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On the cover:
An E-2C Hawkeye From the "Sun Kings" of Carrier Airborne Early Warning Squadron (VAW) 116 in the Arabian Sea *(U.S. Navy Photo by Mass Communication Specialist 2nd Class Greg Hall).*

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Whether it's a pilot flying a fighter jet through the air at Mach 2 or a driver speeding a race car around an oval speedway at 200 mph, when it comes to crash safety, many commonalities exist in the associated physics, research, and successful protection of operators (and occupants) during sudden acceleration events. Regardless of the type of vehicle involved, there are generally two main attributes that must be addressed in crash safety—(1) the maintenance of a "survival space" around the operator throughout the crash sequence, and (2) a properly designed and sufficiently strong restraint system for the operator. Beyond these attributes, of course, there are many other principles, maxims, and best practices in applying these safety measures to specific occupant environments, acceleration magnitudes, directions, and other factors and requirements. But even here, much can be leveraged and learned by crash safety researchers in a myriad of fields.

15 AUTOMATED COMBAT INCIDENT REPORTING: AN OVERVIEW

by Stanley Salamon and Robert Burkhart

The Automated Combat Incident Reporting (ACIR) project is an initiative funded by the Joint Aircraft Survivability Program Office (JASPO) to improve the collection and dissemination of data associated with hostile fires against aircraft. The project's objective is to develop the methods and associated tools required to automatically collect data from Aircraft Survivability Equipment (ASE) and aircraft mission computers, correlate the collected data with the incident, and package them for distribution to a representative database (e.g., the Combat Data Incident Reporting System [CDIRS] database).

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by William D. Bryant and Robert E. Ball

In Part 1 of this series, we introduced the cyber weapon as a new category of antiaircraft weapons that can attack and "kill" aircraft in flight in the same functional manner as kinetic energy (KE) guns and guided missiles attack, damage, and kill aircraft. In addition, we proposed that the fundamentals of the existing Aircraft Combat Survivability (ACS) discipline, developed for the KE antiaircraft weapons, be used to develop a new survivability discipline for the cyber weapon, with the designation of Aircraft Cyber Combat Survivability (ACCS). In Part 2, we showed how cyber weapons function in the sequenced ACS probabilistic kill chain (PKC), resulting in the analogous ACCS PKC. Part 3 then presented the 12 broad categories of cyber survivability enhancement concepts (CSECs), analogous to the KE survivability enhancement concepts (SECs), that can be used to reduce the probability of a successful cyber attack. In this fourth and final part of the development of the fundamentals of ACCS, we turn to describing the methodology for developing specific cyber survivability enhancement features (CSEFs) for an aircraft in development that is based upon the analogous methodology for developing specific aircraft survivability enhancement features (SEFs) for KE antiaircraft weapons. This methodology can then be used by aircraft developers and designers to develop combat cost-effective CSEFs that will make our aircraft more survivable when under attack from cyber weapons.

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NEWS NOTES

by Dale Atkinson and Eric Edwards

JMUM: ADAPT AND OVERCOME

As most readers are aware, the 2020 Joint Aircraft Survivability Program (JASP) Model Users Meeting (JMUM) was cancelled due to the widespread travel restrictions and safety concerns associated with the ongoing COVID-19 pandemic. The cancellation of this meeting, like that of many others, was regrettable in that there were many key model updates, methodology enhancements, and model distribution news of benefit to the aircraft survivability community. Fortunately, the proceedings of the briefings were compiled and are currently available through the Defense Technical Information Center (DTIC) and the Defense Systems Information Analysis Center (DSIAC).

As we look forward to this year's JMUM, we find ourselves again in a place where holding a large face-to-face meeting is still not a realistic or reasonable approach. Therefore, we are planning to hold a virtual JMUM that will still allow representatives of the various JASP-funded models to provide updates, discuss enhanced methodologies developed/implemented, discuss future developments required by the models to meet user needs, and hold Configuration Control Board (CCB) meetings to determine the paths forward for various development efforts.

The models currently supported by JASP include the following:

- Brawler
- Computation of Vulnerable Area Tool (COVART)

U.S. Air Force Photo by Maj. Joshua Turner

- FAST Shotline Generator (FASTGEN)
- Rocket-Propelled Grenade Engagement Model (RPGEM)
- Next Generation Fire Model (NGFM)
- BlueMax
- Survivability and Lethality of Aircraft in a Tactical Environment (SLATE).

The meeting will also include status updates, roadmap presentations, and development plans on other models used by JASP-supported codes—including Fast Air Target Encounter Penetration (FATEPEN), the Projectile Penetration Model (ProjPen), and those of the Intelligence centers (e.g., the National Air and Space Intelligence Center [NASIC], the Missile and Space Intelligence Center [MSIC], TETRA, and the National Ground Intelligence Center [NGIC])—as well as discussions on the architectures that JASP-supported tools are planned to interface with, such as the Advanced Framework for Simulation Integration and Modeling (AFSIM).

While this year's JMUM may not look like it has the previous 21 years, the meeting will still be a great opportunity for model users and developers to interface in a manner not otherwise possible. A major key behind the JMUM's longstanding success is the recognition that model users are the true backbone of survivability modeling and simulation (M&S) and that their active participation in working forums and CCB discussions provides invaluable information not readily available otherwise. In addition, the gathering allows those users to present example use cases, any updates they have made to fit their specific needs, and any identified deficiencies they would like to have addressed.

Although the specific dates and times for the virtual JMUM have not yet been finalized, a community-wide announcement will be released through DSIAC when those decisions are made.

(NOTE: JMUM attendance is limited to U.S. military and DoD civilian personnel and DoD contractors possessing a SECRET-level [or higher] clearance and valid need-to-know.)

U.S. Navy Photo by Mass Communications Specialist 3rd Class Ethan Morrow

NAVY AND MARINE CORPS HAPPY TO SCORE A ZERO FOR FY20

When it comes to aircraft safety and survivability metrics, the best numbers are usually the lowest ones. And one can't get much lower than zero. In October, the Navy Safety Center announced that fiscal year 2020 marked the first year in nearly a century of recordkeeping that not a single aviation-related death occurred in either the U.S. Navy or the U.S. Marines Corps. The center cited several contributors to this unprecedented milestone, including:

- Training
- Personnel proficiency
- Enhanced safety measures
- The adoption of a culture of safety
- The sharing of lessons learned and best practices among squadrons
- Increased fleet readiness via improved aviation centers and depot supply chain.

Ironically, another contributing factor was the COVID-19 pandemic, which reportedly led to a slight (10%) decrease in Navy flight hours.

The Navy officially started keeping records of its aviation-related accidents and fatalities in 1922. And in the 98 years since that time, every year has seen at least one death. Until this one. For comparison, there were 39 aviation-related fatalities across all 4 Services in 2018, which marked a 6-year high.

This significant safety accomplishment is yet another testament not only to the excellence of U.S. Navy and Marine Corps aviation operators and support personnel but also to the hard work of aircraft safety and survivability practitioners, both past and present, that have remained firmly committed to helping keep U.S. aircraft flying and U.S. aircrews safe.

MURPHY BECOMES WPAFB TEST REP FOR AFTC

In October, Mr. John Murphy stepped down as Technical Director of the 704th Test Group's Aerospace Survivability and Safety Office

(TG/OL-AC) at Wright-Patterson Air Force Base (WPAFB) to accept the position of WPAFB Test Representative for the Test and Evaluation Division of the Air Force Test Center's (AFTC's) Engineering and Technical Management Directorate. In his new role, Mr. Murphy will be responsible for representing AFTC T&E interests and test capabilities to numerous WPAFB organizations, including the Air Force Materiel Command (AFMC), the Air Force Life Cycle Management Center (AFLCMC), and the Air Force Research Laboratory (AFRL).

As OL-AC's Technical Director for more than 15 years, Mr. Murphy served as an Air Force aircraft survivability/Live Fire Test and Evaluation (LFT&E) and landing gear systems safety and sustainment subject-matter expert on a wide range of critical programs. His work at WPAFB began in 1984, working as a co-op engineering student for the Fire Protection Branch of the AFRL Propulsion Directorate's Fuels and Lubrication Division. He supported development of the anti-static gray fuel tank foam currently used in many Air Force and other aircraft, and he worked on the On-Board Inert Gas Generation System (OBIGGS) before becoming a full-time test engineer with the Survivability Branch of the AFRL Flight Dynamics Directorate's Vehicle Subsystems Division in 1986. Mr. Murphy then went on to assume numerous leadership positions, including Chief of the Survivability Flight and Acting Director and Technical Director/Chief Engineer of the OL-AC.

Additionally, Mr. Murphy was inducted as an Associate Fellow of the American Institute of Aeronautics and Astronautics in 2017 and as a Technical Fellow of the Arnold Engineering Development Center in 2018.

JASP congratulates Mr. Murphy on his new position and wishes him well as he continues to support the aircraft survivability community. ASJ

JCAT CORNER

by CW4 Mark Chamberlin and CDR Matthew Kiefer

Though the past year's global pandemic has greatly limited domestic and international travel, as well as cancelled or postponed many meetings, conferences, training classes, and other in-person events throughout the Department of Defense community, the Joint Combat Assessment Team (JCAT) has been able to rise to the occasion and adjust daily operations to ensure that the team remained actively involved in current combat damage assessments, JCAT qualification training, Threat Weapon Effects (TWE) training, and the Susceptibility Reduction Work Group (SRWG).

Over the last year, JCAT continued its primary mission of collecting data and assessing threat information regarding combat damage events. One outlet to share information with the DoD community, as well as raise awareness of the JCAT team and mission, is the SRWG. This year, the SRWG agenda has expanded to include focus on testing and validating available models, radar countermeasures, and aircraft maneuvers. This is a multi-year project intended to validate existing models, reduce cost and schedule, and improve warfighting capabilities in the electronic warfare environment. This fiscal year, we are laying the foundation to incorporate into live tests in subsequent years.

Joint and individual Service doctrine is currently being shaped to meet the operational needs of the multi-domain battlespace. JCAT-Navy continues efforts to defining a Joint Universal Task to collect, assess, and archive combat damage. JCAT-Navy has defined a task for JCAT operations and is awaiting an opportunity to go before an acceptance board. Concurrent to this action, JCAT-Army is working with the Directorate of Training and Doctrine to revise ATP 3-04.13, TC 3-04.2, TC 3-04.9, and TC 3-04.11 to incorporate the collection of combat battle damage in the future of Army doctrine.

Due to ongoing DoD travel restrictions, JCAT Phase I and Phase II training will be combined in a single event, which is tentatively scheduled for March 2021. The training event will be hosted by the Kinetic Experimentation Branch, located at Aberdeen Proving Ground, MD. Presently, JCAT is designing a new curriculum—which flexibly integrates its new temporary location and compressed timeline—to equip newly appointed JCAT assessors with the tools and experience to flawlessly leverage in future missions.

This year's TWE training is still scheduled for August 2021 (tentatively); however, to comply with local policies, the event has been moved to the Enlisted Hall at Eglin Air Force Base, rather than Hurlburt field, where the event has historically been conducted.

JCAT-Army continues improvements to the Aviation Combat Forensics Lab (ACFL) both in training articles and routine maintenance. The ACFL training article inventory will be expanded to incorporate a CH-47—with undisclosed threat damage—to be used for this year's TWE live fire event (see Figure 1). Furthermore, JCAT-Army was able to resource Fort Rucker flight school students assigned to B Company, 1-145th, to conduct maintenance and repairs to the ACFL privacy fence, which was heavily damaged during the record-breaking 2020 hurricane season. This maintenance (shown in Figure 2) provided a critical facelift to the AFCL that is commensurate with the training aids available within.

JCAT-Navy has also worked to take delivery of two SH-60 helicopters, which will be used as JCAT assessor training aids and subjects for live fire testing. In fact, the officers of In Service Engineering and Logistics Detachment B at China Lake, CA, have already organized a shot on one of them. LT Haman was successful in leading the live fire test of an SH-60 with a new threat weapon system. The article is the first T/M/S to be added to the JCAT training facility at the Naval Air Warfare Center Weapons Division in China Lake and will be used to train future JCAT assessors.

Figure 1. CH-47 Hulk Target for Live Fire Demonstration at Upcoming TWE.

Figure 2. Flight School Students Repairing the ACFL Privacy Fence.

Finally, the Aviation Survivability Development and Tactics Team, JCAT-Army, would like to hail CW5 Scottie Moore as the Team Chief. CW5 Moore is joining the JCAT community from Fort Campbell, KY, where he was the Division Aviation Mission Survivability Officer. He is a Master Army Aviator qualified in the UH-1, AH-1, AH-64, CH-47 (D, F, and G models), AH-6, and Mi-17, with more than 4,000 hours of flying time. ASJ

HEARD ANY NEWS?

If you know of a community-related event, announcement, or other news item that you would like to submit for consideration as a News Note, please contact Mr. Dale Atkinson at daleatk@gmail.com.

LESSONS FROM THE TRACK: CRASH SAFETY PRINCIPLES AND PRACTICES FROM THE WORLD OF MOTORSPORTS

by John P. Patalak

Photo Courtesy of Christian Peterson/Getty Images

Whether it's a pilot flying a fighter jet through the air at Mach 2 or a driver speeding a race car around an oval speedway at 200 mph, when it comes to crash safety, many commonalities exist in the associated physics, research, and successful protection of operators (and occupants) during sudden acceleration events. Regardless of the type of vehicle involved, there are generally two main attributes that must be addressed in crash safety—(1) the maintenance of a "survival space" around the operator throughout the crash sequence, and (2) a properly designed and sufficiently strong restraint system for the operator. Beyond these attributes, of course, there are many other principles, maxims, and best practices in applying these safety measures to specific occupant environments, acceleration magnitudes, directions, and other factors and requirements. But even here, much can be leveraged and learned by crash safety researchers in a myriad of fields.

Just like many combat aircraft pilots, drivers for the National Association for Stock Car Auto Racing, Inc. (NASCAR) often operate in a small, confined, hot, loud, and stressful environment. They are also routinely exposed to low-level (<3 G's), sustained (>1 s) lateral and vertical accelerations while navigating high-banked racetracks at high speeds and experiencing severe accelerations during on-track crashes. Accordingly, many common characteristics and approaches exist in the driver safety research and development (R&D) efforts that are occurring in the fields of professional motorsports, aircraft/aerospace, and even the general automotive industry.

MOTORSPORTS AND MILITARY AVIATION: A SHARED HISTORY IN CRASH SAFETY

The modern NASCAR driver restraint system is highly customized for its motorsport environment; however, its operating principles, origins, and developments are actually rooted in military aviation safety research. In the 1940s and '50s, Air Force colonel, flight surgeon, and early aerospace medicine and safety research pioneer John Paul Stapp (shown in Figure 1) conducted a series of test studies assessing the effects of rapidly applied accelerations on the human body [1]. Dr. Stapp—who would come to be called "the fastest man on earth"—and other test volunteers would be strapped onto a rocket sled and shot down tracks at high speed (in excess of 600 mph) to place high deceleration forces on their bodies. The significant contributions of Dr. Stapp to our understanding of these effects benefitted not only aircraft pilots but also race car drivers, passenger car operators/occupants, and others.

In 1959, Martin Eiband summarized the work of Dr. Stapp in a National Aeronautics and Safety Administration (NASA) literature review of human tolerance to rapidly applied accelerations [2]. Over the following decades, many other researchers likewise quantified human acceleration tolerances, often coinciding with the development of increasingly advanced restraint systems for successful protection. In 2002, Rolf Eppinger also published an excellent collection of restraint maxims (summarized in Table 1) [3].

After World War II, the approach to improving motorsport driver safety was often based on driver's instincts rather than the application of science

Many common characteristics and approaches exist in driver safety R&D efforts that are occurring in professional motorsports, aircraft/aerospace, and the general automotive industry.

Figure 1. COL Stapp and Sonic Wind, the Rocket Sled That Made Him "The Fastest Man on Earth" (*Photos Courtesy of the U.S. Air Force*).

Table 1. Eppinger Good Occupant Restraint Maxims [3]

Maxim	Reason
Maximize time over which restraint forces are applied	Minimizes applied force magnitudes
Maximize distance that the point of force application on the body moves over ground	Maximizes kinetic energy extraction from the body and minimizes energy stored in body
Apply greatest possible restraint force as early as possible in crash	Maximizes kinetic energy extraction
Minimize body articulations, localized deformations, and their rates and inertial accelerations during restraint	Lowers risk of tissue failure
Distribute force over the largest possible surface area	Reduces deformation and local surface pressures
Restrict restraint forces to bony anatomy, avoiding loads to compliant anatomy	Bony structures carry the most load with the least deformation and least injury

and engineering. By the 1990s, however, as increased emphasis and regulation were placed on motorsport safety by sanctioning bodies, drivers, car manufacturers, etc., the science, engineering, and test methods of the general automotive industry were increasingly applied to motorsport safety research efforts [4].

Today, more than 7 decades after COL Stapp's historic high-G rides, many new tools to study injury mechanisms have become available for safety researchers in a wide range of applications. These tools include the rapid advancement of computer processing technologies that allow for complex human body modeling and simulation. For example, the Global Human Body Models Consortium (GHBMC) and the Toyota Total Human Model for Safety (THUMS) are two commonly used human body models for today's crash safety studies [5, 6]. These types of models have allowed for new levels of research and exploration, delving deep into nuisances far beyond what the traditional anthropomorphic test devices (ATDs) have been capable of capturing.

With the sudden deaths of four NASCAR drivers in less than 1 year, tremendous efforts surrounding driver safety in professional motorsports occurred during the first several years of the 21st century. The primary areas identified for improvement focused on the driver restraint system, the vehicle, and the racetrack. The most well-known of these driver deaths was that of NASCAR champion Dale Earnhardt (pictured, along with his father and son, and some of the driver safety features of their respective eras, in Figure 2). The 20th anniversary of this incident, which occurred on the final lap of the Daytona 500 in February 2001, provides a poignant opportunity to look back over the last 2 decades of NASCAR driver safety development and highlight some notable principles and practices that are relevant not only for the motorsports industry but also for safety researchers in military aviation and other fields.

> With the sudden deaths of four NASCAR drivers in less than 1 year, tremendous efforts surrounding driver safety occurred during the first several years of the 21st century.

While there are thousands of projects and areas of research that could be highlighted herein, the following four items (which are listed in no particular order) are especially notable in that each of them represents a step-function improvement to overall NASCAR driver safety:

- The Steel and Foam Energy Reduction (SAFER) Barrier
- Head and Neck Restraints
- Seats
- Seatbelt Restraint Systems.

SAFER BARRIER

Most oval racetracks traditionally used rigid, reinforced concrete walls to contain race vehicles on the track. In 1999, however, the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska-Lincoln began developing the SAFER Barrier. The barrier works by increasing crash displacement, which extends the duration of crash pulses, thereby reducing the peak accelerations experienced by the vehicles and drivers. As shown in Figure 3,

Figure 2. NASCAR Driver Safety Advancements. Left to Right: Ralph Earnhardt (1953), Dale Earnhardt (1981), and Dale Earnhardt, Jr. (2009) *(Photos Courtesy of ISC Archives).*

Figure 3. Traditional Rigid Concrete Wall (Left) vs. SAFER Barrier Stroking (Right) Crash Tests.

energy-absorbing foam modules placed behind high-strength steel skin deform upon impact, allowing for this additional displacement and enabling the SAFER Barrier to lower peak vehicle accelerations by 30 to 80% [7].

HEAD AND NECK RESTRAINTS

The use of head and neck restraints virtually exploded after Dale Earnhardt's widely publicized death at the Daytona 500 in 2001. What many people do not realize, however, is that a handful of the 43 drivers in that race were already wearing the now-well-known Head and Neck Support (HANS) device [8]. Developed in the late 1980s, the HANS device (shown in Figure 4) is still the predominant head and neck restraint used by NASCAR drivers [9]. During a frontal impact, the primary purpose of any head and neck restraint is to limit head excursion and neck kinetics. The driver's seatbelt restraint system applies restraining loads to the pelvis and thorax. These restraining forces, along with the mass of the driver's head and helmet, can induce dangerous neck loads during frontal impacts. A head and neck restraint thus limits this cervical loading by providing an alternate load path between the skull and the thorax.

Figure 4. HANS Device *(Photo Courtesy of Simpson Performance Products).*

In the case of the HANS device, this alternate load path is accomplished through bilateral anchors on the helmet that are connected to HANS tethers. The HANS tethers connect to the HANS collar behind the drivers' helmet. The collar is integral to bilateral yokes, which are fit underneath the driver's shoulder belts. This system has proven highly effective in coupling the skull, through the helmet, to the torso via the shoulder belts, thereby limiting cervical neck loads and head displacement. Furthermore, ongoing design improvements have continued to increase the device's effectiveness while also reducing the driver's awareness of—and associated distraction/irritation by—the presence of the device when behind the wheel [10].

Since 2005, all NASCAR drivers have been required to use a NASCAR-approved head and neck restraint. The first step of the NASCAR approval process is for the device to pass the SFI Foundation (SFI) 38.1 test specification [11]. SFI 38.1 requires sled testing with a Hybrid III 50th-percentile male ATD, which is used to evaluate the performance capabilities of head and neck restraints. ATD criteria such as peak neck axial force and Neck injury criteria (Nij) are both limited in SFI 38.1.

SEATS

In the early decades of NASCAR racing, a driver's seat was typically the factory stock seat. Modifications and additions to provide lateral supports and stiffen seat structures were then made to the stock seats as speeds increased. Eventually, purpose-built race seats, primarily fabricated from aluminum, replaced the stock seats. While these initial aluminum seats improved driver comfort and support during normal driving, they were still structurally insufficient during crashes. Thus, early in the 21st century, biomechanically based work was undertaken to quantify seat strength requirements [12]. This seat research was continued using sled and quasi-static testing, resulting in the creation of SFI 39.1 [13].

During side and rear impacts, the seat itself provides the primary means of driver restraint. Because NASCAR seats are rigidly mounted at the base and shoulder level, rear impact performance is already well

In 2015, all drivers seats were required to be "all-belts-to-seat" (ABTS), meaning that all seatbelt restraint system mounting anchorages must terminate within the seat structure itself rather than the vehicle chassis.

established. So SFI 39.1 focuses its test requirements on lateral stiffness, specifically setting minimum performance criteria for lateral head, shoulder, and pelvic stiffness [14].

In 2015, all drivers seats were required to be "all-belts-to-seat" (ABTS), meaning that all seatbelt restraint system mounting anchorages must terminate within the seat structure itself rather than the vehicle chassis. ABTS seats use shorter seatbelt lengths, permit improved seatbelt geometry, and eliminate seatbelt pass-through holes in seat structures. In addition, minimum performance criteria were implemented for the ABTS seats [15].

The interiors of all seats and head surrounds are also required to be lined with SFI 45.2 energy-absorbing foam [16]. This foam effectively couples the driver's body to the ABTS seat structure by filling any voids between the driver's body and the seat and custom-fitting the seat to each individual driver. This fitting is initially done by positioning the driver inside of a seat shell with foam shims. The driver is positioned on top of a plastic liner, which is then filled with a liquid foam. The liquid rapidly expands and hardens, producing a form-fit foam liner. This liner is then trimmed and sanded to the driver's preferences. While this liner can be used as-is, in most cases the liner is then scanned and reproduced with CNC machining from SFI 45.2 foam billets.

Likewise, leg restraint is accomplished with bilateral leg supports that attach to the bottom of the seats and extend to the driver's feet. A padded knee knocker also separates the driver's knees and prevents knee-to-knee contact and potential injury during lateral impacts.

The combination of appropriately strong lateral seat supports and the energy-absorbing foam effectively couples the driver's body to the seat across large bony surface areas. Through effective coupling, early in time, peak forces on the body are reduced. By providing complete lateral restraint from the head to the feet, local body articulations, deformations, and surface pressures are also decreased. Figure 5 shows computer-aided design (CAD) images of a typical carbon fiber composite ABTS seat and SFI 45.2 foam insert.

SEATBELT RESTRAINT SYSTEMS

Even though seatbelts were typically not available in passenger vehicles when NASCAR ran its first race at Daytona Beach, FL, in February of 1948, rule no. 34 of NASCAR's first rulebook wisely required that all drivers use seatbelts. And as with passenger vehicle and aviation seatbelt restraint systems, the NASCAR seatbelt restraint system has become increasingly sophisticated and effective over time.

In the 2000 NASCAR race season, five-point seatbelts were required, consisting of left and right shoulder and lap belts with a single crotch (negative-G) belt. As seatbelt restraint systems were improved, however, additional belts or mounting points were added. These additional points were typically used to reduce the time over which an individual belt could produce a restraining load in particular directions. The new mounting points were placed for specific crash directions, thereby promoting the maxim of earlier coupling of the occupant. Figure 6

Figure 5. CAD Images of a Carbon Fiber Composite ABTS Seat (Left) and SFI 45.2 Foam Seat Insert (Right).

illustrates the evolution of seatbelt restraint systems that occurred from 2000 through 2015.

Currently, only seven- and nine-point seatbelt restraint systems are permitted in NASCAR. These systems use three crotch belts instead of the five-point system's single crotch belt. The center crotch belt, which is referred to as the negative-G belt, is centered laterally, is anchored forward of the groin, and follows the shoulder belt line down the driver's chest. This negative-G anchor location provides highly efficient vertical restraint during rollovers since the negative-G belt does not need to move to immediately react a tensile load. The two outboard crotch belts are referred to as antisubmarine belts. These belts have anchors beneath the driver's buttocks, which wraps the belt webbing around the inner thighs.

Combined with the lap belts, the antisubmarine belts are effective in reducing forward motion of the pelvis during front impacts and helping to promote proper positioning of the lap belt across the strong anterior superior iliac spine of the pelvis. This forward pelvic restraint reduces groin contact injuries from the negative-G belt during frontal impacts. These three crotch belts, with their specific mounting locations, also effectively reduce chest deflection during frontal impacts and head excursion during vertical impacts [17].

Another way to follow the maxims of increasing the time over which restraint forces can be applied and applying the largest possible restraint forces as quickly as possible in a crash is through the use of webbing pretensioner systems. These systems, which are found in many passenger vehicle seatbelt restraint systems, remove belt slack and lock the belt retractor moments before a driver's body begins to move relative to the vehicle during a crash. Similarly, aviation ejection seat systems sometimes use haulback devices to help position limbs as well as pretensioners to tighten webbing moments before ejection.

Because NASCAR crashes often include multiple impacts during a single crash event, and because NASCAR drivers commonly receive pit road service and continue racing after experiencing minor impacts (many of which would trigger pretensioner firing algorithms), NASCAR's seatbelt restraint system does not currently include pretensioners. Instead, drivers manually pretension their restraint systems. Typical motorsport seatbelt pretensions have been measured at 91.2 N (20.5 lbs) for shoulder belts and 110.3 N (24.8 lbs) for lap belts [18]. Similar to head and neck restraints and seats, the seatbelt restraint systems must also comply with SFI performance requirements.

As the speeds and capabilities of race cars, passenger cars, airplanes, and other vehicles continue to grow, so will the need for improved and different occupant crash protection research and equipment.

SUMMARY

As the speeds and capabilities of race cars, passenger cars, airplanes, and other vehicles continue to grow, so will the need for improved and different occupant crash protection research and equipment. While the protection maxims for such work are currently well-established, there remain nearly endless opportunities to iterate, revise, modify, and improve existing safety systems for better adherence to those maxims. In addition, the leveraging of newer and increasingly advanced tools, such as

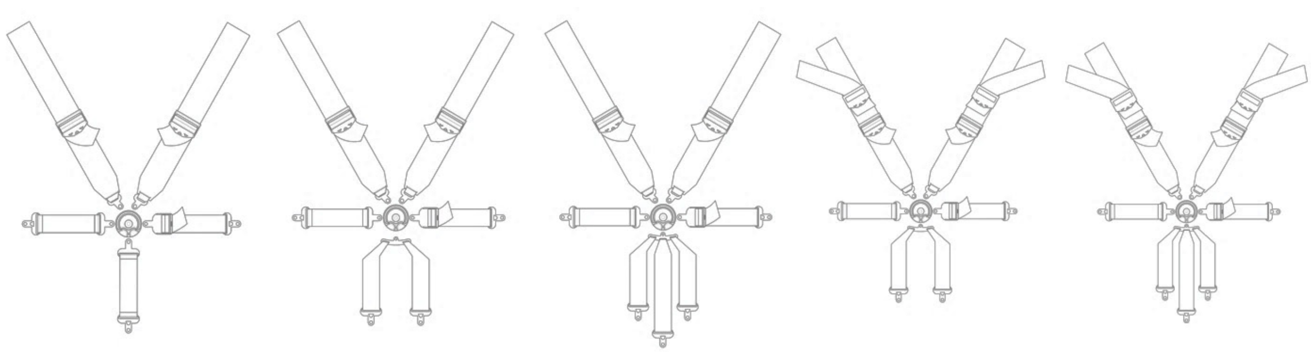

Figure 6. The Evolution of Seatbelt Restraint Systems From 2000 to 2015 (From Left to Right: Five-, Six-, Seven-, Eight-, and Nine-Point *Systems*).

numerical simulation, along with time-tested approaches in the field, promise to help researchers and developers continue to improve the protection of vehicle operators and occupants, regardless of the type of vehicle in which they travel. ASJ

ABOUT THE AUTHOR

Dr. John Patalak is the Senior Director of Safety Engineering for the National Association for Stock Car Auto Racing (NASCAR). He specializes in occupant crash protection and biomechanical and mechanical engineering and has extensive experience in accident investigation, occupant safety research and development, crash testing, sled testing, quasi-static testing, vehicle crash databases, experimental design, and computer modeling. Dr. Patalak currently oversees all aspects of NASCAR driver safety, including accident and injury investigations, safety equipment research, testing and approvals, computer modeling efforts, and the NASCAR crash database. His work has resulted in many peer-reviewed journal publications, several patents, and multiple awards and recognition, including the Society of Automotive Engineers Ralph H. Isbrandt Automotive Safety Engineering Award. Dr. Patalak holds a B.S. in mechanical engineering from The Pennsylvania State University and an M.S. and Ph.D. in biomedical engineering with concentrations in biomechanics from the Virginia Tech - Wake Forest University School of Biomedical Engineering and Sciences. He is also a licensed Professional Engineer in North Carolina.

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AUTOMATED COMBAT INCIDENT REPORTING: AN OVERVIEW

by Stanley Salamon and Robert Burkhart

U.S. Navy Photo by Mass Communication Specialist 2nd Class Sean Castellano

The Automated Combat Incident Reporting (ACIR) project is an initiative funded by the Joint Aircraft Survivability Program Office (JASPO) to improve the collection and dissemination of data associated with hostile fires against aircraft. The project's objective is to develop the methods and associated tools required to automatically collect data from Aircraft Survivability Equipment (ASE) and aircraft mission computers, correlate the collected data with the incident, and package them for distribution to a representative database (e.g., the Combat Data Incident Reporting System [CDIRS] database).

The ACIR project will culminate in demonstrations of two technical solutions, differing primarily in the means of data removal from the aircraft. Future phases of the effort may include the ability to off-board the data in-flight to other aircraft and agencies to enhance situational awareness, contribute to a Common Operating Picture, or provide suppressive fires on the threat.

WHY IS ACIR NEEDED?

The collection of combat incident data occurs so that analysts can examine the variables surrounding hostile action against Department of Defense (DoD) aircraft in relationship to the type of mission, altitude, airspeed, phase of flight, and countermeasure response. The resultant analysis can be used to help develop more effective defensive technologies and/or inform tactics, techniques, and procedures (TTPs). Current methods of collection are greatly dependent on human observation of the incident and often lack necessary details to support a thorough analysis. In some cases, the incident is not discovered until post-flight; in others, there may be no survivors. By automatically collecting and storing data generated by sensors that are optimized to detect threat activity, aircrew response, and the associated countermeasures response, analysts will have a more complete data set with which to apply their trade.

WHAT TO EXPECT?

Phase I of the JASP ACIR project identified stakeholders and examined the policy and regulatory environment that would influence ACIR. Working groups identified the anticipated end users of the data produced by ACIR, as well as tactical users that would benefit from enhanced systems and TTPs. In addition, the Technical Working Group identified system capabilities in terms of access to and generation of the ACIR data; processing and storage capabilities; and the relative effort required to extract, correlate, and translate the ACIR data from Avionics and Electronic Warfare buses related to combat incidents.

The initial focus of the project is to employ the capability on the AN/ALE-47 Countermeasure Dispenser System (CMDS)—which is common to nearly all U.S. Navy, Marine Corps, and Air Force aircraft, as well as a small number of U.S. Army rotorcraft—and is typically integrated with avionics and ASE systems. The additional benefit of using the CMDS is that the U.S. Government organically develops the associated Operational Flight Program (OFP) and Mission Data File (MDF) software components. This organic development will allow for quicker and less costly modifications of these software components. Furthermore, one of the demonstrations will rely on the organic development of a tablet application. Lower costs, reduced schedules, and fewer concerns about proprietary software are all distinct advantages of the selected approach. Also, although the CMDS is the initial focus, it is expected that the lessons learned from developing ACIR solutions will be useful for similar applications in other Service ASE systems, such as the Army's Common Missile Warning System.

Phase II, initiated in FY20, includes multiyear efforts to develop the applications and representative database that will be used in the technology demonstrations. The Phase III FY22 effort will demonstrate the ACIR capabilities at the Naval Air Station Patuxent River's Manned Flight Simulator (MFS), which provides aircraft/system hardware-in-the-loop simulation capabilities.

There will be two demonstrations performed at the MFS. The first effort (illustrated in Figure 1) will rely on the current download capabilities of the CMDS to collect flight test instrumentation (FTI) data. The FTI data will be downloaded, interpreted, and then correlated with the incident of interest. The correlated data will then be paired with the user's account of the incident and then formatted as required by the target end user (for demonstration purposes, this will be a representative database).

The second demonstration (illustrated in Figure 2) will use a tablet application to collect the ACIR data and provide a means for easier identification of the incidents of interest. Users will then correlate the incidents with their user report, and this information will be formatted for transmission to the representative ACIR database.

WHO IS ON THE TEAM?

Mr. Robert Lyons is leading the effort as the Program Manager from JASPO. The ACIR project was proposed by Mr. William Dooley, formerly of the Naval Air Systems Command (NAVAIR) Combat Survivability Division. The technical lead for the project is Mr. Robert Burkhart, the Lead Systems Engineer for the ALE-47 CMDS in PMA-272. Mr. Andy Yang from the PMA-272 AN/ALE-47 team has been providing support as project lead.

In addition, CW5 Scott Brusuelas (now retired), who led the Army's Aviation Survivability Development and Tactics (ASDAT) Team, contributed by providing

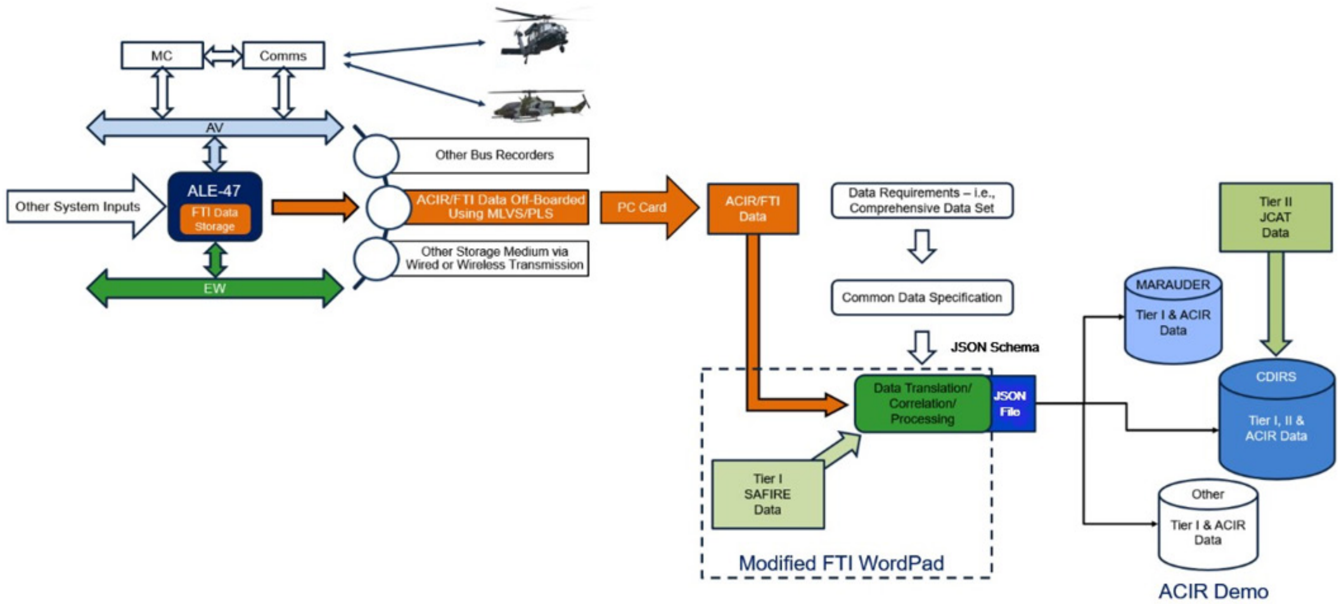

Figure 1. CMDS FTI to PC Card Demonstration.

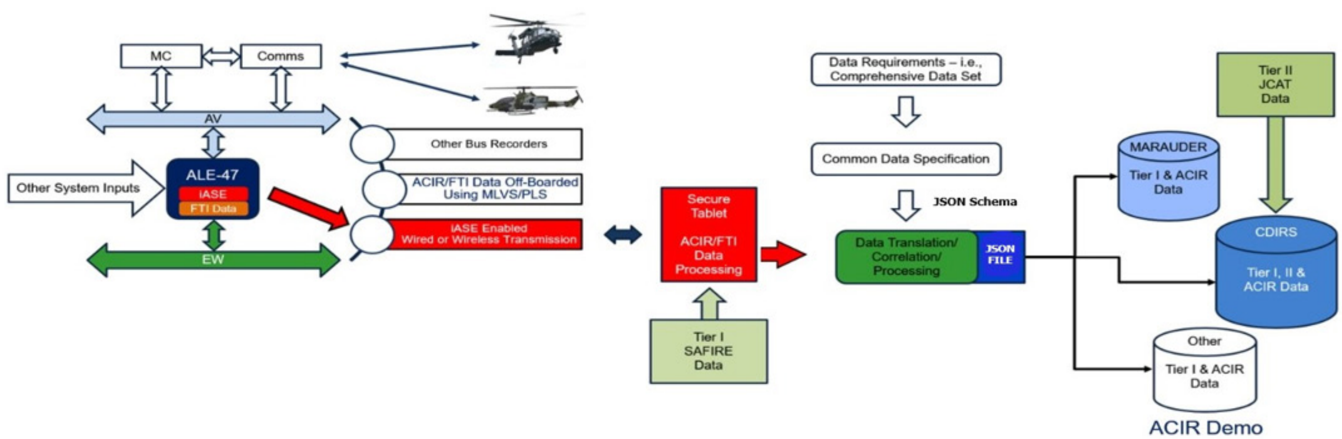

Figure 2. CMDS to iASE Tablet Demonstration.

the Warfighter perspective.

CW4 Tyson Martin now leads the ASDAT Team, responsible for collecting forensic evidence from combat incidents. Mr. Jim Rhodes from the Institute for Defense Analyses is the primary survivability analyst and is principally responsible for analyzing the CDIRS data. Finally, subject-matter experts (SMEs) Stan Salamon and Michael McNellis from the Air Combat Effectiveness Consulting Group are assisting the project and technical leads and coordinating the overall effort. ASJ

ABOUT THE AUTHORS

Mr. Stanley Salamon is one of the founding partners of Air Combat Effectiveness Consulting Group LLC (ACE Group), which specializes in program management, engineering, and analytic support to NAVAIR and the DoD community. Mr. Salamon supports NAVAIR's Combat Survivability Division as a Senior Operational SME with a focus in survivability and lethality. His background includes serving 26 years of active duty as a Marine Corps aviator flying the CH-53D and the AV-8B and working for the past 12 years as a Military Operations Analyst.

Mr. Robert Burkhart is currently the lead systems engineer for the AN/ALE-47 team, as part of NAVAIR's Advanced Tactical Aircraft Protection Systems (PMA-272). His background includes more than 20 years of supporting the AN/ALE-47 program. As a subject-matter expert, he has served as the AN/ALE-47 Software Support Activity lead, as a PMA272 technical coordinator role, and, most recently, as the AN/ALE-47 Class Desk.

DEVELOPING THE FUNDAMENTALS OF AIRCRAFT CYBER COMBAT SURVIVABILITY: PART 4

by William D. Bryant
and Robert E. Ball

U.S. Air Force Photo by Todd Cromar

PART 4 – DEVELOPING FEATURES FOR ENHANCING CYBER COMBAT SURVIVABILITY

- *Learning Objective 8 — Describe a Cyber Survivability Enhancement Feature (CSEF)*
- *Learning Objective 9 — Describe How to Develop CSEFs for a Particular Aircraft Cyber System*

INTRODUCTION

In Part 1 of this series, we introduced the cyber weapon as a new category of antiaircraft weapons that can attack and "kill" aircraft in flight in the same functional manner as kinetic energy (KE) guns and guided missiles attack, damage, and kill aircraft [1]. In addition, we proposed that the fundamentals of the existing Aircraft Combat Survivability (ACS) discipline, developed for the KE antiaircraft weapons, be used to develop a new survivability discipline for the cyber weapon, with the designation of Aircraft Cyber Combat Survivability (ACCS). In Part 2, we showed how cyber weapons function in the sequenced ACS probabilistic kill chain (PKC), resulting in the analogous ACCS PKC [2]. Part 3 then presented the 12 broad categories of cyber survivability enhancement concepts (CSECs), analogous to the KE survivability enhancement concepts (SECs), that can be used to reduce the probability of a successful cyber attack [3].

In this fourth and final part of the development of the fundamentals of ACCS, we turn to describing the methodology for developing specific cyber survivability enhancement features (CSEFs) for an aircraft in development that is based upon the analogous methodology for developing specific aircraft survivability enhancement features (SEFs) for KE antiaircraft weapons. This methodology can then be used by aircraft developers and designers to develop combat cost-effective CSEFs that will make our aircraft more survivable when under attack from cyber weapons [4].

The definitions of the terms SEC and SEF for both ACS and ACCS (given in Table 1, Part 3 [3]) and the 12 SECs for both ACS and ACCS (given in Table 2, Part 3 [3]) are repeated here for completeness (see Tables 1 and 2). These tables are followed first by the methodology for developing the SEFs for the KE weapons and second by the analogous methodology for developing the SEFs for the cyber weapons.

Finally, the general Applied Information Economics (AIE) approach of using probability distributions (not single values) for each event or outcome probability in conjunction with the iterative Monte Carlo method

Table 1. ACS and ACCS Definitions for the SECs and SEFs

Kinetic Energy Weapons (ACS)	Cyber Weapons (ACCS)
Survivability Enhancement Concept (SEC) - a general function or concept fundamental to KE survivability enhancement that reduces either the susceptibility or the vulnerability of the aircraft.	***Cyber Survivability Enhancement Concept (CSEC) –*** a general function or concept fundamental to cyber survivability enhancement that reduces either the cyber susceptibility or the cyber vulnerability of the aircraft.
Survivability Enhancement Feature (SEF) - any particular characteristic of the aircraft, specific piece of equipment, design technique, armament, or tactic that reduces either the susceptibility or the vulnerability of the aircraft and thus has the potential for increasing survivability.	***Cyber Survivability Enhancement Feature (CSEF) -*** any particular characteristic of the aircraft, specific piece of equipment, design technique, design of supporting systems, or operational procedures that reduces either the cyber susceptibility or the cyber vulnerability of the aircraft and thus has the potential for increasing cyber survivability.

Table 2. ACS and ACCS SECs

Kinetic Energy Weapons ACS Survivability Enhancement Concepts (SECs)	Cyber Weapons ACCS Cyber Survivability Enhancement Concepts (CSECs)
Susceptibility Reduction Concepts (SRCs)	**Cyber Susceptibility Reduction Concepts (CSRCs)**
Situational Awareness	Situational Awareness
Signature Control	Signature Management
Electronic Noise Jamming and Deceiving	Deception
Expendables	Cybersecurity hardening
Threat Suppression and Offensive Weapons	Threat Suppression
Mission Planning, Tactics, Flight Performance, and Crew Training and Proficiency	Training and Tactics
Vulnerability Reduction Concepts (VRCs)	**Cyber Vulnerability Reduction Concepts (CVRCs)**
Component Location	Component Location and Logical Separation
Component and System Redundancy (with Effective Separation)	System Redundancy (with Effective Separation and Diversity)
Passive and Active Damage Suppression	Malfunction Suppression (Passive and Active)
Component and System Capability Recovery	System Capability Recovery
Component Elimination or Replacement	Component Elimination or Replacement
Component Shielding	Component Shielding

is used here on the PKC to determine the probability distribution the aircraft is killed, P_K [5]. This more realistic approach to random outcomes mitigates some of the problems associated with the traditional single-value PKCs for both the ACS and ACCS threats described in Part 2. The AIE approach is used to demonstrate how to develop the P_K probability distribution with one specific SEF not included, and then included, in an aircraft's design for both the KE and the cyber antiaircraft weapons. These P_K distributions for an aircraft can then be used in any pertinent iterative computer campaign trade study program that includes a random variable for the aircraft's P_K to determine the distribution of the number of aircraft that would be killed in a campaign both with and without SEFs.

FIRST – THE METHODOLOGY FOR DEVELOPING SEFs FOR KE WEAPONS

Our aircraft have been contending with KE antiaircraft weapons for more than 100 years now. As a consequence, hundreds—if not thousands—of SEFs have been developed for individual aircraft in the past. In our ACS discipline, starting in the late 1970s, we developed a formal methodology that can be used to develop the SEFs for aircraft threatened by KE weapons. This methodology can also be used in our ACCS discipline to develop CSEFs for cyber weapons. The following text briefly describes this methodology for KE antiaircraft weapons.

In general, the survivability of an aircraft threatened by KE weapons can be enhanced or increased 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 use of the aircraft. Any particular characteristic of an aircraft, specific piece of equipment, design technique, armament, or use that reduces either the susceptibility P_H (the probability the aircraft is hit by one or more warhead damage mechanisms) or the vulnerability $P_{K|H}$ (the probability the aircraft is killed given one or more warhead damage mechanism hits on the aircraft) has the potential for increasing the aircraft's survivability P_S and is thus referred to as an SEF [4].

Figure 1, which is derived from Ball (2003), is a representation of the one-on-one KE PKC presented in Part 2, with a number of SEFs or

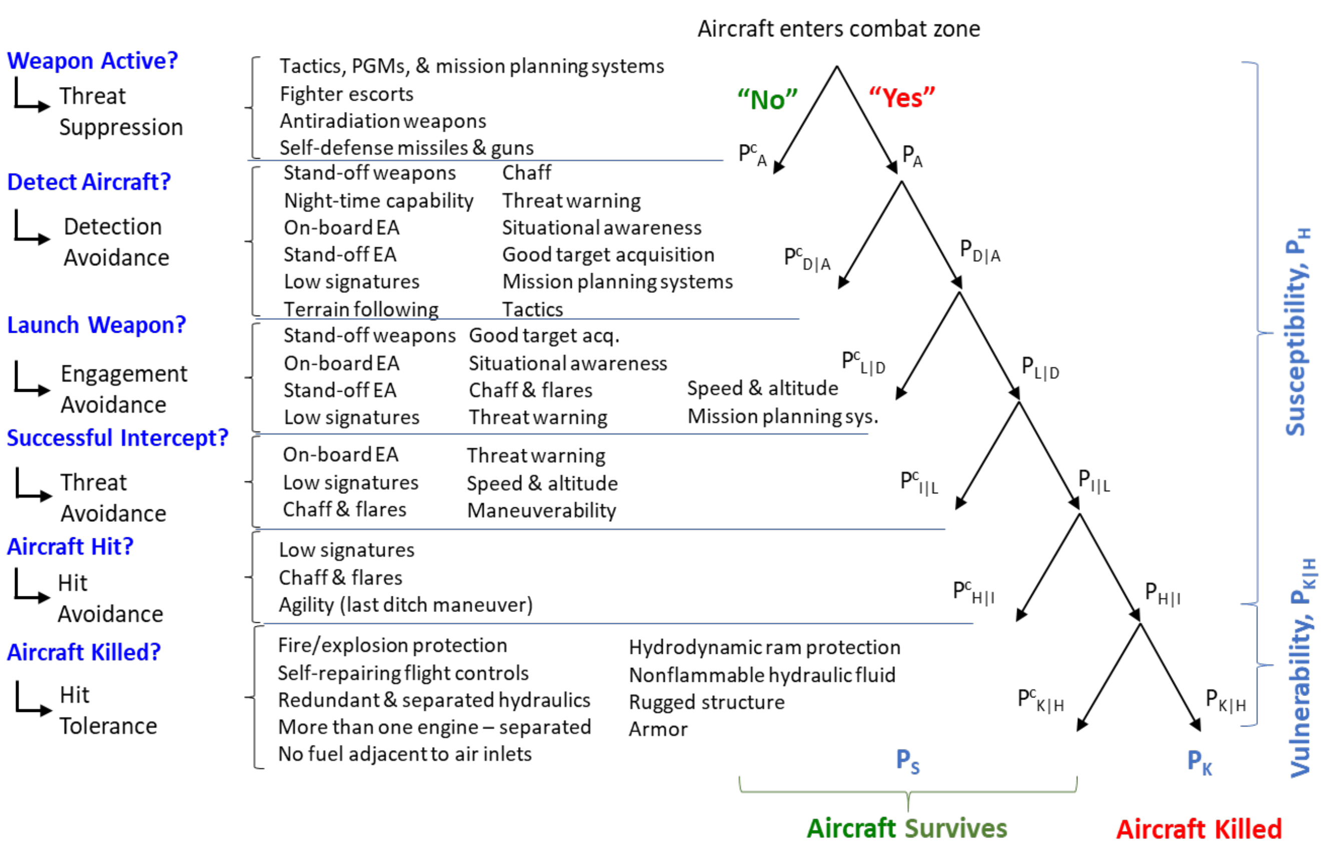

Figure 1. ACS PKC With SEFs [4].

concepts located within each phase of the PKC that the feature is designed to affect [4]. Every SEF, or SEC, in Figure 1 is intended to reduce the applicable right-branch probability of a successful outcome or event (from the perspective of the enemy air defense), and therefore increases the likelihood that the outcome of each of the sequential phases will branch to the left, and the aircraft will survive the attack.

Each of the SEFs listed in Figure 1 is an example of one of the 12 SECs. Each SEF either:

(1) reduces the aircraft's susceptibility, or likelihood the aircraft is hit by one or more warhead damage mechanisms (e.g., ballistic penetrators and HE warhead blast and fragments), by reducing the likelihood that one or more of the first five essential events in the KE weapon kill chain (weapon active, target detected, missile launched, target intercepted, and target hit by one or more of the missile warhead damage mechanisms) are successfully completed

or

(2) reduces the aircraft's vulnerability by enhancing the aircraft's ability to withstand one or more unavoidable damage mechanism hits.

First, consider the susceptibility reduction SEFs shown in Figure 1. Avoiding the man-made hostile threat environment can be achieved by suppressing or destroying the enemy air defence elements (Threat Suppression), or by the use of low signature aircraft that cannot be detected in sufficient time to engage our aircraft (Signature Control); by the use of stand-off weapons that allow our nonstealthy aircraft to launch long-range, precision-guided weapons, thus avoiding engagements with enemy weapons (Offensive Weapons); and by ejecting infrared (IR) flares from our aircraft that can prevent a launched IR missile from intercepting our aircraft by appearing as a more attractive target to the missile (Expendables).

In the end, the important point here is that every susceptibility reduction feature listed in Figure 1 is an example of one of the six SRCs; is specifically intended to reduce the conditional probability of occurrence of one or more of the five essential events in the susceptibility phase of the ACS PKC, as indicated in Figure 1; and thus reduces the aircraft's susceptibility measure, P_H.

(For more detail on the three major tasks in a susceptibility program—namely, identifying the essential elements and events [what makes an aircraft susceptible?], performing a susceptibility assessment [how susceptible is the aircraft?], and designing for low susceptibility using susceptibility reduction technology [what can be done about it?]—the interested reader is referred to chapter 4 of Ball (2003) [4].)

Now consider the vulnerability phase of the PKC shown in Figure 1. Aircraft vulnerability, or the inability of the aircraft to "withstand one or more unavoidable damage mechanism hits" (i.e., to withstand the man-made hostile environment), is reduced by preventing a kill of one or more of the aircraft's critical components when the aircraft is hit by one or more damage mechanisms. An aircraft's critical components are those components whose kill, loss, or degradation in capability, either individually (known as a nonredundant critical component) or jointly with other components (referred to as redundant critical components), results in the loss of either a flight-essential function (lift, thrust, control, and structural integrity) or a mission-essential function (any component whose proper functioning is essential for continued mission prosecution) when the aircraft is hit.

(Note: The inability of a component to provide the function it was designed to provide because of hits by one or more damage mechanisms on the aircraft is referred to variously as a component *dysfunction, malfunction, damage, failure, loss,* or *kill*, depending upon the type of analysis being performed and the performing organization.)

Examples of nonredundant critical components are a single pilot (loss of control), a single engine (loss of thrust), and a wing fuel tank that explodes when hit, causing the loss of a wing (loss of lift, control, and structural integrity). Examples of redundant critical components for an attrition kill are a pilot and copilot, both engines on a two-engine aircraft, and an electrically powered flight control system with multiple electrical power sources.

Every critical component on an aircraft has one or more possible component kill modes that could occur when an aircraft is hit. In general, a critical component can be killed either directly by a direct hit on the component by one or more warhead damage mechanisms that causes physical damage to the component or indirectly by the physical consequences of secondary damage mechanisms, such as the radiated heat from an onboard fire or the blast from a fuel tank explosion. An indirect kill without physical damage could also occur when an essential input to the component such as electrical power is lost directly due to a hit on the aircraft's electrical power system (or indirectly due to a hit-caused fire affecting the electrical power system). System kill modes refer to the ways that flight- or mission-essential functions provided by systems or subsystems can be lost when one or more critical components are killed.

Examples of a system kill mode are the loss of sufficient thrust that occurs when both engines are killed and the loss of control that occurs when all sources of electrical power to flight control surfaces are lost.

(Note that more detail on critical component kill modes, with all of their ramifications, can be found on pp. 621–631 of Ball (2003) [4].) In the end, the measure of an aircraft's vulnerability, $P_{K|H}$, can be reduced when the aircraft is designed using SEFs that reduce the probability that one or more critical component, or critical system, kill modes occur when an aircraft is hit by one or more warhead damage mechanisms.

For example, the fire/explosion protection SEF shown in Figure 1 is an example of the Passive and Active Damage Suppression VRC, in which fires or explosions are either prevented passively or the physical and functional effects of the fire or explosion are suppressed. The "more than one engine, separated" is an example of the Component and System Redundancy (with Effective Separation) VRC, and the "no fuel adjacent to air inlets" SEF is an example of the Component Location VRC.

In this brief summary of the methodology for developing SEFs for the KE weapons, aircraft susceptibility, P_H, is reduced by incorporating both design and operational SEFs that are intended to reduce the probability that one or more of the first five essential events in the ACS PKC occur; and $P_{K|H}$ is reduced by incorporating design SEFs that are intended to reduce the likelihood that one or more critical component, or critical system, kill modes occur when the aircraft is hit by one or more warhead damage mechanisms.

(For more detail on the three major tasks in a vulnerability program—namely, identifying the critical components and their kill modes [what makes the aircraft vulnerable?], performing a vulnerability assessment [how vulnerable is the aircraft?], and designing for low vulnerability using vulnerability reduction technology [what can be done about it?], the interested reader is referred to chapter 5 of Ball (2003) [4].)

SECOND – DEVELOPING SEFs FOR CYBER WEAPONS

The process of developing cyber weapon CSEFs is fundamentally the same as it is for developing KE SEFs. Accordingly, Figure 2 is a representation of the one-on-one cyber PKC presented in Part 2, with a number of CSEFs or CSECs located within each phase of the PKC that the feature is designed to affect. Every CSEF or CSEC in Figure 2 is intended to reduce the applicable right-branch probability of a successful outcome or event (from the perspective of the enemy air defense), and therefore increases the likelihood that the outcome of each of the sequential phases will branch to the left, and hence the aircraft will survive the attack.

Cyber survivability can be reduced by developing CSEFs that reduce the probability that one or more of the first five essential events in the ACCS kill chain occurs.

Cyber susceptibility can be reduced by developing CSEFs that reduce the probability that one or more of the first five essential events in the ACCS kill chain described in Part 2 occurs. Cyber vulnerability is reduced by developing CSEFs that reduce the probability that one or more critical component malfunction modes occur after an aircraft is hit and one or more malfunction mechanisms associated with the cyber warhead are implanted and triggered. For explanations of how the various CSECs and CSEFs listed in Figure 2 function, refer to Part 3 of the ACCS development [3]. The ACCS SEFs shown in Figure 2 track closely with the ACS SEFs shown in Figure 1, but there are some areas where the differences between KE and cyber weapons drive some changes.

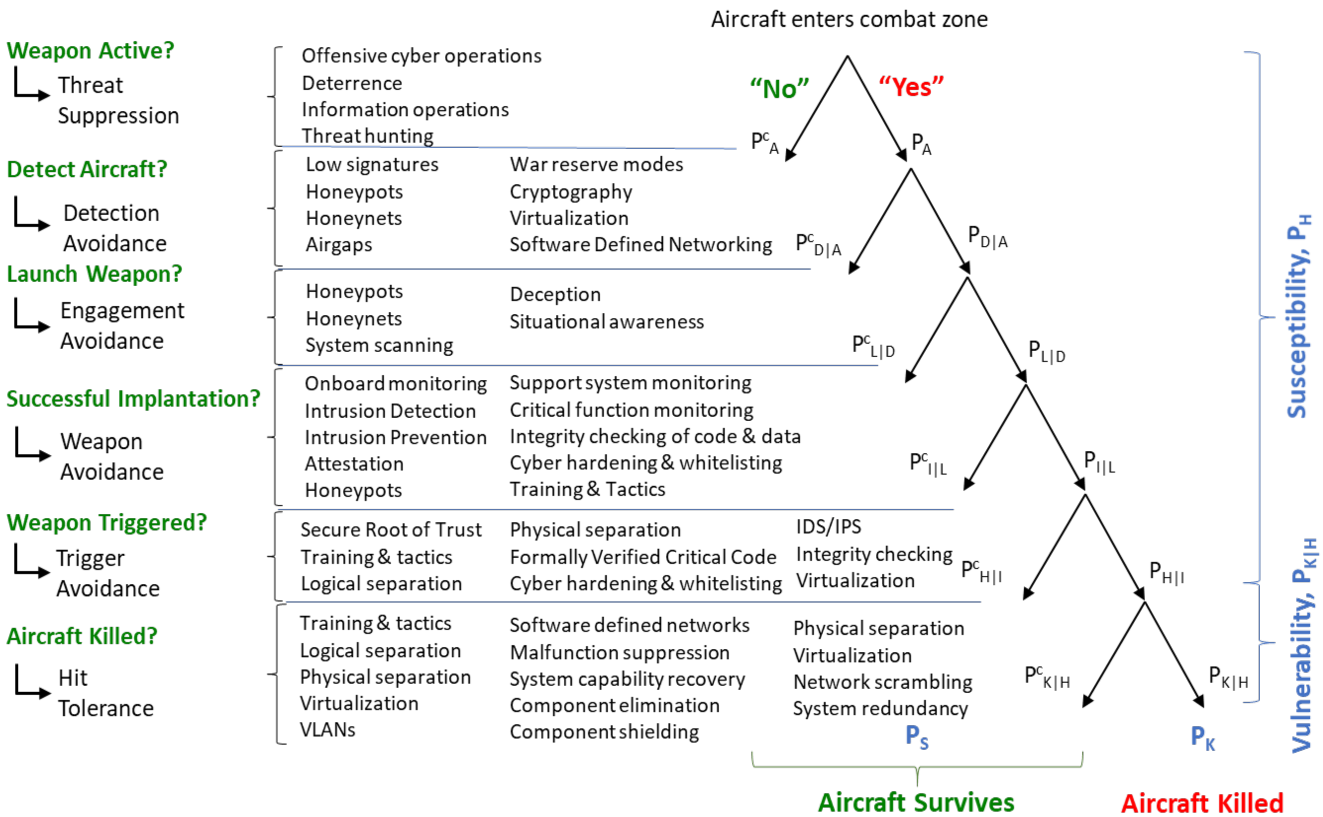

Figure 2. ACCS PKC with CSEFs.

THIRD – OPTIMIZING KE WEAPON SURVIVABILITY

Listing all of the SEFs that can reduce the probability at each link in the PKC is a useful exercise, but it does not help an engineer select between different SEFs or determine which ones will have the most increase in survivability relative to the dollar cost or the operational capability degraded. Every program is going to have limited resources at some point; thus, it is important for designers to be able to optimize their designs for the maximum increase in survivability available within their budgets, both in terms of dollars and mission performance. For example, is the increase in survivability achieved using explosion suppression reticulated foam in the ullage of an aircraft's fuel tanks "worth" the relatively "small" reduction in range or time on station due to the fuel displaced by the foam? Only a dedicated study can answer that question.

The procedure used in the ACS discipline at the time of the appearance of Ball (2003) [4] to determine those specific SEFs that should be included in the design of the aircraft to enhance the combat cost effectiveness of the aircraft as a weapon system consisted of (1) the assessment of the aircraft's survivability in the predicted threat environment to determine the combat survivability measure P_S (the probability the aircraft survives an encounter with a KE weapon or a mission) and (2) the conduct of operational effectiveness and survivability trade studies to determine those SEFs that increase the combat cost effectiveness of the aircraft as a weapon system. (This is not an easy task.)

Use of the PKC, with its six probabilities shown in Figure 1, to determine first P_K (the probability the aircraft is killed in an encounter with a KE weapon or is forced to abort the mission) and then P_S, is tempting but ultimately unsatisfactory. A major problem with using the PKC approach to assess, or quantify, an aircraft's survivability is the fact that so much of combat is random and any prediction of a single accurate value for P_S using the product of the six conditional outcome probabilities shown in Figure 1 can be highly questionable due to so many assumptions that have to be made and so many inherent dependencies throughout the kill chain. For example, consider the outcome probability $P_{K|H}$ in Figure 1 that the aircraft is killed (mission or permanent) given a hit on the aircraft by a particular weapon warhead (e.g., a 12.7-mm armor-piercing incendiary [API] projectile).

The next question after the identification of the threat warhead with its damage mechanisms is where the hit occurred on the aircraft? The $P_{K|H}$ value depends upon where the aircraft is hit; and the aircraft could be hit anywhere, from any direction, and at a range of velocities. These facts are difficult to account for in the PKC because the pertinent outcome probability in the chain that affects the P_K is the probability the aircraft is killed **given** a hit, with no conditions specified on the hit scenario. So, in essence, the individual outcome probabilities in the PKC are treated as independent of the details associated with the other outcome probabilities (e.g., a hit occurs; we just don't know where it occurred). As long as the hit takes place, the chain remains unbroken.

(Note that a detailed computerized modeling and simulation [M&S] of the physics and actions of the attack scenario, with or without randomness included, could determine where the aircraft is predicted to be hit and the conditions at the time of the hit. However, if we knew where it was hit and the hit conditions, we would need to know the particular value for the $P_{K|H}$ for that location under those conditions, which significantly increases the complexity and size of the assessment and the pertinent data base.)

As a consequence of this "single value for every probability" problem for each link in the PKC for the KE weapons, and for the cyber weapons as well, we introduced in Part 2 a statistical procedure for determining not a single value for P_S for an attack or a mission but rather a distribution for P_S values. This approach—known as the AIE approach—is applicable to both types of weapons. The AIE approach applied here for the KE weapons uses the PKC's sequence of six outcome probabilities, one for each link in the kill chain shown in Figure 1. Each of the six outcome probabilities is then assigned a probability distribution or density function, such as the normal distribution or the uniform distribution, with a mean and an estimated 90% confidence interval (90CI) around the mean. The 90CIs could be estimated by subject-matter experts (SMEs) in ACS for the KE weapons and by the SMEs in ACCS for the cyber weapons.

Every program is going to have limited resources at some point; thus, it is important for designers to be able to optimize their designs for the maximum increase in survivability available within their budgets, both in terms of dollars and mission performance.

So, instead of inputting that the single probability an adversary will detect an aircraft in a particular scenario is 0.70, a normal probability distribution could be assumed with a mean of 70% and a 90CI that would be 50% to 90%. This ensures that not only is the mean probability value captured, but a measurement of its uncertainty is captured as well. A probability that is based on extensive physical testing and historical experience should have a relatively narrow 90CI, while one that has significant uncertainty based only on one SME's experience with minimal testing and historical experience would be expected to have a much wider 90CI. The knowledgeable SME, with resources, might base his/her 90CI estimate on the possible hit conditions, such as the probable hit direction and location, if known. Finally, the assigned probability distributions for each of the six outcome probabilities are then "multiplied" together using the Monte Carlo iterative approach with thousands of iterations. The final result is a distribution for the values of P_K.

The 90CI distribution for each vector shown in the PKCs illustrated in Figures 1 and 2 cannot be simply multiplied as point probability values are, to determine a single value for P_K; but the process of multiplying a sequence of probability distributions can be accomplished using a process called a Monte Carlo simulation.

First, an assumption is made about the shape of the probability distribution of the data. The shape of the distribution depends on the nature of the underlying data, and it can take any number of different shapes. For the calculations in this simple example, a normal distribution is assumed, but a normal distribution will not always be the correct choice; power law, triangular, or even more general distributions may more accurately model the underlying probabilities.

Next, a point value is pulled or drawn from each assumed distribution in accordance with the probability distribution of that link in the chain. In a normal distribution, a point near the mean is much more likely to be selected by the draw than a point far out on the "tail." Those pulled or selected values from each of the six outcome probabilities for this iteration are then multiplied, and the results for the single P_K value for this sample draw is recorded. That procedure is repeated thousands of times.

Finally, each of the thousands of numerical results for P_K are then located in one of a number of discrete bins or increments along a horizontal axis from 0% to 100%, where each increment is, say, 1% wide. The number of draw results in each increment forms a final probability distribution that is the product combination of the six input 90CI distributions.

This resulting distribution will have a mean value, a standard deviation, and a 90CI. Larger uncertainties and greater divergence will give a distribution with a wide 90CI; smaller uncertainties and scores that are closer together will give narrower 90CIs. If there are several SME estimates of the 90CI for any one, or more, of the outcome probabilities, they can be combined by using another Monte Carlo random process. This Monte Carlo selects random points from each SME's distribution in accordance with the probabilities and then takes an average across all of them and repeats that process many thousands of times to create a new combined probability distribution.

To illustrate this new process of measuring the survivability associated with a particular SEF, we use one of the current aircraft survivability features: explosion suppression reticulated foam inserted in the ullage of aircraft fuel tanks to reduce the chance of an explosion inside of the tank. The aircraft being designed or updated in this example is a generic multirole fighter that currently does not have explosion suppression features in its fuel tanks. The threat weapon is a small surface-to-air missile (SAM) with a contact-fuzed high-explosive (HE) warhead. Note that for this particular SEF, the only outcome probability in the PKC that will change due to the presence of the foam is the $P_{K|H}$. For purposes of illustration, $P_{K|H}$ was reduced from 75% to 55%.

The probabilities developed throughout this example are not reflective of any particular aircraft and were created using round numbers purely to illustrate the process and avoid any possible classification issues. The normal probability distribution has been assumed for each of the outcome probabilities in our example. Ten thousand iterations were chosen for the Monte Carlo method. The results for our baseline example of a generic multirole fighter without any fuel tank foam are shown in Figure 3; and the results when there is foam in the fuel tanks are shown in Figure 4.

Note in Figure 3 that the product of the six individual outcome probability means in the input data = PK = (0.975* 0.70*0.70*0.60*0.70*0.75) = 0.1505 and that the single AIE distribution

Inputs						
	Probability adversary has active weapon and is searching for the aircraft (P_A)	Probability adversary detects aircraft ($P_{D|A}$)	Probability adversary tracks aircraft, generates a fire control solution and launches ($P_{L|D}$)	Probability the warhead transporter successfully intercepts the aircraft ($P_{I|L}$)	Probability the warhead transporter hits the aircraft ($P_{H|I}$)	Probability the aircraft is killed by the damage caused by the hit ($P_{K|H}$)
90%CI Upper	100.0%	90.0%	80.0%	80.0%	90.0%	95.0%
90% CI Lower	95.0%	50.0%	60.0%	40.0%	50.0%	55.0%
Mean	97.5%	70.0%	70.0%	60.0%	70.0%	75.0%

Outputs		
	Probability that the Aircraft/Mission will be killed (PK)	Probability that the Aircraft/Mission will survive (PS)
90%CI Upper Bound	24.67%	94.31%
90%CI Lower Bound	5.69%	75.33%
Standard Deviation	0.0577	0.0577
Mean	15.18%	84.82%

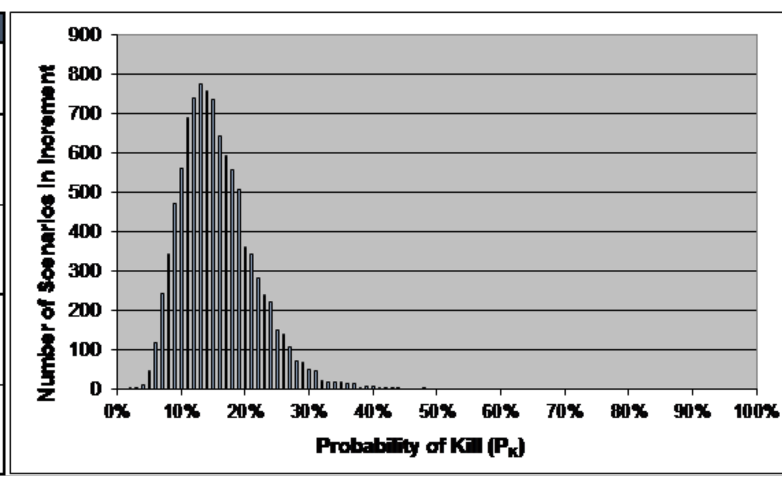

Figure 3. Notional Probability That a Generic MultiRole Fighter Will Be Killed by a Generic SAM Without Fire Suppression Features in Its Fuel Tanks.

Inputs						
	Probability adversary has active weapon and is searching for the aircraft (P_A)	Probability adversary detects aircraft ($P_{D\|A}$)	Probability adversary tracks aircraft, generates a fire control solution and launches ($P_{L\|D}$)	Probability the warhead transporter successfully intercepts the aircraft ($P_{I\|L}$)	Probability the warhead transporter hits the aircraft ($P_{H\|I}$)	Probability the aircraft is killed by the damage caused by the hit ($P_{K\|H}$)
90%CI Upper	**100.0%**	**90.0%**	**80.0%**	**80.0%**	**90.0%**	**75.0%**
90% CI Lower	**95.0%**	**50.0%**	**60.0%**	**40.0%**	**50.0%**	**35.0%**
Mean	97.5%	70.0%	70.0%	60.0%	70.0%	55.0%

Outputs		
	Probability that the Aircraft/Mission will be killed (P_K)	Probability that the Aircraft/Mission will survive (P_S)
90%CI Upper Bound	**18.25%**	**96.42%**
90%CI Lower Bound	**3.58%**	**81.75%**
Standard Deviation	0.0446	0.0446
Mean	**10.91%**	**89.09%**

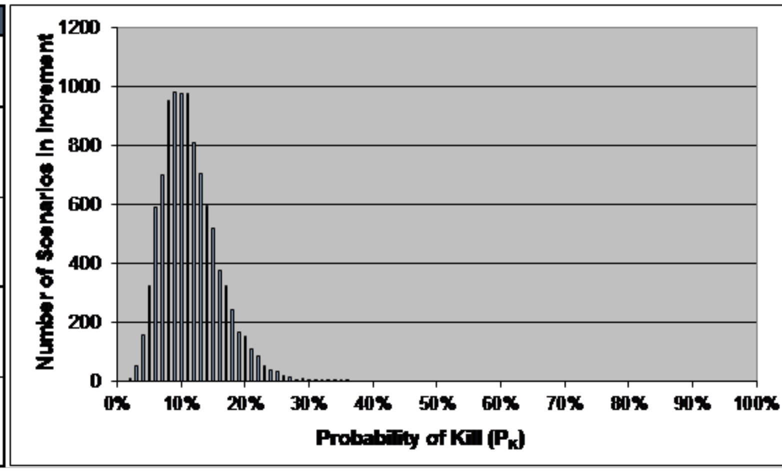

Figure 4. Notional Probability That a Generic Multirole Fighter Will Be Killed by a Generic SAM With Explosion Suppression Foam in Its Fuel Tanks.

mean generated by the Monte Carlo method = 0.1518. The slight difference indicates that the two probabilities have not converged yet due to the relatively small number of iterations. Furthermore, note the skewed lean of the PK distribution in Figure 3 toward the lower value. Also note that the probability distribution the aircraft survives the mission, PS = 1 – PK, is given in the figure in terms of the 90%CI upper and lower values, the standard deviation, and the mean values.

Examining the results of the foam trade study given in Figures 3 (without the SEF) and 4 (with the SEF), we can conclude that if we send 100 aircraft on this particular mission, and if we use the mean probabilities of P_K = 0.152 without foam and P_K = 0.109 with foam, we would expect to lose 100*0.152 = 15.2 unprotected aircraft (and possibly the 15.2 pilots) and only 100*0.109 = 10.9 protected aircraft (and possibly the 10.9 pilots), for a net savings of 4.3 aircraft (and possibly 4.3 pilots) due to the foam.

In general, a reduced P_K, with the accompanying reduction in aircraft and pilot losses in combat, does not yet tell senior decision-makers enough for them to make an informed decision on whether or not adding a particular SEF contributes to the combat cost effectiveness of the aircraft. Note that, as is the case with many survivability features, there may be a dollar and a performance or operational effectiveness cost associated with the SEF. For the fuel tank foam, there is the cost of purchasing, installing, and maintaining the foam, as well as the loss in range and time on station due to the fuel displaced by the foam.

To determine the overall increase in the combat cost effectiveness associated with the SEF, an understanding of how the addition of a particular SEF will affect operational results—such as aircraft killed (and possibly the pilots) and targets killed—at the campaign level is needed. Fortunately, a number of campaign-level M&S tools—such as the Advanced Framework for Simulation, Integration and Modeling (AFSIMS)—are available, allowing for a simulation of an overall campaign with one set of assumptions (e.g., no foam in the fuel tanks of multirole fighter X) to be run and then run again with an updated set of assumptions (e.g., foam in the fuel tanks) to compare the results. (If the M&S program has the capability to consider random variables, such as the P_K, the AIE approach described here can be used.) If fewer of our aircraft are shot down due to a reduced P_K, that can also translate into more targets hit later as those pilots and aircraft are still available. Negative effects, such as reduced range, can also be modeled. The results of campaign-level simulations on campaigns relevant to the aircraft under consideration give decision-makers a clearer understanding of the expected costs and benefits of various SEFs under consideration and compare their expected cost in money and performance and expected benefits in saved aircraft and their flight crews. (We want to remind the reader here that for every aircraft killed in combat, there is a good chance that we will also lose the pilot. This is an important consideration that must be taken into account when evaluating the costs and benefits associated with the SEFs.)

The aforementioned analysis can then be repeated for various potential SEFs, and then the final part of the trade study process is to determine what set of SEFs within available budget optimizes survivability. Three less expensive SEFs may be more effective than one expensive SEF or vice versa, and this problem can be effectively analyzed using a "knapsack algorithm" that determines the optimal cost-benefit combination of various sets of SEFs at various budget levels. For an excellent discussion of this process, see pp. 323–326 of Saydjari (2018) [6].

FOURTH – OPTIMIZING CYBER WEAPON SURVIVABILITY

To illustrate the process of using M&S to select CSEFs, we give another example similar to the kinetic SEF example given previously. In this cyber weapon example, we use the same generic multirole fighter as before, but we examine its survivability against a generic cyber weapon intended to access the internal avionics on the aircraft and cause either an attrition kill (the aircraft is physically destroyed) or a mission kill (the aircraft has to terminate the mission but can return to fight another day). Obviously, attrition kills are more significant to the defender; and attacks that could lead to them, such as those that could cause significant malfunctions in engines or flight controls, should in most cases be prioritized by defenders.

High levels of uncertainty in the probabilities in the ACCS kill chain can highlight areas where more analysis and measurement can have great value. For example, if the uncertainty of $P_{I|L}$ (or the probability that the weapon warhead's malfunction mechanism is successfully implanted) is wide, further decomposing the probability using attack trees can help the analysis. Attack trees were popularized by Mr. Bruce Schneier, and an excellent introductory-level discussion can be found on pp. 116–127 of Saydjari (2018) [6]. In addition to further analytical decomposition, cybersecurity testing can have great value in reducing uncertainty. For example, if different analysts have divergent ideas on how likely a particular attack is, a test of that particular attack against representative hardware can illustrate how easy, or difficult, the attack actually is and reduce uncertainty. For an introductory discussion of cyber testing of weapon systems, see the recently published article by Bryant and Odom (2020) [7].

For this cyber example, we used a group of expert SMEs involved in developing defenses to cyber weapons to determine reasonable generic 90CIs for the probabilities, but none of these probabilities refers to any particular aircraft or cyber weapon. The inputs from the cyber experts were combined using a Monte Carlo simulation to

High levels of uncertainty in the probabilities in the ACCS kill chain can highlight areas where more analysis and measurement can have great value.

create a combined distribution. The results of the baseline model can be seen in Figure 5.

It is not surprising that the P_K of the cyber weapon is relatively high, since the baseline case assumed minimal defenses, as is common on older legacy aircraft.

To make the first mitigation example comparable to the explosive suppressant foam kinetic case, we modeled a single engineering mitigation that would be designed into the hypothetical multirole fighter for our first example. After consultation with a range of cybersecurity experts, we chose to model adding an Intrusion Detection System (IDS) to the main bus of the aircraft's avionics as the CSEF. As there is currently no visibility for defenders to see adversary attacks on the notional data bus, the addition of any monitoring was expected to have a significant effect on the probability that the adversary would be able to successfully implant their weapon ($P_{I|L}$) and minimal to no significant change to the other probabilities. The scoring with the addition of a data bus IDS is given in Figure 6.

Inputs	Probability adversary has active cyber weapon and is searching for the aircraft (P_A)	Probability adversary detects aircraft in cyberspace ($P_{D|A}$)	Probability adversary determines path and launches cyber transporter ($P_{L|D}$)	Probability the cyber warhead is successfully implanted ($P_{I|L}$)	Probability the cyber warhead is triggered ($P_{T|I}$)	Probability the aircraft is killed by the system malfunctions caused by the cyber warhead ($P_{K|T}$)
90%CI Upper	85.4%	70.8%	71.7%	73.0%	88.0%	93.2%
90% CI Lower	72.8%	58.0%	58.1%	59.7%	75.9%	86.8%
Mean	79.1%	64.4%	64.9%	66.3%	81.9%	90.0%

Outputs	Probability that the Aircraft/Mission will be killed (P_K)	Probability that the Aircraft/Mission will survive (P_S)
90%CI Upper Bound	19.57%	87.28%
90%CI Lower Bound	12.72%	80.43%
Standard Deviation	0.0208	0.0208
Mean	16.15%	83.85%

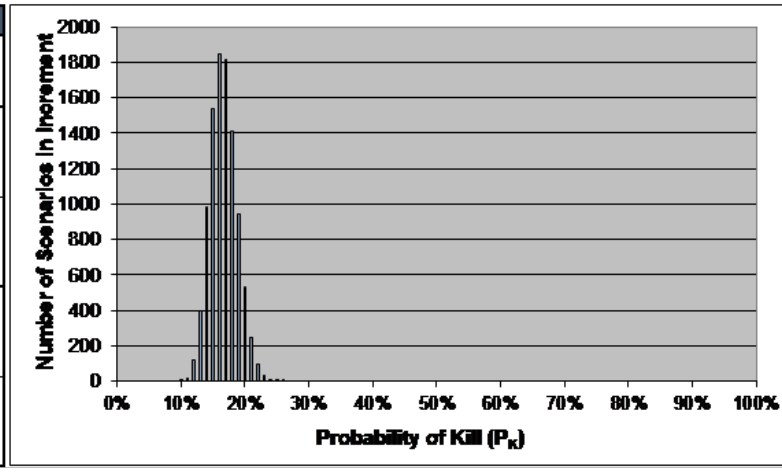

Figure 5. Probability That a Generic Multirole Fighter Will Be Killed by a Generic Cyber Weapon Without Cyber Defenses.

Inputs	Probability adversary has active cyber weapon and is searching for the aircraft (P_A)	Probability adversary detects aircraft in cyberspace ($P_{D|A}$)	Probability adversary determines path and launches cyber transporter ($P_{L|D}$)	Probability the cyber warhead is successfully implanted ($P_{I|L}$)	Probability the cyber warhead is triggered ($P_{T|I}$)	Probability the aircraft is killed by the system malfunctions caused by the cyber warhead ($P_{K|T}$)
90%CI Upper	85.4%	70.8%	71.7%	35.6%	88.0%	93.2%
90% CI Lower	72.8%	58.0%	58.1%	24.4%	75.9%	86.8%
Mean	79.1%	64.4%	64.9%	30.0%	81.9%	90.0%

Outputs	Probability that the Aircraft/Mission will be killed (P_K)	Probability that the Aircraft/Mission will survive (P_S)
90%CI Upper Bound	9.22%	94.61%
90%CI Lower Bound	5.39%	90.78%
Standard Deviation	0.0116	0.0116
Mean	7.30%	92.70%

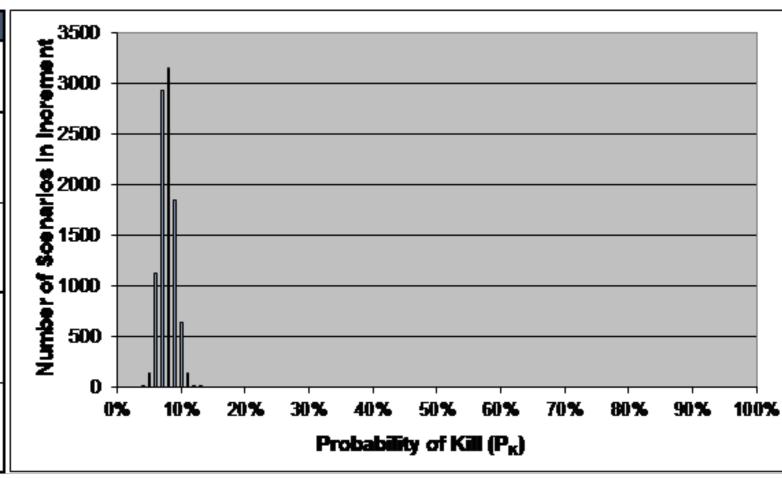

Figure 6. Probability That a Generic Multirole Fighter Will Be Killed by a Generic Cyber Weapon With a Data Bus IDS.

Data bus IDS systems are conceptually similar to traditional information technology (IT) IDS systems although they operate in different architectures using different protocols and rule sets. While not yet commonly deployed, they are maturing rapidly, and a number of commercial aviation-focused IDS systems are currently on the market. The mission impact of the increase in survivability given by adding an IDS can be modeled at the campaign level with a modeling system such as AFSIMS in exactly the same way as was discussed previously for foam in the fuel tanks.

For a second mitigation example, the cybersecurity engineers selected their preferred set of mitigations or CSEFs. As they were unconstrained by budget, they selected a robust set of defenses, including the following:

1. Secured bus communications between avionics components (CSEFs: cryptography, cyber hardening)
2. A bus monitoring solution looking at both data and physical characteristics of signals across all buses (CSEF: IDS)
3. A "firewall-like solution" or "crypto data validator" for all data "installs/uploads" to onboard systems (CSEFs: Intrusion Prevention System [IPS], integrity checking)
4. Critical avionics secured with a hardware root of trust (CSEF: secure root of trust)
5. Formal verification of critical elements of avionics software, to ensure clean code from vendors (CSEF: formally verified critical code).

All of these defenses and CSEFs exist today and have been implemented in various settings, although some of these defenses would certainly be challenging and expensive to implement on a legacy platform. As shown in Figure 7, with these robust defenses, the rescored P_K dropped by 2 orders of magnitude from the baseline case.

If the high cost of implementing such a robust set of defenses was unachievable for a real aircraft program, the program could use the knapsack algorithm discussed previously to determine what subset of these defenses provided the greatest survivability within available budget.

CONCLUSIONS

Over this four-part series of articles, we have shown that the fundamental principles and approach used in the ACS design discipline provide an extremely useful framework for ACCS, though some modifications are needed to account for the different "physics" of cyber vs. kinetic weapons.

In Part 1, we discussed the major elements of a cyber antiaircraft weapon, in terms of the analogous KE weapon elements, and how cyber antiaircraft weapons can kill aircraft. Part 2 provided definitions for the fundamental ACCS terms drawn from kinetic ACS terms, described the ACCS kill chain in terms of the KE weapon kill chain, and explained how probabilities can be used to model that kill chain. In Part 3, we pivoted to CSECs and discussed both the susceptibility and vulnerability reduction concepts that apply to cyber weapons. Finally, in this fourth and final part, we have shown how specific CSEFs can be developed, modeled, and scored to determine which set of specific design features will provide the greatest survivability enhancement within an available budget.

In conclusion, it should be noted that there are two equally wrong ways for combat aircraft designers to think about cyber weapons. The first is to ignore or discount them because we have not yet seen their large-scale use in combat (much like infantry and

Inputs						
	Probability adversary has active cyber w eapon and is searching for the aircraft (P_A)	Probability adversary detects aircraft in cyberspace ($P_{D\|A}$)	Probability adversary determines path and launches cyber trasnsporter ($P_{L\|D}$)	Probability the cyber w arhead is successfully implanted ($P_{I\|L}$)	Probability the cyber w arhead is triggered ($P_{H\|I}$)	Probability the aircraft is killed by the system malfunctions caused by the cyber w arhead ($P_{K\|H}$)
90%CI Upper	81.2%	61.9%	53.5%	19.6%	19.5%	44.1%
90% CI Lower	63.9%	46.8%	41.5%	10.4%	10.4%	26.0%
Mean	72.5%	54.3%	47.5%	15.0%	15.0%	35.1%

Outputs		
	Probability that the Aircraft/Mission w ill be killed (P_K)	Probability that the Aircraft/Mission w ill survive (P_S)
90%CI Upper Bound	0.23%	99.94%
90%CI Lower Bound	0.06%	99.77%
Standard Deviation	0.0005	0.0005
Mean	0.15%	99.85%

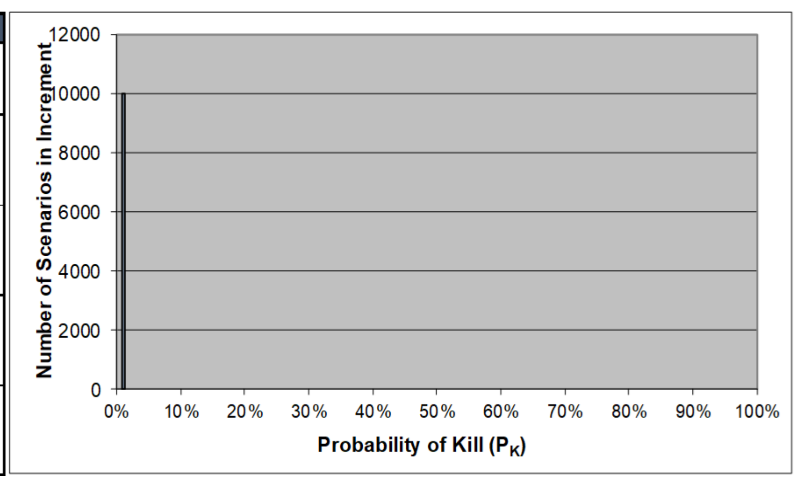

Figure 7. Probability That a Generic Multirole Fighter Will Be Killed by a Generic Cyber Weapon With Robust Defenses.

U.S. Air Force Photo by Joshua Seybert

> The second wrong way to think about cyber weapons is to place too much emphasis on them and see them as nearly unstoppable. Building aircraft that are so cyber secure that they are not combat effective can be the result of this line of thinking.

cavalry officers ignored aircraft just prior to World War I). Conversely, the second wrong way to think about cyber weapons is to place too much emphasis on them and see them as nearly unstoppable. Building aircraft that are so cyber secure that they are not combat cost effective can be the result of this line of thinking—such as with the flying tank aircraft analogy.

Accordingly, the middle road of considering cyber weapons in the same way that we think about guns and guided missiles, is, in our opinion, the right way forward. Defenses and survivability enhancements against cyber weapons need to be considered and designed into combat aircraft in the same way that defenses and survivability enhancements against KE threats are, and then balanced against each other. Admittedly, design optimization is always a hard problem, and now we need to add one more performance area that must be balanced with all of the rest to ensure that we build the most capable and most cost-effective combat aircraft possible for our Warfighters. ASJ

ABOUT THE AUTHORS

Dr. William D. "Data" Bryant is a cyberspace defense and risk leader who currently works for Modern Technology Solutions, Incorporated (MTSI). His diverse background in operations, planning, and strategy includes more than 25 years of service in the Air Force, where he was a fighter pilot, planner, and strategist. Dr. Bryant helped create Task Force Cyber Secure and also served as the Air Force Deputy Chief Information Security Officer while developing and successfully implementing numerous proposals and policies to improve the cyber defense of weapon systems. He holds multiple degrees in aeronautical engineering, space systems, military strategy, and organizational management. He has also authored numerous works on various aspects of defending cyber physical systems and cyberspace superiority, including *International Conflict and Cyberspace Superiority: Theory and Practice* [8].

Dr. Robert E. Ball is a Distinguished Professor Emeritus at the Naval Postgraduate School (NPS), where he has spent more than 33 years teaching ACS, structures, and structural dynamics. He has been the principal developer and presenter of the fundamentals of ACS over the past four decades and is the author of *The Fundamentals of Aircraft Combat Survivability Analysis and Design* (first and second editions) [4, 9]. In addition, his more than 57 years of experience have included serving as president of two companies (Structural Analytics, Inc., and Aerospace Educational Services, Inc.) and as a consultant to Anamet Labs, the SURVICE Engineering Company, and the Institute for Defense Analyses (IDA). Dr. Ball holds a B.S., M.S., and Ph.D. in structural engineering from Northwestern University.

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CALENDAR OF EVENTS

ATTENTION:

Due to the many last-minute event postponements, cancellations, and travel restrictions related to the COVID-19 outbreak, readers are encouraged to double-check with event sponsors and websites to confirm the status of an event before making associated travel reservations and other plans.

MARCH

2021 IEEE Aerospace Conference
6–13 March (Virtual)
https://aeroconf.org

Counter UAS Summit 21
31 March–2 April
https://www.idga.org/events-counteruas-usa/faq

APRIL

Insensitive Munitions and Energetic Materials Technology Symposium
7–8 April (Virtual)
https://www.ndia.org/events/2021/4/7/imem-technology-symposium

2021 Integrated Communications Navigation and Surveillance Conference
20–22 April (Virtual)
https://i-cns.org

2021 Army Aviation Mission Solutions Summit
21–23 April in Nashville, TN
https://s15.a2zinc.net/clients/aaaa/aaaa21/Public/Enter.aspx

MAY

Vertical Flight Society Forum 77
11–13 May in West Palm Beach, FL
https://vtol.org/events/77th-annual-forum-and-technology-display

64th Annual Fuze Conference
11–13 May in Renton, WA
https://www.ndia.org/events/2021/5/11/fuze-2021

SOFIC 2021
17–21 May in Tampa, FL
http://sofic.org

JUNE

2021 AIAA Aviation and Aeronautics Forum
7–11 June in Washington, DC
https://www.aiaa.org/aviation

AUGUST

Sea-Air-Space 2021
1–4 August in National Harbor, MD
https://seaairspace.org/

MSS Tri-Service Radar Symposium
7–11 June in Monterey, CA
https://mssconferences.org

2021 AIAA Propulsion and Energy Forum
9–11 August in Denver, CO
https://www.aiaa.org/propulsionenergy

2021 JCAT Threat Weapons and Effects Training
17–19 August at Eglin AFB, FL
https://www.dsiac.org/events/2021-joint-combat-assessment-team-jcat-threat-weapons-effects-training-twe

2021 Military Sensing Symposia Parallel Conference
30 August–2 September in Orlando, FL
https://mssconferences.org

SEPTEMBER

47th European Rotorcraft Forum
7–10 September in Glasgow, Scotland
https://vtol.org/events/47th-european-rotorcraft-forum

Note

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