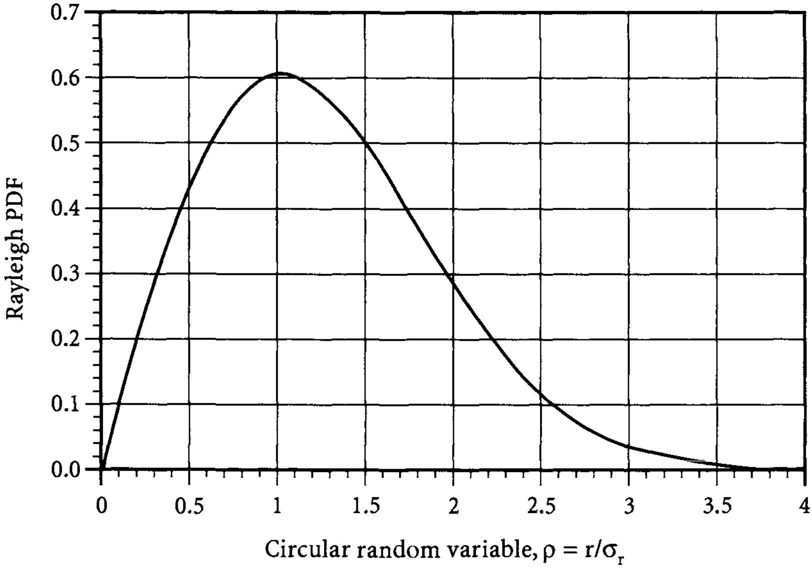

Fig. B.28a Rayleigh PDF.

The integrand in Eq. (B.52) is referred to as the Rayleigh probability density function and is shown in Fig. B.28a. The value of the integral in Eq. (B.52) for the special case where $\rho_a = 0$ is shown in Fig. B.28b as a function of ρ_b.

A special case of Eq. (B.52) is when $\rho_a = 0$ and ρ_b is that particular value, called the circular error probable (CEP) or circular probable error (CPE), which results in a 0.5 probability that the error lies within the interval from zero to the CEP. For this case

$$\mathrm{CEP}(\rho) = 1.177 \quad \text{or} \quad \mathrm{CEP}(r) = 1.177\sigma_r \tag{B.53}$$

according to Fig. B.28b. The CEP for the circular symmetric situation is analogous to the error probable for the one-dimensional variable given by Eq. (B.48). The relationships between the dimensional variables r, x_1, x_2 and the probable errors are illustrated in Fig. B.29. The darkly shaded square area between the error probables represents the 0.25 probability that r lies within the square area, and the CEP encloses the 0.5 probability.

Go to Problem B.7.7.

B.8 Expected Value, Monte Carlo, and Markov Chain Models

A model can be defined as a representation of an entity, such as a physical object or a real-world process. According to Ref. 4, models are iconic, for example, photographs; analog, for example, an electrical analog in which voltages represent another physical variable; and symbolic, that is, a descriptive or mathematical model. Mathematical models typically treat processes and are classified as analytic or simulations. Analytic models are used to determine exact solutions to relatively

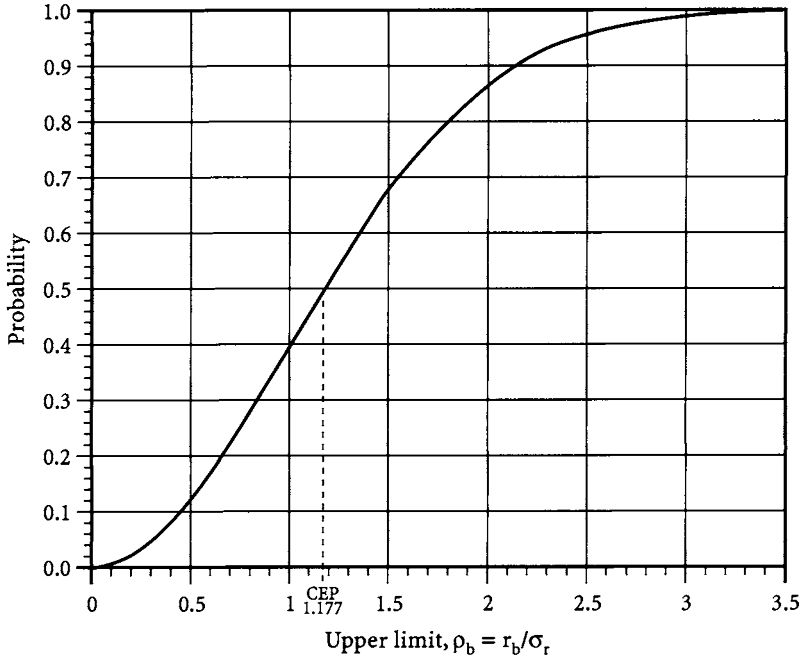

Fig. B.28b Probability ρ is within the interval $\rho_a = 0$ to $\rho = \rho_b$.

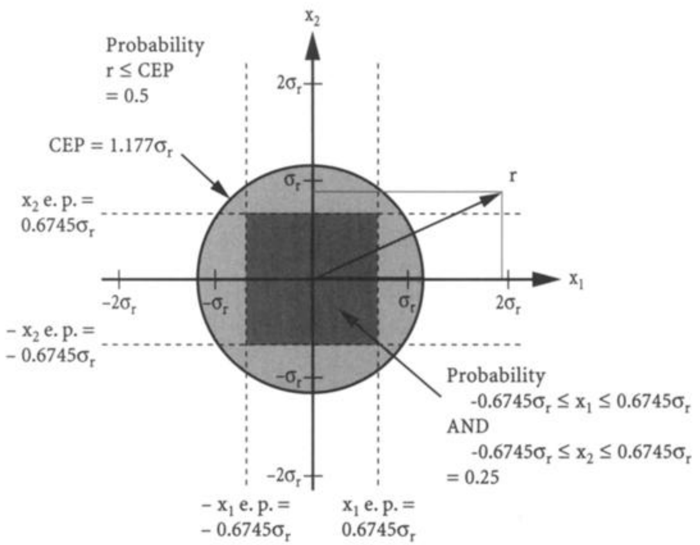

Fig. B.29 Relationships between r, x_1, and x_2, the probable errors, and the CEP.

simple processes with deterministic outcomes, for example, the height of a ballistic projectile in a vacuum. Simulation models are used to determine approximate solutions to complicated real-world processes. The outcomes of the processes can be deterministic or random. Probability models are used to simulate random processes, such as an endgame, or a one-on-one encounter, or a many-on-many scenario. There are three major types of probability models used in survivability assessment: expected value, Monte Carlo, and Markov chain.

B.8.1 Expected Value Model

Learning Objective B.8.1 Use the expected value model to determine outcome probabilities.

An example of the expected value model is the tree diagram in Fig. 1.3 and the corresponding killability equation, Eq. (1.5c). Each of the probabilities on the right-hand side of Eq. (1.5c) is assigned a value, and the value for P_K is the joint probability that all of the outcomes occur, that is, the path proceeds down the right-hand side of the tree diagram in Fig. 1.3. Another example of an expected value model is the tree diagram shown in Fig. B.13 for the outcomes of three independent, one-on-one encounters. The probability of each outcome at the bottom of the tree is given by the joint probability of the individual branches on the path. A third example of an expected value model is the encounter scenario where the detection of the aircraft and the flight of a missile from launch to intercept to warhead detonation is modeled using deterministic equations. The probability the aircraft is killed is then determined based upon the given detonation point. Many one-on-one encounters are modeled in this manner. However, when the scenario is too complex because of many branching points in the process, or when the randomness of several processes or parameters, such as the detection of the aircraft and the length of burn time of the boost motor, is included, the Monte Carlo model is often used.

Go to Problem B.8.1.

B.8.2 Monte Carlo Model

Learning Objective B.8.2 Use the Monte Carlo model to determine outcome probabilities.

The Monte Carlo model, like the expected value model, is also used to determine the probability that certain outcomes occur. For example, it could be used to determine the outcomes at the bottom of the tree diagram for the three independent encounter scenario shown in Fig. B.13. However, instead of multiplying the probabilities of the individual branches to determine the joint probability of a path or event, as is done in the expected value model, a random number draw is made at each branch point, starting at the top of the tree, and the draw is compared to the assigned branch probabilities at that point to determine which outcome occurs. The procedure

Table B.6 Monte Carlo results (1000 trials)

Model	0 killed	$A3$ killed	$A2$ killed	$A2, A3$ killed	$A1$ killed	$A1, A3$ killed	$A1, A2$ killed	$A1, A2, A3$ killed
Monte Carlo	329	151	173	58	140	65	60	24
Expected value	343	147	147	63	147	63	63	27

continues from branch point to branch point until the bottom of the tree is reached, and the event is recorded. The entire process is then repeated many times.

The Monte Carlo procedure for the random process shown in Fig. B.13 is as follows. The path begins at the top of the tree at O. There are two branches it could follow, OA and OB. According to the data given, the probabilities associated with these two branches are 0.7 and 0.3, respectively. A random draw of a number between 0 and 1 is made, say 0.47. This number is compared with the probability of proceeding down branch OA; aircraft $A1$ is not killed in encounter 1, which is 0.7. Because it is smaller than 0.7, the path goes from O to A (aircraft $A1$ has survived its encounter). At branch point A another random draw is made for the second encounter to determine which branch is followed, AC or AD. Suppose 0.87 is drawn. Because 0.87 is larger than 0.7, the path proceeds from A to D, and aircraft $A2$ is killed. Finally, at branch point D another draw is made, say 0.13 which is less than 0.7, and the path proceeds along the survival path to point I. Because I is at the end of the process, the first trial ends. The result of this first Monte Carlo trial is aircraft $A1$ survived, $A2$ was killed, and $A3$ survived. Another trial is then conducted starting at the top of the tree and proceeding to the bottom. Suppose that trial resulted in the path from O to A to C to H. After many trials each of the eight outcomes at the bottom of the tree will have been reached a number of times. Suppose after 1000 trials, the results were those presented in Table B.6. Also presented in the table are the results from the expected value model, which are assumed to be the correct results. As the number of trials increases, the Monte Carlo results will approach the expected value results.

Parameters with discrete and continuous probability distributions, such as the receiving radar range bin and the burn time of the missile booster motor, can also be included in a Monte Carlo model. A random draw will result in a value for the parameter to be used in the model computations.

Go to Problem B.8.2.

B.8.3 Markov Chain Model

Learning Objective **B.8.3 Use the Markov Chain to determine outcome probabilities.**

Briefly, the Markov chain, also known as the state transition matrix method, assumes that a sequence of independent events associated with a system can be modeled as a Markov process. In a Markov process the system is defined to have two or more states or conditions in which it can reside. These states are contained within the state vector $\{S\}$. An event occurs, such as three aircraft go on a mission or an aircraft is hit, and each state of the system will transition to all other possible states with a specific probability for each transition. The sequential process of evaluating the probability the system exists in each of the several possible states after events $1, 2, 3, \ldots, J$ is based upon the probability the system existed in each of the possible states after events $0, 1, 2, \ldots, J-1$, respectively, and is referred to as a Markov chain. The transition matrix $[T]$ transforms the $\{S\}^{(j)}$ state vector to the $\{S\}^{(j+1)}$ state vector in the form

$$\{S\}^{(j+1)} = [T]\{S\}^{(j)} \qquad j = 0, 1, 2, \ldots J-1 \tag{B.54}$$

Rather than dwell on the mathematical theory, however, several examples in survivability will be presented.

B.8.3.1 Individual aircraft state vector. The scenario shown in Fig. B.13 consists of the three aircraft: $A1$, $A2$, and $A3$. Initially, at event $j = 0$ all three aircraft are alive. Then they go on a mission, and each aircraft is encountered by one weapon. Each aircraft survives the encounter with the probability 0.7 and is killed in the encounter with the probability 0.3. After the mission some of the aircraft might still be alive, and some might be dead. Thus, two possible states are considered for each aircraft: alive and dead (Note 20). Because there are three aircraft and each aircraft can exist in one of two mutually exclusive states, the state vector of the system after the jth event could be defined as

$$\{S\}^{(j)} = \begin{Bmatrix} A1S \\ A1K \\ A2S \\ A2K \\ A3S \\ A3K \end{Bmatrix}^{(j)} \tag{B.55a}$$

where AiS refers to the survival state for aircraft Ai and AiK refers to the killed state. Before the first mission, when $j = 0$, all three aircraft are alive. Thus, the probability that the ith aircraft is in the AiS state is unity. Hence the state vector prior to the first mission $\{S\}^{(0)}$ is given by

$$\{S\}^{(0)} = \begin{Bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{Bmatrix}^{(0)} \tag{B.55b}$$

After the first mission, where $j + 1 = 1$, each aircraft either survived the mission with a probability of 0.7 or was killed with a probability of 0.3, that is, aircraft Ai will remain in the AiS condition with a probability of 0.7 and will transition to the AiK condition with a probability of 0.3. The two transition probabilities for each aircraft state appear in the state transition matrix $[T]$ shown in Table B.7.

Table B.7 State transition matrix [T]

Probability of transitioning from this state						
$A1S$	$A1K$	$A2S$	$A2K$	$A3S$	$A3K$	To this state
0.7	0	0	0	0	0	$A1S$
0.3	1	0	0	0	0	$A1K$
0	0	0.7	0	0	0	$A2S$
0	0	0.3	1	0	0	$A2K$
0	0	0	0	0.7	0	$A3S$
0	0	0	0	0.3	1	$A3K$
1	1	1	1	1	1	Sum

The elements in each column in [T] are the probabilities of transitioning from the state corresponding to the column (containing the element) to the state corresponding to the row (containing the element). Thus, the first column of the matrix shown in Table B.7 includes the P_S and P_K probabilities for the transition of aircraft $A1$; $A1$ remains in the $A1S$ state with the probability of 0.7, and it transitions to the $A1K$ state with the probability 0.3. The remaining elements in the first column are zero because aircraft $A1$ cannot transition to a state for $A2$ or $A3$. Note that the sum of the elements in the column must equal unity in order to account for all possible transitions. In the second column of [T], the aircraft $A1$ is in a killed state. Aircraft that are killed cannot transition out of the killed state. Such a state is called an absorbing state, and the probability the aircraft remains in the absorbing state is 1. Because of the assumed equality in encounters, the two pairs of remaining columns for $A2$ and $A3$ contain the same elements as $A1$, in the appropriate locations.

The general state transition matrix equation for this example is

$$\begin{Bmatrix} A1S \\ A1K \\ A2S \\ A2K \\ A3S \\ A3K \end{Bmatrix}^{(j+1)} = \begin{bmatrix} 0.7 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} A1S \\ A1K \\ A2S \\ A2K \\ A3S \\ A3K \end{Bmatrix}^{(j)} \tag{B.56a}$$

Before the first mission $j = 0$ and $\{S\}^{(0)}$ is given by Eq. (B.55b). Hence, Eq. (B.56a) becomes

$$\begin{Bmatrix} 0.7 \\ 0.3 \\ 0.7 \\ 0.3 \\ 0.7 \\ 0.3 \end{Bmatrix}^{(1)} = \begin{bmatrix} 0.7 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{Bmatrix}^{(0)} \tag{B.56b}$$

Comparing the state vector $\{S\}^{(1)}$ given in Eq. (B.56b) to the outcomes given at the bottom of the kill tree in Fig. B.13 requires some interpretation of the results in the figure. The union of the four mutually exclusive events $A1K$ OR ($A1K$ AND $A2K$) OR ($A1K$ AND $A3K$) OR ($A1K$ AND $A2K$ AND $A3K$) shown in the figure includes all possible kills of aircraft $A1$ and results in a probability of kill of aircraft $A1$ of $0.147 + 0.63 + 0.63 + 0.27 = 0.30$, which is the result for the probability that $A1$ is in the killed state. Similar conclusions can be made for the other two aircraft.

If the aircraft that survive the first mission, defined by $\{S\}^{(1)}$, go on a second mission, and if each mission aircraft encounters one weapon with $P_S = 0.7$ and $P_K = 0.3$, Eq. (B.56a) becomes

$$\begin{Bmatrix} 0.49 \\ 0.51 \\ 0.49 \\ 0.51 \\ 0.49 \\ 0.51 \end{Bmatrix}^{(2)} = \begin{bmatrix} 0.7 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 0.7 \\ 0.3 \\ 0.7 \\ 0.3 \\ 0.7 \\ 0.3 \end{Bmatrix}^{(1)} \tag{B.57}$$

Thus, the probability that each aircraft survives both missions is 0.49, and the probability it has been killed after two missions is 0.51. This agrees with the results for the two sequential one-on-one encounters shown in Fig. B.20a.

B.8.3.2 'Three aircraft as a system' state vector. Because the state vector was defined in the form given by Eq. (B.55a), there is no transition from the state of one aircraft to the state of another aircraft. In essence, each aircraft could have been considered alone. However, if the state vector is defined to be

$$\{S\}^j = \begin{Bmatrix} 3S \\ 2S, 1K \\ 1S, 2K \\ 3K \end{Bmatrix} \tag{B.58a}$$

the distinction between the individual aircraft is gone. Here, the system consists of three aircraft, and the states of the system are all three aircraft survive ($3S$), two aircraft survive and one is killed ($2S$, $1K$), one aircraft survives and two are killed ($1S$, $2K$), and all three aircraft are killed ($3K$). The state transition matrix equation for this state vector is

$$\begin{Bmatrix} 3S \\ 2S, 1K \\ 1S, 2K \\ 3K \end{Bmatrix}^{(j+1)} = \begin{bmatrix} 0.343 & 0 & 0 & 0 \\ 0.441 & 0.49 & 0 & 0 \\ 0.189 & 0.42 & 0.7 & 0 \\ 0.027 & 0.09 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 3S \\ 2S, 1K \\ 1S, 2K \\ 3K \end{Bmatrix}^{(j)} \tag{B.58b}$$

The elements in the first column are the transition probabilities from the ($3S$) state. These probabilities are obtained from the tree diagram shown in Fig. B.13. At the top of the tree, the system is in the ($3S$) state. As the path proceeds down the tree, the state can change. The first element in first column is the path *OACG* where all three aircraft survive the mission, that is, the state remains the same with the probability 0.343. The second element in the first column is the probability the state transitions from ($3S$) to ($2S$, $1K$) and is given by the union of the mutually exclusive events along the paths where one aircraft is killed: *OACH*, *OADI*, and *OBEK*, or $0.147 + 0.147 + 0.147 = 0.441$. The third element is the probability the state transitions from ($3S$) to ($1S$, $2K$) and is the union of the mutually exclusive events along the paths where two aircraft are killed: *OADJ*, *OBEL*, and *OBFM*, or $0.063 + 0.063 + 0.063 = 0.189$. The last element is the path *OBFN*, where all three aircraft are killed with a 0.027 probability.

The elements in the second column in $[T]$ shown in Eq. (B.58b) apply to the situation where only two aircraft are available for the mission because the system is in the ($2S$, $1K$) state. Assuming that each of the two aircraft will encounter one weapon, the tree consists of the two encounters shown in Fig. B.11. The first element in the column is the transition from ($2S$, $1K$) to ($3S$), which is impossible because one aircraft is dead; hence, the transition probability is 0. The second element in the column is the path *OAD*, where both aircraft survive with the probability 0.49 and the state remains the same. The third element is the transition from ($2S$, $1K$) to ($1S$, $2K$), that is, one of the two mission aircraft is killed, and the probability is given by the union of the two mutually exclusive paths *OAD* and *OBE* shown in Fig. B.11, or $0.21 + 0.21 = 0.42$. The last element in the second column is the transition from ($2S$, $1K$) to ($3K$), where both mission aircraft are killed. This probability is given by the path *OBF*, or 0.09. The third column represents transitions from the state ($1S$, $2K$); hence, only one aircraft is available for the mission. This state can only remain the same, with the probability 0.7, or transition to the ($3K$) state with the probability 0.3. The fourth column represents the absorbing state ($3K$), where all three aircraft are killed and no transitions to any other state are possible. Note that the sum of the elements in each of the four columns is one.

Prior to the first mission, the state vector is

$$\{S\}^{(0)} = \begin{Bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{Bmatrix}^{(0)} \tag{B.59a}$$

Therefore, the state transition matrix equation for the first mission is given by

$$\begin{Bmatrix} 0.343 \\ 0.441 \\ 0.189 \\ 0.027 \end{Bmatrix}^{(1)} = \begin{bmatrix} 0.343 & 0 & 0 & 0 \\ 0.441 & 0.49 & 0 & 0 \\ 0.189 & 0.42 & 0.7 & 0 \\ 0.027 & 0.09 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{Bmatrix}^{(0)} \tag{B.59b}$$

The state vector $\{S\}^{(1)}$ given by Eq. (B.59b) is the same as the results shown at the bottom of the tree diagram in Fig. B.13. If another mission is flown, the state vector after two missions is

$$\begin{Bmatrix} 0.118 \\ 0.367 \\ 0.382 \\ 0.133 \end{Bmatrix}^{(2)} = \begin{bmatrix} 0.343 & 0 & 0 & 0 \\ 0.441 & 0.49 & 0 & 0 \\ 0.189 & 0.42 & 0.7 & 0 \\ 0.027 & 0.09 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 0.343 \\ 0.441 \\ 0.189 \\ 0.027 \end{Bmatrix}^{(1)} \tag{B.59c}$$

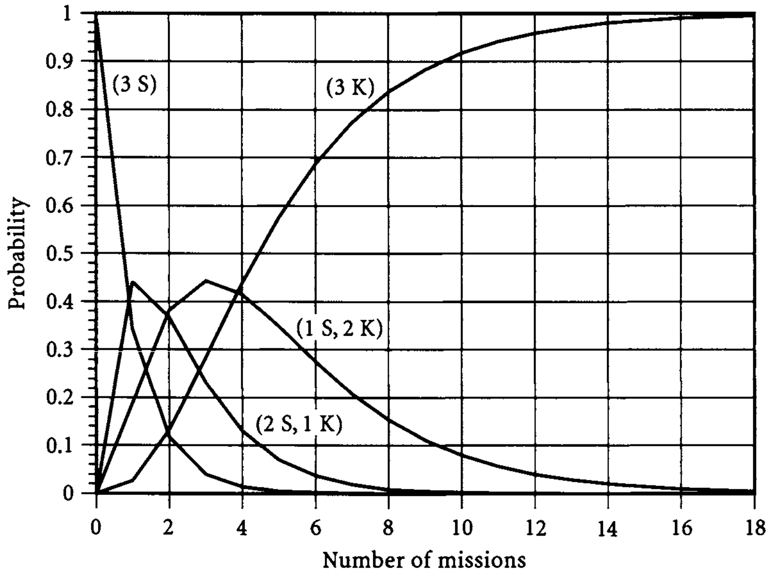

Fig. B.30 Markov chain results for three aircraft as a system.

Thus, there is a 0.118 probability that all three aircraft are still alive, a 0.367 probability that one aircraft has been killed, a 0.382 probability that two aircraft have been killed, and a 0.133 probability that all three aircraft have been killed after two missions. The Markov chain represented by Eq. (B.58b) can be continued for as many missions as desired. Figure B.30 shows the probabilities for each state as a function of the number of missions.

B.8.3.3 'All possibilities' state vector. The state vector defined in Eq. (B.58a) does not distinguish which of the three aircraft are killed. Another state vector that does distinguish between aircraft is

$$\{S\}^j = \begin{Bmatrix} 3S \\ A1K \\ A2K \\ A3K \\ A1K \text{ AND } A2K \\ A1K \text{ AND } A3K \\ A2K \text{ AND } A3K \\ 3K \end{Bmatrix} \tag{B.60a}$$

where the state $A1K$ means only aircraft $A1$ is killed and the new terms AiK AND AjK represent the state where only Ai and Aj are killed. All possible combinations of aircraft survival and kill are in this state vector. The elements of the state transition matrix for this state vector are obtained from the tree diagram in Fig. B.13. The state transition matrix equation for this state vector is given by

$$\begin{Bmatrix} 3S \\ A1K \\ A2K \\ A3K \\ A1K \text{ AND } A2K \\ A1K \text{ AND } A3K \\ A2K \text{ AND } A3K \\ 3K \end{Bmatrix}^{(j+1)} = \begin{bmatrix} 0.343 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.147 & 0.49 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.147 & 0 & 0.49 & 0 & 0 & 0 & 0 & 0 \\ 0.147 & 0 & 0 & 0.49 & 0 & 0 & 0 & 0 \\ 0.063 & 0.21 & 0.21 & 0 & 0.7 & 0 & 0 & 0 \\ 0.063 & 0.21 & 0 & 0.21 & 0 & 0.7 & 0 & 0 \\ 0.063 & 0 & 0.21 & 0.21 & 0 & 0 & 0.7 & 0 \\ 0.027 & 0.09 & 0.09 & 0.09 & 0.3 & 0.3 & 0.3 & 1 \end{bmatrix} \begin{Bmatrix} 3S \\ A1K \\ A2K \\ A3K \\ A1K \text{ AND } A2K \\ A1K \text{ AND } A3K \\ A2K \text{ AND } A3K \\ 3K \end{Bmatrix}^{(j)} \tag{B.60b}$$

The first column in $[T]$ consists of the eight probabilities at the bottom of the tree diagram shown in Fig. B.13. The second column contains the probabilities for transitioning from the $A1K$ state to the other states when two aircraft fly the mission. Note the many zeros in the column where a transition is not possible. The elements in the remaining columns can be identified in a similar manner.

Go to Problem B.8.3.

Endnotes

1. Probability theory is also used in statistical inference to determine the confidence in the statistical value for a population parameter inferred from a sample statistic.
2. The assumption is made that g is a constant value throughout the trajectory of the projectile.
3. The necessity to include any random behavior in a survivability assessment depends upon the significance or impact of the randomness upon the outcome of the incident. If the random behavior of V_0, θ, and the wind force significantly affect the likelihood the projectile hits the aircraft, this randomness should be included in the assessment.
4. The probability associated with any deterministic outcome is always unity.
5. The scenario consists of the particular air defense weapon, the aircraft and its flight path, the environment, and every other factor that can affect the outcome.
6. Another possible outcome of the encounter is that the aircraft is hit and damaged but not killed. This particular outcome is contained within the survival outcome.
7. The fact that two rolls of the die might or might not have the same outcome is a result of the randomness in the toss itself and not to the physical properties of the die; its properties are deterministic.

8. An incident with a deterministic outcome theoretically requires only one experiment.
9. The expression 'a random selection' is used only with equiprobable spaces.
10. Although the events associated with multiple rolls or tosses are independent, the events associated with any one roll or toss are not independent; they are in fact mutually exclusive.
11. From a completely general point of view, every universal set is a subset of a larger universal set. As a consequence, many of the conditions associated with a process are omitted because they are obvious. For example, the probability that an aircraft is killed by a weapon is denoted as P_K, but, in fact, the kill is conditional upon the aircraft being exposed to the weapon. In other words, P_K refers to the probability that a weapon will kill an aircraft, given an opportunity to do so.
12. According to Eq. (B.16), the joint probability of the events aircraft hit H and aircraft kill K is given by $P_{K\,\mathrm{AND}\,H} = P_{H\,\mathrm{AND}\,K} = P_H P_{K|H}$. Strictly speaking, the product of P_H and $P_{K|H}$ is the joint probability the aircraft is hit and killed. However, this probability is usually referred to simply as the probability that the aircraft is killed and is denoted by P_K rather than $P_{H\,\mathrm{AND}\,K}$. The requirement that the aircraft be hit in order to be killed is implied in the equation $P_K = P_H P_{K|H}$.
13. The observation that $P_{A|B} = P_A$ (based upon the data collected) is not sufficient proof that A and B are independent.
14. The binomial coefficients are the coefficients of the expansion for $(p+q)^N$. In survivability assessment p is P_S, and q is P_K. Thus, $p+q$ is unity, and therefore the sum of the binomial coefficients for all K is unity.
15. The fact that P_K was computed using the number of aircraft killed in the 10 aircraft experiment presented in Table B.1 means that the assumption was made that the number of aircraft killed in the experiment was the expected number, which, of course, might not be true. To improve the estimate for P_K, many 10-encounter experiments should be conducted. As the number of experiments increases, the estimate for P_K improves.
16. The assumption is made that the kill assessment process used by the air defense prevents the assignment of weapons to killed aircraft.
17. The uniform distribution is described in the next section. Essentially, it means each weapon is equally likely to be found anywhere within the defended area.
18. Other probability density functions for the random variable x, where $x \geq 0$, include the following:

$$\text{Lognormal PDF} = \frac{e^{-(\ln x/2)^2}}{x}$$

$$\text{Maxwell PDF} = x^2 e^{-x^2/2}$$

$$\text{Beta PDF} = x^b(1-x)^c$$

$$\text{Gamma PDF} = x^n e^{-x}$$

$$\text{Weibull PDF} = \gamma x^{(\gamma-1)} e^{-x\gamma}$$

where b, c, and γ are positive numbers and n is an integer. (http://www.weibull.com and http://www.itl.nist.gov/div898/software/dataplot/.)

19. Numerical values for σ and μ are determined from the data available for the random variable as described in Chapter 4, Sec. 4.3.4.2.
20. A damaged state could also be included for each aircraft if information were available regarding the probabilities of an aircraft hit and kill given a hit.

References

[1]Marriott, F. H. C., *A Dictionary of Statistical Terms*, Longman Scientific and Technical, New York, 1990.

[2]Lipschutz, S., *Probability*, 1st ed., Schaum's Outline Series, McGraw–Hill, New York, 1965.

[3]Spiegel, M. R., *Statistics*, 1st ed., Schaum's Outline Series, McGraw–Hill, New York, 1961.

[4]Przemieniecki, J. S., *Mathematical Methods in Defense Analysis, Second Edition*, AIAA, Washington, DC, 1944, p. 319.

Problems

B.1.1 Statistics has been defined as the science of collecting, analyzing, and interpreting numerical data relating to an aggregate of individuals: True or False.

B.1.2 Probability theory could be described as the method of determining what has happened in the past: True or False.

B.1.3 A gun fires a ballistic projectile at an aircraft. One outcome of the engagement is the projectile hits the aircraft: True or False.

B.1.4 A gun fires a ballistic projectile at an aircraft. One outcome of the engagement is the maximum height of the projectile above the gun: True or False.

B.1.5 A 100-grain cubic fragment impacts the outer skin of a stationary aircraft at a velocity that is slightly higher than the V_{50} velocity for the given combination of penetrator, plate, and impact conditions. What are the outcomes of the hit and are they deterministic?

B.1.6 An API round penetrates the wall of a fuel tank and enters into the ullage. The outcome of the penetration into the ullage is deterministic: True or False.

B.1.7 The maximum gain of a particular type of radar antenna is a parameter in the aircraft detection process: True or False.

B.1.8 The weight of the propellant in a particular SAM is a parameter during missile flyout: True or False.

B.1.9 Why is the muzzle velocity of a gun-fired ballistic projectile a random variable?

B.1.10 Time is an independent variable in the flyout of a missile toward an aircraft: True or False.

B.1.11 Ten aircraft enter into an area defended by two guns. Each gun fires at all 10 aircraft. The number of aircraft that can be killed by the guns is a discrete random variable. Why?

B.1.12 Why is the height of a gun-fired ballistic projectile 2 s after firing a continuous random variable?

B.1.13 Is the endgame between a proximity-fuzed HE warhead and an aircraft a stochastic process in probability theory? Why?

B.1.14 What are some of the possible outcomes of interest in the endgame?

B.1.15 What is an experiment, and what is a trial in probability theory?

B.1.16 When is the flyout of a missile toward an aircraft an experiment?

B.1.17 What is an event in probability theory?

B.1.18 The warhead detonation in the endgame is not an event: True or False.

B.1.19 The warhead detonation followed by six fragment hits on the aircraft is an event: True or False.

B.1.20 The endgame outcomes of aircraft kill and aircraft hit are mutually exclusive outcomes: True or False.

B.1.21 An aircraft is engaged by a weapon. The outcomes of aircraft kill and aircraft survival are the exhaustive outcomes for the engagement: True or False.

B.1.22 Determine the probability that a jack of spades will be the next card drawn from a well-shuffled pack of 52 playing cards using the classical theory of determining probabilities.

B.1.23 Find a deck of playing cards. Use the experimental method to determine the probability that a diamond will be the card drawn from a well-shuffled deck. Conduct 20 trials to determine $P(\text{diamond})$. Replace the card, and shuffle the deck after each trial. What is the probability of drawing a diamond if you use the classical approach for determining probabilities?

B.1.24 The CO of your air wing asks you to determine the lethality of a particular weapon against your attack aircraft in a particular one-on-one air-to-surface scenario. You decide to use the experimental method to determine the various probabilities of interest. You find an unbiased observer and 36 volunteers to fly and attempt to kill the surface target defended by the weapon. The observer collects the following data from the 36 encounters:

$$\text{Number of aircraft detected} = 28$$
$$\text{Number of aircraft engaged} = 22$$
$$\text{Number of aircraft hit} = 12$$
$$\text{Number of aircraft killed} = 8$$

Determine the probabilities $P_{D|A}$, P_E, $P_{E|D}$, $P_{K|H}$, and P_K.

B.2.1 The universal set of aircraft in the experiment described in Problem B.1.24 consists of the 28 aircraft detected: True or False.

B.2.2 Using the aircraft experiment described in Question B.1.24, describe one sample point in the sample space.

B.2.3 The first six aircraft in the experiment described in Question B.1.24 have the following outcomes.

Aircraft #1 was detected but not engaged.
Aircraft #2 was not detected.
Aircraft #3 was detected and engaged and hit and killed.
Aircraft #4 was not detected.
Aircraft #5 was detected but not engaged.
Aircraft #6 was detected and engaged and hit but not killed.

Develop the sample space for these six aircraft, and indicate the set of aircraft that were hit.

B.2.4 Draw the Venn diagram for the experiment described in Problem B.1.24.

B.2.5 The strike planners in your air wing are interested in how many targets were killed by the aircraft in the experiment described in Problem B.1.24. According to the briefing given by the observer, two targets were killed by aircraft that were not detected, two were killed by aircraft that were detected, one was killed by an engaged aircraft, and one aircraft that was hit nevertheless continued on in and killed the target. Include this target kill set in the Venn diagram you developed in Problem B.2.4.

B.2.6 The vulnerability people are interested in the aircraft that were hit and killed in the experiment described in Problem B.1.24. According to the observer, the following nonredundant critical components were killed on the eight aircraft that were hit and killed.

Only the pilot was killed on one aircraft.
Only the fuel tank was killed on four aircraft.
Only the engine was killed on two aircraft.
Both the fuel tank and the engine were killed on one aircraft.

Draw the Venn diagram showing these component kill outcomes using the 12 aircraft hit aircraft as the universal set.

B.2.7 In general, the set of aircraft hit in combat is a subset of the aircraft killed: True or False.

B.3.1 The intersection of events of pilot only kill and engine only kill in Problem B.2.6 is_____ ?

B.3.2 The union of events of engine kill with fuel tank kill is_____?

B.3.3 The set of aircraft not killed is the complement of the set of aircraft killed: True or False.

B.3.4 The set of aircraft not killed is mutually exclusive to the set of aircraft killed: True or False.

B.3.5 The difference of the set of aircraft hit and the set of aircraft killed is called_____?

B.4.1 Consider the results of the experiment described in Problem B.2.6. Using these sample data, determine the following probabilities: 1) the probability the hit aircraft is killed as a result of a kill of the fuel tank only; 2) the probability the hit aircraft is killed as a result of a kill of the fuel tank and a kill of the engine; 3) the probability the hit aircraft is killed as a result of a kill of the fuel tank or the engine; and 4) the probability the hit aircraft is killed as a result of a kill of the pilot or a kill of the fuel tank.

B.4.2 You have been given the following data that were collected from several fuel tank inerting tests. The threat was a 12.7-mm AP-I round fired into the ullage of the fuel tank. The tests were conducted on stationary fuel tank simulators at sea level, and the temperature was 20°C. The level of fuel in the tank was 3 in. The purpose of the tests was to determine the relationship between the ability of the tank structure to withstand the overpressure caused by the ignition of the incendiary material within the ullage and the amount of ullage oxygen. The hypothesis was that the lower the amount of oxygen in the ullage, the lower the ullage overpressure, and the more likely the tank would withstand the overpressure. The outcomes noted on each test included the amount of oxygen in the ullage, whether or not the incendiary material ignited or functioned, and an estimate of the inability of the damaged tank structure to carry the design load, that is, was the tank killed or was it not killed by the shot. The results from 10 tests with oxygen occupying 10% of the volume were as follows (Y = yes and N = no):

Trial	1	2	3	4	5	6	7	8	9	10
Incendiary ignition	Y	Y	N	Y	N	Y	Y	Y	Y	N
Tank killed	Y	N	N	N	N	Y	N	N	Y	N

Determine the following probabilities: 1) the conditional probability the tank was killed given that it was hit; and 2) the conditional probability the tank was killed given incendiary ignition.

B.4.3 Examination of the test data given in Problem B.4.2 reveals that the outcome of a tank kill is independent of the outcome of incendiary ignition: True or False.

B.4.4 You are told that over the last 10 years 150 air strikes were conducted against petroleum, oil, and lubrication (POL) sites in Xanadu. Of these 150 strikes, 75 were deemed successful. You are also told that over the last 10 years, the San Francisco 49ers football team has won 120 out of 150 games played.

1) Develop the Venn diagram that includes both the strike outcomes and the 49ers football game outcomes. Assume independent outcomes.

2) An air strike is scheduled for next Monday. The 49ers are also scheduled to play next Monday night. What is the probability the air strike will be successful and the 49ers will win? Indicate this event on your Venn diagram.

3) What is the probability the mission will be successful or the 49ers will win? Indicate this event on the Venn diagram.

4) What is the probability the mission will not be successful and the 49ers will lose? Indicate this event on the Venn diagram.

5) Over the next 20 weeks, air strikes are planned to be conducted once a week, and the 49ers are scheduled to play a football game every week. How many weeks out of the 20 weeks do you expect the strike to be successful and the 49ers victorious?

6) Someone else examined the data just given in more detail and gave you the following additional data. Over the last 10 years the 49ers won the football game whenever a successful air strike was conducted on the same day. This occurred 10 times. What has changed? Write the equation relating the probabilities for this situation.

7) Do you really believe that there is a dependence between the game outcome and the strike outcome when they are played on the same day? If you do not, how do you explain the data?

B.4.5 You are the air operations officer. You are given the following information. Three aircraft are scheduled to launch on a mission at 0600 tomorrow. Examination of the combat data from similar missions reveals that the sortie loss rate for this mission is 0.004. What is the probability that Aircraft #1 is killed OR Aircraft #2 is killed OR Aircraft #3 is killed. Develop the Venn diagram for this situation, and relate this event to the total number of mission aircraft killed?

B.5.1 Five assault helicopters are sent on a mission to deliver troops to an area near the FLOT. Each helicopter encounters two weapons. Using the appropriate probability terminology, describe the following: 1) the number of helicopters that could be killed while on the mission, 2) the function that is used to compute the probability that a specific number of helicopters will be killed, 3) the set of probability values associated with each number of helicopters killed, and 4) each helicopter–weapon encounter.

B.5.2 You are in the ready room, waiting for the call to scramble in your interceptor and engage incoming enemy bombers. You pass the time by playing cards with your fellow pilots. You offer them a wager they can not refuse. First, you draw a card and lay it on the table, face up. Let us say it was the three of hearts.

Next, you say to them that you will pay them $5 (Monopoly money) if you fail to draw a matching card (another three or a heart) on the second draw. If you do draw a matching card, what is the minimum they should pay you for you to break even in the long run? Use the tree diagram to determine the answer, and explain your answer in probability terms.

B.5.3 You and your wingman are on a mission in hostile territory defended by a SAM site. The SAM's lethality against both of you is 0.3 per missile shot. You are carrying an antiradiation missile that has a probability of killing the SAM radar of 0.5. Without the radar a SAM cannot be launched. Unfortunately, you must pass through the SAM envelope before you can fire your missile at the radar. The fire control doctrine at the site is to shoot one missile at each aircraft. The command center selects you as the first aircraft to be engaged. If the missile does not kill you, you launch your missile at the radar. Now here comes your wingman into the SAM envelope. If the radar has not been killed, a missile is launched at your wingman. Determine the following probabilities:

1) What is the probability that both you and your wingman survive the mission?
2) What is the probability that both of you are killed?
3) What is the probability that one of you is killed?

B.5.4 Four attack aircraft are scheduled to conduct a low-altitude nighttime strike on a POL site defended by four AAA weapons. What is the probability that only one of the aircraft returns? Assume four independent one-on-one encounters and $P_K = 0.2$ for each encounter.

B.6.1 You are assigned to fly on the next mission to Xanadu. There are five helicopters scheduled to fly this mission. The sortie loss rate for this mission is 0.1. The mission outcomes are independent. Use the binomial probability function to determine the following:

1) What is the expected number of helicopters killed?
2) What is the probability that zero, one, two, three, four, and five helicopters are killed?
3) What is the probability that more than one helicopter are killed?

B.6.2 Assume that each of the five helicopters in Problem B.6.1 is encountered by one weapon while on the mission and each encounter is identical and independent of all other mission outcomes. The encounter outcomes of interest are helicopter survival and helicopter kill. The five identical, independent encounters, with two possible outcomes, are referred to as a Poisson process in probability theory: True or False.

B.6.3 Use the Poisson function to determine the probability that none of the five helicopters will be killed when the number expected to be killed is 0.5. If this result is different than the result using the binomial probability function, explain why.

B.6.4 You are ingressing into hostile territory at low altitude to avoid detection by the SAM sites in the vicinity of your target. At this low altitude you pass by two guns:

1) Each gun fires one round at you as you fly by. Your probability of being killed by the round is 0.02. Draw the tree diagram and the Venn diagram for this scenario. What assumptions did you make?

2) Your probability of being hit by each of the two rounds is 0.1. Your probability of being killed by the gun projectile hit is 0.2 when you have no damage prior to the hit and is 0.4 when you have been previously hit. Draw the tree diagram for the two encounters. What is your probability of surviving with no damage, of surviving with damage, and of being killed?

B.6.5 You are transporting 12 troops in your helicopter to a zone that has come under fire recently. As you are descending, 12 enemy soldiers with rifles fire one shot at you. The probability that any one shot kills you is 0.001. (Remember, P_K depends upon the joint probability your helicopter gets hit and the probability the hit kills the helicopter.) Use both the binomial approach and the Poisson approach to determine the answers to the following questions:

1) What is the probability you survive all 12 shots?

2) What is your survival probability if the soldiers have automatic weapons and each one fires 10 rounds at you? Again, assume $P_K = 0.001$.

3) Suppose the defenders have three radar-directed 23-mm guns, each gun fires a burst of 10 rounds, and $P_K = 0.05$ for each round.

B.7.1 The binomial and Poisson probability functions can be used to determine the probability that a tracking error is 0.01 radians: True or False.

B.7.2 The Gaussian PDF can be used to determine the probability that an aircraft is killed after encountering three weapons whose P_K is 0.3. True or False.

B.7.3 A football punter's punts are uniformly distributed between the 20-yard line and the goal line. What is the probability his next punt will fall between the 5-yard line and the 1-yard line?

B.7.4 Assume the probability a shooter can hit a duck in a shooting gallery is uniformly distributed over an area of 10 ft^2. What is the probability she will hit the duck if the duck's presented area is 1 ft^2.

B.7.5 The bombs dropped by a particular pilot are normally distributed along the axis that runs from the front of the target (-10 ft) to the back of the target ($+10$ ft). After dropping 100 practice bombs, the normal distribution parameters μ and σ are estimated to be 15 and 25 ft, respectively.

1) What is the probability the next bomb dropped by this pilot will fall within the target limits of -10 ft and $+10$ ft?

2) What is the error probable? What is the interval on the axis where the probability the next bomb will land is 0.5? What is the interval where the probability is 0.8?

B.7.6 The distribution of bombs dropped by the same pilot along the axis that runs from the left side of the target (-5 ft) to the right side of the target ($+5$ ft) is also normal. The normal distribution parameters μ and σ for this axis are estimated to be 3 and 8 ft, respectively. What is the probability the next bomb dropped by this pilot will hit the target

B.7.7 After a gunner shoots 100 rounds at a stationary circular target in a shooting contest, the evaluator estimates that the rounds are symmetrically distributed around the center of the target with a standard deviation of 4 in.

1) What is the CEP of the shooter?

2) What is the probability the shooter will hit the bull's eye on the next shot if the area of the bull's eye is 1 in.^{2}?

3) What is the circular area in the center of the same target where the probability of a hit is 0.25?

B.8.1 A sequence of two processes produces a product. If the tolerance in each process is exceeded, the output of the process is rejected. Suppose the tolerance in the first process is such that the process is successful 99 out of 100 times. The next process works on the successful output from the first process and is successful 98 out of 99 times. What is the probability the two processes will produce an acceptable product?

B.8.2 Flip a fair coin. If the outcome of the flip is a head, draw a card from a deck of playing cards. If you draw a red card, draw another card. If the outcome is a tail, do not draw a card. Repeat this process five times using a full deck of cards on each trial. Based upon the results, what is the probability you will draw two cards after a flip? Now flip and draw 10 times. What is the probability you will draw two cards?

B.8.3 A fourth aircraft is added to the "all possibilities" state vector given by Eq. (B.60a). Determine the new state vector and state transition matrix. Assume $P_K = 0.2$ for the added aircraft.

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