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DISSERTATION

A FORMAL APPLICATION OF SAFETY AND RISK ASSESSMENT IN SOFTWARE SYSTEMS

by

Christopher Loyal Williamson

September 2004

Dissertation Supervisor: Luqi

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A FORMAL APPLICATION OF SAFETY AND RISK ASSESSMENT IN SOFTWARE SYSTEMS

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Submitted in partial fulfillment of the
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The current state of the art techniques of Software Engineering lack a formal method and metric for measuring the safety index of a software system. The lack of such a methodology has resulted in a series of highly publicized and costly catastrophic failures of high–assurance software systems. This dissertation introduces a formal method for identifying and evaluating the weaknesses in a software system using a more precise metric, counter to traditional methods of development that have proven unreliable. This metric utilizes both a qualitative and quantitative approach employing principles of statistics and probability to determine the level of safety, likelihood of hazardous events, and the economic cost–benefit of correcting the flaws through the lifecycle of a software system. This dissertation establishes benefits in the fields of Software Engineering of high–assurance systems, improvements in Software Safety and Software Reliability, and an expansion within the discipline of Software Economics and Management.

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I wish to express my sincere gratitude to the United States Navy for affording me the opportunity to pursue this and other degrees while simultaneously serving an operational tour in the Forward Deployed Naval Forces. In the days of dwindling budgets and resources, opportunities to pursue advanced educational opportunities are rare. I am gracious that the Navy and the Naval Postgraduate School have the foresight to offer this degree program to those who are called to serve at the tip of the spear.

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This dissertation is dedicated to the airmen and seamen who served with me, protected me, guided me, encouraged me to strive for greater things, and who gave me the experience to write this dissertation; and finally to my wife who patiently waited for my return from many a distant voyage. No man alone can accomplish such an endeavor.

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EXECUTIVE SUMMARY

Despite significant efforts to improve the reliability and success of software system development, there exists an inherent level of failure within all software based systems. A decision to select one software system over another must be made considering the level of failure and its consequences. Due to the proliferation in technological requirements and control, government and private organizations increasingly require high–assurance software development that cannot be satisfied by standard techniques. I introduce in this dissertation a stepwise method for measuring and reporting the potential safety of a software system, based on an assessment of the potential for event failure and the corresponding potential for that failure to result in a hazardous event.

The lack of such a methodology and assessment has resulted in a series of unforeseen, highly publicized, and costly catastrophic failures of high–assurance software systems. This dissertation introduces a formal method for identifying and evaluating the weaknesses in a software system using a more precise metric, counter to traditional methods of development that have previously proven unreliable. This metric utilizes both a qualitative and quantitative approach employing principles of statistics and probability to determine the level of safety, likelihood of hazardous events, and the economic cost–benefit of correcting flaws through the lifecycle of a software system.

From this dissertation, the state of the art of Software Safety and Software Engineering benefits from a review of the faults and complexities of software development, a formal model for assessing Software Safety through the development process, the introduction of a common metric for evaluating and assessing the qualitative and quantitative factors of a Software System, improvements and awareness of the facets of Software Safety Economics, and a formal study of the state of the art of Software Safety. This dissertation serves as a primer for future research and improvements to the development process and to increase awareness in the field of Software Safety and Software Engineering.

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I. INTRODUCTION

"To err is human, but to really foul things up requires a computer"[1]

The Farmers' Almanac for 1978

A. PROBLEM AND RESULTS

When the first modern computer based systems were deployed, just a mere fifty years ago, they were designed to make simplistic calculations at a processing speed greater then those possible by man and at a higher rate of reliability.[2, 3] In their initial stages, their operators would manually verify calculations and procedures to ensure accuracy and compliance with established standards. Today, software based computer systems are no longer used exclusively to simply make radiometric calculations – they are developed to monitor, process, and control a wide variety of complex operations whose failure could result in significant danger and damage to the operators, the general public, and to the environment.

Despite significant efforts to improve the reliability of software system development, there exists an inherent level of failure within all software based systems. A decision to select one software system over another must be made considering the level of failure and its consequences. The research of this dissertation has failed to identify a viable measure of software safety in the current state of the art. It is the purpose of this dissertation to establish a method for measuring and reporting the potential safety of a software system, based on an assessment of the potential for event failure and the corresponding potential for that failure to result in a hazardous event.

From this dissertation, the state of the art of Software Safety and Software Engineering will benefit from a review of the faults and complexities of software

[1] *Capsules of Wisdom, The Farmers' Almanac for 1978,* Yankee Publishing; 1977.

[2] *Computer History Collection*, The Smithsonian Institute; 2003.

[3] War Department, Branch of Public Relations, Press Release, *Ordnance Department Develops All-Electronic Calculating Machin*e, War Department, United States Government; 16 February 1946.

development, a formal model for assessing Software Safety through the development process, the introduction of a common metric for evaluating and assessing the qualitative and quantitative factors of a Software System, the improvements and awareness of the facets of Software Safety Economics, and a formal study of the state of the art of Software Safety. It is the intent that this dissertation serves as a primer for future research and improvements to the development process and to increase awareness in the field of Software Safety and Software Engineering.

B. LEARNING AT THE EXPENSE OF FAILURE

1. Failure Due to a Factor of 4.45[4]

On December 11, 1998 at 18:45:51 UTC[5] (13:45:51 EST), the Mars Climate Orbiter (MCO) departed the Cape Canaveral Air Force Station aboard a Delta II Launch Vehicle on a six year mission to collect information on the Martian climate and serve as a relay station for future Mars Missions.[6] After nine months of interplanetary travel, the MCO was scheduled for Mars orbital insertion on the morning of September 23, 1999. At 09:00:46Z the MCO's main engines commenced a preplanned 16 minute and 23 second aerobreaking maneuver to slow the craft prior to entry into the Martian atmosphere. At the time of main engine burn, the vehicle was traveling at over 12,300 mph or 5.5 km/sec. Four minutes later, as the vehicle passed behind the Martian Planet, signal reception from the MCO was lost. Signals were lost 49 seconds earlier than predicted due to planetary occultation.[7] After 09:04:52Z, no signal was regained. For 48 hours, NASA and JPL made exhaustive attempts to reacquire the signal and locate the MCO. On September 25, 1999, the Mars Climate Orbiter was declared lost.

[4] The figure 4.45 is analogous to the metric to pounds force conversion factor that was overlooked during the mathematical processing of the Mars Climate Orbiter navigational algorithm, referenced later in this sub-chapter.

[5] Also referred to as "Z" or "ZULU" Time Zone, Coordinated Universal Time, *The Merriam-Webster's Collegiate Dictionary, Tenth Edition*, Merriam Webster, Incorporated; Springfield, Massachusetts; 1999.

[6] *Mars Climate Orbiter Mission Overview*, Jet Propulsion Laboratory, Mission Overview, National Aeronautics and Space Administration and Jet Propulsion Laboratory; 1998 – 1999. http://mars.jpl.nasa.gov/msp98/orbiter/launch.html

[7] Def: The phenomenon that occurs when a vehicle passes behind another celestial body, obscuring the vehicle from view and reducing its ability to communicate with other receivers in line of sight.

Investigations into the loss of the Mars Climate Orbiter revealed that the orbiter was over 170 km below its planned entry altitude at the time of main engine firing. The MCO Mishap Investigation Board found the cause of the mishap to be a failure to use Metric (Newton) units in the coding of the ground software file of the trajectory models, in direct contradiction of system development requirements.[8, 9] In contrast, thruster performance data was reported and stored in the system's database in English (pounds force) units. The lack of a conversion factor placed the orbiter in too low a trajectory to be sufficiently slowed prior to entry into the atmosphere. At its estimated rate of entry, the Mars Climate Orbiter most likely burnt up on orbital insertion, skipped off the atmosphere and reentered space with catastrophic damage, or impacted the Martian surface and was destroyed (see Figure 1). None of the planned mission objectives were achieved. Mission expenditures totaled $327.6 million with $193.1 million for spacecraft development, $91.7 million for launch, and $42.8 million for mission operations. In addition, future Mars missions were placed in jeopardy without a dedicated radio orbiter; a mission that would have been filled by the MCO.

[8] *Mars Climate Obiter Mishap Investigation Board Report, Phase I Report*, National Aeronautics and Space Administration and Jet Propulsion Laboratory; 10 November 1999.

[9] Note: English thrust units are in Pounds–Force – Second, while Metric thrust units are in Newton – Second. The conversion factor is 1 Pound Force = 4.45 Newton.

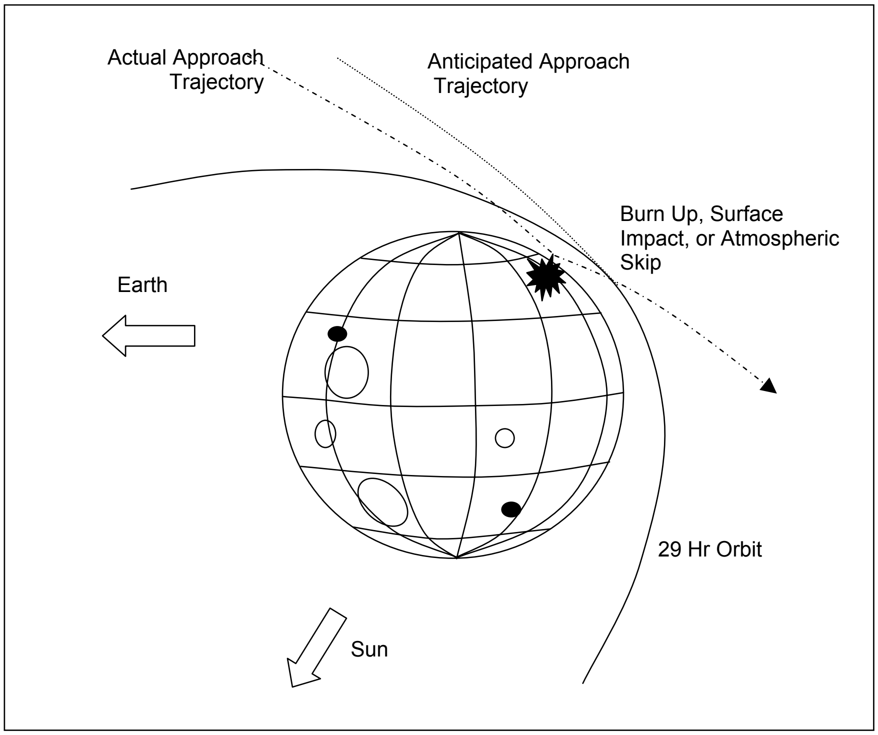
Actual Approach Trajectory
Anticipated Approach Trajectory
Burn Up, Surface Impact, or Atmospheric Skip
Earth
29 Hr Orbit
Sun

Figure 1 Mars Climate Orbiter Failure

2. Premature Shutdown

Just three months after the loss of the MCO, on the morning of December 3rd, 1999, the Mars Polar Lander, the second in a series of Mars Planetary Explorers, experienced a premature shutdown of its main engines and deployment of its lander legs during its terminal decent propulsion phase to the Martian Planet.[10] The premature shutdown and deployment was attributed to a loss of system telemetry data. The premature shutdown resulted in the lander free–falling to the planet's surface and eventual destruction. Investigation revealed an inability in the software system's base logic to correct for the loss of telemetry data or execute a failsafe maneuver.

Mishap Investigation Boards determined the fault in both spacecraft mishaps to be poor project management practices and oversight, improper development techniques, the failure to completely test the control systems, the failure to properly detect potential

[10] *Mars Polar Lander Mishap Investigation Board Report*, National Aeronautics and Space Administration and Jet Propulsion Laboratory; Washington D.C.; 28 March 2000.

hazards and faults, and the failure to take precautions to prevent such catastrophic mishaps. Both systems were developed under the NASA principle of "Better, Faster, Cheaper."[11] The second failure resulted in the total loss of over half a billion dollars of sophisticated space equipment and the failure to establish the deployed base infrastructure for future Mars missions.

C. A HISTORICAL TREND OF FAILURE

At the end of the 20th Century, Software Failure has proven one of the greatest detractors of public confidence in the technology.[12] A 1995 study by the Standish Group noted that over 31.1% of the projects sampled were cancelled before they were ever completed.[13] Of the remaining 68.9%, 52.7% exceeded projected costs by a staggering 189%. It was estimated that American companies and the Federal Government lost over $81 billion to cancelled projects in a single year, and an additional $59 billion to software systems that were delayed or were completed past their expected delivery time. It is inappropriate to use the term "expense", as was referred to in the study, but rather to the term "lost", as organizations received no additional reward or gain for additional money spent.[14] While the phrase may be a matter of semantics, it is essential that researchers and evaluators of Software Safety do not attempt to soften or mitigate their vocabulary at the cost of hiding the significant dangers that lurk within software system failures.

Through the end of the decade, the statistics failed to improve. A large sampling of over 8,000 software systems revealed that over 40% of the Information Technology (IT) projects end in failure. Of the remaining 60%, 33% were either over budget, completed past their expected delivery date, or lacked primary features specified in system requirements, or both. The total cost in lost productivity and material, lost

[11] Goldin, Dan; *Public remarks to JPL Employees*, NASA Public Affairs, National Aeronautics and Space Administration; Washington, D.C.; 28 May 1992.

[12] Interagency Working Group (IWG) on Information Technology Research and Development (IT R&D), Information Technology: The 21st Century Revolution, Overview, *High Confidence Software and Systems, National Coordination Office for Information Technology Research and Development*, *www.ccic.gov/pubs/blue01/exec_summary.html.*

[13] *Chaos*, The Standish Group, The Standish Group International; West Yarmouth, Massachusetts; 1995.

[14] See Chapter Endnote I.I.1. – *Software Failure Cost*

revenue, and legal compensatory damage due to failed or flawed software was beyond computation. Some estimates put the total American loss well in excess of $150 billion annually,[15, 16] an amount greater then the GDP of Hong Kong, Greece, Israel, or Ireland.[17, 18] One of most disturbing consequences of Software Failure is the increasing trend in deaths and human maiming.[19]

Despite over 50 years of software development, the discipline of Software Engineering (SE) has failed to improve in cadence with the technology that it marches alongside of. Statistically speaking, software development is a failing industry, buoyed up only by the demand and requirement for systems to control the same technology that it fails to keep pace with. Consumers have grown callous to the fact that the software they have purchased will be flawed, require updates and service packs, and will crash at the most inopportune moment. Businesses budget for and expect to pay for extended delays and faults, take out insurance against the inevitable failure, and develop manual contingency plans to continue operations in the event that automation fails. Due to the complexity of some high–assurance systems, there is no manual contingency to fall back upon in the event of a loss of automated control.

Software Engineering is often confused and misconstrued with the simplistic discipline of software programming; where software programming is the basic process of putting code to keyboard, Software Engineering is the complex process of developing and implementing the logic and methodology behind the code. The Software Engineering discipline encompasses the study of:

[15] Note: It is estimated that the American public spent over $250 billion on application development in 1995, according to the 1995 *Chaos* study by The Standish Group – The Standish Group International; West Yarmouth, Massachusetts; 1995.

[16] Neumann, Peter G.; Moderator, *Risks – Forum Digest, Forum On Risks To The Public In Computers And Related Systems*, ACM Committee on Computers and Public Policy, Published weekly, SRI Inc.

[17] CIA World Factbook, 2000 Edition, *United States Central Intelligence Agency (CIA); 2000.*

[18] Note: In addition to the countries listed, there are over 195 countries with GDPs less then $150 Billion, according to the *CIA World Factbook, 2000 Edition*.

[19] Neumann, Peter G.; Moderator, *Risks – Forum Digest, Forum On Risks To The Public In Computers And Related Systems*, ACM Committee on Computers and Public Policy, SRI Inc.

- Efficiency and practicability of code,
- Modernization techniques,
- Reusability,
- The compiling processes,
- Process assurance,
- Technological management of information,
- The applied psychology of the developers,
- The management and maturity of the design process,
- The ultimate integration of the software product into the final system.[20]

The IEEE Standard simply defines Software Engineering as "the application of a systematic, disciplined, quantifiable approach to the development, operation, and maintenance of software."[21], [22] What Software Engineering has not mastered is the discipline of Software Safety.

Since the 1960, when the term was first coined, Software Engineers have attempted to design and develop safe and reliable systems that are cost effective and technologically advanced to control and manage sophisticated systems. Despite valiant efforts, history has demonstrated that software fails to remain economical, efficient, reliable, or safe, and that a vast number of projects fail to use systematic and disciplined approaches to design. The results are evident by the growing number of failures and faults that are recorded annually (s*ee APPENDIX B – INCIDENTS AND MISHAPS*).

[20] Weinberg, Gerald; *The Psychology of Computer Programming*, Dorset House Publishing; 1999.

[21] def: Software Engineering, *IEEE Standard Glossary of Software Engineering Terminology, IEEE Standard 610.12*, Institute of Electrical and Electronics Engineers, Inc.; 1990, 1991.

[22] See Chapter Endnotes I.I.2 – NATO Software Engineering Definition

D. QUESTIONING SOFTWARE SAFETY

1. Software is Prone to Failure

Failure is an inevitability that must be anticipated, investigated, and compensated for. The current state of the art of Software Development has failed to solve the problem of quantifying Software Safety and reducing Software Failure. The statistics of Software Failures are well documented in academic and industry literature, as well as in the public press. Previous efforts have been made at quantifying the risks of software development as well as identifying the procedures for dealing with these risks.[23] While these efforts have made great strides at categorizing development risks,[24] they have failed to identify a common criterion for development risk and system safety. Coincidental with the absence of a common risk criterion is the lack of a common safety or quality assurance criterion.

Due to the proliferation in technological requirements and control, government and private organizations increasingly require high–assurance software development that cannot be satisfied by standard techniques. According to the Defense Advanced Research Projects Agency's (DARPA) Joint Technology Office Operating System Working Group, comprised of DARPA, NSA, and the Defense Information Systems Agency (DISA), many critical government applications require a high–assurance for safety, security, timeliness, and reliability.[25] Examples of such applications include nuclear power plant control systems, biomedical devices, avionics and flight control systems, systems that protect classified information, and command, control, computers, communications, and intelligence (C4I) systems.[26] Due to rapidly changing development techniques, little work has been done in the development and integration of high–confidence systems. Currently, interactions and integrations are poorly understood and

[23] See Chapter II.E – *STANDARDIZED FOUNDATION OF SOFTWARE SAFETY*

[24] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

[25] Bury, Lawrence; *Software Engineering Tools, A Technology Forecast*, NSA Office of INFOSEC Research and Technology; February 1999, http://www.nsa.smil.mil/producer/forecast/reports/set/set.html.

[26] Note: For this dissertation, Command, Control, Computers, Communications, and Intelligence (C4I) is analogous to Command and Control (C2); Command, Control, and Communications (C3); and Information Warfare (IW).

analytic tools for specifying and decomposing complex properties are flawed or non–existent. Formal methods and specifications typically are used in developing high–assurance type systems. Formal methods must also be integrated to include Software Safety and assurance techniques.[27] To enhance the process, the U.S. Government is attempting the integration of "program understanding" tools.

A DARPA/NSA/DISA Joint Technology Office (JTO) working group has stated that, "mission–critical systems are subject to a number of stringent design and operation criteria, which have only recently begun to emerge as significant requirements of commercial systems." These criteria, which include dependability, security, real–time performance and safety have traditionally been addressed by different communities yielding solutions that, at best, fail to meet constraints imposed by other criteria and, at worst, may interact to degrade the overall level of confidence that the system can fulfill its mission. While little work has been done to integrate high–confidence systems, it has become clear that these constraints are not orthogonal and cannot be jointly met through simple layering or the composition of independently derived services. Interactions are poorly understood and analytic tools for specifying and decomposing complex properties are non–existent.

Software is prone to failure. While no system can ever be 100% safe and fool proof, every effort should be made to identify and reduce the number or potential for unsafe incidents.

2. How Can Software Be Determined Safe?

Increasingly, the fields of military defense and commercial industry require technologically complex software tools to maintain and manage their critical systems. These critical systems have become far too intricate to be maintained by humans or by simple and easily proven hardware. Historically, the failure of such systems has resulted in the detrimental loss of essential military components, weakening our national defense;

[27] *Research Challenges in Operating System Security*, DARPA/NSA/DISA Joint Technology Office Operating System Security Working Group; August 1998.

of governmental support systems, sending our national data stores and operations into chaos; and of manufacturing and fabrication units, directly affecting productivity and our country's gross national product. Far too many lives have been lost and far too many resources have been wasted on untested and unproven software that failed at the most critical and inopportune moments.

Presently, Software Safety and the development of critical software systems focus on four principles of hazard control, namely:

- Eliminating the potential hazard from the software system.
- Prevent or minimize the occurrence of the hazard.
- Control the hazard if it occurs.
- If the hazard occurs, minimize the severity of the damage.

Despite the best efforts to manage system hazards, software cannot be developed and referred to as safe unless the spark that resulted in the hazard can be identified and isolated, and the system can be judged against an accepted criterion for safety.

QUESTION: Is it possible to develop a common assessment criterion that can determine if software is safe?

The needed assessment criterion must be cost effective, efficient, and easy to implement. This assessment criterion must be structured and well defined, and easily integrated into the development process. This assessment criterion must include techniques for evaluating potential safety flaws from the requirements level through the implementation and use. The assessment criterion must identify the potential catastrophic consequences of the Software Failure. Additionally, this assessment criterion must include a safety investigation and determination process for regression testing necessary after software requirement changes. While it is popular to simply rely on a single assessment to determine the safety of a system, such an assessment is not cost effective. A complete assessment requires analysis and test data that supports the conclusion of the analysis.

Chapter II and III outline many of the failures in software testing and assessments that are crucial to the success of a safety related software system. Chapter IV and V describe the principle elements of successful assessment process and the data necessary to certify the validity of the assessment.

3. What Can Be Done to Make Software Safer?

In parallel with determining the safety of a software system, it is essential to improve techniques for the continual development of safe software. The field of Software Safety is no more in its infancy than the field of Software Engineering. Software Engineering is based on general principles of logic, rooted in mathematics and science. While the application of software to electronics is only half a century old, the fundamental core of software operation is rooted in the timeless concepts of logic and reasoning. Such concepts can be related or traced to early schools of philosophy and applied psychology.[28] Due to the increasing rate in technological advancements in computer science and Software Engineering, and the heavy reliance on automated management systems, software failures have become increasingly costly and pronounced. As automation reliance increased, the ability for existing safety measures to prevent an accident has decreased. As technology advances and broadens its scope of control, the numbers of catastrophic events that can be triggered from a single software failure become near limitless.

The method must be applicable to traditional and new types of development techniques. This method must be able to identify and prevent the new types of accidents and failure modes that can arise with automated assurance systems. This method must be capable of detecting, tracking, and indicating trends in unsafe programming and development to prevent future mishaps through a change in procedures and environment. This method must span the entire lifecycle of the development and integration, and include using integrated systems, software, and human task models to analyze the safety of the complete system. This method must review system–level requirements for

[28] Young, Norman; *Computer Software Cannot Be Engineered*, Private papers; 1999, http://the2ndcr.mg1.net/cscbe.html.

completeness and constraints control, including examining the ramifications of automation and human task design decisions on overall system safety. This method should devise design techniques and tools for performing integrated hazard analyses on formal system, software, and operator task models. For the benefit of mishap reviews and software forensics, this method must permit backward tracing of hazardous states to determine what human errors and software behaviors are most critical with respect to hazardous system states.

E. GENERAL APPROACH

Software or System Safety is traditionally defined as a system's ability to operate within the accepted and expected parameters of its requirements.[29] Additionally, safety includes a system's ability to prevent an unacceptable act, hazardous condition, or mishap from occurring. To the contrary, risk can be defined as the frequency or probability that an unacceptable act or hazardous condition could occur; "How risky is the system?" Risk can also be quantified with a measure of the consequences of the unfavorable action or severity of the mishap, or as an expression of possible loss in terms of severity and probability.[30] "Is the system *safe* to use?" "What is the *risk* of something going wrong with the system?" Each of these viewpoints contributes to the overall concept of software system safety, despite their somewhat contradictory principles.

A thorough study and investigation of subject matter literature has revealed a series of definitive factors that lead to degradations in Software Safety, including:

- Lack of experience in software development and assessments,
- Disjointed educational emphasis and training in the field of Software Safety,
- Proprietary software development practices, definitions, requirements towards Software Safety,

[29] Nesi, P.; *Computer Science Dictionary, Software Engineering Terms*, CRC Press; 13 July 1999, http://hpcn.dsi.unifi.it/~dictionary.

- A lack of understanding of the relationship between Software Development and Software Safety,
- The over emphasis of quantifying failure while lacking appropriate emphasis to qualifying failure.

We present a format to address or resolve these shortcomings through or by:

- Establishing a knowledge base of Software Safety and risk management, as it applies to safety through the lifecycle of a system,
- The introduction of a generalized series of practices and definitions for defining Software Safety,
- The presentation of metrics for determining the safety index of a software system,
- The review of the relationship between developmental actions and operational failures,
- Improving efforts and practices towards identifying potential failures of Software Safety and methods for improvement,
- The study of the quantitative and qualitative factors of Software Safety,
- The development and introduction of the Instantiated Activity Model for depicting failure logic flow to determine the potential for malfunction.
    - The development and introduction of mathematical equations for the computation of the probability of occurrence of a malfunction.
    - The development and introduction of a computation of a software system's Safety Index.
- The discernment between developmental risk and software safety,
- The ability to depict software safety mechanics in a common graphical format.

[30] *Draft Reference Guide for Operational Risk Management,* Naval Safety Center, Department of the Navy; 09 September 1999.

In current practices, Software Safety and Risk Management consists of a checklist and metric–based practice that requires a formal detailed and documented process that relies on human subject matter expertise and automated investigation systems.[31, 32, 33, 34, 35] The goal of any measure would be to make it as intuitive as possible to eliminate any variable or chance that the user would deviate from the measure's practice and procedures. It would be essential that measures be refined sufficiently to ensure that users could objectively observe the variables of a system.

The following chapters present a foundation for establishing a knowledge base of Software Safety and risk management, as it applies to safety through the lifecycle of a system. Included are outlines and details for creating methods and metrics to determine the safety index of a software system.

Investigation reveals the relationship between the development process and Software Safety. A detailed investigation has been made on the methods of software risk management and software development, to determine the commonality and conflicts between the two as well as where refinements can be made to ultimately enhance Software Safety. Efficiency and productivity dictate that Software Engineers must strike a delicate balance between the needs to reduce development risk and increase product safety, while inflicting as small as possible an impact on the engineering timeline and expense of development.

Previous studies and efforts have concentrated on quantifying the risks associated with software development,[36] and the actual evaluation of the development process to

[31] Cigital Solutions and Cigital Labs, Cigital, Inc, Dullas, Virginia; 2004

[32] Kaner, Cem; *Software Negligence and Testing Coverage*, Software QA Quarterly, vol. 2, num. 2, pg. 18; 1995/1996.

[33] *Support Capabilities of the Software Engineering and Manprint Branch*, Systems Performance and Assessment Division, Materiel Test Directorate, White Sands Missile Range; September, 2000.

[34] *Newsletter: from Risknowlogy*, Risknowlogy, Schinveld, The Netherlands; 14 January, 2004

[35] Safety Hazard Analysis and Safety Assessment Analysis (Probabilistic Software), Reliability Engineering at the University of Maryland, Department of Mechanical Engineering, College Park, Maryland.

[36] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

determine the optimal method for creating the software. While these previous methods benefited the development process and worked to ensure the successful completion of the project with minimal risk of exceeding planned budgets and schedules, they failed to detail the hazards of operating the product or the events that could cause specific hazards, either during the development or implementation process. These previous studies have also failed to study the implications of unsafe incidents or hazards. Addressed within this Dissertation are the development processes and risks to development, with the intent to design a method to efficiently engineer software with the greatest assurance of success and safety. Also included is a review and study of the software development process[37], concentrated on the identification of potential failures *related to* Software Safety and probable methods for improving the *overall* safety of the system.[38]

Software Safety encompasses the study of the potential hazards of a software system, the subsequent consequences of the hazard, and the prevention of these hazards to ensure a safe product. Software Safety comprises all of the phases of a software product's lifecycle, from conception to implementation, re–composition, cross integration, and eventual retirement. Software Safety is a subset of the greater System Safety concern that includes all causes of failures that lead to an unsafe state such as:

- Hardware failures
- Software failures
- Failures due to electrical interference or due to human interaction
- Failures in the controlled object.

For the purpose of this dissertation, the study and methodology are restricted solely to Software Safety. While many equate Risk Management to a quantifiable science,[39] Software Safety is both quantitative and qualitative. There are many intangible aspects of Software Safety that are not found on a spreadsheet or checklist, but are

[37] See Chapter III.

[38] See Chapter V.E.4.

[39] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

learned and mastered by understanding the principles of safety and fundamentals of software design. This dissertation outlines, quantifies, and qualifies the factors of Software Safety as they apply to high–assurance systems.

Software Safety can be pictorially and textually depicted in a rational fashion with many logic based development methods including Fault Tree Analysis (FTA), Petri Nets, Failure Modes Effect and Criticality Analysis (FMECA), HAZOP, Impact Analysis, and Cigital's Safety Net Methodology based on a technique called Extended Propagation Analysis.[40] I have reviewed and included a study of applicable methods of hazard and safety analysis and their relationship to Software Development and Safety. Where necessary, I have modified common methods to specifically apply to the unique characteristics of Software Engineering, Development, and Safety.

[40] *Software Safety, Resources – Definitions,* Citigal Labs, Citigal; Dulles, Virginia; 2001.

- Complexity
- Veritability of Inputs
  - Cleanliness of Inputs (*Quality*)
    - Dependability / Reliability Factor of Inputs
  - Ability to Sanitize Inputs (*Correction*)
    - Consequences of Sanitization
  - Ability to Filter Inputs (*Prevention*)
    - Consequences of Filtering
- Permeability of the Requirements
- Permeability of the Outputs
- Veritability of Outputs
  - Ability to Verify Outputs (*Quality*)
    - System quality control
  - Ability to Sanitize Outputs (*Correction*)
    - Consequences of Sanitization
  - Ability to Filter Outputs (*Prevention*)
    - Consequences of Filtering
- Probability of a Fault
- Consequence of Fault
- Probability of Failure
- Consequence of Failure
- Product Safety or Dependability Index.

Table 1 Quantitative and Qualitative Factors of Safety

The shortcomings of Software Safety can be improved upon by equating and assessing of quantitative and qualitative point values.

Further chapters investigate and define the above factors of safety. These quantitative values are demonstrated for independent, modular, and composite software systems.

F. THE FOCUS OF SOFTWARE SAFETY

The field of Software Safety has been understudied and underrepresented in literature until late due to the fact that, historically many of the previous software systems were controlled and protected by mechanical firewalls and human intervention. Today's technology can no longer be controlled by yesterday's antiquated system techniques. The current rate of decision–making processes demands an automated system beyond the capabilities of systems designed just a decade ago. The logic complexities of today's software systems overshadow the abilities of earlier languages and processor limitations.

The impacts of today's Software Failures are magnified by the complexity and cost of the systems for which they control. The primary focus of this study is on identifying factors that create the unsafe conditions through all phases of the software's lifecycle.

History has demonstrated that most mistakes and hazards are based on actions and occurrences that could have been prevented if proper methods and procedures were followed, or if well based and proven precautions and measures were implemented through the lifecycle of a system. This study focuses on the methods and procedures that, if followed, would increase Software Safety and in turn decrease the failure rate of high–assurance systems. Additionally, this study identifies the measures and precautions that historically have proven successful in improving system safety in other disciplines and can be readily adapted to Software Engineering.

Once the methods and practices that create a safer software product are understood, this dissertation outlines and describes a formal method for developing safe software, through the expansion and refinement of existing development methods and metrics. Safety is not something that occurs, it is something that is developed and achieved – A system reaches a level of safety by preventing some factor of undesirable actions and not by the absence of all hazards. Once there is an understanding of why software fails and the potential hazards of that failure, a formal metric and methodology can be designed that depicts the measure of that safety and appropriate procedures for improving the measure through development. A product of this study includes a formal metric and methodology for measuring Software Safety and the processes for potentially improving the resulting product.

The success of Software Safety relies on solving the dilemma of hazard avoidance through the entire lifecycle of the software system.

As previously stated, Software Safety is a subset of System Safety and the associated failures and hazards. For the purpose of this dissertation, this research and model are limited to and encompass the effects of Software Safety as it applies to the overall system. This dissertation limits its research up to the point of software integration into the complete software–hardware–human system. A brief discussion is included to address hardware failures as they relate to software systems and the safety mechanisms that should prevent harmful incidents from such failures. Included is an addressing of the effects of human interaction and interference as part of the investigation of potential software faults and failures.

Risk management is a fundamental aspect of software development. A significant number of studies, dissertations, and articles have delineated the constructive properties of risk management in the development process. The concept of a risk–based approach to development has been proven to reduce or prevent procedure–based flaws and increase software development efficiency.[41] This study reviews the concepts of risk and risk management as it applies to Software Engineering, and its applicability to Software Safety.

G. CONTRIBUTIONS

The contribution of this dissertation and study to the state of the art of Software Engineering include, but are not limited to:

- A review of the faults and complexities of software development resulting in potential failures. These potential failures are then evaluated to determine their contributory affect on hazard occurrence.
- A formal model for assessing Software Safety through the development process to reduce or eliminate hazard occurrences.
- The introduction of a common metric for evaluating and assessing the qualitative and quantitative factors of a Software System and development process.

[41] Hughes, Gordon; *Reasonable Designs, The Journal of Information, Law and Technology (JILT)*, Safety Systems Research Center, Computer Science Department, University of Bristol; Bristol, United Kingdom; 1999.

- Improvements and awareness of the facets of Software Safety Economics, based on accepted practices and principles.
- A formal study of the state of the art of Software Safety.

The first contribution of this dissertation to the state of the art of Software Engineering is the identification and classification of software events, faults, and complexities in the development process, potentially resulting in a system failure. Hazardous events can then be related the potential failures for determining cause and effect. This dissertation outlines methods for controlling or mitigating the effect of system failures to prevent hazardous events.

The second contribution of this dissertation to the state of the art of Software Engineering is the formalization of a model to incorporate Software Safety into the development process. This formal model directly impacts and improves the state of the art by refining current methods of development to better identify unsafe practices and methodologies through the software lifecycle that could lead to failure.

The third contribution of this dissertation is the introduction of a common metric for evaluating software and the development process to qualitatively and quantitatively determine a safety index of a particular software system. This value can then be evaluated against potential hazards and faults to determine the cost–benefit ratio of efforts to remedy or prevent the hazard.

A fourth contribution of this dissertation is an introduction and improvement of Software Safety economics, based on accepted practices and principles of statistics and probability. Software economics are directly affected by the cost and ability of a software system to prevent or mitigate hazardous events. This study will address the factors related to changes in the economic benefits of the system.

The overall contribution of this dissertation to the state of the art of Software Engineering is the formal study and research in the under–represented field of Software Safety. The success of this software development methodology is the increased awareness of safety in high–assurance software systems, the reduction of risk through the software lifecycle, with corresponding increases in efficiency, decreases in overall software system costs, and a decrease in occurrence of hazards in a software system.

H. ORGANIZATION OF DISSERTATION

This dissertation is organized in eight chapters. The introduction is included in the present chapter.

Chapter II develops the theoretical foundation of the dissertation by defining the practice of Software Safety, and safety and risk as it applies to software development and engineering; by summarizing relevant works, literature, and studies on the field of Software Engineering. Chapter II includes a review of the current state of the art of Software Safety Assurance, applicable standards, and safety assessment. Chapter II also includes a refinement and introduction of definitions of Software Safety based on personal observations and the consolidation of existing designations.

Chapter III characterizes the common flaws and faults of software development, referencing examples of failed systems derived from observation and investigation. This chapter includes failures related to implementation and developmental failures, development requirements, testing methods, and assumptions. A review is made of development requirements and testing methods as they pertain to Software Safety. Specific examples are given for each of the failure method types as well as efforts possible to amend the failure probabilities.

Chapter IV outlines the conceptual framework for the evaluation of a software system and development of a safety assessment metric. The conceptual framework includes the introduction of the goal of a safety development and metric development. Chapter IV will introduce a discussion of the aspects of software safety, incorporating definitions and potential techniques. Finally, the chapter will discuss the efforts necessary to graphically and textually depict Software Safety and Hazard Probability.

Chapter V depicts the application of the framework as a formal method for evaluating a software system. Introduced is a presentation of an Instantiated Activity Model (IAM) that supports a formal approach for system safety analysis and risk assessment (SARA).[42] This chapter details the development and implementation of a criterion that can be used to assess the stability and validity of a software system, as it applies to Software Safety. The formal method for assessing software safety is introduced and demonstrated against a notional software system. Through the development of the assessment method, this chapter discusses factors and controls capable of mitigating hazard probabilities.

Chapter VI discusses the applicability of the formal method towards advancing Software Safety. Special effort is given towards outlining efforts and factors of development automation, metric introduction, software management, and requirement completeness. A discussion of perspective clientele for the safety assessment is introduced, as well as the applicability of the software assessment towards other safety engineering disciplines.

Chapter VII discusses the justification for Software Safety Assurance, concentrating on legal responsibilities, certification, and economics. A portion of this chapter's concentration is on the legal, moral, and ethical requirements of software safety. Additional emphasis is placed on the cost–benefit of Software Safety and the applicability of the formal model to software development decisions.

[42] Luqi; Liang, Xainzhong; Brown, Michael L.; Williamson, Christopher L.; *Formal Approach for Software Safety Analysis and Risk Assessment via an Instantiated Activity Model*, Software Engineering Automation Center, Naval Postgraduate School; Monterey, California.

Chapter VIII presents the conclusions and recommendations for integration of the model and metric into general practice. Specific contributions are addresses and reviewed, including the factors of safety failures, definitions, metrics, and process improvements. Suggestions for future work and perspective changes to legal protections are concluded within this chapter. Finally, Chapter VIII presents a dissertation conclusion to briefly summarize and complete the intent of this study.

Appendix A lists applicable definitions as they refer to Software Engineering and Software Safety. Appendix B summarizes recent public and private software development efforts that have failed, their associated consequences, and historical background where applicable. Appendix C lists abbreviations referred to in this dissertation. Appendix D provides supplemental material beneficial to understanding Software Safety. Appendix E provides an example of code sizes contrasting against various logic statements.

For the purpose of brevity, this dissertation omits or summarizes some topics that are obvious to individuals familiar with the practices of software development and Software Engineering.

I. CHAPTER ENDNOTES

The following endnotes are included as part of the research document, and may or may not be included in the final dissertation submission.

1. Software Failure Cost

The dissertation uses the term *"Lost"* when describing the expense of funds to correct failures, software defects, management oversights, and compensatory costs. The terms *"Lost"* or *"Loss"* directly contradict the commonly used term of *"Expense"* or *"Spend"* used in various management documentations. A "Loss" is defined as the act of failing to gain, win, or obtain something for a said effort; while "Lost" is the past participle of "Loss."[43] An "Expense" is defined as something being expended to secure a benefit. Simply stated, an expense implies that something of value was received in turn for the transfer of some monetary unit. In the case of the additional cost of a software failure, it is inappropriate to assume that something was gained by expending more resources, because the resource expense was unplanned. The consumer gains no additional return for the additional fee, but rather he received what he was originally expecting to receive for an additional cost. Economically this is corrupt.

In the case of software development, a software system is contracted to be developed for a specific price. That price should include all foreseen expenses, developmental issues, and forecasted lifecycle costs. The recipient of the product should be safe to assume that the product will be delivered at the agreed upon rate, on time, free of defects, and with a reasonable level of assurance of the safety of the product. It perpetuates a great disservice to the software industry when a customer accepts an incomplete or defective product and then agrees to make compensatory compensation to the developer to correct the developer's flaw. Additionally, it robs the process when a customer agrees to pay for the research and development of an unproven software technique or methodology, or pays to train a developer to do his job. Such a practice would rarely be tolerated in other fields of industry.

Could a patient imagine first paying to train a doctor to perform for a heart surgery, then pay for the surgery, and then finally to have to pay an additional fee when the doctor fails to do the surgery properly or in a timely manner? The patient should be given the reasonable expectation that the doctor has been properly trained before being presented with the case, and that the doctor would perform the case properly the first time. Failure to properly perform such a case would result in the malpractice prosecution and disbarment of the doctor from the practice. In the field of Software Engineering, such practices are commonplace.

[43] *The Merriam-Webster's Collegiate Dictionary, Tenth Edition*, Merriam Webster, Incorporated; Springfield, Massachusetts; 1999.

In the automotive industry, a defective vehicle is recalled and repaired at the expense of the developing company. In 2000, over 39,424,696 vehicles and automotive accessories in the United States were recalled for defective components or systems in over 250 recalls.[44, 45] The owner of the vehicle bears no responsibility for the defective product, nor is he required to pay for the required repairs. This process is only made possible by an aggressive legislative effort, government regulation and oversight, and through the ability of the consumer to find alternative automobiles if the primary choice has demonstrated a history of failure.

Historically, software customers have not had the luxury of a large selection of software products to meet specific high–assurance needs. Many safety based software products are developed real time to meet a specific need of the consumer and are not easily re–marketed to other consumers without modification. The level of modification constitutes the difference between properly defined COTS and non–COTS products. There are few developers for a consumer to select from that have the specific subject matter expertise required for specific projects.

An increase in Software Safety can only be accomplished through a three–fold process of training, supply, and accountability. Software developers need to properly train and educate themselves with the proper techniques and methods for high–assurance software development. The market needs to be expanded to support more competition. This may require governmental regulation to disestablish monopolistic practices or through grants and benefits for new companies that demonstrate success. Finally, the software developer needs to be held accountable for software failures. Customers need to no longer bear the cost of software failures and poor development techniques. If a software project fails, the developer has to be held liable for the failure.

[44] Compilation of various National Highway Transportation Safety Administration Press Releases, National Highway Transportation Safety Administration, Department of Transportation; 2000 – 2001.

[45] Note: The sum reflects the total of all NHTSA Recall Bulletins. Some vehicles and accessories may be counted twice if referenced in separate and unrelated recalls during the annual period. The actual number of vehicles and accessories may be lower.

2. NATO Software Engineering Definition

In 1967, the NATO Science Committee referred to the state of the art of Software Engineering as the discipline of "...promoting the establishment of theoretical foundations and practical disciplines for software, similar to those found in the established branches of engineering."[46] Two years later, NATO refined its definition of Software Engineering as "the establishment and use of sound engineering principles in order to obtain economically software that is reliable and works efficiently on real machines."[47]

[46] *Software Engineering*, Report on a conference by the NATO Science Committee, NATO Science Committee; 1967.

[47] Naur, Peter; Randall, Brian; Editors; *Software Engineering, Report on a conference by the NATO Science Committee*, NATO Science Committee; January 1969.

II. THEORETICAL FOUNDATION

"Every software error blamed on the computer can be traced to two faults: The first being the fact that blame was placed on the computer; and secondly the fact that a human developed the error."

– *computer wisdom*

Computers, and in turn – software, have unfairly been left to blame for an assortment of failures and catastrophes over the last half–decade. Man depicts computers as thinking and self–acting entities capable of taking deliberate or irresponsible actions. Users portray computers as a manifestation that can make conscious thought with flaws, imperfections, and an ability to disregard commands and exercise free will. One may strike the screen or keyboard in the same way he would a disobedient dog with a rolled newspaper with the veiled notion that he taught the computer a lesson. He might feel that the computer would behave better with the next command, without regard to the fact that the system will continue to act the same way given the same inputs. Yes, "to err is human, but to really foul things up requires a computer," developed by a human who was unaware or incapable of comprehending the system that he has designed or is now operating.

Recent history has illustrated that software is potentially unsafe when it is assigned to control critical systems. Safety, or a level of "unsafety," is primarily based on probability of a system to prevent or experience a hazardous event, and secondarily based on the severity of such an event. There is no system that can be considered failsafe, as there continues to exist the minute probability of failure in all things. The objective of safe software development is to reduce the probability of failure to a level acceptable to the developer, client, and society. The United Kingdom has gone so far as to define "safe" as to when the probability of failure has been reduced to a level "as low as reasonably practicable."[48] The term reasonably practicable can be judged uniquely for

[48] *Ship Safety Management System's Handbook*, United Kingdom Ministry of Defense, JSP 430, United Kingdom.

diverse users in unique circumstances, each circumstance dependent on a distinct series of specific indicators, triggers, and consequences.

From a review of common practices and literature from governmental, commercial, private, and academic institutions on the subject matter of Software Safety and Software Failure, it can be concluded that there are six inhibiting factors restricting the state of the art of software development and failure, including:

- A failure to realize that there is a problem with the current state of Software Safety.
- A failure to recognize potentially unsafe circumstances in software systems.
- A failure to identify the flaws of the Software Development Process.
- An inability to quantify flaws, faults, and failures into a measurable value.
- An inability to qualify the solutions to potential flaws for evaluation and efficient rectification.
- A failure to comprehend the solution to Software Failure.

There exists a greater maturity within the small circle of safety experts, however their practices are not commonly used in mainstream development. Such a decision is based on economic, political, and educational factors that limit the spread and acceptance of such practices. While such subject matter practices provide a strong improvement to the state of the art of Software Engineering, their common incorporation is absent outside of a small circle of safety experts. My study will focus its emphasis on the ability to quantify and qualify the values of software development, failure, and success. These values can then be expressed in manageable and meaningful units for evaluation of the software life–cycle development process with the intent of reducing failure and increasing safety.

To generate a foundation for the development of a Software Safety Metric, it is essential to first define and organize a basis of understanding regarding Software Safety and Failure. To generate this foundation and basis, this chapter is organized into the following units:

1. **Philosophy and Interaction:** To best break down the impression that software/hardware are self–aware entities and incapable of failure, this chapter outlines a discussion on the philosophy of software development and the "human" interaction within the development process.

2. **Vocabulary–specific software failure and safety:** Software development is a semantics–rich discipline with a multitude of proprietary based vocabularies. These vocabularies do not easily translate or transfer to other dialects within engineering fields. Many international and national agencies and standards differ on their interpretation of specific phrases of development and safety. This chapter defines and clarifies the vocabulary specific to Software Failure and Safety as it applies to this dissertation.

3. **Safety State Definitions:** Software Safety, Failure, and Risk Management are commonly misunderstood and misapplied concepts in software development. This chapter defines and clarifies these three terms as they directly apply to Software Safety of High Assurance Systems.

4. **Failure and Hazard Flow:** Software Faults, System Failures, and Mishaps flow through a software system in a distinct manner. This chapter outlines the flow and transition of faults and failures through a system, as well as the measures that capture and arrest faults before they propagate.

5. **Relative Works to the State of the Art:** To base the foundation for Software Safety Improvement, this chapter makes a review of relevant works in the field of Software Safety and Failure, giving an appraisal of previous efforts and standards.

6. **Metrics and Methodologies:** Once this foundation has been introduced and established, this chapter outlines the required metrics and methodology necessary to manage, denote, and define Software Safety.

A. DEFINING SOFTWARE SAFETY

For the purpose of this dissertation, it should be understood that the term Software Safety and Software Failure differs from Software Development Risk; Safety focuses on the failures of the system as they relate to the occurrence of a hazardous event while Software Development Risk primarily focuses on the risks to development and the potential for a system to fail to meet development goals. In the past, the term Software Risk and the associated study of Software Risk Management have focused primarily on predicting the success of a software project's development or the risk of the software project failing to be completed within planned resource limits.[49] Dr. Nogueira focused his research on the computation of software risk using a new approach at assessing system complexity and volatility. Additional research has focused on the potential for system failures during various states of operation, once the product has been employed.[50, 51]

Within the development environment, software success is judged against a comparison of planned and actual schedules, costs, and characteristics. Software Safety is focused on the reduction of unsafe incidents throughout the lifecycle of the system (it can be assumed that some systems are capable of hazardous events during development should they fail during testing with hazardous elements, fail to meet critical deadlines consequently failing to prevent a hazardous event, or fail to be developed at the

[49] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

[50] Murrah, Michael R.; Luqi; Johnson, Craig S.; *Enhancements and Extensions of Formal Models for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; 2001.

catastrophic loss of expended resources). Unsafe incidents may be the result of a failure of the software system to meet design requirements, an error or shortsightedness in system requirements to prevent such an incident, or the reality that such hazards are unpreventable – merely manageable. A system can be determined "*safe*" when the probability of occurrence of a hazardous event has been reduced to some defined acceptable level.[52] That acceptable level is dependent on the identification of potential hazards; the requirements of the system; the necessity or importance of the product; and the type, circumstance, and consequences of the failure.

Safety is not a Boolean value of purely safe or unsafe, but a continuous variable that ranges from completely unsafe towards safe

Individual impressions may have it that a software system is either safe or unsafe, depending on its requirements, design, and controls. In reality, a system progresses through various levels of safety depending on its requirements, design, controls, methods of operation, potential hazards, and time/state of execution, as well as countless other stimuli that could affect the operation and safety of the system, as depicted in Figure 2. It is when these stimuli are analyzed and measured, can an accurate appraisal of system safety be made.

[51] Musa, John D.; Iannino, Anthony; Okumoto, Kazuhire; *Software Reliability, Measurement, Prediction, Application*, McGraw-Hill Book Company; New York, New York; 1987.

[52] *International Standard ISO/CD 8402-1*, *Quality Concepts and Terminology Part One: Generic Terms and Definitions*, International Organization for Standardization; December 1990.

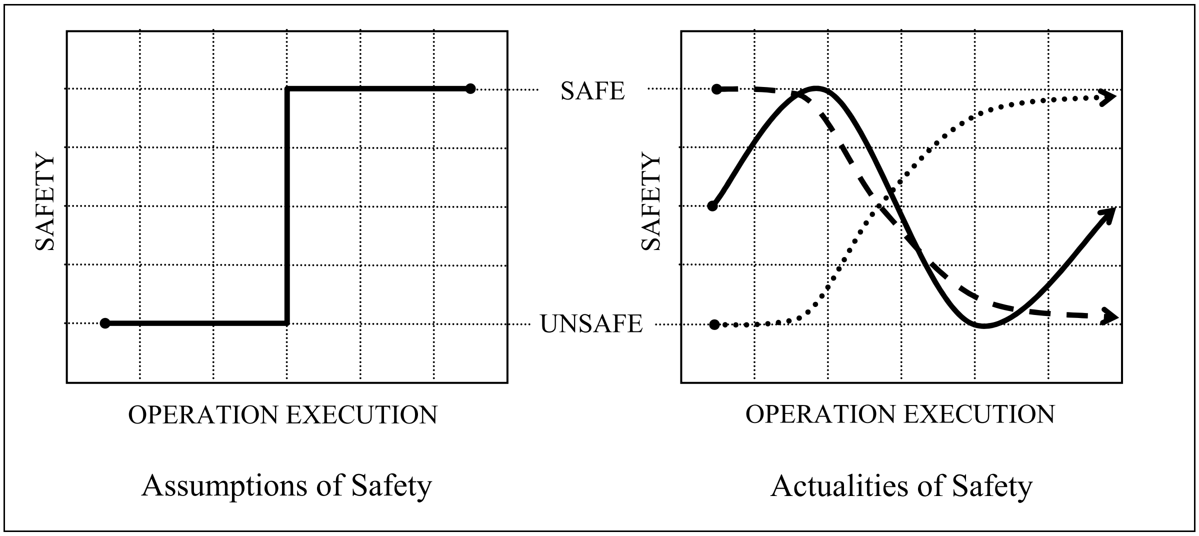

Figure 2 Dual Impressions of Safety

There are few correlations to be drawn between Software Development Risk and Software Safety as the subjects are only indirectly related. One discipline deals with the potential to complete the product while the second discipline deals with the ability to prevent the system from taking a hazardous action. Software Safety, a child of the greater System Safety practice, includes the "application of engineering and management principles, criteria, and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time, and cost through all phases of the system lifecycle."[53]

For the purpose of this study, the term *Software Risk* is defined as the threat to proper system operation that could potentially result in a hazardous event and consequently reducing the level of Software Safety. The probability for such a hazardous event ranges from zero to one, expressed quantitatively as [$0 \leq P_H \leq 1$]. In an optimal case, P_H would be zero. Qualitatively, it would be optimal for software risk to be *low* or *none*. The process of deriving and defining the qualitative and quantitative measures will be defined later in Chapter V. The term *Software Risk Management* refers to the management of the risks to Software Safety. The term *Software Development Risk* denotes to the risks to successful software development, as quantified by the ability to

[53] *MIL-STD-882C System Safety Program Requirements*, Department of Defense; 19 January 1993.

meet project requirements within acceptable limits regardless of the potential for or incident of hazardous events during the operation of the software.

The use of automated systems have become essential to the control and safety of critical applications such as nuclear power plants, medical devices, aircraft, chemical plants, and national defense systems. The level of sophistication required to maintain these systems is far beyond the capability of an unaided human. The processing speed and logic control of today's system enables a level of performance far beyond that of manual systems. Logic control can guarantee some level of safety, depending on implied reliability, system requirements, and design constraints. When applied, Software Safety assures a systematic and logical approach to identifying, classifying, categorizing, controlling safety, and the occurrence of hazardous events.

B. THE PHILOSOPHY OF SOFTWARE DEVELOPMENT

In 1851, in his historical writing of *"Cellular Pathology,"*[54] Rudolf Virchow noted that biological cells are neither good nor bad, yet that they merely carry out the role for which they were anatomically designed.[55] Software is characteristically like an anatomical cell as it merely carries out the function for which it was programmed, even if that function is flawed by design.

1. Software as Intelligence
Software is Stupid.

Before one can develop a safe software system, they must understand and admit, "Software is Stupid." They must also admit that software is obedient, to the point of blind obedience to any task, order, or command that may be put upon it. A Software System's intellect originates from the developer himself. It is from the developer's ideas and logic that the system acquires its basis of operation. Software logic can be derived from the adaptation of previous systems, failures, and successes. While this adaptation is not always guaranteed, it can be assured that the system is based primarily on the present representation of its developer.

The psychological personality of the developer, in harmony with the individual's discipline and professional knowledge, determines the true nature of the software system, its logic, its flow, and its character. Every software system has a distinct personality, as unique and as different as the fingerprints on a human being. This uniqueness has bred a myriad of logic patterns and commands capable of accomplishing essentially identical tasks, each set varying in complexity, size, and potential for failure. As noted in Table 2 below, it is possible to execute any one of three independent functions, each capable of selecting an item from a given list. The size of the function (lines of code) is based on the programming code language, the function chosen, and the number of selections in the data list. The choice of which function to use depends greatly on the developer's ability to program, his interpretation of the development requirements, and personal preference to one style over the next.

Function	Complexity	Lines of Code
IF THEN ELSE END	Simple	((S * 2) + 2) Lines of Code
CASE SELECT	Moderate	(S + 3) Lines of Code
ASSIGNED ARRAY	Complex	5 Lines of Code
Where as: S – as Number of Selections		

Table 2 Code Complexity and Size Comparison.

Despite the notion that computers are intelligent, that impression delicately hinges on the software system that controls it. The software system, and its corresponding level of safety, is likewise delicate, reliant on the developers and methodologies that gave it life.

[54] Burke, James; *The Pinball Effect*, Little, Brown and Co; 1996.

[55] Note: Rudolf Virchow is credited for originating the quote "Prevention is better than cure."

The safety of software does not hinge solely on the software concept itself, but on the individuals who wrote it and their own conception of design, logic, and assurance.

Safety is reliant on the method and completeness of the development, the comprehension and interpretation of the requirements, and the training and discipline of the developers. Until such time as software reaches self–awareness and can think for itself; until it becomes able to simply write code; not because it is commanded to, but because it is aware of the rationale for doing so and can evaluate how well a design meets that rationale, can we never forget that "Software is Stupid".

It has been mentioned that if you gave a thousand monkeys each a piano, eventually one will play Mozart; or each a typewriter, one will eventually write the great American novel.

The problem is not that you will have to wait an eternity to hear sweet music or to be moved by fine literature, it is that you will first have to listen in perpetuity to the wretched sounds of a thousand monkeys banging on ivory, and sift through a mountain of paper to find one discernible word. There are those who still utilize the Mongolian Horde Technique[56] to Software Development and have an army of "Monkeys" pounding code to keyboard. Software cannot be developed in an assembly line fashion with individuals simply banging code into place and expect it to be safe. Safety requires the development of software with precision methods by trained individuals whose ultimate goal is to design a product with an acceptable degree of defects or flaws. In high–assurance systems, such failure is not tolerable and one cannot afford the quality of monkeys to develop such a solution. Software Safety requires the discipline of development using formal models and methods, the concentrated evaluation and scrutinization of the product through its entire lifecycle, and the absolute adherence to accepted standards and doctrine.

[56] Analogous to the Mongolian Horde technique of warfare in which the armies of Genghis Khan would amass an overwhelming force of untrained warriors against a smaller enemy and conquer them through disproportional numbers.

Software is not capable of thinking for itself. It requires the thought of the developer to direct its actions. Once directed, it will function as commanded, operating within the designed parameters that were established at its inception and crashing where the developer failed to prevent a fault. If it fails, it is because the developer did not validate the functionality of the system. If it is unsafe, it is because the developer did not assure the needed protections within the system.

2. The Motivation to Build

Man has had a dream and obsession to create and mold something out of nothing. It is something "God–Like" in nature with biblical reference to the Genesis of this world. "In six days, the Lord created the Earth from the void of space and rested on the seventh."[57] Christianity teaches its disciples that His creation was perfect and without fault. Many individuals attempt to emulate this form of creation by developing a piece of software without fault or intentional blemish from only a concept and idea. Companies have self–proclaimed their divine ability to create with registered trademarks and names such as **Godlike**[58], **Perfect**[59], **Divine**[60], **Immortal**[61], and **Genesis**[62].

It is the software developer's ego that demands that he create the greatest system, in the same motivation that man strives to build the tallest building[63], race the fastest car[64],

[57] *Holy Bible, King James Version.*, Genesis Chapters 1, 2:1-3.

[58] Godlike Technologies, Provider of system administration and MUD server development; Sunnyvale, California; est. 1991..

[59] Perfect Commerce, Inc., Provider of strategic e-sourcing and decision support; Palo Alto, California; est. 1999.

[60] Divine, Inc., Provider of web-based software solutions and management applications; Chicago, Illinois, est. 1999.

[61] Immortal, Inc., Provider of dedicated server and backup resources to small and medium size companies, Las Vegas, Nevada; est. 1997.

[62] Genesis Computer Corporation, Provider of network and host based security and management solutions; est. 1999.

[63] The tallest structure is the CN Tower, Toronto, Canada, at a height of 1,815 ft 5 in. The second largest buildings are the twin towers of Associates Petronas Towers I and II, Kuala Lumpur, Malaysia at 1,483 ft. Source, *Guinness World Records Limited*; London, England; 2001.

[64] The fastest land vehicle is the Thrust SSC at 763.005 MPH, set by Andy Green on 15 October 1997 in the Black Rock Desert, Nevada, USA. Source, *Guinness World Records Limited*; London, England; 2001.

or dive to the deepest depth of the ocean[65]. The result of his success would put him on the same level as a deity, while his failure might be blamed on the inadequacy of the operating system rather then on his own inability. In this rush to create a system, many developers overlook basic common sense approaches and methods for more untested and unproven options. The engineer's motivations become so wrapped up in ego gratification and social power accumulation[66] that he fails to heed the lessons of previous failures or warnings of his co–workers.[67] They ignore the basic philosophy of **KISS** (Keep It Simple, Stupid) and attempt to create not only a new system, but also a revolutionary new logic to empower that system. Many failures can be related to development with untested and unproven "revolutionary new" tools that fail when delivered to the customer. In reality, the ego of the developer would be better defined by the value his work provides to customers; rather then how impressed he is with his own notion of cleverness.

Software serves as a mirror to the mind of the developers.

Software reflects the psychological perspective and philosophy of the engineers who gave it life. It absorbs the personality, the flavor, and even the faults of the hands that mold it. "The potter is the master over the clay pot. Yet the pot will never exceed the capability of the potter."[68] This analogy applies equally of the potter as to the Software Engineer. Essentially, the engineer cannot get more capability out of his system then his own mentality permits, and in parallel, he cannot make the computer accomplish what he first did not in himself conceive. His abilities and that of his system are limited only by his own intellect. It is when he attempts to reach beyond the limits of that intellect that he introduces faults. While he may have the greatest of logic, if his intellect does not permit the thorough inspection of his efforts, he is bound to overlook even the most blatant of faults and jeopardize his entire creation to catastrophe.

[65] The deepest diving vehicle is the manned bathyscaphe Trieste, at a depth of 35,8000 ft, in the Challenger Deep off the island of Guam, on 23 January 1960. Source, *Naval History Center*, Department of the Navy; 1999.

[66] Weinberg, G.; *The Psychology of Computer Programming*, Von Nostrand Reinhold Co.; New York, New York; 1971.

Man will build, and in his folly, will attempt to reach for the stars without comprehending that the star is nothing more then just a flaming ball of gas. Without proper oversight and supervision, careless Software Engineers will corrupt even the most reliable of programs by attempting to build their own *Tower of Babel*. Software Engineers need to be motivated to design and build new systems, be given the freedom of expression, the faculty to explore, and the benefit of credit and recognition. Along with that freedom comes the understanding that his product progression must be controlled, checked, supervised, and regulated to ensure that it complies with the actual requirements and meets the standards of a high–assurance system. Presented, is a method for permitting that freedom of expression while ensuring compliance with standards and requirements.

[67] Sawyer, S; Guian, P. J.; *Software Development: Processes and Performance*, IBM System Journal, vol. 37, num. 4, IBM; 01 May 1998.

[68] Wood, Larry; *Personal writings on the Philosophy of Software*; 30 August 1996.

C. THE ANATOMY OF FAILURE

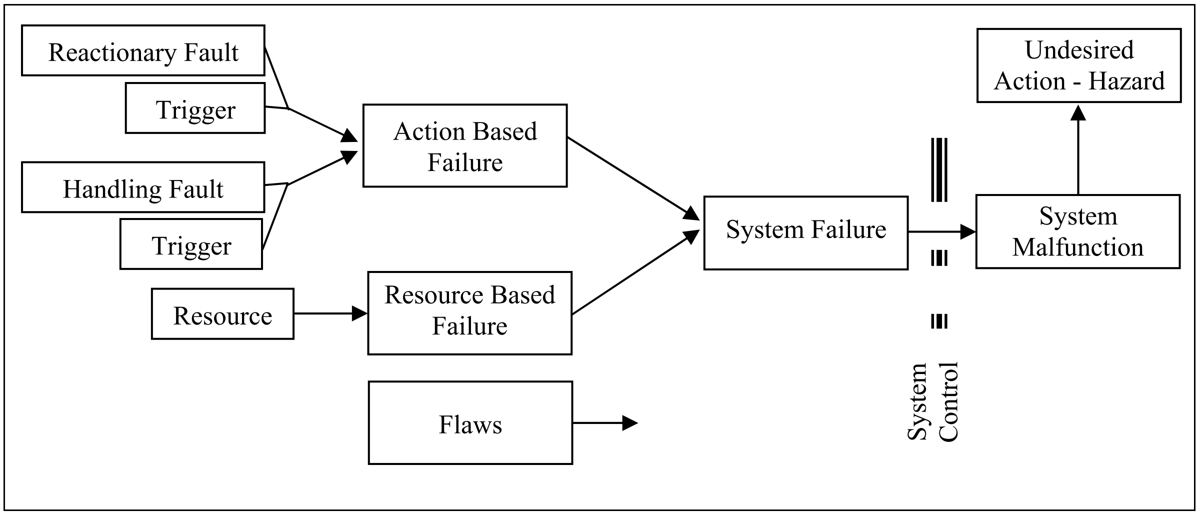

Figure 3 Software Failure Flow

Software Failure, as with Software Development, has its own terms and vocabulary to define the discipline. Software Failure can be depicted as a chain of events and actions whose outcome could eventually lead to the destruction or functional loss of a system. To understand how to break the chain of failure, it is first important to understand the links that make up the chain, from the basic flaw to the culmination of the actual failure. Figure 3 represents a personal depiction of a Software Failure Flow, based on the dissertation's definition of failure elements. The resultant depiction serves as a contribution of the dissertation.

The definitions introduced in this study are a re–tailoring of existing popular definitions with an emphasis on safety, as well as an introduction of new terms and definitions designed to satisfy the existing absence in Software Safety Engineering. These terms are intended to fulfill the unique language requirements placed on the development of high–assurance system. The introduced terms are not all encompassing; yet establish a foundation for the induction of further terms as necessary to meet the semantic needs of software development.

In the simplest of terms, software fails because the system was unable or incapable of preventing an uncommanded action or undesirable output, the potential failure was never recognized, or a fault in the design actually induced such an output or action. The question to software development lies with why the system was unable or incapable of preventing such an action. Optimally, a system would be designed to control and contain every possible fault and failure that could potentially occur, or be developed with sufficient redundancy or controls to mask or conceal the underlying fault. To best understand why software fails and how failure can be prevented, it is essential to understand and agree upon a convention for the breakdown and categorization of Software Failure and Software Safety terms and definitions.

Software failure is formally defined as the state in which a system has failed to execute or function per the defined requirements due to a design fault;[69] or where failures are a result of incomplete, ambiguous, erroneous, or missing requirements leading to an unforeseen or undesirable event. For the purpose of this dissertation, the following Type Failure List in Table 3 has been devised to characterize software failures by the indicators or actions that the system may take preceding to or during the failure, as:

- **TYPE 1** When a system executes an uncommanded action.
- **TYPE 2** When a system executes an inappropriate action for a specific command.
- **TYPE 3** When a system fails to execute a required action for a specific command.
- **TYPE 4** When a system fails to function.

Table 3 Failure Types List

The Failure Type List introduced in this study is not inclusive of all potential types of failures that could be experienced, but gives a plausible baseline for establishing failure types. Additional failure types could be appended to the current list (i.e., **TYPE 5, 6, 7**…) or included as a subordinate failure to an existing failure (i.e. **TYPE 1A, 2A, 2B**…)

The Failure Type Numeric is used for simplification and reference later in the dissertation. A **TYPE 1** Failure is characterized by the system executing an uncommanded action while the system is in and out of operation. A **TYPE 1** Failure is the only type of failure that can occur when the system is not in operation, as it would be expected that the system would not receive any commands when not in operation. The absence of a command uniquely sets this type apart from other failures. This type of failure is not related to any command or provocation, and occurs outside of the system requirements. This failure may be triggered by the state of the system or by an input not related to a command.

A **TYPE 2** Failure is characterized by the system executing an inappropriate action for a specific command during system operation. When a user or procedure generates a command to the system, it should be expected that the system would respond with a predetermined series of actions or responses. In the case of a **TYPE 2** Failure, the system executed a false response to a system command. It should be noted that the system attempted to execute a response to the command, though be it incorrect. If the system cannot execute any action for a command, the system may be experiencing a **TYPE 3** Failure.

In a **TYPE 3** Failure, the system could not or did not execute an action for a given command. A **TYPE 3** Failure differs from a **TYPE 2** Failure by the fact that no action was taken for the command, instead of the system executing an inappropriate action. A **TYPE 4** Failure occurs when the system fails to respond or execute any action for all commands, essentially with the system "*locking–up*". A **TYPE 4** Failure is a special case

[69] *Computer Science Dictionary, Software Engineering Terms*, CRC Press; ver. 4.2; 13 July 1999.

of the **TYPE 3** Failure, where in a **TYPE 3** Failure concerns the inability to execute a single command a **TYPE 4** Failure concerns the inability to execute a preponderance of the system's commands.

Software failure does not always result in the complete shutdown of a system. Rather, failure can range from the single undetected anomaly to a cascading failure and eventual catastrophic collapse of a system's functionality. This level of failure can eventually, but not necessarily, lead to a system malfunction. Even an undetected anomaly is still a form of a software malfunction as the system continues to operate with a lingering failure in the background. Optimally these anomalies would work themselves out and the system continues to function. The fact still exists that the system executed a function, regardless of how perceptible, that was undesired and uncommanded.

To understand System Malfunctions, each must first be broken down into two basic phases or subcategories – system faults and system failures. As depicted in Figure 3, a fault is categorized as an object within a system which, when acted upon or triggered, can reduce a system's ability to perform a required function, assuming the complete availability of all necessary resources. A failure is the actual inability of a system to perform a required function, or the departure of a system from its intended behavior as specified in the requirements. A system can contain a fault that may eventually, but not necessarily, lead to a failure. The failure will result in a malfunction of the system, which in turn will create a corresponding hazard. Additional components of Figure 3 will be addressed through this chapter of the dissertation.

1. Software Flaws

Within the semantic chain that defines Software Failure, the bottom of that chain is anchored by the term "flaw." A flaw is simply defined as "a feature that mars the perfection"[70] or rather "an imperfection or weakness and especially one that detracts from

[70] *The Random House Dictionary of the English Language – The Unabridged Edition*, Random House, Inc.; New York, New York; 1980, 1998.

the whole or hinders effectiveness."[71] While attempting to define the terms of Software Failure, this research has revealed an obvious lack of formal definitions for the discipline, making it necessary to coalesce or combine existing definitions and usage phrases to apply to Software Failure. For the purpose of this discipline, a "flaw" should be understood as *"a specific item that detracts from the operation or effectiveness of the software system without necessarily resulting in a failure or loss of operability."* A flaw may not affect the ability of the system to execute its required functions, but can cause a noticeable deterioration in the system's performance or aesthetic quality of the product. Should a flaw ever reach the ability to cause a failure, it ceases to be referred to as a flaw and becomes a fault.

Some documenting resources, editorials, and publications incorrectly relate a flaw to the failure of a system. For example, a report from NASA was quoted as:

> An in–depth review of NASA's Mars exploration program, released today, found significant flaws in formulation and execution led to the failures of recent missions, and provides recommendations for future exploration of Mars.[72]

It should be understood that a flaw *does not* lead to the failure of the system, while a fault serves as the true basis for a failure.

A flaw should be understood as minor in nature and does not affect the overall ability of the system to accomplish its requirements. Most flaws might cause discomfort, inconvenience, or a reduction in efficiency, but not a reduction in efficiency below the specified requirements of operation. In the case of a disk drive, an event might reduce the speed of the data transfer rate, but as long as the data rate does not fall below the specified required transfer rate, the error would be classified as a flaw. If the transfer rate did fall below the required level, if even for a moment, then the event would be categorized as a fault, which led to a failure of the system's ability to meet requirements.

[71] *The Merriam-Webster Collegiate Dictionary*, Merriam-Webster, Inc.; Springfield, Massachusetts; 2001.

In most cases, flaws are subtle, almost indiscernible elements in the operation of the system, and their execution is accepted by users as a quirk or idiosyncrasy of normal operation. This does not imply tolerance of a flaw or infer that some level of flaws should be accepted in the normal development of a system. A flaw is still an imperfection that should be investigated, combated, and controlled like any other system irregularity. By definition, a flaw does not lead to a failure of the system. While a flaw does not directly contribute to the failure of a system, its existence may serve as an indicator of existing imperfections and faults within the system, those imperfections eventually surfacing as a failure. Should an event once defined as a flaw lead to a failure then the event would be redefined as a fault. If a lack of care caused the creation of flaws, then the same lack of care might have produced the same proportion of faults. The same discipline that should be used to counter a fatal error should be used to prevent even the smallest of flaws, resource dependent. It is recognized that it is not economically feasible to remove all flaws within a system, but that their presence may ultimately reduce the perceived value of the product (Economics).

2. Software Faults

Where *Software Failure* denotes an action performed by a system, *Software Faults* denote the object that induces the action. Faults are the objects within the system that contains an error in logic, that when triggered could induce a failure. Errors in logic can be the result of errors in system requirements that fail to consider the proper operation of the system, implementation errors in which the system is operated in a manner for which it was unintended or controlled, or development faults in which the system's logic is erroneously programmed. The term *"Fault"* has been synonymously used with the term *"Bug"* to define an error within a system.[73] As stated previously, a fault can reside in the system indefinitely without ever inducing a failure until initiated by a trigger, in the same way that a firework can remain safe and stable until someone

[72] Wilhide, Peggy; *Mars Program Assessment Report Outlines Route To Success* - Release: 00-46, Headquarters, Washington, DC, 28 March 2000.

[73] Nesi, P.; *Computer Science Dictionary, Software Engineering Terms*, CRC Press; 13 July 1999, http://hpcn.dsi.unifi.it/~dictionary.

applies a spark to the fuse. Faults are exclusively related as Action Based Failures, as they are logic based and internal to the system. System faults can be further broken down into two subcategories:

- First, to faults related to the internal deficiencies of a system with acceptable inputs, which shall be referred to as ***Reactionary Faults*,**
- Secondly, to a system's inability to function with incorrect or erroneous inputs, referred to as ***Handling Faults*.**

a. Reactionary Type Faults

In an optimal system, an input would be received, processed, and executed in compliance with the requirements of that particular module. For reactionary type faults, it is assumed that that input was correctly formatted and within the acceptable range for the given requirement. The system is expected to take action or react to the input through a predefined set of responses, based on the value of the input. If the input is within the proper tolerances and the system is unable to execute its requirements, then it would be considered a Reactionary Type Fault. The term *"Reactionary"* comes from the system's design to react to commands and inputs. The fault is not in the input, but in the design of the system and its inability to take appropriate action for the input. In the case of such a fault, the trigger would be the actual input. The combination of the trigger and fault then result in a failure within the particular module. These triggers and faults could have their basis in requirement, implementation, and/or programming logic.

An example of a Reactionary Type Fault could be found within an automobile cruise control system. Let the automobile be cruising at below the set cruise speed. The system will attempt to accelerate the automobile towards the desired speed, comparing its current velocity against the desired speed. As the speed of the automobile reaches the desired speed, the cruise system should disengage the acceleration sequence. If the system continues to accelerate past the desired speed with no change in its status, has received the accurate speed signal of the vehicle, and is unable to process the fact that the automobile has exceeded the required speed then the system would have experienced a Reactionary Fault. In this particular case, the Reactionary Fault is characterized by the inaction of the system to the acceptable input – a **TYPE 3** failure[74]. If the automobile would have reached the desired speed and then commenced to immediately decelerate, then the Reactionary Fault would be characterized by the incorrect action of the system to the acceptable input – a **TYPE 2** failure.

b. Handling Type Faults

Despite the best of system designs, it can never be assumed that a system would be without erroneous entries or parameters out of the normal bounds of the system. To effectively manage such a system, developers must design checks, filters, and controls within the system to handle such entries. Optimally, these filters would catch erroneous entries and execute a series of pre–specified procedures or functions based on the entry value. When the system is unable to detect the erroneous entry, is incapable of executing the applicable handling procedure, or the handling procedure itself experienced a fault related to its execution, then the system would have experienced a Handling Type Fault. If the system recognizes the erroneous entry and attempts to handle the error, and then fails within this secondary execution, then such a fault would still be regarded as a Handling Type Fault because it is isolated by the systems inability to *"Handle"* the error. As with the Reactionary Type Fault, the fault is not in the input but in the design of the system and its inability to take corrective action for the erroneous input. In the case of such a fault, the trigger would be the erroneous input. The combination of the trigger and fault then result a failure within the particular module.

An example of a Handling Type Fault could be found within an account data entry system where the user would be required to make keyboard entries. Let the account data entry system require the Account Balance Value of the current account, in numeric format. Assume the user has the ability to make alpha–numeric–symbolic entries from a keyboard. If the user attempts to make an alpha–symbolic entry for the numeric requirement, the system should handle the action with an appropriate response,

[74] See Table 3 Failure Types List

either by disregarding the entry, displaying an error prompt, or other appropriate action. If the system does not handle the erroneous input and subsequently attempts to execute a mathematical function, then the system would experience an incompatibility error and halt, as the string value would be incompatible with the numeric requirement, hence a Handling Type Fault. In this particular case, then the Handling Type Fault is characterized by the system failing to handle the erroneous input by permitting the mathematical function – a **TYPE 3** failure. Depending on the design of the system, the fact that each keystroke was accepted would be classified as a **TYPE 2** failure. The fact that the erroneous character was not filtered would constitute a **TYPE 3** failure, where in both cases it was inappropriate for the alpha–symbolic character to be permitted into the system.

3. Software Failure

Failure, in terms of Software and System Failures are defined as “the inability of a system or component to perform its required functions within specified performance requirements.”[75] To further delineate failure types, this study introduces two additional failure categories, based on the source of the initiator or fault:

- ***Resource Based Failures (RBF)*****:** Failures associated with the uncommanded lack of external resources and assets. Resource Based Failures are generally externally based to the logic of the system and may or may not be software based.

- ***Action Based Failures (ABF):*** Failures associated with an internal fault and associated triggering actions. Action Based Failures contain logic or software–based faults that can remain dormant until initiated by a single or series of triggering actions or events.

[75] Software Engineering, *IEEE Standard Glossary of Software Engineering Terminology, IEEE Standard 610.12*, Institute of Electrical and Electronics Engineers, Inc.; 1990, 1991.

a. Resource Based Failures

Resource Based Failures are usually associated with the hardware and external resources required to support the system's logic operation. System hardware includes components directly connected to the unit to include the unit processor or CPU, mass storage devices, monitor, or Graphical User Interface (GUI). External resources include the electrical power supply, input and output resources and peripherals such as printers and transmission mediums, memory partitions to support operation, and manipulated control hardware directly controlled by the system such as robotic arms, and mechanical drive systems. RBFs are usually triggered by the absence or failure of an associated resource and are very difficult if not impossible to mask, as the resource usually serves as the functional input or output to the system. In cases of memory failure or overrun, secondary support logic may fail to properly partition and manage system memory beyond the logic requirements of the primary system. In specific cases, error handlers and controls can trap the absence of a resource and take pre–specified actions such as reverting to a backup system, prompting the user for an alternative or redundant resource, or by displaying a BIT (Built In Test) indication of the fault. In a worst case, the absence of the resource would result in the complete failure of the system, such as the loss of electrical power or destruction of the CPU with no redundant backup.

In High–Assurance Systems, RBFs are usually prevented by the inclusion of redundant systems such as an Uninterrupted Power Supply (UPS) system for backup power, or parallel lines of communication capable of providing continuous data transfer. Factors such as cost, feasibility, or physical limitations can prevent the inclusion of acceptable redundant or failsafe control systems. In the most catastrophic of failures, redundant mechanisms may be destroyed or disabled along with the primary system. In the case of space vehicles, the loss of a heat shield would reduce a vehicle's ability to withstand the temperature extremes of space flight or protect its sensitive components during planetary reentry. As the vehicle passes through the atmosphere, vulnerable telemetry sensing instruments could be damaged which would reduce the craft's ability to control its decent. Without a controlled descent, the vehicle and all redundant systems would be destroyed during reentry or upon impact with the planetary surface.

Despite the best system development practices, the loss of a critical system resource is extremely difficult to prevent. In the study of Software Failure, system resources must be evaluated and measured for their vulnerabilities, potential hazardous effects of the system, and the system's ability to protect against the hazardous event. A factor of Software Safety can then be based on the results of the measures and evaluations.

b. Action Based Failures

While Resource Based Failures are associated with the hardware and external resources, Action Based Failures are exclusively associated with the software side of the system. An ABF requires the combination of a fault and its associated trigger to initiate the undesirable action. Faults can include a flaw in logic and code design, a misinterpretation of system requirements, or a defect in the language compiler or code generator. A fault can lie dormant for the entire life of the system and never surface unless the specific trigger initiates the event. Triggers can include user inputs to the system, incompatible outputs and communications from system modules, miscalculation from one function or procedure to the next, or a propagated flaw compounded from one action to the next. Error handlers and filters can be designed to trap or prevent most erroneous inputs or records. In the case of ABF, a filter, control, or error handler is an internal function designed to prevent a specific hazard or undesirable action. The procedure is designed to prevent a known action, initiated by the trigger, handling the error, and thereby preventing the failure.

In High–Assurance Systems, these controls, error handlers, or filters are designed to capture a specific trigger or even a range of triggers, depending on their design. Once captured, the error handler must take appropriate action by either prompting the system for another input with the intention that the second input will pass where the first had failed, or by halting the operation of the system in such a fashion as to not induce a secondary failure. The primary purpose of a control, error handler, or filter is to prevent the trigger from ever reaching the fault.

A common error handler might be one to prevent against a system dividing by zero; without it the system would fall into an infinite mathematical loop, as the division of anything by zero would resolve towards infinity. An error handler might add a predetermined minute value to the zero to permit the division or it might simply exit the procedure altogether, depending on the desired results and implications of each action. A simplistic error handler is easy to write and can filter or capture many ABFs, while it is extremely difficult to write an error handler that can prevent the creation of the faulty input from its source. Such prevention can only be accomplished through an output filter that conforms to a predetermined set of output requirements, including content and format.

It is possible for a failure, based on its trigger and fault, to be categorized as both an Action and Resource Based Failure. In the case of a Memory Overflow, depending on the triggers and reactions of the system, such a failure can be classified as either an Action Based or Resource Based Failure. Should the failure occur due to a lack of physical memory, the failure could be assumed as a Resource Based failure of the operating hardware platform. Should the failure occur due to a fault of logic control of the physical memory, the failure could be assumed as an Action Based Failure. Memory Overflows may exhibit characteristics of both Resource and Action Based Failures as adding additional physical memory and revising the memory logic controls could mitigate the fault.

4. Software Malfunctions

The term *Malfunction* is derived from the French term *mal*, meaning “bad” or “wrongful”; and the self–defined Latin word of *function* to create an item that “functions imperfectly or badly, or fails to operate normally.”[76] Upon the software system experiencing a failure, the system’s ability to operate and meet design requirements may be degraded. The level to which the system is degraded will determine the type and extent of the malfunction as well as the system’s ability to counter the malfunction to

[76] *The Merriam-Webster Collegiate Dictionary*, Merriam-Webster, Inc.; Springfield, Massachusetts; 2001.

prevent a hazard. As the definition states, a malfunction is the condition wherein the system functions imperfectly or fails to function at all. A malfunction is not defined by the failure itself, but rather by the fact that the system now fails to operate. The term malfunction is a very general term, referring to the operability of the entire system and not to a specific component.

Optimally, a system would be developed that could sustain the failure of a specific component, while not experiencing a system malfunction. This sustainability could be accomplished by the use of redundant systems, overrides, or checks and balances that could counter the effects of the failure. If the failure could be masked or compensated for in some way that it does not affect the performance of the system, then the system would not be considered to have suffered a malfunction. The severity of a malfunction is primarily judged by the observation and perspective of the user and his perceived inability to utilize the system. Many systems may experience a failure in operation, but the failure is so minute in scale to be indiscernible to the user.

A Software Malfunction should be characterized in terms of what has failed to function properly rather then in terms of the actual failure. One would not say that the Mars Climate Orbiter experienced a *Mathematical Malfunction* because of the metric conversion error, but rather that there was a fault in the mathematics logic of the trajectory module. The format of database entries, triggered by the planetary entry evolution, resulted in a failure to accurately report the vehicle's position (See Chapter I.A). The vehicle experienced a failure to compute its position properly, resulting in a malfunction in the trajectory module. The trajectory module could not relate the erroneous position data; the database entry formats were incompatible; and the system logic was misinterpreted from development requirements. The combination of the three failures resulted in the system malfunction.

5. Software Hazards and Mishaps

Time and technology have ensured and encouraged software–based systems to increase in complexity and reduce their reliance on human intervention for logic and decision–making. This greater complexity and absence of human intervention has increased the likelihood of hazardous actions. The increased proliferation of such systems additionally increases the general number of hazardous incidents.

A Software Hazard is the potential occurrence of an undesirable action or event that the software based system may execute due to a malfunction or instance of failure. The next step in this logical progression is the Mishap – defined as the occurrence of an unplanned event or series of events and action that results in death, injury, or damage to or loss of functionality of equipment, property, or otherwise reducing the worth of the system[77].

A software system is required to execute a set of predetermined logic functions and procedures based on the system's inputs and interactions. When the system fails to properly execute its functions, it has malfunctioned. Due to the external reliance upon that malfunctioned system, there is a consequence for the failure. Hazards are judged or measured by the cost of the action or event in terms of a tangible or intangible value, but noting that most intangible values later relate to a tangible value. Tangible values include the loss of real economic worth to the developer, monetary compensation to the consumer or damaged person for the failure, the loss of human life, or the loss of physical property. Intangible values such as trust, confidence, and reliability later affect the economic worth to the developer or the customer who may rely on the system.

Hazards can be grouped into three categories, based on states of the system at the times for which they occur, namely:

[77] Attributed to *NASA – STD – 8719.13A, Software Safety*, NASA Technical Standard, National Aeronautics and Space Administration; 15 September 1997.

- Hazards that occur when the system fails to function correctly.
- Hazards that occur when the system fails to function.
- Hazards that occur when the system functions correctly

Traditionally, we appreciate the fact that a hazard may occur when a safety–critical system fails to function correctly, given that the system's function was to control or prevent the occurrence of a hazardous event. Additionally, it is recognized that a hazard may occur when the system fails to function in its entirety since the lack of functionality equates to a lack of hazard control. In safety–critical systems, the existence of a potential hazardous event grants some probability that the event may occur despite the operation of the system. In some cases, despite attempts by the system to prevent such an event, it is possible that a hazardous event could occur during the normal course of operation.

Software Safety is characterized by reducing the number or scope of hazardous events or mishaps to a level that is economically, socially, and strategically acceptable. It is economically infeasible to ensure that a high–assurance system will have no defects and will equally have no failures. Some acceptable margin must exist and be agreed upon as a goal towards system development. *"Bean Counters"* constantly measure the economic implications of a failure, the probability of that failure, and the cost to reduce or remove the likelihood of that failure. It is not economically justified to spend ten million dollars to repair a fault that could damage the manufacture of a one–dollar profit component on an assembly line, unless the sum of all of the damages and repercussions might exceeded the total cost of the repair. If the likelihood was sufficiently low that a failure would damage an equitable number of components, then production may continue as scheduled.

Socially acceptable levels of Software Hazards are emotionally driven and charged with debate and question. The failure of a fire control system may result in the loss of human life or limb, or a flawed voting system might destroy the confidence of a nation in the electoral process. The tolerable level of that hazard depends on the specific circumstances of the time and situation. In wartime, the loss of human life may be acceptable to a certain degree, as long as it can be countered by some greater degree of success. Despite the burdens of war, our society continues to demonstrate a great intolerance for the loss of human life and have condemned systems that have resulted in such loss, even in cases where the system provided some level of benefit.[78]

Depending on the development environment, the demand for the product, and the anticipated uses of the system, some level of Software Hazards are expected and acceptable. In the case of the Patriot Missile Battery, the missile defense system had a concealed fault that was not triggered in its intended configuration as an anti–aircraft system. The fault was a rounding error that multiplied over time and was never revealed as a factor against slower moving targets. When the Battery was reconfigured against faster moving ballistic missiles, the rounding error became a greater factor and lowered the system's ability to accurately track and engage targets. Due to the strategic demands of the system and the "fog of war," a decision was made to utilize a software system that was untested for its new configuration, with the manufactures and users aware that there was questionable risk and potential hazards. To improve the level of success and reduce the hazard of a missile getting through the battery's screen, multiple layers of batteries were set up in the theater of operation.

6. Controls of Unsafe Elements

Software Systems, due to various external triggers and design factors, stand at risk to experience a failure during various stages of their lifecycle. The ability to prevent, handle, or mitigate this failure to prevent a malfunction is referred to as a *control* – meaning to control the system's functionality to within acceptable bounds should the functionality deviate.

[78] See APPENDIX B.4 –
PATRIOT MISSILE FAILS TO ENGAGE SCUD MISSILES IN DHAHRAN.

If devised properly, the control would permit the normal operation of the system, reacting as necessary should the system depart from that operation. The software failure control may consist of filters, redundant operators, or any of a number of other objects that can decrease the potential for a system malfunction, should an error occur. Optimally, the control object will prevent the occurrence of a malfunction and subsequent hazardous event. Understanding the limitations of any design system and the potential damage from significant malfunctions, the inclusion of a control object might not prevent the occurrence of a hazardous event, instead only mitigate or lessen its effect. The control object itself may be organic or independent of the system, depending on the architecture of the system and control that is to be employed.

7. Semantics Summary

Software has been simplistically characterized as a set of logic instructions to computer operations.

When those instructions fail to function properly or fail to control safety–critical operations, the system will potentially execute a hazardous event. That event may include the control of an electro–mechanical, hydraulic, or pneumatic system; or be the control of a critical data system. The loss of control to either system could conceivably constitute a hazardous event, depending on the potential consequence of the failure. A safety–critical event does not require human interaction or input.

Research and investigation has revealed that the discipline of Software Engineering has lacked a common definition for failure and the resulting consequences. Other disciplines have spent considerable time and effort to define the practices and characteristics of failure, as well as the measures to prevent them. Software Engineering, while still in its infancy, is not exempt from fault or failure. Many software engineering requirement and specification documents relate to Software Safety and Failure in the broadest of terms, noting solely that efforts will be done to prevent failure and increase safety.

NASA, in its Software Safety Standard referred to *Faults* as "preliminary indications that a failure may have occurred,"[79] contrary to the Standard English definition of the term *Fault* – as in imperfection, a weakness, or impairment.[80] A fault does not occur, it does not develop – it exists, timeless in state and nature, and reveals itself only when triggered. It is not the number of faults in the system that should be the concern; rather it is the effect that each fault may have should it be triggered. Optimally that triggering would occur in controlled testing and not in use by the customer. Software Safety has been defined as the "…discipline of Software Safety Engineering techniques throughout the software lifecycle that ensures that the software takes positive measures to enhance system safety and that errors that could reduce system safety have been eliminated or controlled to an acceptable level of risk."[81] If Software Safety were as simple as "Make the Software Safer," then we would not be in the predicament that we are today.

To better understand the discipline of Software Safety and Failure – the following definitions are introduced:

Software Flaw: A specific item that detracts from the operation or effectiveness of the software system without resulting in a failure or loss of operability. A software flaw does not result in a failure. A flaw may reduce the aesthetic value of a product, but does not reduce the system's ability to meet development requirements.

Software Faults: An imperfection or impairment in the software system that, when triggered, will result in a failure of the system to meet design requirements. A fault is stationary and does not travel through the system.

[79] *NASA – STD – 8719.13A, Software Safety*, NASA Technical Standard, National Aeronautics and Space Administration; 15 September 1997.

[80] *The Merriam-Webster's Collegiate Dictionary, Tenth Edition*, Merriam Webster, Incorporated; Springfield, Massachusetts; 1999.

[81] *NASA – STD – 8719.13A, Software Safety*, NASA Technical Standard, National Aeronautics and Space Administration; 15 September 1997.

Reactionary Type Faults: A fault characterized by an inability of the system's logic to react to acceptable values of inputs, as defined in the system requirements.

Handling Type Faults: A fault characterized by an inability of the system's logic to handle erroneous entries or parameters out of the normal bounds of the system.

Software Failure: The state in which a system has failed to execute or function per the defined requirements due to a design fault.[82] Failure is usually the result of an inability to control the triggering of a system fault. Faults can be categorized in one or more of four types, depending on the circumstances leading to the failure and the resulting action. Failures can be further divided into one of two categories based on the source of the failure. The occurrence of a failure may or may not be detected by the user depending on the type of failure and the protections and interlocks of the system.

Resource Based Failures (RBF): Failures associated with the uncommanded lack of external resources and assets. Resource Based Failures are predominantly externally based to the logic of the system and may or may not be software based.

Action Based Failures (ABF): Failures associated with an internal fault and associated triggering actions. Action Based Failures contain logic or software–based faults that can remain dormant until initiated by a single or series of triggering actions or events.

Software Malfunctions: The event within the system that creates a hazardous event. A malfunction is not defined by the failure itself, but rather by the fact that the system now fails to operate properly, operates improperly, or fails to operate at all, resulting in a hazardous event. It may be possible for a system to experience a failure without resulting in the occurrence of a malfunction. It may be possible for a system to experience a malfunction without resulting in the occurrence of a hazardous event,

[82] *Computer Science Dictionary, Software Engineering Terms*, CRC Press; ver. 4.2, 13 July 1999.

depending on the protections and interlocks of the system. The term malfunction is a very general term, referring to the operability of the entire system and not to a specific component.

Software Hazards: The potential occurrence of an undesirable action or event that the software based system may execute due to a malfunction or instance of failure. The hazard may be categorized by potential consequence and severity of its occurrence.

Software Mishap: The occurrence of a software hazard. Once a system fails, the events may trigger a malfunction to execute, resulting in the occurrence of a hazardous event – referred to as a Mishap. Formally, a mishap is defined as the occurrence of an unplanned event or series of events and action that results in death, injury, or damage to or loss of functionality of equipment, property, or otherwise reducing the worth of the system.[83]

Control: The system object capable of preventing or mitigating the effects of a system malfunction should a failure occur. Controls may consist of any of a number of filters, redundant operators, or other hardware or software objects depending on the architecture of the system and control that is to be employed. A control may be able to filter unacceptable values and triggers from contacting a fault, preventing the occurrence of a failure.

In a natural progression, a Software System might have a number of flaws that exist and detract from the overall system but do not result in any failures or inability to meet system requirements. In other parts of the system, there might exist faults that linger in the background, awaiting a trigger to launch a failure. Once that trigger is received by the fault, the fault generates a failure. Depending on the level of failure, the ability of the system to contain the failure, and failure propagation, the system may experience a malfunction. Investigation and planning could outline a number of potential hazards that could occur if the system were to fail. The resulting malfunction could trigger one of these hazards, ensuing in a mishap. If possible, that mishap may be averted or mitigated through the use of control objects.

Due to the semantic rich nature of Software Engineering and Software Safety, it is necessary to establish a basis of understanding for defining applicable terms within this body of work. The use and definition of the terms *flaws, faults, failures, malfunctions, hazards, mishaps, and controls* are widely contrasting and sometimes contradictory. Definitions introduced in this study refine the use of these terms to better represent a logical progression and flow from one term to another. Previous definitions referenced throughout this chapter and in state of the art publications[84, 85] refer to many of these terms as isolated events without a method of evolution through the safety process. It is intended that these refined terms create a better understating of vocabulary to represent the fluid nature of safety within the field of Software Engineering.

D. DEGREES OF FAILURE[86]

Once a basis for defining faults and failures is understood, it becomes important to define the degrees or levels of failure so that they can be categorized and referenced within a metric that this dissertation defines. I introduce a new series of failure definitions as well as complement existing definition series. The following definitions in no way encompass all possible failure definitions, but serve to present a graduated series of failure types for use in failure examinations. Failures are categorized based on the following characteristics: their effect on the system, their propagation, and the "*cost*" that they could inflict upon the system. *"Cost,"* in the case of failure, can be defined as both the tangible and intangible value of resources lost as a consequence of the mishap. Again,

[83] Attributed to *NASA – STD – 8719.13A, Software Safety*, NASA Technical Standard, National Aeronautics and Space Administration; 15 September 1997.

[84] Leveson, Nancy G.; Safeware, *System Safety and Computers*, University of Washington, Addison-Wesley Publishing Company; April 1995.

[85] Herrmann, Debra S.; *Software Safety and Reliability, Techniques, Approaches, and Standards of Key Industry Sectors*, IEEE Computer Society, Institute of Electrical and Electronics Engineers, Inc.; Los Alamitos, California; 1999.

[86] Nesi, P.; *Computer Science Dictionary, Software Engineering Terms*, CRC Press; 13 July 1999, http://hpcn.dsi.unifi.it/~dictionary.

the term *"lost"* is used to signify the unexpected or unplanned expense due to the failure of operation in the system.

1. Failure Severity

The loss of system operability from a software failure is not absolute but varying from a subtle to a comprehensive failure. To develop a metric of Software Safety, it is essential to understand and define a common set of resulting consequences of failure. These definitions can then be applied to a metric and numerically ranked for a common evaluation criterion for failure.

a. Failure Severity Definitions

Failure Severity: The seriousness of the effect of a failure can be measured on an ordinal scale (e.g., classification as major, minor or negligible) or on a ratio scale (e.g., cost of recovery, length of down–time). This value may depend also on the frequency of the error. The following definitions are a combination of successive English terms, increasing in severity from the most benign of failures to the most critical. Failures may be categorized as follows:

Invalid Failure: "A failure that is, but isn't." An apparent operation of the primary system that appears as a failure or defect to the user but is actually an intentional design that is not understood by the user. These types of defects or failures are difficult to trace, as the user may not realize that they are actually intended features or design limitations of the primary system. Invalid Failures may also exist when the developer does not design the system to the expectations of the user. Such invalid failures are commonly found when the user does not fully understand the functionalities of the system that they are operating or the user attempts to combine seemingly similar systems without understanding the bounds and limits of such a connection. Due to the fluid design and rapidly changing environment of "MS Windows" based software, such compatibility issues and invalid defects are prevalent in the Microsoft Windows OS:

> The information contained in this document for each device is current as of the date first posted; however, since these products are subject to modification, revision, or replacement by individual manufacturers at any

> time without notice, Microsoft cannot guarantee their continued compatibility with our operating systems.[87]

The term “Invalid Failure” is not synonymous and should not be confused with current error prompts that warn the user of an invalid entry, and invalid operation, or other invalid execution. The term implies that the actual fault or failure is invalid to the current system and does not locally exist or exist at all.

> Incorrectly stated for the purpose of this dissertation – TA00155 – Error Message ‘MSIMN causes an *invalid fault* in module MSOERT2.DLL at 017f: 79ef5358.’[88]

Key points of an Invalid Failure include the fact that:

1. The system conforms to the established requirements used by the developers, not withstanding the fact that the requirements may not meet the functional needs of the user. It is possible that the misrepresentation or expectation of functionality could lead to the occurrence of a hazardous event.

2. The user may attempt to operate the system in an environment for which the system was not designed or certified to function. The developer bears the burden of informing users of applicable operating environments through proper documentation and training, while it is the user’s obligation to ensure compliance with outlined requirements. In an optimal design, the software system would validate its environment at the commencement of operation, prior to the execution of any critical functions.

Minor Flaw: A flaw does not cause a failure, does not impair usability, and the desired requirements are easily obtained by working around the defect.

[87] *Microsoft Windows Hardware Compatibility List*, Microsoft Corporation; Redmond, Washington; 2000.

[88] *Windows 98 Exception Errors Page*, TechAdvice.Com; 2001.

> We found a *minor flaw* in the 1.6.5 release. It was fixed and re–inserted in Polaris 1.6.5.tar.gz on the ftp site. If you download prior to March 7, 2000 at 11:13 am, you should download again to eliminate this bug.[89]

Latent Failure: A failure that has occurred and is present in a part of a system but has not yet contributed to a system failure. Such a failure can remain hidden in the background of the system, but does not surface to result in a malfunction or hazard. A Latent Failure may be masked by the speed of the system, in which the processor brushes past the failure and compensates for the error by starting a new procedure that replaces the incorrect internal information with a corrected value before a system failure occurs. The error may be so insignificant that it does not gain the attention of the operating system or the user. A Latent Failure may surface later as part of a more severe failure, but by its nature would not gain the attention of the system independently.

> It is also important to note that, while all the *latent failures* we observed were transitory and were eventually detected and repaired, their durations were by no means always negligible. If the latent failure modes introduced by plant modifications tended to be short–lived, they would not necessarily be a major concern.[90]

Local Failure: A failure that is present in one part of the system but has not yet contributed to a complete system failure. Such a failure is commonly interpreted as a **Latent Failure.**

> Applications and data are secured until the *local failure* is corrected, or the user goes to another WID connection to the same server. Upon logging in, the user's application and data appear exactly as they were when the failure occurred without data loss, even if never saved to disk.[91]

Benign Failure: A failure whose severity is slight enough to be outweighed by the advantages to be gained by normal use of the system. A Benign

[89] *Warning: Minor Bug Fix, Polaris Compiler Questions Forum*, Polaris Research Group, University of Illinois, Urbana – Champagne Campus; March 2000.

[90] Bier, Vicki Prof.; *Illusions of Safety, A White Paper on Safety at US Nuclear Power Plants*, Department of Engineering, University of Wisconsin, Madison, Wisconsin; 1989.

[91] WID/Server Software, *Unique Capabilities Further Reduce Cost and User Frustration*, EIS, Bull Communications, Versailles, France; 2001.

Failure assumes that a failure has occurred but its consequences are so slight as to be overshadowed by the benefits gained by using the system. Such a judgment has to be made taking into consideration the severity of potential hazards and likelihood of further mishaps.

> These turbo pumps are designed to be completely interchangeable with the existing Rocketdyne pumps, have more *benign failure* modes for greater safety, and will have only 4 welds compared to the present 297.[92]

Intermittent Failure: The failure of an item that persists for a limited duration of time following which the system recovers its ability to perform a required function without being subjected to any action of corrective maintenance. Such a failure is often recurrent. An intermittent failure may or not lead to a malfunction or mishap, but is observable by the system and user. The system may utilize redundant modules or error handlers to compensate for the intermittent failure, which explains why the system was capable of continuing operation. Intermittent Failures are easier to isolate and diagnose then more severe failures because the system is capable of continuing its operation, presenting the user with a controllable platform from which to trouble shoot.

> Most insidious is the partial or *intermittent failure* of a cable. The symptoms of this kind of failure include partial data transmission, garbled data transmission, loss of Internet of network packets.[93]

Partial Failure: The failure of one or more modules of the system, or the system's inability to accomplish one or more system requirements while the rest of the system remains operable. Such a failure is also referred to as a Degraded Failure in that the system is degraded in its operation, but still remains capable of completing some tasks. A Partial Failure does not reset or correct itself like an Intermittent Failure, but rather reaches a constant state once it has occurred. The Partial Failure may continue to propagate through the system and induce additional failures as time persists. A Partial Failure may lead to a Malfunction and eventually a Mishap while other parts of the

[92] *Alternate Turbopump Development, Space Shuttle Evolution, Chapter 3*, National Aeronautics and Space Administration.

system remain unaffected. Such a Failure can be misleading in severity and the continued operation of other components may convince the user to continue operation. This continued operation could give the system the required time to generate a significant Mishap which would have been averted had the system been halted at the start of the Failure.

> A business phone system may experience partial failure in some subset of its features. In most cases, a dial tone will still be available and the phone may seem to function normally. The problem may occur with the reports that detail the duration of each phone call. For organizations that use this information for billing and/or tracking, the erroneous reports may not be immediately recognized and automated billing systems may generate faulty invoices.[94]

Complete Failure: A failure that results in the system's inability to perform any required functions, also referred to in military and aviation circles as "Hard Down." Aviators and military members refer to a system that is completely broken and requires extensive repair as "Hard Down," while a working system is referred to as "Up":*'Hard Down'* Aircraft are usually sent to the hanger deck and are replaced with *'up'* aircraft from below.[95]

The term also applies to times when the system may be electively brought down for maintenance, such as:

> Both NOAA Orions also flew coordinated patterns with NASA aircraft. Tomorrow will be a no fly day and Friday a tentative hard down day.[96]

[93] *Input Devices, Cable Failures*, Quinebaug Valley Community-Technical College; 03 February 2000.

[94] *Y2K FAQs, Examples of a Partial Breakdown*, The Economic Times, Times Syndication Service, New Delhi, India; 1999.

[95] Pike, John; *Military Analysis Network*, CVN-72 Abraham Lincoln Departments and Divisions, Air Department, Federation of American Scientists; 23 April 2000.

[96] *25 Aug 1998 Entry, CAMEX-3/TEFLUN-B Flight Activities, Hurricane George puts on a light show*, NASA Science News, Marshall Space Flight Center, National Aeronautics and Space Administration; 23 September 1998.

> Because the size of this laser was not known in advance of the Fall IOP, it does not have FAA approval or an approved Standard Operations Procedures (SOP) at this time. Therefore, this laser is hard down until such approvals…[97]

Cataclysmic Failure: A sudden failure that results in a complete inability to perform all required functions of an item. For the purpose of this definition, the use of the term "*Cataclysmic*" refers both to the rate in which the system failed, and to the severity degree of the Mishap that resulted from the failure. The word cataclysmic refers, similar to its medical definition, to the fact that the system deadlocked or otherwise ceased to function without notice. Users may not receive any warning that a system was to fail, and consequently may not have had time or resources to take corrective action or shift to alternate systems. Due to the processing speed of today's systems, software is particularly prone to sudden complete failure.

b. Failure Severity Summary

It is essential to understand that failures come in a myriad of degrees, and that a common set of terms must be established to define these failures and their effects on the system. An **Invalid Failure** is the flawed design of the system, failing to meet the user's expected functionality while conforming to formal design requirements. Proper system operation may be mistaken as a failure, or the operation of the system in incompatible or uncertified environment. A **Minor Flaw** is inconsequential to the operation of the product and does not affect the system's ability to meet its operating requirements. A **Latent Failure** existing in the background and does not affect the outward functionality of the system. The logic of the system may compensate for the failure or may bypass it as part of normal operation. A **Local Failure** is a failure that has occurred and is isolated to one part of the system and does not contribute to the system's ability to meet its primary requirements. A **Benign Failure** is a failure whose severity is slight enough to be outweighed by the advantages to be gained by normal use of the system. An **Intermittent Failure** may only persist for a limited duration, after which the

[97] Sisterson, Doug; *Draft Fall 1997 Integrated IOP Operations Plan*, Penn State Lidar, Atmospheric Radiation Measurement Program (ARM); 18 September 1997.

system recovers its ability to perform. A **Partial Failure** disables one or more modules of the system, or the system's inability to accomplish one or more system requirements while the remainder of the system remains operable. A **Complete Failure** results in the system's inability to perform any required functions. Finally, a **Cataclysmic Failure** refers to the sudden and complete failure of a system, noted both in time and Consequence Severity.

It is possible to examine system failures in a progressive linear format, as noted by Figure 4. My study introduces a refined format for categorizing and defining software system failures by using a progressive format to cover all extremes of software failure. These formats and definitions benefit the state of the art of software development and software system safety by introducing a more comprehensive terminology for defining possible failures and their relationship within failure types. It is then possible to classify and rate failures against an established scale to better acknowledge their severity, prioritize resources for their correction, and establish possible goals for development.

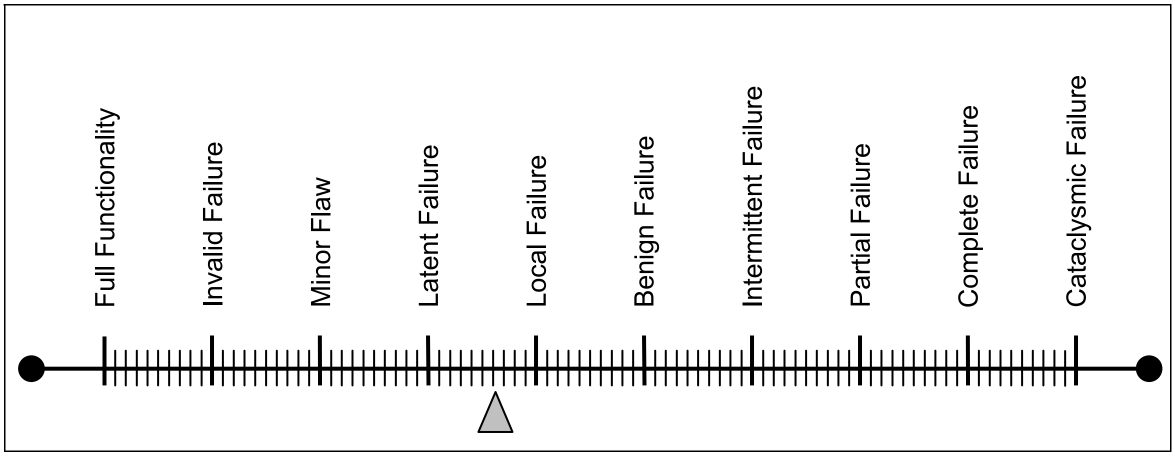

Figure 4 Degrees of Failure

E. STANDARDIZED FOUNDATION OF SOFTWARE SAFETY

1. Software Safety Standards[98]

A variety of technical standards have been introduced in the past decade that delineate proprietary Software Safety philosophies and standards suited to specific disciplines and practices, as well as a number of general standards that outline the basic principles of Software Safety. The development of a metric for Software Safety requires a review and understanding of existing standards as well as their application. This section provides a brief survey of standards, their applicability to Software Safety, the motivation of development, and scope of coverage. This survey is by no means all–inclusive, as the complete list of safety standards is too large to be reviewed in this dissertation. This section includes a review of six safety standards, selected for their prominence and acceptance as valid safety standards, their mandated use in military and governmental systems development, and their applicability as foundations to other standards for the development of high–reliance systems.[99, 100, 101] Additional standards are referenced in APPENDIX D.1 of this dissertation.

a. *AECL CE–1001–STD – Standard for Software Engineering of Safety Critical Software*

CE–1001–STD was developed as a joint project by the Ontario HydroPower Company and the Atomic Energy of Canada Limited (AECL) in 1990 and later revised in 1995.[102] The standard was intended to foster code hazard and requirements analysis for the engineering of real–time protection and safety–critical

[98] *IEEE SESC Software Safety Planning Group Action Plan*, Institute of Electrical and Electronics Engineers, Inc.; 15 October 1996.

[99] *Software System Safety Handbook, A Technical & Managerial Team Approach*, Joint Software System Safety Committee, Joint Services System Safety Panel; December 1999.

[100] *IR 5589, A Study on Hazard Analysis in High Integrity Software Standards and Guidelines*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Computer Systems Laboratory; Gaithersburg, Maryland; January 1995.

[101] *IEEE SESC Software Safety Planning Group Action Plan*, Institute of Electrical and Electronics Engineers, Inc.; 15 October 1996.

[102] *Standard for Software Engineering Safety Critical Software*, Ontario Hydro and the Atomic Energy Canada Limited; Canada; 1990, 1995.

software in nuclear power generating stations. CE–1001–STD was designed to provide methods and standards for the integration testing of independent modules into a larger system.

CE–1001–STD demonstrates the intent of private corporations to generate internal and proprietary standards to meet the specific needs of their organization. The standard covered topics on software development, verification, support, and documentation for nuclear power based software systems. While this standard contains many of the principles of developing safety–critical systems, its format is tailored to the nuclear industry and the specific needs of the Ontario Power Company.

b. NASA–STD–8719.13A – NASA Software Safety Technical Standard

STD–8719.13A was developed as a successor to previous Software Safety standards to provide a methodology for activities required to design software for NASA's safety–critical systems.[103] The standard mandates requirements for projects and project managers to ensure compliance with the procedures and measures outlined to build high–reliance systems.

The standard is broken down into project requirements for the lifecycle phase and phase independent tasks, and for Software Safety analysis. Additional emphasis is placed on quality assurance provisions and system safety definitions. The weak point of the standard is that it only describes safety and the methods for its remedy in great generalities, even to the point of stating "Software safety shall be an integral part of the overall system safety and software development efforts." The standard contains no specific instructions, procedures, or numerical measures that must be taken to evaluate and design a safe system. Rather the standard outlines general steps and references to encourage safety.

[103] *Software Safety NASA Technical Standard, NASA-STD-8719.13A*, National Aeronautics and Space Administration; 15 September 1997.

c. MOD 00–56 – The Procurement of Safety Critical Software in Defence[104] Equipment Part 2: Requirements

MOD 00–56 is part two of a two-part United Kingdom standard for safety–critical software, specifically emphasizing the requirements for hazard analysis and risk reduction, also referred to as "Requirements for Analysis of Safety Critical Hazards", approved in 1989.[105] The standard was created as a requirement specification for the development of defense software systems through the entire lifecycle, from development to disposal. Major portions of the document include General Principles, Management and Associated Documentation, Safety Requirements, System Safety Analysis, Data Management, Test Program, and Work Program.

MOD 00–56 specifically outlines mandatory activities, accident severity categories, probability ranges, risk class definitions, and safety–integrity levels for the development. This clarity in requirement definition leaves no ambiguity to the classification within a Software Safety Assessment. Many other specifications reviewed fail to specify the exact quantifying criteria for determining the safety level of a software system as well as the British model does. The specification outlines Hazard Analysis Activities such as hazard identification, risk analysis, hazard analysis, software classification, change hazard analysis, safety review, and documentation. Requirements and hazards are processed and classified through the use of Fault Tree Analysis and effects and criticality analysis. The MOD concludes with detailed checklists and examples to identify and classify hazards and their safety remedies.

While there are fundamental flaws in the foundations and assumptions of the UK model, the MOD 00–56 serves as a beneficial basis for developing a quantitative and qualitative measure for Software Safety. My study and presentation expands on the groundwork established by MOD 00–56 by formalizing the mathematical products that can be derived from its checklists and taxonomies. MOD 00–56 limits its determination of specific safety levels within the UK standard, leaving the final determination of such a

[104] Note: "Defence" is the British variation of the American spelling of "Defense."

level to the developer or individual making the safety analysis. Following chapters will outline methods to formalize the determination of a software system's safety level by improving on methods for statistically computing Software Safety. These methods are based on inspection and historical knowledge, similar to the inspection methods of MOD 00–56.

d. MIL–STD–882C/D – System Safety Program Requirements / Standard Practice for System Safety

Military Standard 882D is a broad–based defense standard, established to define the requirement for safety engineering and management activities on all systems within the U.S. DoD. This standard provides a uniform set of programmatic requirements for the implementation of Software Safety within the context of the military system safety program.[106] Written in 1993 as MIL–STD–882C and later updated as MIL–STD–882D in 2000,[107] the standard is not exclusive to the Software Engineering and Development discipline but rather to all disciplines of systems engineering development, including mechanical, electrical, and aerospace engineering. It serves as a "what–to–do" guide for software developers and engineers when designing System Safety Programs. 882C can be tailored and modified to fit the specific needs of the required field of development, while the 882D cannot be tailored.

MIL–STD–882D is an encompassing standard that covers every aspect and activity of the system's development and implementation lifecycle, including research, technology development, design, test and evaluation, production, construction, checkout/calibration, operation, maintenance and support, modification and disposal. The standard is broken into varying levels of requirements including General Requirements, Data Requirements, Safety Requirements, and Supplementary Requirements. Additionally, the standard outlines tasks and procedures for assigning risk and margins of safety to an engineering project. Appendix metrics are used to categorize

[105] *MOD 00-56, The Procurement of Safety Critical Software in Defence Equipment Part 2: Requirements*, Ministry of Defence; Glasgow, United Kingdom; 1989.

[106] *MIL STD 882C, System Safety Program Requirements, Software System Safety Handbook*, U.S. Department of Defense; 19 January 1993.

[107] *MIL STD 882D, Standard Practice for System Safety*, U.S. Department of Defense; 20 February 2000.

and quantify system hazards by the severity of potential consequences and the probability of the occurrence.

e. IEC 1508 – Functional Safety: Safety–Related Systems (Draft)[108]

Developed in 1995, by the International Electrotechnical Commission SC65A, IEC 1508 serves as a generic outline for the requirements for the development of safety–related systems.[109] Chapter II.E.1 specifically details the requirements for software based control systems. While the draft 1508 document was later replaced by the meta–standard IEC 61508, it continues to serve as a basis for international standards for the development of high–reliance software and hardware–based systems.

IEC 1508 relies on the development of a safety plan for the description of the safety lifecycle phases and the inter–dependencies between each of them. It is recognized that safety is unique to each module of development, but also that safety is intertwined through each of the subsystems of the product and through each stage of development. While IEC 1508 notes that a safety based Software Architecture is the core for a safety strategy of development, the standard fails to outline or define a specific architecture for such development or to provide any useful guidance in selecting an architecture. 1508 is broken up into a seven–part document to include general development requirements, requirements for electrical/electronics/programmable electronics systems, software requirements, definitions and abbreviations, guidelines for the application of requirements in two parts, and a bibliography of techniques and measures. The goal of 1508 is to ensure that systems are engineered and operated to the standards appropriate to the associated risk.

f. Joint Software System Safety Handbook

Initially written in the fall of 1997 and later revised in December 1999, the Software System Safety Handbook (SSSH / JSSSH) serves as a joint instruction for the

[108] Note: IEC 1508 has later been ratified and published as *IEC 61508, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems - Parts 1-7*, International Electrotechnical Commission, Geneva, Switzerland; 12 May 1997.

consolidation of the multitude of governmental and defense Software Safety standards.[110] The SSSH includes "best practice" submissions from the U.S. Army, Navy. Air Force, Coast Guard, Federal Aviation Administration, National Aeronautics and Space Administration, defense industry contractors, and academia.

The handbook reviews current and antiquated software development methods and safety standards including DoDD 5000.1, DoD 5000.2R, DoT and NASA standards, as well as commercial and international standards of Software Safety Assurance. Additionally, the standard contains an overview of the history of and management responsibilities of Software Safety. The remainder of the text is broken down into introductions of Risk Management and System Safety, Software Safety Engineering, and an extensive set of reference appendices. Appendices include the management of COTS systems in Safety Development, generic requirements and guidelines for Safety Development, worksheets for safety analysis, sample contractual documents, and lessons learned from previous safety mishaps and successes. The standard is designed as a "how to" handbook for the general understanding and implementation of software system safety into the development process. The specific level of safety of a system is still left up to the measurements of the developer and levels acceptable to the client.

g. Standards Conclusions

The number and scope of Software Safety Standards is as varied as the number of potential safety–related failures that can occur in a system. CE–1001–STD is a specialized standard tailored to the Canadian nuclear power industry while NASA–STD–8719.13A is an in–house standard for the National Space Agency. Both standards are equally beneficial within there own scope of application and design, but are limited in their relevance outside of the specific context for which they were developed. Both standards rely on a framework of administrative protocols and procedures to ensure

[109] *IEC 1508, Functional Safety of Electrical / Electronic / Programmable Systems: Generic Aspects*, International Electrotechnical Commission; Geneva, Switzerland; 13 April 1998.

compliance. MOD 00–56 is a governmental Software Safety standard for the Ministry of Defence of the United Kingdom, while MIL–STD–882D is a product of the Department of Defense of the United States. Both standards improve on existing methods and measures for creating a Software Safety Program while taking different approaches on the determination of system's level of safety. IEC 1508 is an international safety standard that includes an extensive review of safety principles and contains a chapter specifically dedicated to Software Safety. Using proprietary standards, national standards, and finally international standard, the DoD has consolidated its efforts to create the Joint Software Safety Standard Handbook. APPENDIX D.1 – Table 19 lists a compiled set of standards and their techniques for identifying and handling Software Safety.

The development of any Software Safety Standard or Safety Metric requires the review of available standards, to serve as a basis or foundation. These standards are themselves based on previous standards, tailored to meet the specific needs of the user agency or client. While these standards provide a basis for developing Software Safety, they do not completely define the measurement of software's level of safety. Using the principles of these and other standards, as well as principles of statistics and probability, this study outlines additional measures for determining the safety of a software system.

2. Traditional Methods to Determine Software Safety

As with Software Safety Standards, there are methods and algorithms that can be used to determine the safety of a system or the probability of failure. Each method is unique in its approach, its product, and in its interpretation of Software Safety as well as many of the methods being proprietarily to specific standards. The key components of a Software Safety Assessment are:

- The identification of hazards.
- The identification of the ability of the system to handle the specific hazard.

[110] *Software System Safety Handbook, A Technical & Managerial Team Approach*, Joint Software System Safety Committee, Joint Services System Safety Panel; December 1999.

- The measurement of probability of the system to prevent the hazard.
- The measurement of the consequence of the hazard.

Based on the defined criteria for a Software Safety Assessment, many existing methods and standards are eliminated. The purpose of a Software Safety Assessment is to evaluate the quantity and level of hazards that exist within the system and to determine the level of mitigation or handling of each hazard's risk. A Software Safety Assessment evaluates all software components capable of creating a hazard under normal operating conditions as well as under extreme and abnormal operating conditions. A Software Safety Assessment includes the testing of all components, modules, and interfaces of the system including COTS / GOTS components incorporated into the system, regardless of the previous success of the testing of the components. A system implies the incorporation of multiple units to make a complete structure. Each component must be evaluated independently, as well the incorporated results of those components.

A product of a Software Safety Assessment includes the identification of corrective actions necessary to eliminate or mitigate the risk of hazards. Optimally testing is conducted throughout the development process to determine the fragility of the system and its increased robustness with each cycle of development. There is a distinct difference between testing a Software System for functionality and testing a Software System for Hazards and Safety. A system may function properly and within the proper bounds it was developed for, but may still execute an action that results in a mishap.

With experience and proper reasoning, it would be possible to derive the probability of failure if:

- The distribution of inputs are known,
- The hazardous situations are known,
- The program logic and code are known, and / or
- There are sufficient resources for making the assessment.

It would be difficult to emulate every possible state environment that the software system could experience in relation to every potential input. As a start, bounding the inputs would limit the field that must be searched. As a second, understanding the logic and code of the system would open some potential for understanding vulnerabilities. Unfortunately, these are only two of the many factors that contribute to an accurate assessment. While it is very difficult to accomplish without adding excessive overhead to the system, the control and bounding of potential system environments would be another level of system design capable of increasing system safety.

The equations and assessment logic would be similar for both large and small system, while the resources required to make the assessment may differ dramatically. Depending on the nature of the system, measurements of runtime frequencies may require an impracticable amount of time if failure frequencies are very low. A judgment and limit must be made of the assessment method to ensure that resources are not grossly expended. Note: The resources for assessment must be balanced against the benefit gained from the assessment and consequential improvements.

a. Coverage Testing

Software Coverage Testing (CT) is the testing of a series of cases and fields with a pass/fail criterion.[111] Coverage is measured by the level and extent of the testing of each case from a scale of 0% to 100%. Examples of Coverage Test cases include the testing of each line of code, the testing of data coverage, and error state handling. APPENDIX D.2 lists over 100 different test cases that apply to software–based systems. Much of CT is considered traditional "White Box Testing" in that the testing is done from a viewpoint from inside the component itself vice from the end user's viewpoint of view. CT can become exponentially time consuming as the goal for a coverage measure increases towards 100%. Many aspects of CT can be automated and executed from compilers and third party software testing tools. CT is not a measure of safety, as it does not regard the hazards of failure but rather the ability for a test to return

[111] Kaner, Cam; *Software Negligence & Testing Coverage*, Software QA Quarterly, vol. 2, num. 2, pg. 18; 1995.

a pass or fail response for a given level of coverage. CT does serve as a measure of functionality and process completeness, inferring an ability of the system to handle and prevent specifically identified failures within the bounds of the testing.

Coverage Testing is widely used in software reliance testing for its ability to certify a system's completeness through the use of system inspection based on defined development and operation points. A score can be given to the certification by summing the number of tests that pass against those that may fail. Such summation scoring of Coverage Testing fails to take into consideration the weight of particular test points or consequence results. These points are addressed with potential correction in this dissertation.

b. Requirements Based Testing (RBT)

Requirements Based Testing is a function of systematically testing the operation of a Software System for compliance within the bounds established by a given set of project development requirements. Requirements can be measured or gauged by their complexity or by the number of functional points generated. Optimally, requirements are established early in the development of the system though they may be revised and refined repeatedly through the development cycle. As requirements are established, they can be verified, measured for complexity, weighted for their effect on the system, and assigned a test case to validate the function of the system within the bounds set by the requirement. The result of RBT is a pass/fail grade for each Requirement or Function Point Test.

The proper function of the system dictates that requirements are well written and validated for completeness as well as they are reasonable and practical to the development of the system. Requirements must be written in such a manner that they lead to the development of a test case and can be validated. If requirements are unclear, incomplete, too general, or not testable they jeopardize the functionality of the system and do not support a test case. NASA stated in its paper on requirements testing metrics that, "There are no published or industry guidelines or standards for these testing metrics—intuitive interpretations, based on experience and supported by project feedback, are used….”[112] Many industry development standards specify unique requirements documentation formats that are proprietary to the standard itself and may not lead directly to test cases, based on their formats. Automated Requirements Management Tools must be refined or developed for each System Requirement Specification (SRS) format or the requirements must be converted to the tool.

Requirements and Function Points are measures that can be obtained early in the development cycle. They provide a textual and mathematical value that can be compared against previous development efforts. Function and Feature Points, coupled with the COCOMO[113] and Putnam[114] methods of software evaluation can provide a subjective estimated measure of the complexity, effort, and cost of the system as well the probability of developmental failure (failure to complete the development), based on a comparison method against known projects.[115]

RBT is not a complete method of Software Safety Testing, as its purpose is to test for the ability to develop the system based on criteria and bounds established in the requirements. RBT must be complimented by additional methods that validate the requirement content for completeness, in conjunction with a comprehensive safety program to provide oversight throughout the development process.

Requirements are function based, while hazards are the product of the function.

Measurements such as the vagueness, imperativeness, continuance, or weak phrases within a requirement's specification do not imply a hazard but impinge

[112] Rosenberg, Linda H., PhD; Hammer, Theodore F.; Huffman, Lenore L.; *Requirements, Testing, & Metrics***,** Software Assurance Technology Center, National Aeronautics and Space Administration; October 1998.

[113] Boehm, Barry; Clark, Bradford; Horowitz, Ellis; Madachy, Ray; Shelby, Richard; Westland, Chris; *Cost Models for Future Software Lifecycle Processes: COCOMO 2.0*, Annals of Software Engineering; 1995.

[114] Putnam, Lawrence H; Myers, Ware; *Measures for Excellence. Reliable Software On Time Within Budget*, Yourdon Press Computing Series; January 1992.

[115] Nogueira de Leon, Juan Carlos; A Formal Model for Risk Assessment in Software Projects, Naval Postgraduate School; Monterey, California; September 2000.

upon the functionality of the system. Lines of text within the requirement are not a measure of safety but of the complexity of the system and the requirements to build. A system may function properly but may still induce a hazard simply by the fact that the system executes a hazardous operation that may be specified by an unsafe set of requirements.

RBT does not completely satisfy the needs of critical system development, as its emphasizes tests of what is known of the system and not of what is unknown. I have included a review of the software product from the point of view of the hazard that the system is designed to prevent, and then work backwards to ensure that requirements satisfy the prevention of their occurrence. Requirements may not consider the consequence of hazard prevention, unless such prevention was the focus of the requirement. Requirements Based Testing only ensures that the requirements were satisfied, regardless of the hazard that may need to be prevented. An outlined method is presented for reviewing the development of the system, through all stages of development of development to ensure that hazards are prevented, to an acceptable level.

c. Software Requirements Hazard Analysis (SRHA)

First introduced in MIL–STD–882B as a 301 Series Task,[116] a Software Requirements Hazard Analysis involves the review of system and software requirements and design in order to identify potentially unsafe modes of operation. This review ensures that system safety requirements have been properly defined against potential hazards, and that safety requirements can be traced from the system requirements to the software requirements; software design; testing specifications; and the operator, user, and diagnostic manuals.[117] Preceding this review must be a hazard analysis that identifies missing, ambiguous, incomplete, or incoherent requirements that are safety related and incorporate them into the system and software specification. The SRCA or SRHA

[116] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; Washington, D.C.; 30 March 1984.

[117] *NISTIR 5589, A Study on Hazard Analysis in High Integrity Software Standards and Guidelines*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Computer Systems Laboratory; Gaithersburg, Maryland; January 1995.

becomes the means of tracking them to resolution. The analysis starts in the system requirements phase of the system lifecycle to include a review of system and software requirements and documentation. Safety recommendations and design and test requirements are incorporated into the development specifications, documentation, test plan, configuration management plan, and project management plan.

Where the Preliminary Hazard Analysis is the first stage, the SRHA is the second stage of system hazard analysis. Upon completion of the SRS a thorough review of the requirements, specifications, and any previously known hazards are completed. The product of this review becomes a part of the system requirement's documentation and is used in conjunction with further test plan development.

The SRHA is subjective in nature and requires an intuitive knowledge of the system and subject matter being developed as well as the foresight to see potential system hazards from the review of a textual product. There is no defined format for the SRHA review report.

Primary values of the report would include known and potential hazards, their triggers, related requirement(s), methods to mitigate the hazard, and test criteria.

This dissertation uses portions of the SRHA philosophy by reviewing the hazards that could result as a consequence of specific requirements by assigning a numeric value to the assessment of specific elements. While the SRHA may be subjective in its review, I introduce methods for formalizing the review to ensure standardizing practices and methodologies.

d. Software Design Hazard Analysis (SDHA)

Design Hazard Analysis is the third in the evolutionary step of Hazard Analysis, following Requirement Hazard Analysis. As with SRHA, SDHA was formalized in MIL–STD–882B as a 302 Series Task.[118] Using the SRHA and its

[118] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; Washington, D.C.; 30 March 1984.

resulting product as input, SDHA involves the identification of safety–critical software components; assessing their degree of risk and relationship to other components, establishing a design methodology, and developing a test plan for validating the component's safety. The SDHA identifies specific software components that relate to the hazard. It also determines software failure modes that could lead to a hazard, identifies the components associated with that failure mode, and finally designates respective elements as safety critical. Based on the assignment of hazards to components, the system can then be reviewed for independence, relationship, or reliance conditions that could propagate the fault or hazard. The analysis starts after the software requirements review and should be near completion before the start of software coding.

Most software, due to its lack of self–awareness, requires some form of external interaction to launch its procedures or to receive its results. Hundreds of interface devices have been developed and are currently being developed that permit human interaction with the software system.[119] Additional devices provide the ability for animal, nature/climatic, or secondary system interaction with a software system. The Design Analysis requires an extensive review of potential interface conflicts and hazards that can be induced by the interaction of external users or systems including those associated with failure modes of the interfacing devices.

Based on the assessment of the component design, changes are then made to the software design document to eliminate and/or mitigate the risk of a hazard or simply to raise the awareness of the programmers who will be designing the component. The SDHA may suggest a unique method of development for different components as the hazard probability and complexity of one component may differ from the next. The assessment may result in a review of the system requirements or simply result in recommendations for design and development.

[119] Myers, Brad A.; *A Brief History of Human Computer Interaction Technology*, ACM interactions. vol. 5, num. 2, pg. 44-54; March 1998.

The SDHA is also subjective in nature as the software product is still in theoretical form. Subject matter expertise on the product as well as on methods of development is required to ensure a thorough analysis.

Where the Software Requirements Hazard Analysis focused on the safety–related hazards of the requirements, the Software Design Hazards Analysis focuses on the design and development of components to satisfy the requirements and avoid hazards. The concepts of the Software Design Hazards Analysis are mirrored in the NASA Safety Manual NPG 8715.3.[120]

There is no defined format for the SDHA review report, while it should follow a similar format chosen for the SRHA. In complement to MIL–STD–882, the DoD created DID DI–SAFT 80101B – System Safety Hazard Report Analysis[121] (SHRA) to describe the data items of a hazard analysis report. The report should include a summary description of the system and its components, their capabilities, limitations, and interdependence as they relate to safety. The analysis should include a listing of:

- Identified hazards,
- Hazard related components, modules, or units,
- Hazard failure mode(s) resulting in the hazard,
- System configuration, event, phase, and description of operation resulting in the hazard,
- Hazard description,
- Hazard identification properties,
- Effects of the hazard,
- Recommended actions,
- Effects of the recommendations, and

[120] *NPG 8715.3, NASA Safety Manual, NASA Procedures and Guidelines*, National Aeronautical and Space Administration; 24 January 2000.

[121] *DI-SAFT-80101B, Data Item Description, System Safety Hazard Analysis Report*, Department of Defense; Washington, D.C.; 31 July 95.

- Notes, cautions, or warnings applicable to the operation of the component and its related hazards.

This study relies heavily on the practices outlined in SDHA. These methods and study improve on the practice by establishing a progression from SRHA to SDHA, establishing a format for the review, and the use of a numerical / textual format for assessing the findings of the SDHA.

e. Code–Level Software Hazard Analysis (CSHA)

Code–level Software Hazard Analysis is a fluid analysis of the source and or object code, the code writing process, and results, as it corresponds to Software Safety. It is one of the most common forms of hazard analysis to test high–risk software or when there exists test anomalies that are not the result of errors in test setup or procedures. The CSHA is an analysis of the software code and system interfaces for events, faults, trends, and conditions that could cause or contribute to a system hazard.[122] The term *fluid* refers to the fact that the software analysis is ongoing through the development of the software code and into the testing phase of development. Most often, the product of code level hazard evaluations result in modifications to the code to ensure the correct implementation of requirements or to improve the ability of the code to handle specific failure conditions. Additional changes may be made to the requirements specifications and software test plan to ensure that the software meets the intended developer and customer.

The Code–Level Safety Hazard Analysis differs from Requirements and Design based analysis in that the Code–Level deals with a tangible product that can be evaluated and manipulated real–time with the evaluation. Previous evaluations could only be done through theoretical methodologies or using simulation tools that replicated the function of the component or requirement. The CSHA examines the code for form, structure, flow, and completeness not previously detected by system compilers. This

[122] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; Washington, D.C.; 30 March 1984.

examination includes inspection for input–output timing, multiple and out–of–sequence events, failure mode handling, and compliance with safety requirements. The evaluation may be subjective as well as objective due to the tangible nature of the software code.

It should be clearly understood that "Lines of Code" is not a measurement of Software Safety.

This dissertation makes only limited use of CSHA due to its narrow application to Software Safety. CSHA is reviewed in this dissertation only due to its popularity as a software development assessment tool, and to its applicability towards Software Safety.

f. Software Change Hazard Analysis (SCHA)

At the completion of a development cycle, software may be re–evaluated for functionality and applicability to requirements and safety concerns. With each change of the software system, new safety concerns are introduced that require identification and evaluation. The Software Change Hazard Analysis is an evaluation of changes, additions, and deletions to the software system and of their impact on safety.[123] SCHA is performed on any changes made to any part of the system, including documentation, to ensure that the change does not induce a new hazard or mitigate the defense against an existing hazard. This hazard analysis is performed at the end of the software development cycle before the commencement of new development.

British Defence Development Standards state that, "If the system, application, or the operating conditions are changed, it cannot be directly inferred that the system will be tolerably safe for use in the new situation. Any changes to the system, its application or its operational environment must be reviewed for possible impact on safety and appropriate steps must be taken to ensure tolerable safety is maintained."[124] It is

[123] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; Washington, D.C.; 30 March 1984.

[124] *MOD 00-56, Safety Management Requirements for Defence Systems, Part 1/Issue 2: Requirements*, Ministry of Defence; Glasgow, United Kingdom; 1989.

essential that each change be evaluated for its impact on the safety of the system and not be taken for granted as a minor modification or improvement.

The SCHA concept was reviewed in the work accomplished by Nogueira de Leon.[125] This dissertation reviews the application of change analysis in the development process by ensuring that a complete review of the software system is accomplished in each iteration cycle.

g. *Petri Nets*

Petri Nets were developed in 1961 by Carl Petri to graphically and mathematically model a distributed system.[126] While Petri Nets were not originally developed to model software systems, they are applicable to all systems requiring modeling of process synchronization, asynchronous events, concurrent operations, and conflicts or resource sharing**.** Petri Nets have been successfully used for concurrent and parallel systems modeling and analysis, communication protocols, performance evaluation and fault–tolerant systems. The system is pictorially modeled using conditions and events represented by state transition diagrams as:[127]

- **States** – Possible conditions represented by circles
- **Transitions** – Events represented by bars or boxes
- **Inputs –** Pre–conditions represented by arrows originating from places and terminating at transitions
- **Outputs –** Post–conditions represented by arrows originating from transitions and terminating at places
- **Tokens –** Indication of true conditions represented by dots

[125] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

[126] *NISTIR 5589, A Study on Hazard Analysis in High Integrity Software Standards and Guidelines*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Computer Systems Laboratory; Gaithersburg, Maryland; January 1995.

[127] *AFISC SSH 1-1, Software System Safety*, Headquarters Air Force Inspection and Safety Center; 05 September 1985.

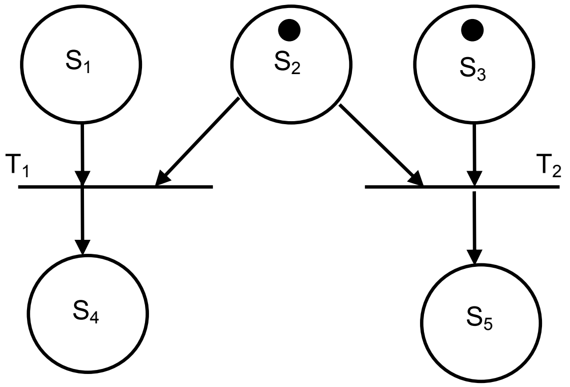

Figure 5 Petri Net Example

As depicted in Figure 5, S_1 is an unpopulated state, while S_2 and S_3 are states with tokens. The tokens permit T_2 to fire while T_1 remains stagnant. The output of S_2 and S_3 transitions through T_2, passing their token on as an input to S_5.

Developed to track the flow and states of a system, Petri Nets can be "executed" to depict how the system will function and flow under certain conditions. Assigning logic conditions to transition points and places permits higher–level modeling and evaluation of the system. The Petri Nets can be used to determine all the states that a system can reach, given an initial set of conditions. Due to the graphical nature of Petri Nets and their ability to portray only a single state in each depiction, Petri Nets can become too large to practically examine all possible states of a system. A Petri analysis can be done for only those portions of the system that present the potential for a hazardous event.[128]

Using mathematical logic statements, Petri Nets can be used to describe structural transition relationships between potential cases via potential steps.[129] By adding an initial state, the description can be modified to describe actual cases and steps. Mathematically, Figure 5 would be depicted as:

[128] Peterson, J. L.; *Petri Net Theory and Modeling of Systems*, Prentice Hall; 1981.

$N = (S, T, F)$
$S = \{S_1,\ldots,S_5\}$
$T = \{T_1, T_2\}$
$F = \{S_1, T_1\}, \{S_2, T_1\}, \{S_2, T_2\}, \{S_3, T_2\}, \{T_1, S_4\}, \{T_2, S_5\}$

Where N is a Petri Net
Where S are States
Where T are Transitions
Where F are Flows

This mathematical notation can be universally understood and applied to any number of proofs and metrics. The notation can also be applied to automated testing software that can dramatically increase the rate of software inspection for potential hazards. The Petri Model can be created early in the development cycle and refined as the program increases in scope and potential hazards are recognized.[130]

This dissertation expands on the benefits of Petri Nets in two ways:

1. By expanding on the benefit of a flow depiction diagram to show the process flow and system interaction of the software system, and

2. The use of a mathematical terminology and method for depicting the process flow.

Each of these techniques is based in the Petri Net methodology, but must be improved and developed to ensure the relationship with high–assurance systems.

[129] Balbo, Gianfranco; Desel, Jorg; Jensen, Kurt; Reisig, Wolfgang; Rozenberg, Grzegorz; Silva, Manuel; *Introductory Tutorial Petri Nets*, 21st International Conference on Application and Theory of Petri Nets, Aarhus, Denmark; 30 June 2000.

[130] Leveson, Nancy G.; Janice L. Stolzy; *Safety Analysis Using Petri Nets*, IEEE Transactions on Software Engineering*,* vol. SE-13, num. 3, Institute of Electrical and Electronics Engineers, Inc.; March 1987.

h. Software Fault Tree Analysis (SFTA)

[131, 132]Fault Tree Analysis has proven extremely successful in identifying faults in a variety of engineering design disciplines,[133] including the fields of aeronautical, electrical, mechanical, and Software Engineering. A Fault Tree Analysis is designed to pictorially model contribution of faults or failures to the top-level event, concentrating on aspects of the system that impact the top event. The Fault Tree depiction provides a flow model through the system to facilitate the identification of points or methods possible to eliminate or mitigate the hazardous event. A SFTA is created from the base or root of the tree by listing all known hazards identified in previous analyses. Once an initial hazard analysis has been completed and hazards identified and plotted, SFTA is worked backwards to discover the possible causes of the hazard. The SFTA is expanded until each branch concludes at its lowest level basic events, which cannot be further analyzed.

The purpose of a SFTA is to demonstrate that the software will not permit a system to reach an unsafe state. It is not necessary to apply the SFTA to the entire system but only to portions that present a risk to system operation or are considered safety–critical. If properly designed, a Fault Tree can reveal when a correct state becomes unsafe and can lead to a failure. The failure can then be traced as it propagates through the system. The use and applicability of Fault Trees is readily understood within the engineering field and easily related to Software Engineering. A SFTA may include symbols such as:

[131] Leveson, Nancy G; and Peter R. Harvey; *Analyzing Software Safety,* IEEE Transactions on Software Engineering , vol. SE-9, num. 5, Institute of Electrical and Electronics Engineers, Inc.; September 1983.

[132] Leveson, N.G.; *Software Safety: Why, What, and How,* Computing Surveys, vol. 18, num. 2, Association for Computing Machinery; June 1986.

[133] *PD-AP-1312, The Team Approach To Fault Tree Analysis*, *Preferred Reliability Practices*, Marshall Space Flight Center (MSFC), National Aeronautical and Space Administration.

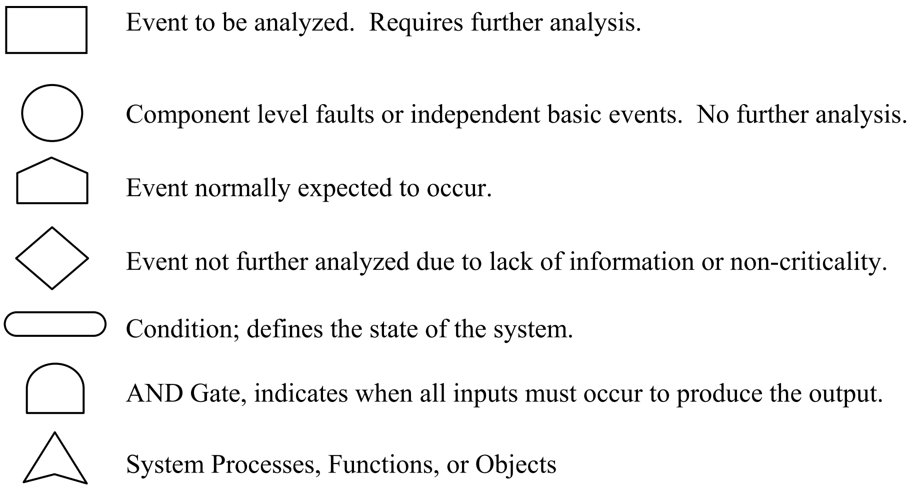
Event to be analyzed. Requires further analysis.
Component level faults or independent basic events. No further analysis.
Event normally expected to occur.
Event not further analyzed due to lack of information or non-criticality.
Condition; defines the state of the system.
AND Gate, indicates when all inputs must occur to produce the output.
System Processes, Functions, or Objects

Figure 6 Fault Tree Symbology[134]

A Fault Tree may be a depiction of the entire system or simply of the sub–system pertaining to the particular hazard being analyzed. A Software Fault Tree (Figure 8) is actually a sub–tree of the greater System Fault Tree (Figure 7) in which a hazard exists that a car can cross a railroad track at the same time when there is a train. The Software Fault Tree examines one of the possible triggers of the hazard, namely the failure of the If–Then–Else Statement. Such a Fault Tree could be further decomposed to illustrate all of the other possible branches of potential hazards and failure propagation.

[134] *NISTIR 5589, A Study on Hazard Analysis in High Integrity Software Standards and Guidelines*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Computer Systems Laboratory; Gaithersburg, Maryland; January 1995.

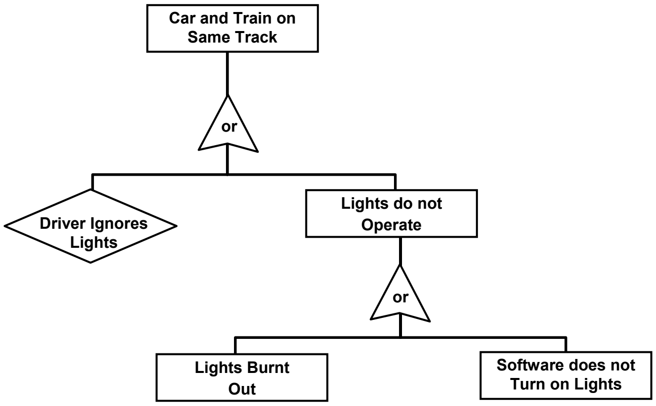

Figure 7 System Fault Tree Example

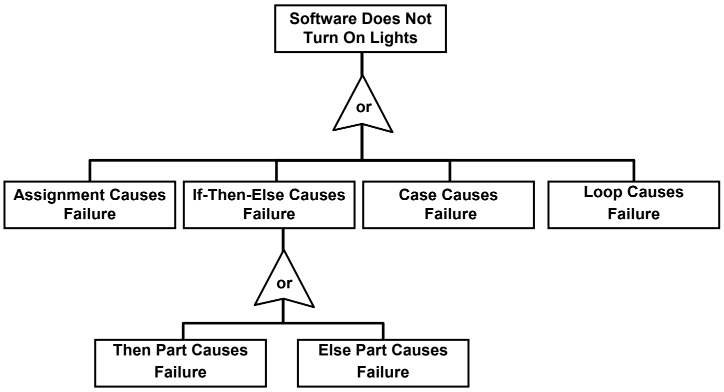

Figure 8 Software Fault Tree Example

Event Tree Analysis, similar to Fault Tree Analysis, is designed using a bottom up approach to model the system.[135, 136] Each root item is an initiating event of the system.[137] Two or more lines are drawn from each root item to the next event to make up the event tree. These lines depict the positive and negative consequences of the event, as well as variable consequences that do not fall within the limits of Boolean expression. The Event Tree is expanded for each subsequent consequence until all

[135] *IEC/TC65A WG9, IEC 65A (Secretariat) 94, 89/33006 DC -(DRAFT) Software for Computers in the Application of Industrial Safety-Related Systems*, British Standards Institution; November 1989.

[136] *IEC/TC65A WG10, 89/33005 DC - (DRAFT) Functional Safety of Programmable Electronic Systems*, British Standards Institution; November 1989.

[137] Raheja, Dev G.; *Assurance Technologies - Principles and Practices*, McGraw-Hill, Inc.; 1991.

consequences are considered. Each branch of the Event Trees can then be used to calculate the probabilities of each consequence to generate a mathematical probability for success or failure.[138]

Based on the analysis of the Fault or Event Tree, decisions can be made to balance the efforts of development against the desired measure of safety. Changes can then be made to the development process to take action to mitigate or eliminate the hazards as desired. Tree Analysis is easy to construct and is aided by a significant number of COTS systems available to developers. Depending on the system, such an analysis may become extremely large and difficult to maintain without some form of automation.[139, 140]

Fault and Event Tree Analysis is designed around depicting the decision process of the system. Analyzing the decisions and directions that a system process flow can make can assist in eventually isolating many system failures. Such isolation is based on the limits and bounds that the system is to operate within. When the developer is able to depict this decision process pictorially, in a standardized fashion, the developer can more effortlessly identify points that require additional protections and controls.

i. Conclusions of the Estimation of Software Safety

Software Safety can be described in two fashions:

1. As a Boolean expression of the software being safe or unsafe, or

2. As a numeric value representative of the probability of safety or the probability of an unsafe action.

To quantify how safe software is or to determine if software is safe requires the identification and analysis of the potential hazards of the system. This

[138] *NUREG-0942, Fault Tree Handbook*, U.S. Nuclear Regulatory Commission; 1981.

[139] Limnious, N; Jeannette, J.P.; *Event Trees and their Treatment on PC Computers*, Reliability Engineering, vol. 18, num. 3; 1987.

[140] Fussel, J.; *Fault Tree Analysis - Concepts and Techniques, Generic Techniques in Reliability Assessment,* Noordhoff Publishing Co., Leyden, Holland; 1976.

portion of the dissertation outlines many of the popular methods and protocols for evaluating the safety of a software system, and defining the differences between testing for functionality and testing for safety. Methods such as Coverage Testing and Requirements Based Testing only examine a system to ensure that it meets a broad list of predetermined criteria. To test for safety requires the specific goal of the test or analysis to identify potential hazards and the triggers that may produce those faults.

Measurements such as COCOMO and Putnam do not determine the safety of a software system but rather determine the level of effort or complexity of a system.[141, 142] Complexity is not a natural result of the COCOMO and Putnam measurements, but an increased effort can infer an increased complexity.[143, 144] Just because a system is complex in its development does not necessarily mean that it will produce a hazard. A system may function in accordance with its stated requirements, but may still execute an action that results in a mishap.

Hazard Analysis is the only previously proposed method to identify hazards through each phase of the development process. Examples include Requirements Hazard, Software Design Hazard, Code–Level Hazard, and Change Hazard Analysis. These hazard analysis methods may incorporate principles of Coverage and Requirements Testing with the exception that their intent is to specifically identify hazards and not functional irregularities. Their validity and applicability in software development is still not completely accepted or integrated into all aspects of critical systems development. Any decision as to which analysis technique would best apply depends on the techniques and abilities of the developers and the system under investigation.

[141] Boehm, Barry; Clark, Bradford; Horowitz, Ellis; Madachy, Ray; Shelby, Richard; Westland, Chris; *Cost Models for Future Software Lifecycle Processes: COCOMO 2.0*, Annals of Software Engineering; 1995.

[142] Putnam, Lawrence H; Myers, Ware; *Measures for Excellence. Reliable Software On Time Within Budget*, Yourdon Press Computing Series; January 1992.

[143] See Chapter II.E.2.b – *Requirements Based Testing (RBT)*

[144] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

Once hazards are identified and analyzed, they can be pictorially displayed using Petri Nets or Fault Tree Analysis methods. These methods give the developer the ability to graphically depict a system, mapping its flow and logic patterns based on variable system cases states, as well as portraying the system in mathematical form. These methods provide the ability to assign weight to the branches of the system, thereby providing a systematic way to estimate the probability of a specific occurrence. This concept will be applied later in the dissertation to develop a metric for assessing and assigning the level of safety of a system.

There are still no valid metrics for measuring the probability of failure in software. Software processes do not fail in a statistically predictable manner (e.g., mean–time–between–failures), they fail as a result of encountering an environment, either input or internal state (or combination) that they are not designed to accommodate. Every time the process encounters that environment, it will fail; therefore, the statistic is a measure of the probability of encountering that environment. If we can predict the environments that will cause the software to fail, we can also design the software to "handle" that environment. Attempts at measuring software failure rates are generally aimed at the entire program. Additional research needs to be done to quantify the probability of failure of a single function, module, or thread through software. The only software reliability metric that has any relationship to safety is reliability trend analysis. As we see the reliability of software improving, it gives us additional confidence (but by no means certainty) that the number of errors in the software have been substantially reduced. However, we still do not know if the remaining errors are in safety–critical functions within the software.

A key part of the Software Systems Safety process is the development of safety–design requirements for the safety–related functions. The purpose of these requirements is to ensure that the safety–related software will not fail as a result of encountering certain conditions, generally failure modes or human errors. We analyze the design of these requirements to ensure that they implement the intent of the requirements vice the letter of the requirements (i.e., we want to ensure that they aren't misinterpreted). We will also develop tests throughout the process to verify that these requirements mitigate the risks we have identified. The purpose in this is to reduce the probability of a hazardous failure in the safety related

> functions to as close to zero as possible. We may therefore specifically design the software to fail in a non–hazardous manner (there goes our reliability). While we can never assume that the probability of a hazardous failure is zero, we can, after careful application of the software systems safety process, justify an assumption that it is acceptably low. That is a qualitative estimate but it's the best we can do due to the nature of software.[145]

F. CONCLUSIONS

As systems become further reliant on software to control their operation and prevent hazardous events, the probability of software related mishaps increase. The most complex of systems may have no probability of hazards, while the simplest of systems may be responsible for preventing the greatest of catastrophes. Take for instance the software that controls and regulates the control rods of a nuclear power plant. Using nothing more then a series of If–Then Statements, the system manipulates the control rods up and down to establish a stable medium within the reactor core. The concept is simple but the repercussions are Earth changing. It is essential that a metric and protocol be developed that can identify hazards, determine their probability of occurrence, and establish the level of safety of a software system.

Current standards and metrics try to standardize the development process into a canned evolution of documentation and reports followed by structured coding and testing. Software is fluid in nature and but still follows the structured rules as other disciplines of engineering. If a bridge is too weak, you can add more structural support but that support will add to the weight of the bridge, thereby adding a new burden to the foundation. While today' software is modular in nature, adding one unit to the system will directly affect the functionality of other dependent components. While a bridge is bounded by the limits of structural engineering, software is only bounded by logic. A standard is required that is fluid in nature and can capture the unique aspects of software and aid in increasing the safety of the system.

[145] Brown, Michael; *Personal Communications related to LCDR Chris Williamson's Research,* Naval Postgraduate School, Monterey, California, 16 March 2004.

Software Safety is not the burden of the software. It is the burden of the developer to ensure that the software is developed in a manner capable of preventing unsafe actions.

Software Safety is not based on the organization of the development group. It is based on the development group's ability to identify and prevent hazards.

Software Safety is not based on a new development method, but rather the refinement and application of existing methods of development.

A structured flow of development is essential to ensure that hazard analyses and Software Safety is part of the development process. Safety Analysis and Identification is critical to the success of Software Safety. A hazard must be identified before the designer can act to mitigate it or a safety analyst can assess the probability of the hazard causing a mishap.

This dissertation proposes a method for identifying system hazards, depicting the process flow of the system as it relates to Software Safety, and the establishment of a method for mathematically depicting the results of the safety analysis. The current state of the art does not define a numeric method for determining the safety of a software system. This dissertation uses portions of the techniques noted in this chapter to develop a method capable of identifying, depicting, and computing the elements of Software Safety based on the established foundation of the current state of the art.

G. CHAPTER ENDNOTES

1. Comparisons of Safety Definitions

DISSERTATION	DICTIONARY[146]	INDUSTRY
Software Flaw: A specific item that detracts from the operation or effectiveness of the software system without resulting in a failure or loss of operability. A software flaw does not result in a failure. A flaw may reduce the aesthetic value of a product, but does not reduce the system's ability to meet development requirements.	**Flaw:** A physical, often concealed imperfection.	**Flaw:** An error of commission, omission, or oversight in an information system (IS) that may allow protection mechanisms to be bypassed.[147]
Software Faults: An imperfection or impairment in the software system that, when triggered, will result in a failure of the system to meet design requirements. A fault is stationary and does not travel through the system.	**Fault: 1.** A weakness: defect. **2.** A mistake: error	**Fault: 1.** An accidental condition that causes a functional unit to fail to perform its required function. **2.** A defect that causes a reproducible or catastrophic malfunction.[148] **Fault:** The preliminary indications that a failure may have occurred.[149]
Reactionary Type Faults: A fault characterized by an inability of the system's logic to react to acceptable values of inputs, as defined in the system requirements.	**Reactionary:** Marked by reaction. **Reaction: 1.** Response to a stimulus. **2.** The state resulting from such a response.	**None**

[146] *The Merriam-Webster's Collegiate Dictionary, Tenth Edition*, Merriam Webster, Incorporated; Springfield, Massachusetts; 1999.

[147] *National Information Systems Security (INFOSEC) Glossary, Rev 1*, NSTISSI num. 4009; January 1999.

[148] *T1.523-2001 American National Standard for Telecommunications - Telecom Glossary 2000*, T1A1 Technical Subcommittee on Performance and Signal Processing; Washington, D.C.; 15 December 2000.

[149] *NASA – STD – 8719.13A, Software Safety, NASA Technical Standard*, National Aeronautics and Space Administration; 15 September 1997.

DISSERTATION	DICTIONARY[146]	INDUSTRY
Handling Type Faults: A fault characterized by an inability of the system's logic to handle erroneous entries or parameters out of the normal bounds of the system.	**Handling:** An act or instance of one that handles something. **Handle:** To direct, execute, or dispose of.	**None**
Software Failure: The state in which a system has failed to execute or function per the defined requirements due to a design fault. Failure is usually the result of an inability to control the triggering of a system fault. Faults can be categorized in one or more of four types, depending on the circumstances leading to the failure and the resulting action. Failures can be further divided into one of two categories based on the source of the failure.	**Failure: 1.** The condition or fact of not achieving the desired end or ends. **2.** The cessation of proper functioning.	**Failure:** The temporary or permanent termination of the ability of an entity to perform its required function.[150] **Failure:** The inability of a computer system to perform its functional requirements, or the departure of software from its intended behavior as specified in the requirements. Failure can also be considered to be the event when either of these occurs, as distinguished from "fault" which is a state. A failure is an event in time. A failure may be due to a physical failure of a hardware component, to activation of a latent design fault, or to an external failure.[151]
Resource Based Failures (RBF): Failures associated with the uncommanded lack of external resources and assets. Resource Based Failures are predominantly externally based to the logic of the system and may or may not be software based.	**Resource: 1.** Something that can be looked to for support or aid. **2.** An accessible supply that can be withdrawn from when necessary.	**None**

[150] *T1.523-2001 American National Standard for Telecommunications - Telecom Glossary 2000*, T1A1 Technical Subcommittee on Performance and Signal Processing, Washington, D.C.; 15 December 2000.

[151] *Computer Science Dictionary*, *Software Engineering Terms*, CRC Press; ver. 4.2; 13 July 1999.

DISSERTATION	DICTIONARY[146]	INDUSTRY
Action Based Failures (ABF): Failures associated with an internal fault and associated triggering actions. Action Based Failures contain logic or software–based faults that can remain dormant until initiated by a single or series of triggering actions or events.	**Action: 1.** The process of acting or doing. **2.** An act or deed.	**None**
Software Malfunctions: A malfunction is the condition wherein the system functions imperfectly or fails to function at all. A malfunction is not defined by the failure itself, but rather by the fact that the system now fails to operate. The term malfunction is a very general term, referring to the operability of the entire system and not to a specific component.	**Malfunction: 1.** To fail to function. **2.** To function abnormally or imperfectly.	**Malfunction:** The inability of a system or component to perform a required function; a failure.[152]
Software Hazards: The potential occurrence of an undesirable action or event that the software based system may execute due to a malfunction or instance of failure.	**Hazard: 1.** A change happening: ACCIDENT. **2.** A chance of being harmed or injured.	**Hazard:** Existing or potential condition that can result in or contribute to a mishap.[153]
Invalid Failure: "A failure that is, but isn't" **(1)** An apparent operation of the primary system that appears as a failure or defect to the user but is actually an intentional design or limitation; **(2)** A developmental shortcoming resulting from the developer not designing the system to the expectations of the user; **(3)** The operation of the system in an environment for which the system was not designed or certified to function.	**Invalid:** not valid: **1.** Being without foundation or force in fact, truth, or law. **2.** Logically inconsequent.	**None**

[152] *Computer Software Dictionary*, ComputerUser.com Inc., Minneapolis, Minnesota; 2002.

[153] *NASA – STD – 8719.13A, Software Safety, NASA Technical Standard*, National Aeronautics and Space Administration; 15 September 1997.

DISSERTATION	DICTIONARY[146]	INDUSTRY
Minor Flaw: A flaw does not cause a failure, does not impair usability, and the desired requirements are easily obtained by working around the defect.	**Minor: 1.** Inferior in importance, size, or degree: comparatively unimportant. **2.** Not serious or involving risk to life <*minor* illness>	**None**
Latent Failure: A failure that has occurred and is present in a part of a system but has not yet contributed to a system failure.	**Latent:** Present and capable of becoming though not now visible, obvious, or active.	**None**
Local Failure: A failure that is present in one part of the system but has not yet contributed to a complete system failure.	**Local: 1.** Characterized by or relating to position in space: having a definite spatial form or location. **2.** Of, relating to, or characteristic of a particular place: not general or widespread: of, relating to, or applicable to part of a whole.	**None**
Benign Failure: A failure whose severity is slight enough to be outweighed by the advantages to be gained by normal use of the system.	**Benign:** Of a mild type or character that does not threaten health or life <a *benign* tumor>: Having no significant effect.	**None**
Intermittent Failure: The failure of an item that persists for a limited duration of time following which the system recovers its ability to perform a required function without being subjected to any action of corrective maintenance, possibly recurrent.	**Intermittent:** Coming and going at intervals: not continuous.	**None**

DISSERTATION	DICTIONARY[146]	INDUSTRY
Partial Failure: The failure of one or more modules of the system, or the system's inability to accomplish one or more system requirements while the rest of the system remains operable.	**Partial:** Of or relating to a part rather than the whole**:** not general or total.	**None**
Complete Failure: A failure that results in the system's inability to perform any required functions, also referred to in military and aviation circles as "Hard Down." Aviators and military members refer to a system that is completely broken and requires extensive repair as "Hard Down", while a working system is referred to as "Up":	**Complete: 1.** Brought to an end as concluded <a *complete* period of time> **2.** Fully carried out as thorough or total and absolute <*complete* silence>	**Complete failure:** A failure that results in the inability of an item to perform all required functions.[154]
Cataclysmic Failure: A sudden failure that results in a complete inability to perform all required functions of an item, referring both to the rate in which the system failed, and to the severity degree of the Mishap that resulted from the failure.	**Cataclysmic:** A momentous and violent event marked by overwhelming upheaval and demolition; *broadly***:** an event that brings great changes.	As **Catastrophic failure:** A sudden failure that results in a complete inability to perform all required functions of an item.[155]

[154] Nesi, P.; *Computer Science Dictionary, Software Engineering Terms*, CRC Press; 13 July 1999, http://hpcn.dsi.unifi.it/~dictionary.

[155] Nesi, P.; *Computer Science Dictionary, Software Engineering Terms*, CRC Press; 13 July 1999, http://hpcn.dsi.unifi.it/~dictionary.

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III. COMMON TRENDS TOWARDS FAILURE

"Software reliability is not identical to safety, but it is certainly a prerequisite."[156]

– J. Dennis Lawrence, Lawrence Livermore Laboratory

As with the quote by Mr. Lawrence, there is a distinct but related difference between safety and reliability, as there is between safety and risk. For the purpose of this dissertation, *reliability* is understood to be the probability that a software system will perform its required function(s) in a specified manner over a given period of time and under specified or assumed conditions. Despite the fact that a system operated reliably over an extended period of time, it is still possible that an unsafe incident could occur if the design elements did not require safe operation. *Safety* is understood to be the measure of probability that a software system will not perform a hazardous event during its normal course of operation. A software system may prevent the occurrence of an unsafe incident, but fail to meet designed system requirements. A supposed synonym to *safety* and *reliability* is the term *correctness* – in that the "system worked correctly." Correctness can be referred to as the combination of the two values, specifically that the software system correctly prevented the occurrence of an unsafe event while performing functional requirements, or to the degree that the system is free from faults in its specifications, designs, and implementations."[157].

In an attempt to outline and catalog the common flaws of software development and employment, this author has found a definite lack of information. Investigation has revealed an almost intentional or deliberate lack of detailed information on the subject of software failure. Many organizations and companies do not detail, make public, or admit their flaws and errors to prevent self–incrimination. In a popular article co–authored with De Marco, Barry Boehm noted a pessimistic and pragmatic view of self–admission by

[156] Lawrence, J. Dennis; *An Overview of Software Safety Standards*, University of California, Computer Safety & Reliability Group, Fission Energy and System Safety Program, Lawrence Livermore National Laboratory; Livermore, California; 01 October 1995.

[157] *IEEE Standard Computer Dictionary, A Compilation of IEEE Standard Computer Glossaries*, Institute of Electrical and Electronics Engineers, New York, New York; 1990.

stating, "doing software risk management makes good sense, but talking about it can expose you to legal liabilities. If a software product fails, the existence of a formal risk plan that acknowledges the possibility of such a failure could complicate and even compromise the producer's legal position."[158]

Previously, much of the information about software failure existed only as investigative reports in the press or in technical reviews about high–profile failures. Many of these reports critiqued and postulated based on the limited facts of the failures. NASA, as a public entity, is required by its charter to report to the American public of its success as well as its failures. In keeping with this charter, NASA recently has taken advantage of the Internet to electronically post all of its proceedings regarding the recent failure of the Mars Explorer Missions. This incident has made available a wealth of knowledge regarding software failure and safety in the government sector. It should be noted that most of the findings of private sector failures are based on second and third party sources, with the exception of those facts directly revealed as legal testimony in a judicial prosecution. This chapter will outline some of the key elements that lead to Software Safety failure, based on the limited facts available.

The development of High Assurance Systems requires a dedicated System Safety process. Software Safety is then compromised whenever the system is developed using unrefined processes, without sufficient supervision, and without a dedicated test and certification plan. Safety is further compromised when the technology lacks the ability to control or prevent a hazardous event. A paper released over a decade ago critical of Software Safety still applies, stating that, "Traditionally, Engineers have approached software if it were an art form. Each programmer has been allowed to have his own style. Criticisms of software structure, clarity, and documentation were dismissed as 'matters of taste.' In the past, engineers were rarely asked to examine a software product and certify that it would be trustworthy. Even in systems that were required to be trustworthy and reliable, software was often regarded as an unimportant component, not requiring special

[158] Boehm, B; De Marco, T; *Software Risk Management, IEEE Software*, Institute of Electrical and Electronics Engineers, Inc.; May-June, 1997.

examination. In recent years, however, manufacturers of a wide variety of equipment have been substituting computers controlled by software for a wide variety of more conventional products. We can no longer treat software as if it were trivial and unimportant. In the older areas of engineering, safety–critical components are inspected and reviewed to assure the design is consistent with the safety requirements… In safety–critical applications we must reject the 'software–as–art–form' approach."[159] Software Safety is not benefited by aesthetic quality but rather by functionality, completeness, and reliability.

After a review of available material, much of it sensitive, it is evident that there are repetitive triggers that contribute to the failure of software systems and the production of unsafe events. These triggers can occur in either or both of the design or implementation stage of a software system's lifecycle. The causes of Software Failure can be generalized into three basic categories:

- That software fails because it is used outside of its developed limits as established by system requirements,
- That software was developed incorrectly in violation of system development requirements, or
- That system requirements were flawed and failed to prevent software failures.

In many cases, system failures were left undiscovered because the software was not sufficiently tested. Each of these categories can be further decomposed into subcategories that detail the specific causes of software failure. In some cases, the symptoms of failure cross over multiple categories and subcategories due to the complexity of the system or failures in design. Software failure and safety violation subcategories include:

[159] Parnes, David Lorge; *Education of Computing Professionals*, IEEE Computer, vol. 23, num. 1, pg. 17-22, Institute of Electrical and Electronics Engineers, Inc.; January 1990.

- Incomplete and Incompatible Software Requirements
  - The Lack of System Requirements Understanding
  - Completeness
- Software Developed Incorrectly
  - Effects of Political Pressure on Development
  - The Lack of System Understanding
  - The Inability to Develop
  - Failures in Leadership in Development
  - Development with a Lack of Resources
- Implementation Induced Failures
  - Software Used Outside of its Limits
  - Over Reliance on the Software System
- Software Not Properly Tested
  - Limited Testing Due to a Lack of Resources
  - Software Not Fully Tested Due to a Lack of Developmental Knowledge
  - Software Not Tested and Assumed to be Safe

Table 4 Software Failure Cause and Effects

A. INCOMPLETE AND INCOMPATIBLE SOFTWARE REQUIREMENTS

Despite the best of intentions and highest standard of software development practices, the existence of improper or incomplete system requirements creates as fruitless a development environment as one that has incapable developers. The development process is founded on the bedrock established by system requirements. Any crack or fissure within that foundation could potentially result in the failure of the system to prevent an unsafe event.

1. The Lack of System Requirements Understanding

When developers fail to understand the proper intended purpose of a system that they are designing, it is possible that system requirements may become incomplete and not provide critical functionality. It is essential that the requirements cover both the obvious as well as obscure functional needs of the system. To ensure that even the most obscure requirement receives proper consideration, the design team must clearly understand all possible idiosyncrasies of the system.

The design of a system requires the thorough understanding of the developers to the system's intended functionality. If a developer might overlook requirements that the user would intend to exist, then the lack of functionality would be tantamount to a programming fault. Where the user might expect a specific reaction from the system in response to an action, the loss of implied functionality might result in any of a series of unanticipated results.

Software Safety is reliant on the system functioning within the bounds and limitations established by the requirements, assuming that the requirements incorporate adequate safety criteria and accurately depict the proper functioning of the system. It is essential to ensure that requirements correctly reflect the needs of the system as well as the anticipated functionality and bounds expected by the user. Chapter V.E.1 of this dissertation will present a method for graphically depicting the process flow of the system which can then be reviewed by users and developers to ensure that critical functions are well understood and agreed upon early in the development process.

2. Completeness

Software functional testing is usually based upon compliance with established system development requirements. In cases where the requirements are incomplete or have holes that could result in unknown functional events, then the reliability and safety of the system is called into question. It should be possible to trace a software process from start to finish; identifying each of the decisions, actions, and interrupts that the process may encounter. It should also be possible to trace the requirements of a system through the entire function of the system, from each expected action and reaction to meet the functional requirements of the system. Failing to trace the functional requirements and ensure validity and inclusiveness can result in a system that is incomplete and prone to developmental failure.

As with a circle, each point on the curve is required to complete the figure, looping a line back around onto itself – from start to finish. This dissertation presents a pictorial process that permits the depiction and assessment of system requirements, as they apply to system safety, to trace the system process from start to functional completeness.

B. SOFTWARE DEVELOPED INCORRECTLY

Many software failures are directly related to the way in which the software system is developed. The environment, methodology, and skill of the developer all factor to determine the ability of the system to prevent failure and the occurrence of a hazardous event. Additionally, the interaction between the developer and the user and between the developer and the domain experts compliment the ability of the system to prevent failures and hazardous events. It has been noted on countless occasions that it costs more to develop a product that fails than it does to develop new theories, test them by experiment and peer review, and then to develop designs based in these theories.[160] The cost of failed development includes the extra costs of redevelopment, repair, and compensation for items damaged due to system failure.

1. Political Pressure

While the Challenger Space Shuttle Disaster of January 28th, 1986 was initially blamed on the design and use of the solid rocket boosters (SRB), further investigation revealed a trail of software errors that failed to prevent the mishap. During pre–launch workups, a decision was made to remove a key set of booster rocket sensors and replace them with a less functional set due to their cost, time for development, and the “importance of the mission”. It was later revealed "there was a decision along the way to economize on the sensors and on their computer interpretation by removing the sensors on the booster rockets. There is speculation that those sensors might have permitted earlier detection of the booster–rocket failure, and possible early separation of the shuttle,

[160] Hoare, C A R; *Algebra and Models*, SIGSOFT'93 Proc of the 1st ACM SIGSOFT Symposium on the Foundations of Software Engineering; 1993.

consequently saving the astronauts. Other shortcuts were also taken so that the team could adhere to an accelerated launch sequence."[161] The Chicago Tribune later reported, "…that poor organization of shuttle operations led to such chronic problems as crucial mission software arrived just before shuttle launches and the constant cannibalization of orbiters for spare parts." Political pressure, media relations, and NASA desire to stimulate public confidence in the space agency resulted in NASA executives making emotional judgments on critical decision points. The compressed launch window, public affairs campaign, and attempt to put the first civilian into space (a schoolteacher) distorted the decision making process and resulted in the modification and removal of critical software components. While these sensors might not have prevented the breakup of the SRB, they could have given the crew sufficient time to react to the failure and prevent the loss of the Space Shuttle and lives of its seven astronauts.

Political pressuring, infighting, empire building, and self–agendas all jeopardize the success of Software Development.

Engineering is not a science that can succeed through impulsive emotions or through compelled deduction.

Engineering requires mental stimulation, bounded within the resources of development, constrained by the ability to certify what is created. Software Development is no different then any other field of engineering, in that it can be distorted by the external pressures of those who portray a desire for success but actually are self–serving in the outcome. External pressures add a component to the development process that falls outside the confines of metrics by adding a variable of human emotion. This variable results in a component that is not designed using acceptable methodologies, to a realistic timeline, or resourced sufficiently; eventually resulting in a system devoid of safety and a threat to the public.

[161] Neumann, Peter G.; *Computer Related Risks*, Addison-Wesley Publishing; 1995.

The Navy's first "Smart Ship" Yorktown has been a direct consequence of the ills of political pressure. The highly publicized software failures of the ship have been directly attributed to decisions and coercions made outside of the development effort. Military leaders insisted that the ship deploy to meet specified timetables, regardless of the objections of senior developers. The ship prematurely set sail with inadequate operating systems and flawed program logic, both chosen and developed under immense political pressure. After an embarrassing failure in which the Yorktown was rendered dead in the water, the Deputy Technical Director of the Fleet Introduction Division of the Aegis Program Executive Office, stated that, "Because of politics, some things are being forced on us that without political pressure we might not do…"[162, 163]

2. The Lack of System Understanding

Professionals have cynically written of the relationship between Software Engineers and customers, stating that, "Either I have to learn enough about what the users do to be able to tell them what they want, or they have to learn enough about computers to tell me."[164]

Today's software systems are required to be more advanced and sophisticated to keep up with the demands and complexities of our modern society. These complexities lead to a breed of software tailored around specialized requirements and unique logic. Software systems have advanced from the basic single purpose systems to the seemingly unbounded application of today's systems. These advances have required new forms and tools for development, new languages and compilers, and an increased knowledge of system operation. When developers do not understand how a system is to function, how the development tools are integrated or utilized, or understand the limits and logic of the requirements, the system is destined for defect and failure. John Whitehouse was quoted, regarding the certification of Software Engineers, that, "It is my contention that the vast

[162] Slabodkin, Gregory, *Software Glitches Leave Navy Smart Ship Dead In The Water*, Government Computer News, Government News; July 13, 1998.

[163] See APPENDIX B.5 -
USS YORKTOWN FAILURE.

majority of software defects are the product of people who lack understanding of what they are doing. These defects present a risk to the public..."[165] A failure to understand the system being designed is a direct hazard to Software Safety.

On March 28th, 1979, the Three Mile Island nuclear power plant experienced a blockage in one of the feed pipes of the reactor cooling system. With the feed pipe blocked, the fuel rods within the reactor core began to increase in temperature from their normal operating limit of 600° to well over 4000°. The thermocouples used to measure the reactor core temperature were limited to only 700°. Above that limit, the instruments were programmed to return a string of question marks in place of the numerical value of the temperature. The reactor system responded correctly by securing turbine operation when the temperature rose above its assigned limit. The safety breakdown occurred when controllers failed to realize the extent of the temperature gain and that it would soon result in a melt down of the nuclear material if it were not controlled. The developers did not realized nor plan for their thermocouples to track temperatures above that 700° mark due to their lack of understanding of nuclear reactor cores and their method of incorporation. The initial trigger of the incident was a human securing the wrong valve. The mishap occurred when the safety system failed to protect the reactor because the developer did not comprehend the system's requirements.[166]

System requirements are not derived arbitrarily.[167]

They do not exist in a vacuum but rather in the open environment with an infinite number of possible stimulations and limitations. "Software development usually begins with an attempt to recognize and understand the user's requirements… Software

[164] Williams, Marian G.; Begg, *Vivienne; Translation between Software Designers & Users*, Comm ACM, vol. 36, num. 4, pg. 102-103; June 1993.

[165] Whitehouse, John H.; *Message regarding Certifying Software Professionals*, ACM SIGSOFT SEN vol. 16, num. 1, pg. 25; January 1991.

[166] Neumann, Peter G.; *Computer Related Risks*, Addison-Wesley Publishing; 1995.

[167] Berzins, Valdis; Luqi; Yehudai, Amiram; *Using Transformations in Specification-Based Prototyping*, IEEE Transcript on Software Engineering, vol. 19, num 5, pg. 436-452, Institute of Electrical and Electronics Engineers, Inc.; May 1993..

developers are always forced to make assumptions about the user's requirements…"[168] Often the user, and in many cases the developer, has an incomplete understanding of how the system should function or how to develop that functionality. The safety of a software system can be directly related to the level of understanding that the developer has of the product being designed. His understanding of requirements and functionality apply to the structure and completeness of the system. Failing to grasp such an understanding results in a system with holes, flaws, and inherent weaknesses. When developers are experienced with and knowledgeable about the technology to be developed, the potential for hazard avoidance is significantly increased.

In November of 2000, Raytheon was forced to explain to the Department of Defense why it was over a year behind schedule producing an upgraded radio communications system for the Northrop Grumman B–2 Stealth Bomber.[169] As the number three U.S. defense contractor and renowned for its ability to produce high–quality communications electronics, Raytheon was awarded a contract to outfit 21 Air Force bombers with a new suite of radios. These radios would allow B–2 crews to receive improved voice, imagery, and targeting data via un–jammable UHF and VHF satellite links. The contract was awarded with the understanding that Raytheon would produce the equipment with little development, instead only improving on the existing system base. During the development, Raytheon made numerous changes to the software design without completely understanding the ramifications and functions of the system or reliant subsystems. Despite Raytheon's previous success, the development process was more difficult and time–consuming than they had forecast. Raytheon continued to attempt to develop the replacement system, rescheduled for delivery by June 2001. Due to the overrun and continued research and development, Raytheon will absorb over $11.2 million in cost overruns.

[168] Tsai, Jeffrey J P; Weigert, Thomas; Jang, Hung-chin; *A Hybrid Knowledge Representation as a Basis of Requirement Specification and Specification Analysis*, IEEE Transcript on Software Engineering, vol. 19, num. 12, pg. 1076-1100, Institute of Electrical and Electronics Engineers, Inc.; December 1992.

[169] Capaccio, Tony; Raytheon Late, *Over Cost in Delivering Radios for B-2,* Bloomberg.com; 28 November 2000.

3. The Inability to Develop

Safety-based software development is the combined function of applied mathematics, logic and reasoning, resource management, science, artistry, aesthetics (See Figure 9). In its nature, the true development of software is an engineering discipline. That discipline is built upon a foundation of proven principles and methods that, when properly applied, give some measure of protection and security to the development process. No principle or method is infallible or guarantees perfection, but what they do provide is guidance and structure compounded upon from previous experience. Today's software systems fail to benefit from historical experience when developers do not utilize, or lack the ability to utilize, such proven methods.

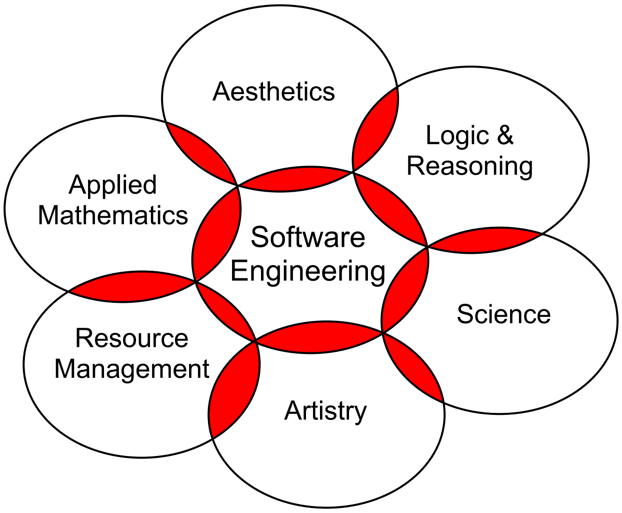

Figure 9 The Composite Pallet of Software Engineering

Leveson & Turner wrote in their analysis and summary of the Therac–25 accidents that, "The mistakes that were made are not unique to this manufacturer but are, unfortunately, fairly common in other safety–critical systems… It is still a common belief that any good engineer can build software, regardless of whether he or she is trained in state–of–the–art software–engineering procedures."[170] Developing software is

[170] Leveson, Nancy G.; Turner, Clark S.; *An Investigation of the Therac-25 Accidents*, IEEE Computer Magazine, vol. 26 num 7 pg. 18-41, Institute of Electrical and Electronics Engineers, Inc.; July 1993.

not a cookie cutter process where one can go from concept, to keyboard, to code and expect a product without the risk of failure.

Safety–critical software demands the developer to utilize methods and procedures that are designed with hazard prevention in mind. Such methods were introduced and reviewed in Chapter II.E of this dissertation. Due to the complexities and non–intuitive nature of some methods, their incorporation may be beyond the level of novice developers and are easily overlooked. Some methods were noted for their lack of specific instruction on how to prevent unsafe events through development; rather, these methods focused on the philosophy of prevention through development practices tailored to specific systems. As noted in the review of predominant safety standards, many lacked a specific methodology for determining the safety of the system, leaving the determination and process to the discretion of the developer.

A system's safety is directly related to the developer's ability to influence his design through the application of these safety philosophies. Historically, a predominant number of software failures can be correlated to a procedural failure to follow accredited methods. This dissertation introduces a method that is not only intuitive to the developer, but is also simplistic and straight forward in its approach. While previous methods expounded on the philosophy of Software Safety, this dissertation outlines a procedure and process for improving Software Safety through standardized assessment and identification of the system process and hazards.

4. Failures in Leadership = Failures in Software

When a system begins to show signs of failure even before the development is complete, the design team is forced to shift from Software Engineers to firefighters. An organization that is "fire fighting" has no ability or resources to actually fix system failures while continuing to maintain their original pace of development. It becomes management's responsibility to intervene and budget resources accordingly to prevent the entire project from collapsing in upon itself. Each member of the development team must have the ability to rely on centralized project leadership to ensure that control is kept on the development of the system. This control is to guarantee that one member's success is not jeopardized by the failure of another member of the team. In the case of "fire fighting," members need to be able to rely on leadership to guide the project through failure resolution and back into production. Leadership has to ensure compliance to the philosophies of Software Safety.

Software Engineering is the delicate balance of numerous disciplines that combine intangible ideas into a tangible product. It becomes the project leadership's task to find equilibrium between these disciplines to ensure that a gross amount of effort is not put towards one theme at the cost of another. Evidence of such mismanagement can be found in systems that have an aesthetically pleasing user interface, yet lack the logic to control user inputs to generate an appropriate output.

Management is forced to make a number of difficult decisions through the process of development. One of those decisions includes the release of a software system before all of the bugs have been detected and corrected. Leadership must decide when enough testing has been accomplished and that any remaining bugs that could be discovered are not significant as to cause an unsafe event. Leadership can be swayed by misinformation and pressure to release a product before it is complete. They may be worried that a competitor will beat them to market, that they will be penalized for delivering a product past deadline, or that other members of the team will be transferred, retired, or seek employment on other projects before completion. When project leadership lacks the tenacity or drive to direct system development, the software project will fail to reach completeness in terms of functionality or safety.

Management can inspire, structure, and encourage great things from developers.[171] Management can not treat the development of software like the making of a device on an assembly line[172] rather it must be treated with the proper care required to inspire intellectual thought. A poor manager may lack leadership skills and berate his

[171] Brady, Sheila; DeMarco, Tom; *Management Aided Software Engineering*, IEEE Software Magazine, vol. 11, num. 6, pg. 25-32, Institute of Electrical and Electronics Engineers, Inc.; November 1994.

[172] Raccoon, L B S; *The Complexity Gap*, ACM SIGSOFT, Software Engineering Notes, vol. 20, num. 3, pg. 37-44; July 95.

developers by accusing them with, "Problems? We do not have problems here. We do not need principles or process or tools. All we need is for you to find a way to make your people work harder and with more devotion to the company."[173] At such point, management becomes part of the problem – lacking leadership, lacking guidance, the project founders, and eventually fails. If it is released at all, the effort required to correct development errors brought on by such a period can potentially destroy all aspects of profitability, without providing any of the necessary system safety assurance.

5. Building With One Less Brick – Resources

Despite their differences in appearance, Software Engineering is not unlike other engineering disciplines in their requirement for developmental and operational resources. The requirement phase of development should outline required resources before actual system production commences. Resources should include, but not be limited to: budget, schedule, personnel, hardware, software, operating system, development and testing tools, and a medium for employing the final product. System development and operation falters or loses its momentum when resources are not adequately identified or provided. This loss of momentum consequently jeopardizes system safety as resources are reallocated from one process to the next in a desperate attempt to keep the system productive. System operation crashes when operational resources are removed or limited beyond the level required for functionality.

A recent Monterey Workshop emphasized the essential requirement for sufficient resources, stating that, "The demand for software has grown far faster then the resources we have to produce it. The result is that desperately needed software is not being developed. Furthermore, the nation needs software that is far more stable, reliable, and powerful then what is being produced today."[174] Today's software systems stress greater demands on system resources by their requirements for specialized operating systems, memory access, and communication media. Resources are not static, but should be

[173] Royce, Winston; *Why Industry Often Says 'No Thanks' to Research*, IEEE Software Magazine, vol. 9, num. 6, pg. 97-99, Institute of Electrical and Electronics Engineers, Inc.; November 1992.

evaluated as dynamic in that they change and grow with the system, can be refined and reduced as the system becomes more efficient, or expands as the system matures. Software safety requires a sufficient reserve of system resources during development and operation or will risk failure when the system surges. These resources must be available through the entire lifecycle of the product, from concept to disposal.

NASA suffered a domino effect of failures during their attempts to visit the planet Mars at the end of the Twentieth Century. The Mars Planetary Projects were some of the first to be developed under the new "Faster, Better, Cheaper" format. Through the postmortem investigation, the NASA Inspector General admitted that FBC lacked the conventional safeguards and management process that protected previous systems. The result was a series of software and hardware systems that were not developed or tested to the level required for deep space flight, stating that, "...missions completed using FBC are outside the strategic management and planning process, and progress toward achieving FBC cannot be measured or reported... NASA has not adequately incorporated strategic human resources management into the Agency's strategic or performance plans. Hence, NASA has not determined the appropriate number of staff or competencies needed to effectively carry out its strategic goals and objectives for its programs, most notably the FBC Mars Program, and may lose core competencies."[175] NASA had redirected monetary and personnel resources from other projects to investigate and repair the Mars program after the loss of the MSP and MCO, resulting in shortfalls in development of the follow on and subsequent failure of the MPL.[176] Reliability, and consequently safety, cannot be assured when developers lack the resources required to produce and operate safety–critical software systems.

[174] *Proceedings of the 2000 Monterey Workshop on Modeling Software System Structures in a Fast Moving Scenario*, Santa Margherita Ligure, Italy; June 2000.

[175] NASA, Office of the Inspector General, *Faster, Better, Cheaper: Policy, Strategic Planning, and Human Resource Alignment Report Number IG-01-009*, National Aeronautics and Space Administration; 13 March 2001.

C. IMPLEMENTATION INDUCED FAILURES

The most likely time that a Software System could result in an unsafe incident is during its implementation or execution phase. While a Software System is in the development phase, failures are contained and systems are rarely coupled with the material required to cause a hazardous event. Once the system is taken out of the production environment and distributed, it is then matched with the components and substances that it is designed to control. The same failure that was a benign event in the laboratory now becomes a critical event with direct exposure to the public.

1. Software Used Outside of Its Limits

Many software systems are developed "near–flawless" in their initial release. This initial release is likely based on a first generation set of requirements which may not take into consideration all of the intricate facets of the potential software system. These requirements, when satisfied, result in an initially "acceptable product". As long as the product is used in the same fashion for which it was initially developed and certified, it should continue to function as per the system development requirements. It is when the system is pushed beyond the intended functional envelope or incorporated into a subsystem for which it was not designed; that the system begins to function improperly with higher frequency and eventually fails.

When requirements are not fully investigated to cover all potential uses of the system, when the system is not constrained to operate within the defined requirements, or when the system is forced to operate outside of the intended scope of the design, no certification can be given for the successful operation of the system. Users may make general assumptions of the system's operational limits on their experience with previous systems.

[176] *Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board Report*, National Aeronautics and Space Administration and Jet Propulsion Laboratory; Washington D.C.; 28 March 2000.

Testing may not reveal all of the potential hazards of the system's operational scope as most testing methods are designed to ensure requirement satisfaction. Testing must be conducted to the negative satisfaction of requirements, in that a system's operational test is conducted to determine what would happen should the software function outside of its limits or if that limit is capable of being exceeded.

Such failures can be directly attributed to shortcomings in the software system's requirements. Had the requirements been developed to properly constrain the system the potential for such a failure would be reduced. Documentation should include the proper limits of system's operation as well as the controls that ensure these limits. Should a hazard result if a system were to be used outside of its limitations, documentation should include the potential effects. Today's systems may not include such dire predictions, as the developer may fear such revelations might deter the marketing effort.

Take for example the Patriot Missile Defense Failure that left 28 U.S. military members dead and another 98 wounded when the system failed to track and intercept an incoming Iraqi Scud Missile.[177] The Patriot Missile system was initially designed as a Surface to Air Missile (SAM) intended to intercept and destroy sub and super–sonic aircraft. In 1990–1991, during Operation Desert Storm, the U.S. military deployed the Patriot as an Anti–Missile Defense shield to counter the ballistic missile threat of the Iraqi Scud Missile. In addition to the Patriot being initially designed to track and destroy targets within the profile of an aircraft, it was also intended to be online only momentarily to engage such a target. During the Gulf War, the deployed Patriot Batteries were left online continuously to be ready to strike at any incoming target.

Investigation later revealed that the speed of the incoming Scud missiles, ballistically falling at over mach 6, compounded with a system induced mathematically rounding error resulted in an inability for the Patriot to engage Scud targets. For each moment the system was left online, the rounding error increased the system's bias outside

[177] See: APPENDIX B.4 –
PATRIOT MISSILE FAILS TO ENGAGE SCUD MISSILES IN DHAHRAN

the targeting tolerance. By the end of the Gulf War, the Patriot's success rate was less then 9%. On February 25th 1991, one such Iraqi Scud Missile penetrated the Patriot Missile shield and detonated on a military barrack in Dhahran, Saudi Arabia resulting in the greatest loss of human life from a single event during the conflict.

When the Patriot system was deployed as an Anti–Missile Defense shield, the context of the deployment was different then that for which the system was tested and certified. The set of potential hazards increased by the addition of new threats that the system was to protect against, namely the protection of allied service members against a missile threat. The consequence of the potential hazards ranged from minor damage from falling debris to a direct missile strike. Previously identified anti–aircraft missile defense threats can be included from previous assessments. The triggers that could induce a system failure already existed in the system prior to its employment but went undiscovered. In the new context for which the system was employed, the probability that an existing trigger could induce a failure increased with each minute the system was left on line.

During the system development requirement phase, a software system's requirements might include:

- Assumptions about the system's environment,
- Functional capabilities required to control the system,
- Algorithms or mathematical logic required to control the system,
- Operating limitations or acceptable envelopes for operation,
- Internal software tests and checks,
- Error and interrupt handling,
- Fault detection, tolerance, and recovery characteristics,
- Safety requirements, and
- Timing and memory requirements.

When a system is pushed beyond the limits for which it was initially designed, its reactions can become unpredictable, chaotic, and even dangerous. Algorithms and logic that relied on predetermined baselines and limits are now faced with stimuli outside of the bounds for which they were developed. System tests and checks may fail outright and render the system inoperable, despite what the user may feel is a normal operating regime. Error handlers may be bypassed and overridden. Memory may fail and safety restraints may become ineffective.

On December 31, 1999, the world sat and waited for what may be called the greatest computer-induced disaster in the world as clocks rolled over to the new millennium. Hundreds of thousands of computer systems performed computations based on a two–digit year format and were potentially unable to comprehend the change from 1999 to 2000 to equate to one year. Many systems were designed with the intent to function for only a short number of years, expiring well before the end of the century. Evidently these systems outlived their projected lives and now forced the user to either test the system for the "Y2K Bug", have faith that the system would not fail on New Year's Day, or purchase a new product that would be developed in a compatible format. The Millennium Scare affected systems ranging from medical, to military, to public infrastructure. On January 1st, 2000, after a worldwide testing and verification campaign, only sporadic failures were recorded. Despite the small number of failures that were recorded, the total losses directly attributed to the Y2K Bug ranged in the hundreds of millions of dollars. The indirect costs are beyond computation.[178]

From a safety aspect, the potential for a serious hazardous event due to the Y2K Bug was significantly increased due to the fact that:

- Obsolete software systems were used to manage safety–critical systems.
- There was no existing list of components or systems that were identified as compliant of non–compliant at the time of development.
- Some software systems could not be tested without a risk to the critical systems that they controlled.

[178] Neumann, Peter G.; Moderator, *Risks-List: Forum on Risks to the Public in Computers and Related Systems*, Risks-Forum Digest, ACM Committee on Computers and Public Policy; 2001.

- If a system was deemed non–compliant, present–day system developers were no longer qualified or trained to work in early generation languages.
- Changes to the software system had the potential of introducing new faults that may not be detected in time, due to the fixed deployment date.
- Software customers with limited budgets might be unable to afford the expense of testing, repair, or replacement.

The symptoms that affected the software industry due to the Y2K Bug are synonymous with any system that might be employed in a fashion that was never intended. This includes systems utilized outside of their normal operating envelope or systems that become so obsolete that existing operating envelope no longer applies.

To prevent the hazardous operation of a software system outside of its limits, developers must include:

- Requirements with sufficient detail to specify proper system operational limits,
- Direct controls capable of constraining system operation,
- Documentation specifying the proper operational limits of the system, and
- Documentation specifying the potential hazards of system operation outside of specified limits.

2. User Over–Reliance on the Software System

Most safety–critical software systems can be categorized as either active or reactive systems:

- ***Active Software Safety System*** – Directly controls some hazardous function or safety–critical system operation, to ensure that the operation of that system remains within some acceptable bound.

- ***Reactive Software Safety System*** – Reacts to the operation of a hazardous function or safety–critical system, to react when the operation falls outside of some predetermined and acceptable bounds.

These two terms are introduced in this dissertation to classify Software Safety systems by the method in which they handle or control hazardous operations.

The requirements of system operation directly affect the type for which the system may be categorized into. One system reacts to prevent a hazardous event while the other reacts to the occurrence of a hazardous event. It is important that system users understand the difference between the two types as well as which type their particular system is. When users do not understand the basic functionality of the system that they operate, it becomes the system that runs the user instead of the user that runs the system. When the user does not understand the operation of the system and removes himself as a sanity check to its operation, he becomes an additional fault within the system should it fail. Such is the same consequence when the user places too much reliance on the operation of the system.

On March 23rd, 1989 the 986–foot long supertanker Exxon Valdez ran aground on Bligh Reef, a charted natural obstruction, outside of its shipping lane in Alaska's Prince William Sound, resulting in the largest domestic oil spill in the United States' history. Investigation revealed a series of seamanship errors and lapses in judgment including the intoxication of the captain, the fatigued deck crew, and the over reliance on a navigation system. During the final moments of the Exxon Valdez's passage from the Trans Alaskan Pipeline into the Prince William Sound, the deck crew assumed the navigation computer and autopilot would guide the vessel around any possible hazards and keep them inline with rules of the road. As the supertanker failed to make its departure turn, the exhausted helmsman made fruitless rudder corrections using the helm's manual wheel. The autopilot system did not disengage and consequently locked out the helmsman's inputs.[179] Fatigue and a lack of systems comprehension led the crew to not understand the limitations of the navigation computer or even how to disengage it when required. System checks verified that the navigation system had performed as designed and had followed the pre–programmed track. The Exxon Valdez spilt over 10.8 million gallons of oil or approximately 1/5th of its cargo. The spill cost the Exxon Corporation over $1 billion in criminal pleas, restitution, and civil settlements, and an additional $2.1 billion for cleanup and recovery.[180, 181]

Some software users have a tendency of becoming over reliant on their control systems without understanding the limitations of these systems or the consequences of their actions. The complexities of today's operations require automation systems controlled by countless microprocessors and software based logic systems. Their operation is beyond the comprehension of most users. For example, many users do not understand the intricate functions of today's dishwasher with its multiple cycles, temperature controls, filters, heaters, and water conservation mechanisms; but will blindly put in dishes, silverware, and soap into the machine and expect everything to come out spotless by simply pushing the ***START*** button. Many users do not even open the operator's manual to personal or workplace related operating systems, yet still expect them to function intuitively.

[179] Neumann, Peter G.; *Computer Related Risks*, Addison-Wesley Publishing; 1995.

[180] The Exxon plea was broken down into a Criminal Plea Agreement of $150 million with $125 million forgiven for cooperation, a Criminal Restitution of $100 million, and a Civil Settlement of $900 million.

[181] *The Exxon Valdez 10 Year Report*, The Exxon Valdez Oil Spill Trustee Council, Anchorage, AK; 1999.

D. SOFTWARE NOT PROPERLY TESTED

Testing has the potential to demonstrate the inaccuracies and frailties in a system, as far as testing is executed properly. Some tests evaluate the behavior of the system (Functionality) while other tests evaluate the consequences of behavior (Safety). It is the assertion of this dissertation, that the occurrence of software based hazardous events is primarily a result of a failure in this testing. Depending on the method of testing, there is no guarantee that there can be an accurate certification on the safety of the system. Edsger Dijkstra is noted for stating that testing proves that a program is free of mistakes, but cannot prove its correctness.[182]

Testing failures include systems that are either not sufficiently tested or testing determined the probability of such hazards occurring were insignificant. If done properly, despite its design, software can be inspected and given some level of functional assurance during and at the completion of development. The dilemma is to determine the level of testing to be done, the manner of testing, and when testing has been determined sufficient. System testing is the final process in the development cycle that permits the recognition and identification of system weaknesses and vulnerabilities. Each of those weaknesses has the potential for an unplanned event. The significance and consequence of that event determines how unsafe that action will be.

1. Limited Testing Due to a Lack of Resources

Software Safety Testing requires the availability of specialized software, hardware, and trained personnel who are equipped and able to diagnose critical systems. These tools and techniques are neither inexpensive nor simplistic to master. Software industry experts estimate that the United States government had budgeted over $30 billion for the testing and conversion of non–compliant Y2K systems. Further estimates predicted that Fortune 500 corporations set aside between $20 million and $200 million

[182] Attributed to Edsger Wybe Dijkstra, Ian Sommerville, *Software Engineering (6th Ed.)*, Addison-Wesley, University of Lancaster; United Kingdom; 2001.

for the same effort.[183] For companies unable to afford such a price, software users risked significant corporate losses, the threat of litigation, and even the risk to public safety by not validating or turning over their software inventory. Software owners were overburdened with determining which software and hardware would be affected. If identified, a decision would have to be made to repair or replace the software. Either decision would require a new series of testing and re–integration of the product to ensure that new vulnerabilities were not introduced into the system. The cost in time, monetary, and physical resources was prohibitive to many users and developers.

The lack of dedicated testing resources directly affects the economic and personnel safety of the public at large. The extra expense of time, specialized software, and trained personnel to test and validate software must be weighed against the potential damage. Optimally, a system would be stress tested in an environment normally in excess of its rated capacities, conceivably in excess of 150% of its required level.[184] This extra expense requires an outlay of resources beyond that which many organizations are prepared to spend. In 1998, the Federation of American Scientists noted in their failure study of the Theater High Altitude Area Defense System (THAAD) that the lack of testing resources played a critical role in the failed development of the missile system. Specifically noted was the lack of sufficient testing timelines, management practices, test facilities, targets, and post production funding.[185] The THAAD Development Team plans for the first operational missile to be deployed in 2007 from the Lockheed Martin Missile and Fire Control Plant in Pike County, Alabama.[186] The project currently has an estimated cost of over $14.4 billion for 1422 missiles and support equipment.[187]

[183] Kuharich, Mark; *How I Stopped Worrying and Learned to Love The Year-2000 Bug*, The Software View, Amazon.com; 2000.

[184] *16 Critical Software Practices*, Software Program Managers Network, Integrated Computer Engineering, Inc.; 2001.

[185] *Report of the Panel on Reducing Risk in Ballistic Missile Defense Flight Test Programs*, Federation of American Scientist; 27 February 1998.

[186] *THAAD Manufacturing Site Detected*, Anti-Missile Defense, Janes' Missiles and Rockets, Janes' Information Group; 01 March 2001.

[187] *Lockheed Martin Army Theater High Altitude Area Defense (THAAD) System, Static and Towed Surface to Air Missile Systems*, USA, Janes' Information Group; 26 January 2000.

One of the most valuable resources in software development is time. Many testing methods require a significant amount of time to investigate all of the potential states for each requirement. As system complexity increases, the number of potential states can increase exponentially. Testers have to make a reasonable threshold assumption that they have tested "enough," and then certify the effort complete. An exhaustive testing of all possible states may be unfeasible, limited by time or technology. This assumption of satisfactory testing could very well lead to a false impression of the operation of the software system. The certification of software performance must take into consideration the resources available for the test method, the formal process utilized, and the potential impressions that could be given for the test.[188]

2. Software Not Fully Tested Due to a Lack of Developmental Knowledge

NASA stated its development philosophy best to:

> Know what you build.
> Test what you build.
> Test what you fly.
> Test like you fly.[189]

Testing is more then the plugging in of specified values to receive specific results. It is the effort to find "bugs" within the system. Hazard avoidance requires finding the important bugs – finding the bugs that will kill the system; the one–in–a–million instance that is not in the requirements; the bug that will create an out of control event that will kill or maim someone else. Finding that one–in–a–million bug requires more then an understanding of software development but rather the understanding of the type of system that is being built.

Developers, many times, are hired to build software systems based on their history of project success. This decision though, may or not be based on their

[188] Attributed to Edsger Wybe Dijkstra, Ian Sommerville, *Software Engineering (6th Ed.)*, Addison-Wesley, University of Lancaster; United Kingdom; 2001.

[189] *Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board*, National Aeronautics and Space Administration; 13 March 2000.

understanding of the subject matter. To bolster an organization's knowledge base, developers hire subject matter experts who then may not be familiar with of software development. Finally, developers employ a testing wing with a methodical approach to analysis, but may lack experience in employing the application in its natural environment. The result is the combination of three very talented groups of people who do not speak the same language nor follow the same philosophy for development.

Engineering is the understanding of an initially unclear situation and selecting the best process to accomplish it.[190, 191] The result of this misunderstanding has been reflected in the many Department of Defense system failures. Currently, the agency is plagued by a lack of continuity between written requirement, developer's interpretation, tester's assumption of functionality, the assurance of safety, and the reality of field deployment. Many systems cannot be tested on deployed units. National security requires these units to be available for critical tasking. Core users deployed worldwide are not available for developmental testing and critique. Subject matter experts are only as current as their last day of military service. When it comes time for system testing, the knowledge breakdown and limitations result in a product that is never pushed to real–world limits. We have proven in blood that the military battlefield is not the place to conduct "field tests" of unproven equipment.

In the early 1980's, Hitachi suffered from a pattern of failed projects and declining revenue. In 1981, the company recorded over 1,000 product–related faults at customer sites. Hitachi reviewed its development process and made a series of simplistic changes including the review of its analysis, design, code, and test process;[192] the training of its consultants in basic Software Engineering principles; and refreshing its Software Engineers on the fundamentals of existing system. Management believed that, "We learn

[190] Dasgupta, Subrata; *Design Theory and Computer Science: Processes and Methodology of Computer Systems Design*, Cambridge University Press; New York, New York; 1991.

[191] Ramesh, Balasubramaniam; Dhar, Vasant; *Supporting Systems Development by Capturing Deliberations During Requirements Engineering*, IEEE Transcripts of Software Engineering, pg. 498-510, Institute of Electrical and Electronics Engineers, Inc.; June 1992.

some things from success, but a lot more from failure," and that "If you detect too many faults reconsider design regulations, procedures, and management policies." Using hindsight, proven testing, and development methods, Hitachi made a dramatic 98% reduction in its customer failure rate. Quality assurance was improved by pairing the knowledge base with the product, resulting in a staff that knew what it was developing and understand how to test it to the client's requirements.

3. Software Not Tested and Assumed to Be Safe

On June 4th, 1996, $500 Million of uninsured satellites were destroyed when their delivery platform, an Ariane 5 Space Launch Vehicle, was command destructed soon after leaving its launch platform.[193] The Ariane 5 rocket was on its maiden launch as the upgrade to the existing Ariane 4 Launch Vehicle. Moments after liftoff, a software based navigation unit that was certified for flight on the original Ariane 4 version failed from its incorporation with version 5. The legacy 16–bit Inertial Reference System (IRS) had received an incompatible signal from an optimized 64–bit On–Board Computer (OBC), resulting in an unexpected Operand Error Failure. The IRS had functioned flawlessly on previous version 4 events, and was designed to secure its operation 40 seconds after vehicle liftoff. Due to the increased liftoff velocity of version 5 and the upgraded processing speed of the OBC, the IRS received mathematical bias values never before experienced in version 4. Upon failure of the IRS, the rocket lost horizontal alignment control and rolled out of control until it was destroyed. The 16–bit IRS was never tested using simulated inputs from the 64–bit OBC in an after launch environment because it was felt that the IRS's success in version 4 met the functional requirements and quality assurance for version 5.

Developers of the Ariane Rocket and others products have made costly assumptions by presuming their systems were faultless and hazard free by:

[192] Onoma, Akira K.; Yamaura, Tsuneo; *Practical Steps Toward Quality Development*, IEEE Software Magazine, vol. 12, num. 5, pg. 68-77, Institute of Electrical and Electronics Engineers, Inc.; September 1995.

[193] See APPENDIX B.1 – *ARIANE 5 FLIGHT 501 FAILURE*

- The environment and method in which they were designed in,
- The fact that the system functioned flawlessly in a previous environment, and
- The fact that the system did not appear to be related to any critical components.

The assumption or appearance of safety in no way outweighs the potential for system risk. Operational failures typically are caused by poor design and implementation, inadequate checkout discipline, and pressures to move on to the next step. Overlooking, short cutting, or bypassing the testing process results in a system that is simply unsafe.

In 1995, the Intel Corporation distributed its Pentium II Processor with an embedded division fault due to a production based software error. The division algorithm was missing only 5 values from its 1066–point look up table, the result of a "FOR–DO LOOP" error during loading. The look up table was never verified. Once the logic was committed to silicon, the error could not be repaired. One software fault led to the creation of another software fault encoded into hardware. This encoded fault would inaccurately compute floating–point divisions to the 4th decimal point. While seemingly insignificant, this fault would compound into in accurate mathematical products for some spreadsheet, sciences, and control software systems that require results to a high degree of accuracy. The microprocessors could not be reprogrammed and no acceptable software patch could handle the error. Intel spent over $400 Million to repair or replace its flawed Pentium II product line.

One cannot assume a system to be safe simply based on requirement satisfaction. As previously discussed in the Section III.C.1 of this chapter, most systems are evaluated based on methods of Requirements Based Testing. These tests are pass/fail conditions designed to determine the system ability to meet defined requirements, assuming complete requirements. Proper operation is assumed should the system satisfy development requirements. This method of testing may not reveal all of the potential hazards of the system's operational scope, limited by the extent of the testing method. Testing must be conducted to the negative satisfaction of requirements, in that a system's operational test is conducted to determine what would happen should the software function outside of its limits or if that limit is capable of being exceeded.

E. CONCLUSIONS

Software Safety Assurance is a very fragile undertaking. It is not chaotic, but structured.[194] It requires discipline and compliance to accepted methods of development and operation. Newspapers, technical journals, and field periodicals each note multiple accounts of Software Safety failures, their faults, triggers, and hazardous results. The majority of these failures in Software Safety can be defined within specific categories and subsequent subcategories. It is less important to try to define a product within a category then it is to attempt to prevent it from failing in the first place. By example, each of these failures posed a direct threat to the health, safety, and economy of the public. Their successes go unnoticed, while their failures become national headlines.

It is possible to measure the depth of each failure in terms of loss either monetarily, time, or human life. The prevention of each of these incidents or the reduction of any measure corresponds to an increase in safety. At present, the measurement of safety is arbitrary and without scale. Would the Exxon Valdez accident been twice as safe if it had spilt half as much oil? Would the Hitachi have been three times as successful if it had reduced two–thirds of its customer–based failures? It is important to base the measurement of safety on the success of a system and the ability to reduce the likelihood of any hazardous event. This measurement should be based on the lessons learned from the previous eleven subcategories and their examples. Software Development is based on logic and patterns. If it is possible to identify those patterns and modify them, then it is possible to develop safer software.

[194] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

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IV. CONCEPTUAL FRAMEWORK AND DEVELOPMENT

"Computer programming has invigorated the study of formal systems, not just because a proper formalization is a prerequisite of any implementation, but because good formalisms can be very effective in understanding and assisting the process of developing programs." [195]

– *Roland Backhouse*

Virtually every activity in life involves some level or chance or risk. There is little dispute that the chance of a flipped coin coming up "heads" is 50:50 or that the odds of rolling a pair of sixes is 1:36.[196] The odds of selecting the correct number on a spinning roulette wheel are 1:38, while the payoff is only 36 times the placed bet, giving the house a five percent advantage on each spin of the wheel.[197] Further, it is mathematically possible to determine the likelihood of dealing a *Royal Flush* as 1:649,739 or $1.5391x10^{-6}$.[198] The payoff or risk depends on the skill of the opponent and the money played to the pot.

The world is filled with a multitude of events containing risks, probabilities, and profits that can be computed, depicted, evaluated, and displayed. Measures, based on mathematic principles of statistics and probability, can be used to derive the occurrence value of even the most complex event. The occurrence of software–based events is no more immune from mathematic measurement then any other logic based process. The requirement is to determine which properties can be measured, what the resultant value scale will measured against, and the ability to have an affect on the measure. When casinos and crooked gamblers of the American Wild West wanted to increase their winning margin, they used loaded dice, marked cards, and roulette brakes. By careful

[195] Backhouse, Roland; Chisholm, Paul; Malcolm, Grant; Saaman, Erik; *Do-it-yourself Type Theory, Formal Aspects*, Computer, vol. 1, num. 1, pg. 19-84; January - March 1989.

[196] Assuming a single roll of two six-sided dice.

[197] Assuming a 38-compartment roulette wheel numbered 1 to 36, plus additional slots of 0 and 00.

[198] Assuming a 52-card deck, being dealt from poker, a royal flush of five cards: an ace, king, queen, jack, and ten of the same suit. 4 / (52! / ((52-5)! * 5!)) = 1/649,740. Packel, E. W.; The Mathematics of Games and Gambling, Mathematics Association of America; Washington, D.C.; 1981.

analysis and developmental management, it is possible to “load” a software program to influence the corresponding probability of safety.

Software Safety Development and Assurance is the field of Software Engineering that institutes methods of safety to produce a more stable product, capable of avoiding or mitigating hazardous events. The philosophies of Software Safety Assurance can be pictorially and mathematically depicted once a decomposition is made of the methods of development, as they apply to safety. Chapter I presents an introduction to the dissertation and delineated a set of variables that could be quantified and qualified through Safety Development. Chapter II outlines the current discipline of Software Safety Assurance including motivations for development, an anatomy of failure, and current Safety Methods. Chapter III discusses the prime causes of failure and specific examples of which will serve as a basis for triggers or objects in the Safety Metric. Chapter IV outlines the conceptual framework for Software Safety Assurance, Safety Metrics, and Safety Depiction.

Despite significant efforts, this dissertation’s literature search has failed to discover a previously developed software metric that could define safety in a quantitative or qualitative format. Subject matter literatures used in this dissertation topic are listed in the reference sections of this dissertation. Additionally, the literature search has failed to find an acceptable pictorial depiction that could demonstrate software functionality as it applies to Software Safety. It is the goal of this dissertation to satisfy both of these shortcomings, using the research previously noted in this study, combined with principles of statistics and mathematical logic. It is essential to define a safety criterion to establish a baseline for the assessment. This dissertation addresses the requirements for establishing a safety criterion, developing the assessment, and implementing corrective measures.

A. SAFETY DEVELOPMENT GOAL

The Goal of Software Safety Assurance is to:

- Measure the likelihood of a system to experience an unsafe action.
- Identify triggers that could cause the system to experience an unsafe action.
- Reduce the likelihood of a system to experience an unsafe action through proper development/redevelopment or inclusion of controls.
- Re–Measure the likelihood of a system to experience an unsafe action.

The Goal of the Software Safety Metric is to:

- Provide a method to catalog system objects and characteristics that can be measured and evaluated to an established standard.
- Provide a method for measuring the system objects and characteristics into quantitative values.
- Provide a method for evaluating the measures through mathematical, logic, and analytical processes.

The Goal of a Safety Depiction is to:

- Pictorially depict the safety vulnerabilities of the software system.
- Pictorially depict the potential propagation of safety failures through the system.
- Present an efficient and aesthetic presentation of system safety for evaluation and development decision making.

B. METRIC DEVELOPMENT

Proper metric development requires the creation of a metric that is:[199]

- ***Robust*** – Capacity of being tolerant to variability of the inputs.
- ***Repeatable*** – Different observers arrive at the same measurement, regardless of how many repetitions take place.
- ***Simple*** – Uses the least number of parameters sufficient to obtain an accurate measurement.
- ***Easy to calculate*** – Does not require complex algorithms or processes.
- ***Automatically collected*** – It is possible to develop such that there is no need for human intervention.

Metrics have the ability to remove emotion and bias from software development decision–making. They are based on a standardized set of principles, agreed to at the commencement of the evaluation. As a result, they present a standardized measure for comparing, contrasting, and summarizing the quality and worth of system components and methods. Putnam and Mah noted that any discussion of metrics has to start with a foundation. "Over the years, a consensus has arisen to describe at least a core set of four metrics. These are: size, time, effort, and defects."[200] A Software Safety Metric is based on the foundation of these four principles, specialized by factors that directly affect safety. It is relevant to include a fifth element of Software System Complexity to denote a depth of convolution of the software element. As with any foundation, there is some chipping away of the base to remove unwanted material and to smooth it for its proper purpose.

1. System Size

Requirements, functions (function points), processes, scripts, frames, methods, objects, classes, or lines of code are all possible measures of a system's *size*. Specific *size* does not necessarily cause a system to be safe or unsafe, rather *size* denotes the

[199] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

[200] Mah, Michael C; Putnam, Lawrence H. Sr.; *Software by the Numbers: An Arial View of the Software Metrics Landscape*, American Programmer, vol. 10, num. 11; 1998.

volume of the system. If we assume that human error rates are constant, a ratio may be developed that relates errors to *size* based on historical data. Such errors do not directly result in a hazardous event unless the specific fault has control of a hazardous event.

Size does not necessarily infer a level of safety, nor does it infer a probability of failure.

Size can exist as a related factor to system failure probability when it is assumed that a fault may potentially exist for a specific measure of code. As the amount of code increases, the potential for further faults to exist increases, assuming a standard development practice, consistent system complexity, and the even distribution of faults. The failure to maintain a balanced development environment negates the measure of system size to safety. As the practices and methods used to develop the system change, the relationship of fault to code size will change – either to the benefit or injury or the system. Such a balance is required for a valid assessment of one system to another from size to size. Typically, system size relates to the requirements of the system. An analysis of stated requirements can be used to determine a prediction of system size, and generally remains constant for a given system. Based on historical models, it is possible to suppose that the number of faults may increase with system size, while though the increase is not proportional to size.[201] It cannot be assumed that requirements, or the compliance to such requirements, will guarantee the avoidance of a hazardous event. In some cases, a hazardous event may be unavoidable, leaving the requirements to attempt the control or lessen the potential for such an occurrence.

2. Time to Develop

Hours, months, and years are all possible measures of a system's *time* to develop. *Time* is a factor of the system's size, complexity, method of development, and personnel actually executing the development. While *time* does not directly apply to System Safety, its sub–components do have an effect. *Time* affects safety when assessing personnel

[201] Mah, Michael C; Putnam, Lawrence H. Sr.; *Software by the Numbers: An Arial View of the Software Metrics Landscape*, American Programmer, vol. 10, num. 11; 1998.

turnover, system oversight and understanding of early generation against optimized components, and in the context of time critical development projects where a delay could fail to prevent a hazardous event (i.e., Y2K Bug).

Time to Develop can serve as a positive and negative factor in the potential for the system failure development.[202] When a development process is completed quickly, it can be assumed that the system was of minor complexity and thereby had a smaller potential for fault introduction. However, this minor complexity may have little to do with system assumptions of safety criticality. To the converse, it could be assumed that the system was completed quickly because critical procedures and requirements were overlooked and not resolved. As additional time is spent on the development, the requirements may risk the chance becoming obsolescent or irrelevant, as they no longer apply to the product that they were intended to control. As development time increases, the resulting system may not be completed in sufficient time to prevent a time critical hazardous event.

When a development process exceeds its expected development time, the process may become safer as more time is spent to resolve errors, or there may be additional errors introduced as development continues.[203] History has demonstrated that:

- Additional errors are discovered as development time increases,
- Additional errors can be potentially introduced through the redevelopment/correction of known errors,
- Continued improvement and requirement modification can potentially introduce new errors that will require additional redevelopment.[204]

Figure 10 shows a hypothetical depiction of the effects of an increased time to develop against complexity and error detection. Actual scale values are based on the particular project and ability of the developers.

[202] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

[203] *Chaos*, The Standish Group International; West Yarmouth, Massachusetts; 1995.

[204] Botting, Richard J. Dr.; *Why we need to Analyze Software Development*, California State University, Santa Barbara; Santa Barbara, California; 1996.

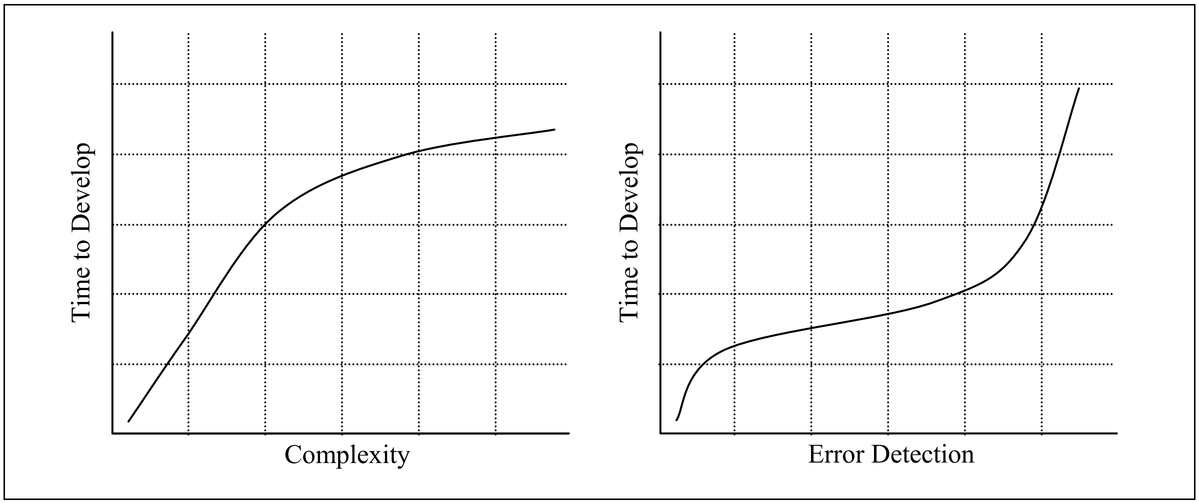

Figure 10 Time to Develop vs. Complexity and Error Detection

The Time to Develop can be reduced by the use of proven COTS / GOTS products, proficient developers, and efficient development techniques. COTS / GOTS products only provide a benefit to the system when they have been proven free of faults and can integrate seamlessly into the developing system without introducing additional failures. Proving a COTS / GOTS product fault free is virtually impossible, as is proving that the interaction between the COTS/GOTS product and the application is fault free. An assumption of the degree of product correctness must be made and factored into the decision to use a COTS / GOTS product. Decreasing system functionality with the intent to reduce the time to develop will result in an inability to meet system requirements. A failure to meet system requirements could potentially result in the system's inability to control hazardous events. A failure to provide sufficient time to develop will result in the failure to develop the complete system, test, and identify potential faults.

The balance between increased safety and increased development time is a fragile element that must be considered to improve software safety. An equilibrium must be struck with sufficient flexibility to permit requirement completion in a judicious manner without introducing new hazards to the system.

3. Effort to Develop

Man–hours, man–months, and processor–hours are all possible measures of a system's *effort* to develop. *Effort* is a factor of the *time* to develop versus verses the number of persons/assets required for the development period, compounded by the complexity of the system and aptitude of the resources. Safety is directly affected by the complexity of the system and aptitude of the resources, and indirectly affected by the *time* required to develop. You can not bake a 325° cake at 650° in half the time any more then you can expect to reduce the time to develop by half when you double the number of developers. Software Development as with cooking, requires a controlled development process that measures the *effort to develop* based on existing assets, aptitudes, and complexities.

Effort has historically been related to development risk and fault introduction. As a system requires greater effort to be developed, the potential that the system will not be completed increases, frequently due to the depletion of resources. As resources are stretched and the developers become weary from process, some portions of the system may fail to be developed. The partial development may result in a lack of some hazard controls and the failure to identify potential faults. Effort may be related to the complexity of the system, the abilities of the developers, and the size and scope of the requirements. Various estimation methods, such as COCOMO or Putnam may be used to determine a perspective value for system development effort for a given set of requirements.[205] While no direct measure exists to relate effort to safety, a correlation can be established that *effort* can be reduced by:

- Refining the requirements, thereby making the system easier to develop,
- Employing a greater quality of personnel, or
- The use of more refined techniques and development tools.

[205] Roetzheim, William; *Estimating Software Costs*, Software Development Magazine, vol. 8, num 9, pg. 66-68; October 2000.

While such a measure would benefit the state of the art of software engineering, the development of such a measure would require significant research and the modeling and would be beyond the scope of this dissertation.

4. System Defects

Failures per hour, errors per line of code, and failures per execution are all valid measures of system's defects. *Defects* are generally measured over *time* or against a measure of system *size*, referred to as frequency or rate. *Defects* are an essential component of Software Safety, to the extent that the specific defect or fault has control over a hazardous event. If the particular defect does not connect to a hazardous element or system design mitigates the defect's propagation or flow, then the element is inconsequential to the measurement. *Defects* found during system development through delivery can be referred to as quality, while *defects* discovered during the period of service can be referred to as reliability.

5. System Complexity

System Complexity may potentially detract from the safety of the system in cases where the development team is incapable of designing a system at such a level of intricacy. The more complex the system, the more difficult it will be to develop and the greater the probability that a fault can then be coded into the system. Complexity can be the result of two factors:

- The requirements of the system, and
- The desired method of development.

It is difficult to reduce the complexities of system requirements and continue to meet system functionality. System complexities can be managed by the use of qualified and proficient production team members experienced with the development of such requirements. Additionally, it is possible to evaluate system development practices to determine the most safety prone method for meeting such requirements. In some cases, the method chosen by some developers may introduce faults by their inherent complexities.

Many organizations and institutions have developed criteria (McCabe's Cyclomatic Number, [206] Halstead's Software Science, [207] and Fan–In Fan–Out Complexity[208]) for judging the complexity of a software system by evaluating the code for size, structure, and format. While these measurements are beneficial to estimating the complexity of software development, they are not measurements of Software Safety. Many measurements of software complexity indicate the probability or risk of software development failure and not the risk of a hazardous event.

In some cases, it may be necessary to introduce complexities to the system to increase safety. In the case of the Boeing 777 Aircraft Data Bus, the system uses a nine–fold redundancy composed of three asynchronous data channels, each channel made up of three independent lanes that utilize dissimilar hardware and software. The complexities and effort required to develop and manage such a system are staggering, but the resultant safety product provides the coverage required to protect the aircraft from the loss of control and possible crash.[209]

A Safety Metric is first derived from the four core Software Metrics including *size*, *time*, *effort*, and *defects* plus *system complexity*. These measurements can be made early in the development process and updated as the system development becomes more mature. In addition to these core components, safety requires a measured evaluation of *specific hazards*, *degrees of hazards*, *protections* and *redundancies*, *stability*, *cost*, *restoration*, and *repair*. Each metric evaluates specific components of the software system's development and lifecycle as they apply to safety. From the combination of these components and metrics, it is possible to derive a measure of Safety – which is the ultimate goal of this dissertation, presented in a stepwise process in Chapter V.

[206] McCabe, Thomas; *Complexity Measure, IEEE Transactions on Software Engineering*, vol. 2, num. 4, pg. 308-320, Institute of Electrical and Electronics Engineers, Inc.; December 1976.

[207] Halstead, Maurice H.; *Elements of Software Science*; New York, New York and Elsevier North-Holland; 1977.

[208] Sommerville, Ian; *Software Engineering*, Addison Wesley Publishing Company, Workingham, England, 6th Edition; 07 August 2000.

[209] Lawrence, J. Dennis; *Workshop on Developing Safe Software: Final Report*, Fission Energy and Systems Safety Program, Lawrence Livermore National Laboratory; 30 November 1992.

C. ASPECTS OF SOFTWARE SAFETY

Software Safety and its Safety Management Concept can be divided into six activities:

- Hazard Identification
- Software Safety Assessment
- Safety Decision Making and Development
- Implementation of Safety Controls
- Supervision of Safety Changes
- Verification

This concept is derived from the Naval Safety Center's research and process of Operational Risk Management.[210] The process is based on the four Principles of ORM, namely:

- **Accept risk when benefits outweigh the cost.** Develop effective safety measures that balance the cost of safety against the benefit of hazard avoidance.
- **Accept no unnecessary risks.** Tolerate no system below an acceptable measure of safety.
- **Anticipate and manage risk by planning.** Investigate, anticipate, and mitigate safety hazards through the entire lifecycle of the system.
- **Make risk decisions at the right level.** Develop an accountable process to prevent hazardous events at all levels and stages of development.

Hazard Identification is the process of identifying potentially hazardous elements and events in the system, flaws in development, protections, mitigations, and limitations. ***Hazard Identification*** is one the most important phase of Software Safety Assurance, as it forms the foundation for all subsequent events. This process may be accomplished using energy barrier trace analysis, checklists, taxonomies, and subject matter expertise to generate a list of system objects and process that contribute to safety.

A Software Safety ***Assessment*** is the qualitative and quantitative analysis of the *identified* properties of development as they relate to safety. The *assessment* is accomplished using applicable metrics that measure and assign worth to the system. The *assessment* may rationalize the probability of an unsafe incident and the impact of such a hazardous event, or to the contrary may suggest a level of safety and benefit to such development.

Safety ***Decision Making*** **and** ***Development*** is the process of determining the optimal process for development and its subsequent execution. Such *decisions* are made taking into account the abilities of the development process, the equities of the *assessment*, and the goal of the *development*. Christendom's Lucifer Principle contends that there is a degree of "evil" in all things. In that same vein, it is understood that there is a level of hazard in all software systems. The dilemma is to determine the most efficient *development* plan that can translate decisions into process, within the capabilities of the developers. The *decision* process determines the level of effort or threshold that is acceptable for *development*. A Software Safety Program supports critical *decision making* at development milestone and transition points.

The Implementation of Safety ***Controls*** is the act of using proven processes that ensure safety and reduce system hazards. Such *controls* include management practices, error handlers, redundancies, safety–design requirements, and systems tests. *Controls* correct and redirect the development process to ensure that safety is paramount through the entire lifecycle of the system.

[210] Naval Safety Center; *Risk Assessment – Risk Management Controls*, Naval Message DTG 231200Z JUN 95 / MSGID / GENADMIN / COMNAVSAFECEN / 40-646 / JUN

Supervision of Safety Changes includes the *re–assessment* and re–evaluation of safety metrics to ensure compliance with development goals. *Supervision* also includes the monitoring of software development, the re–*identification* of any new hazards and flaws that may have occurred due to *development* changes, and the communication and feedback of safety and hazards for peer review.

A Software Safety Assurance process can readily be mapped to traditional Spiral Developments Models. The Spiral Model, popularized by Barry Boehm,[211] is a progressive cyclic version of a stage-wise development model, which begins each cycle of the spiral by performing the next level of elaboration of the prospective system's requirements. Risk management within this stage-wise model contains many of the concepts and ideals required for Software Safety, the difference being the fundamental shift beyond project development to system hazard avoidance. To relate to the Boehm Spiral Model, the Supervision of Safety Controls would occur in PHASE I of the Spiral, with Hazard Identification occurring in PHASE II, the actual Software Safety Assessment taking place in PHASE III, and the ultimate Software Decision Making and Development process in PHASE IV." Assessment and testing for System Safety only adds to the robustness and functionality of the original system requirements. Safety Controls support system development by instituting a second layer of validation and verification to each process cycle. Rather than a shift in focus, Software Safety is accomplished in series with existing development, resulting in a system that is developed safer, with greater control and understanding of the capabilities and limitations of its operation.

[211] Boehm, Barry; *A Spiral Model of Software Development and Enhancement*, Computer, pg. 61-72; May 1998.

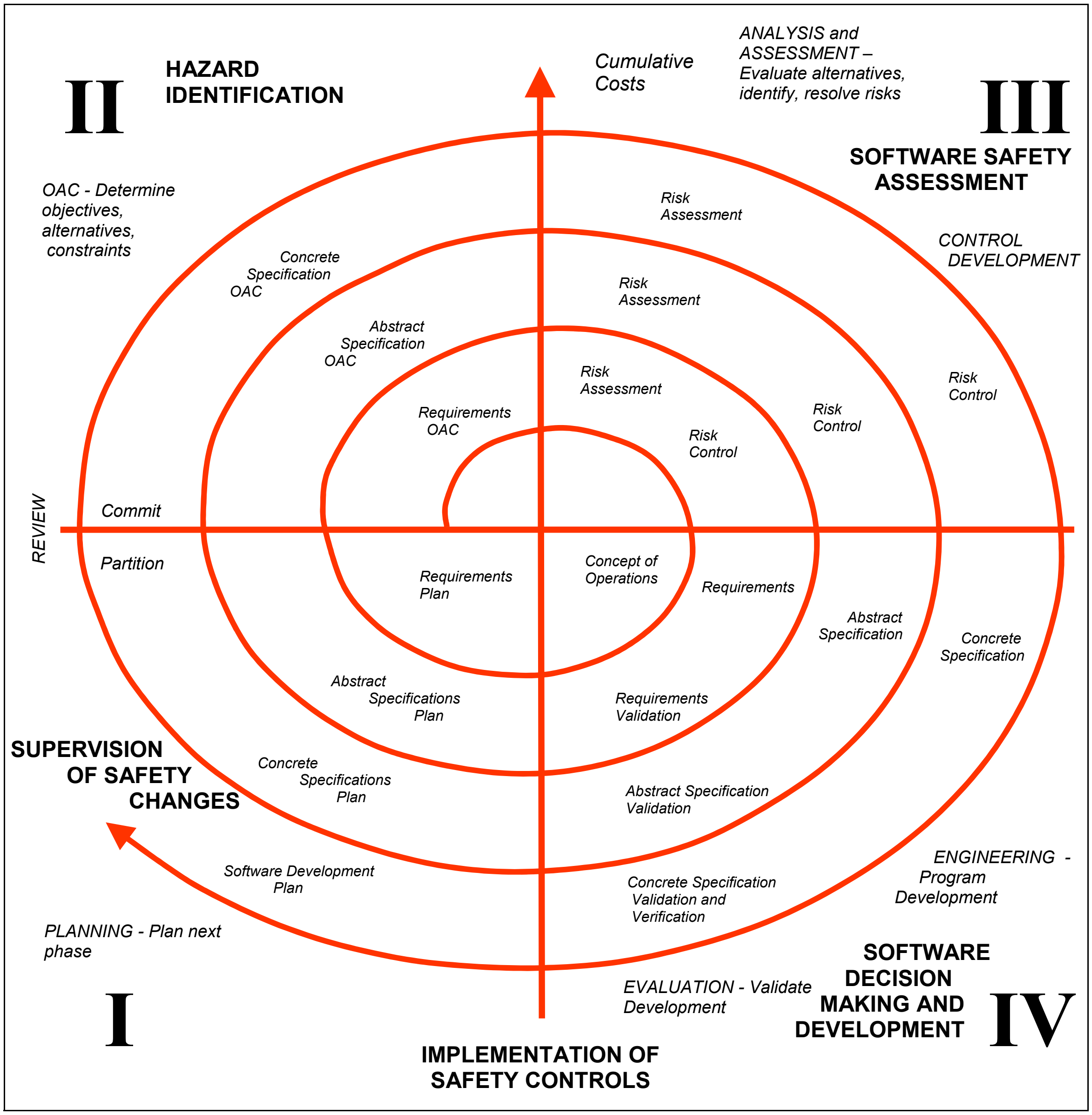
II
HAZARD IDENTIFICATION
Cumulative Costs
ANALYSIS and ASSESSMENT – Evaluate alternatives, identify, resolve risks
III
SOFTWARE SAFETY ASSESSMENT
OAC - Determine objectives, alternatives, constraints
Concrete Specification OAC
Abstract Specification OAC
Requirements OAC
Risk Assessment
Risk Assessment
Risk Assessment
CONTROL DEVELOPMENT
Risk Control
Risk Control
Risk Control
REVIEW
Commit
Partition
Requirements Plan
Concept of Operations
Requirements
Abstract Specification
Concrete Specification
Abstract Specifications Plan
Requirements Validation
SUPERVISION OF SAFETY CHANGES
Concrete Specifications Plan
Abstract Specification Validation
Software Development Plan
Concrete Specification Validation and Verification
ENGINEERING - Program Development
PLANNING - Plan next phase
SOFTWARE DECISION MAKING AND DEVELOPMENT
EVALUATION - Validate Development
I
IV
IMPLEMENTATION OF SAFETY CONTROLS

Figure 11 Safety in the Spiral Model

D. DEPICTING SAFETY

A pictorial depiction is essential to presenting a visual relationship between the software functionality, failure, and hazard prevention of Software Safety. System Development requires the decomposition of action into objective models that can be easily observed, traced, and correlated. These models can be developed into visual presentations that illustrate the potential propagation of software failures through the system. This illustration is then used to portray system vulnerabilities and areas where safety mitigation is capable of preventing a hazardous event. Various software development models include the graphical depiction of the system for presenting an efficient and aesthetic way of viewing functionality including Fault Tree, Class Diagrams, Hypergraphs, PSDL (Prototype System Description Language), Fishbone, and Petri Nets. A Software Safety Graphic would be based on a form of the Fault Tree model with its ability to logically portray system flow and failure dependencies.[212] Examples of potential graphical representation solutions were given in Chapter II.E.2 of this dissertation, with a demonstrated solution in Chapter V, with specific concentration in Chapter V.E.1.

E. SUMMARY

At present, the state of the art of software development lacks a viable metric for quantifying the safety of a Software System. Various metrics mentioned in Chapters II.E and IV.B of this dissertation are capable of predicting the rate of failure of a system without taking into consideration the consequences of the failure. Not every failure may result in an unsafe event. Correspondingly, there exists no model for effectively depicting software process flow and functionality as it applies to failure and Software Safety. Currently, software metrics exists to determine the complexity, effort, and or size of a software system. These metrics, while beneficial for their intended purpose, do not readily adapt to computing the propagation of failure or probability of a hazardous event. Susan Sherer agreed that, "…software can never be guaranteed to be 100% reliable.

[212] See Chapter V.E.1 – Process Flow Mapping; for complementary clarification.

Software systems are discrete–state systems that do not have repetitive structures. The mathematical functions that describe the behavior of software systems are not continuous, and traditional engineering mathematics does not help in their verification."[213] A Software Safety Metric is atypical to other metrics in that safety requires a measurement of probability and assumption of fact based on partial evidence, void of emotion. The resulting measures of safety metrics include the balanced justification to risk human lives, limbs, or economy.

While mean time to failure and other failure rate measures may be capable of determining the probability that a system may experience a failure, in Chapter V, this dissertation introduces a concept for refining that measure to take into account the probability that an event will execute, the probability that the event will fail during its execution, and finally the probability that the failure will result in a hazardous event. The combination of the three measures, in conjunction with the severity of the consequence; ultimately merge to represent the level of safety of the system.

Software Engineering is based on scientific and mathematical theory.[214] Investigation has revealed scores of disasters that occurred when engineers ignored the most basic of principles of science and mathematics. Indeed one definition of Software Engineering is, "the disciplined application of engineering, scientific, and mathematical principles, methods, and tools to the economical production of quality software."[215] In keeping with the objective of Software Safety Assurance, the resulting metrics will comprise the disciplined application of engineering, science, and mathematics in an aesthetic and logical application to safety assessment.

Software Safety and the corresponding metrics are not reactions to a crisis. They serve to prevent crisis by the early recognition of possible hazards and controls that prevent such hazards. They will provide the opportunity to make system improvements

[213] Sherer, Susan; *Software Failure Risk – Measures and Management*; Plenum Press; 1992.

[214] Tichy, Walter F.; Habermann, Nico; Prechelt, Lutz; *Summary of the Dagstuhl Workshop on Future Directions in Software Engineering (February 1992)*, ACM SIGSOFT Software Engineering Notes, vol. 18, num. 1, pg. 35-48; January 1993.

to mitigate hazards and strengthen functionality. In cases where the additional effort is not cost effective to solving hazards, the developers and clients (if warranted to inform) have a greater understanding of the potential failures of the system for which they are about to deploy. In such cases, a decision must be made of what is preferable: an imperfect system, no system at all, or a more expensive but safer system. The cost of risk to human lives is a sensitive and controversial issue, and "cost effectiveness" does not have a universally accepted definition in such a context.

[215] Humphrey, Watts S.; *Managing the Software Process*, Addison-Wesley; Massachusetts; 1989.

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V. DEVELOPING THE MODEL[216]

"Assessment of change, dynamics, and cause and effects are at the heart of thinking and explanation."

– Attr. to Dr. Edward Tufte

Simplistically, a safety assessment would query a system that has failed as to:

1. What did it just do?

2. Why did it do that?

3. What will it do next?

4. How did it reach this state?

5. Is it possible to revert its process to a normal state?

6. Why will it not reach that state?

7. What caused it to reach that state?

8. What can be done to ensure that it does not occur again?

This assessment model attempts to answer some of these questions through a stage-wise process. An assessment of Software Safety is based on computing the:

1. The probability that a hazardous event will occur and

2. The severity of that hazard – *Consequence*

Through the combination of these two elements, it is then possible to derive a value of Safety for the system, mathematically defined as:

[216] Luqi; Liang, Xainzhong; Brown, Michael L.; Williamson, Christopher L.; *Formal Approach for Software Safety Analysis and Risk Assessment via an Instantiated Activity Model*, Proceedings from 21st International System Safety Conference, Ottawa, Ontario, Canada, September 2003

$$S = \sum_{\text{for all H}} P(\text{H}) * C(\text{H})$$

Where *S* = The safety of the Software System
P(H) = The probability that a Hazardous Event (*H*) will occur
C(H) = The Consequence Severity of a Hazardous Event (*H*)

Equation 1 System Safety

In the most ideal circumstances, the equation is the summation of two specific values to derive a specific result. In a perfect world, the values of a system's properties would be clearly defined and easily incorporated into a mathematical computation. In reality, there are far too many variabilities in the dynamic nature of software development to derive specific values for each software property. As a software system's complexity, size, and uncertainty increase, the ability to place finite values on system properties decreases. In such cases, it may become necessary to assign range values to cover specific states or conditions of the system. This chapter outlines methods for deriving both precision and non-precision values for system properties

The value of *P(H)* can range numerically between zero and one ($0 \leq P(H) \leq 1$), or be represented as a textual value rated within a series of numeric limits (see the example in Table 10). The value of one depicts the probability that a hazardous event will occur constantly, while the value of zero represents the probability that a hazardous event will never occur. Textual values and limits are further defined in this chapter. The procedures for determining the value of *P(H)* are defined in this chapter. It is the goal of the development to reduce the probability of a hazardous event (P(H)) to as small a value as possible.

The value of *C(H)* can range numerically between zero and one ($0 \leq C(H) \leq 1$), or be represented as a textual value rated within a series of numeric limits (see the example in Table 7). A *C(H)* value of zero represents a negligible severity consequence while a *C(H)* value of one represents a catastrophic severity consequence. The procedures for determining the value of *C(H)* are defined later in this chapter. It is the goal of the development to reduce the consequence severity of a hazard (C(H)) to as small a value as possible.

The value of Safety (*S*) of the Software System can be represented by a textual value/definition determined by the grid intersection of *P(H)* and *C(H)* values (see the example in Table 12) or as a numeric representation of safety. The procedure for determining the value of *S* is defined in this chapter. It is the goal of the development to drive the level of safety towards zero. The greater the Safety Index, the more unsafe a system becomes.

The safety of a system is based on the combined safety of each component and the ability for the system to control hazards as a whole. In the most general terms, it is based on the probability that hazardous events will occur in combination with the severity of their consequence. In the most detailed terms, it is an examination of each hazard, consequence, and probability of execution that is expressed in the final equation. . The interdependency that is frequently a part of complex systems can results in very complex probability equations.

A. SAFETY REQUIREMENT FOUNDATION

Traditionally, developers would build a system, test it, and then refine it through a series of improvements. This method, while successful, would require a significant amount of unnecessary rework and testing that could have been avoided using proper design and forethought. It is easier to design the software with safety in mind, planning for the potential for hazardous events, implementing controls and mitigation tools, and testing with the foresight to isolate environments and states that could lead to process failure. Such prior planning is beneficial to the success of system development and replies on the use of proper requirement specifications to set the foundation for design and development.

Requirements can be divided into four distinct levels based on their degree of specificity and application to system development. The accepted nomenclature for requirements classification identifies ***Level 1 Requirements*** as the top most mission-level requirements of the system. They are written in very broad terms and rarely change over the course of development. ***Level 2 Requirements*** are referred to as Allocated Requirements, derived from a decomposition of Level 1 Requirements. They are written in greater detail than the previous requirement, introducing specifications necessary for project development. ***Level 3 Requirements*** are Derived Requirements that can be traced back as a subsystem to support Level 2 Requirements. There exists a bi-directional relationship from one Level 2 Requirement to one or many Level 3 Requirements. ***Level 4 Requirements*** are the Detailed Requirements used to code and design the actual system, based on the derived specifications from Level 3. There exists also a bi-directional tracing between Level 3 and Level 4 requirements. System tests are designed to verify the Level 4 Requirements while Acceptance Tests are used to verify Level 3 Requirements. Inspection and Observation is usually sufficient to certify Level 1 and Level 2 Requirements.[217]

Lacking in the state of the art of requirement's specification is an assignment relationship between safety elements and the requirement level concept. Presently, there exists little formal direction towards the proper inclusion of safety elements in any part of the requirement specification document, other than recognizing the importance of their inclusion. In the case of High Assurance Systems, it should be necessary to assign safety elements to specific levels of requirement definitions, thereby increasing commonality and conformity across diverse developers and user's groups. Through this dissertation, I introduce the following Safety to Requirement Level Assignments:

- ***Level 1 Requirements* – Top Level:** Hazard Introduction. All Potentially Hazards Events that could occur during system operation are identified in the requirements. This is to include hazardous events that could occur should the system function normally or fail to operate.

[217] Roseberg, Linda H. Ph.D.; Hammer, Teodore F.; Huffman, Lenore L.; Goddard Space Flight Center; *Requirements, Testing, and Metrics*, Proceedings of the 16th Pacific Northwest Software Quality Conference, Utah; October 1998.

- ***Level 2 Requirements*** **– Allocated Requirements**: Hazard Amplification. Hazardous Event definitions are amplified to include states of operation that could lead to the event, potential process malfunctions that could trigger the event, and consequences of the hazardous event. Consequences, costs, and effort related to the Hazardous Event should be included to justify controls later in the requirement documentation.

- ***Level 3 Requirements*** **– Derived Requirements:** Mitigation and Control of the Hazard. Based on the identified hazard and related process malfunction, mitigation and control elements and techniques should be identified to reduce the severity or probability for occurrence of the hazardous event. Decisions should be based on known cost-benefit factors including effort required to control the event against the probability of occurrence of such an event. Operational bounds and limits can defined at this level.

- ***Level 4 Requirements*** **– Detailed Requirements:** Mitigation and Control Logic. Based on identified Mitigation and Control elements and techniques, logic statements can be defined to isolate hazardous triggers and environmental conditions required to control system operations. Operational bounds and limits can be specifically defined to include their effect on the system and the logic necessary to counter the impact on system operation, should they occur.

Controlling the limits of the operating environment is crucial to developmental success. That success can be dependent upon the ability of the requirement specifications to isolate the acceptable bounds of operation for the system's environment. Using proper logic statements, it is possible to bracket or filter most operating environments to fall within acceptable bounds. Should the environment stray, logic statements could be devised and included in the requirement specifications to counter and correct the error.

The writing of requirements still demands a degree of subject matter expertise in the field of specification authoring, software engineering, and the subject for which the author is writing the requirement. It is impractical to assume that an individual can write a viable safety related requirement specification document without proper education, foundation, and experience from previous efforts. For this intent, the method introduced in this dissertation provides a foundation for specification authors to base future products upon. Optimally, specification authors should integrate the Safety to Requirement Level Assignment concept into their development process as a template, making modifications and improvements necessary to meet the specific needs of the project, the developers, and the client.

1. Requirement Safety Assessments

A significant effort has been made to quantify and qualify requirements using automated analysis techniques. Many of these efforts have concentrated on nine categories of quality indicators for requirement documentation and specification statements, including:[218]

Independent Specification Based:

- Imperatives
- Continuances
- Directives
- Options
- Weak Phrases

Requirement Document Based:

- Size
- Specification Depth
- Readability
- Text Structure

While each of these elements provide some measure of requirement document quality, they do not directly address the specific needs of the High Assurance System, and in some cases contradict the process. To ensure that safety based requirements are properly evaluated, it is necessary to amplify the assessment process to reflect the

[218] Wilson, William M.; Rodenberg, Linda H., Ph.D.; Hyatt, Lawrence E.; *Automated Quality Analysis Of Natural Language Requirement Specifications,* Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland.

introduction of the Safety to Requirement Level Assignments, presented earlier in this dissertation. Based on techniques already established in the state of the art of Automated Requirement Quality Analysis, it is possible to evaluate the requirements in regards to safety as follows:

a. Level 1 Requirements

Completeness: Level 1 Requirements shall be evaluated for their clarity and specification in the requirement statement to address safety related hazardous events in the system. It is essential to identify all potentially hazardous events that could occur related to system operation. Identified hazards should be clearly stated to remove ambiguity and confusion with like hazards not related to the system.

Depth: Level 1 Requirements shall be evaluated for sufficient linkage to subordinate Level 2 Requirements that amplify safety related hazardous events through system operation. This linkage is critical to hazard resolution and adds to requirement specificity not normally expected in the top level requirement specification.

b. Level 2 Requirements

Completeness: Level 2 Requirements shall be evaluated for their clarity and specificity in the amplification of safety related hazardous events in program functionality including operating states, conditions, and/or parameters that contribute to the hazardous event. Specific hazard consequences, costs, and effort related to the hazardous event shall be addressed.

Depth: Level 2 Requirements shall be evaluated for their relevance to and satisfaction of safety related Level 1 Requirements, taking into consideration the necessity for Level 2 requirements to implement the safety intent defined in Level 1 requirements. Additionally, they shall be evaluated for sufficient linkage to subordinate Level 3 Requirements that identify and implement mitigating actions and controls of safety related hazardous events in system operation.

c. Level 3 Requirements

Completeness: Level 3 Requirements shall be evaluated for their clarity and specificity to identify and implement mitigating actions and controls of safety related hazardous events in system operation, taking into account identified states, conditions, and/or parameters contributing to the hazardous event. Requirements shall address considerations for the cost-benefits of techniques, identifying potential alternatives should resources become limited. Specific operational bounds and limits are identified at this level.

Depth: Level 3 Requirements shall be evaluated for their relevance to and satisfaction of safety related Level 2 Requirements, taking into consideration the necessity for Level 3 requirements to implement the safety intent of the Level 2 requirements. Additionally, they shall be evaluated for sufficient linkage to subordinate Level 4 Requirements that specifies specific logic necessary to design, implement, and monitor controls and mitigating elements of hazardous events.

d. Level 4 Requirements

Completeness: Level 4 Requirements shall be evaluated for their clarity and specificity to address logic necessary to design and integrate mitigation and control elements to reduce the potential or severity of safety related hazardous events. Logic statements shall be specific enough to be directly transferred into program functionality. Specific operational bounds and limits shall be defined and amplified to include their affect on the system.

Depth: Level 4 Requirements shall be evaluated for their relevance to and satisfaction of safety related Level 3 Requirements, taking into consideration the necessity for Level 4 requirements to implement the safety intent of the Level 3 requirements.

2. Requirement Safety Assessment Outcome

One of the primary steps in the development of High Assurance Systems is to define the safety criticality and criteria for the program. In Dr. Schneidwind's research, in which he discusses the process and benefits of implementing reliability, safety, requirements, and metrics to a High Assurance System, he makes a distinct point of defining the safety criteria in the system's (*Level 1*) requirements.[219] Numerous other prominent members of the state of the art of Software Engineering emphasize the importance of identifying hazards early in the development process and including them within the requirement's specification.[220] It is generally accepted that it is at least fourteen times more costly to fix a problem discovered during testing then it is to fix it during the initial requirement's phase of development.[221] Using this motivation, the reliability modeling introduced by Dr. Schneidwind, and the requirement safety assessment method introduced in this dissertation, it is possible to gauge a factor of safety early in the development process. From this early assessment, it is possible to determine if the initial requirement set is complete enough to justify project commencement.

Properly written requirement specifications have a natural linkage from higher to lower level elements. An assessment of software safety must validate that the linkage is intact and that hazardous events are satisfied across all levels of the requirement process. Additionally, it is imperative that specifications be reviewed to ensure that they do not impose contradictory or conflicting requirements against each other, essentially nulling out the benefit of one control or element of the hazard prevention chain. Such an assessment can be accomplished using traditional automated assessment techniques or through the review of domain experts. Much of what is accomplished in the requirement's phase of development is based on judgment and experience. It is difficult

[219] Schneidewind, Norman F, *Introduction to Software Reliability, Safety, Requirements, and Metrics with Space Shuttle Example*, Naval Postgraduate School, Monterey, California; 27 July 2000.

[220] Richter, Horst P. PhD, *Accreditation Of Software Systems In The Safety Environment*, Richter Consultants; Scottsdale, Arizona, from the Proceedings of the 18th International System Safety Conference, Fort Worth, Texas; 11-16 September 2000.

[221] Hammer, Theodore; Huffman, Lenore; Wilson, William; Rosenberg, Linda PhD; Hyatt, Lawrence; *Requirement Metrics for Risk Identification*, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland.

to quantify such experience other then to balance the successes of previous efforts with the education and talent gained through the maturation of the state of the art of software engineering.

The assignment of Safety Elements to Requirement Levels would add little additional effort to the requirement development phase. To its considerable benefit, it would add a standardized requirement format that could be early integrated into the state of the art of requirement development. When properly implemented, the requirement's specification document would drive the developer to consider hazard elements and mitigation controls early in the development process; saving time, resources, and effort through the remainder of the development (*One of the key recommendations of the JSSSH*).[222] Such a safety to requirement designation would compliment the existing requirement assessment methods; ensuring safety-based requirements are properly reflected in the preliminary design of the system.

The traditional measure of completeness and quality (i.e., the complete and accurate implementation of requirements) must be modified to properly capture the true benefits of software safety within the requirement specifications. Traditionally, an assessment might measure the ratio of requirements satisfied against the total number of requirements. This plain ratio would overlook the significance or criticality of one or more requirements' relationship to a hazardous event, including consideration of the mission criticality of requirements beyond their relationship to hazardous events. All hazardous events must be evaluated independently as their outcomes hold unique consequences for the program. It may be acceptable to have a low ratio of completed requirements to control an inconsequential hazard while certification may demand a higher ratio of completion to control a single catastrophic hazard. Software safety is only concerned with the requirements that have been shown by their system-level analysis to have an associated hazard. The metric desired for software safety is a safety requirements resolution metric demonstrating requirement satisfaction concentrating

[222] *Software System Safety Handbook, A Technical & Managerial Team Approach*, Joint Software System Safety Committee, Joint Services System Safety Panel; December 1999.

alone on the safety-based elements.[223] Such criteria should be defined in the test specifications of the system's requirement documentation.

3. Safety Requirement Reuse

Reuse benefits the state of the art of Software Engineering by incorporating elements that already meet the stringent design, development, and testing regimes necessary to ensure their success. Once validated, high-confidence safety related requirements could be reused across similar projects of like-specifications. On the surface level, the reuse of any proven safety related requirement specification would provide some assumption of completeness and increased safety of the delivered product, but would still require a level of scrutiny and examination of the component to ensure that it will continue to function properly in the new environment and complete system. As such, the level of scrutiny required is directly related to the potential consequence of the associated hazardous events. The actual measure of safety would still require a stringent level of verification and validation to ensure that the specified safety requirements integrate effortlessly into the overall system. Such a successful integration of reuse would reduce the level of effort to write new requirements, increase confidence by the use of proven specifications, and increase commonality across multiple specification documents. At the lowest level, the use of a safety-based requirement template or "boilerplate" provides a fundamental starting point for specification authors to integrate into the final document.

B. THE INSTANTIATED ACTIVITY MODEL[224]

An Instantiated Activity Model represents the depiction of a function or process within a system during a specific state, based on the interaction of potential elements at a specific instance of operation. While the potential environments may be near infinite, it is possible to model the limits of that environment to examine the interaction of the

[223] McKinlay, Arch; *Software System Safety, Integrating Into A Project,* Proceedings from the 10th International System Safety Conference, Dallas, 1991.

elements of the IAM. The Instantiated Activity Model introduced in this dissertation is designed to provide an assessment value at an instance of the system's activity, based on state and environment. Where software is highly reactive to its environment, it is imperative to devise a model that can measure a system for each possible state instance.

The IAM, Instantiated Activity Model, is a typical IPO (Input–Process–Output) block schema dealing with a set of related activities such as *Input, Process, Output, Failure, Malfunction, etc*, as depicted in Figure 12. As shown, it is possible to associate a potential failure with each activity of the system. For instance, Input I_1 with potential failure F_1, through successive activities Process P_1 and Output O_1 would result in a failure leading to a Malfunction M_1. The IAM reveals the relationship between the essential IPO activities, the potential failures, and the hazardous situation or malfunction.

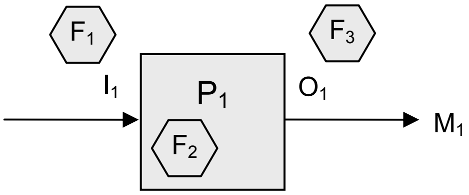


Figure 12 Basic Instantiated Activity Model Example

The IAM representation in this dissertation assumes a direct flow from Input to Output through a Process. In complex IPO cases where loops are part of the process flow, then assessors must consider the simultaneous or selective natures of the loop input and output and their influence on the final process. Should a failure occur in the loop process, the assessment must consider the ability for the loop failure to migrate back into the process flow and ultimately affect the occurrence of a hazardous event. Loops must be evaluated for the number of repetitious events or iterations that they may execute during the evaluation period as well as the probability that the execution will influence the

[224] Luqi, Lynn Zhang, *Documentation Driven Agile Development for Systems of Embedded Systems*, Published in the Monterey Workshop on Software Engineering for Embedded Systems: from Requirement to Implementation, Chicago, Illinois, 24-26 September 2003.

process flow. Unique to loop cases is the fact that the probability of failure will increase towards 100% as the process flow repetitively cycles for a given period as illustrated in Equation 2.

$$P_{\text{period}} = 1 - (1 - P_{\text{event}})^n$$

Where: P_{period} is the Probability of an Event Occurrence over a defined period of multiple cycles
P_{event} is the Probability of an Event Occurrence over a single cycle
n is the number of cycles that occur during a defined period

Equation 2 Loop Probability Equation[225]

The failure of the Patriot Missile System in the 1991 Operation Desert Storm conflict is a classic illustration of a catastrophic event related to a loop based failure.[226] In the Patriot case, the fire control system's clock experienced a minuscule rounding error with each cycle. Over an extended period of time, the clock error compound to a significant value, eventually reducing the integrity of the navigation solution and degrading the ability of the missile system to engage a target. Each iteration of the clock's computation was flawed due to a design weakness that assumed the system's operational interval to be relatively short. Testing, had it taken into account the factor of an extended operational period, would have revealed the compounded probability factor to the failure. As the period cycle number (n) increases, then the effect of the event probability (P_{event}) has a greater influence on the total probability for that period (P_{period}). The tragedy of the Patriot example is that the event could have been prevented and lives saved had (1) the developers taken into consideration the potential for a loop based failure over an extended period, or (2) the users employed the system for the limited purpose for which it was designed for.

[225] Walpole, R.E. and Meyers, R.H., *Probability and Statistics for Engineers and Scientists*, Prentice Hall; 7th edition, Upper Saddle River, New Jersey; January 2002.

[226] See APPENDIX B.4 –
PATRIOT MISSILE FAILS TO ENGAGE SCUD MISSILES IN DHAHRAN

Failures have the potential to lead to a range of actions from malfunctions to mishaps. There can be many failures on inputs, processes, and outputs that do not lead to a mishap, although they may lead to another system malfunction. It is more efficient to assign resources to assess failure modes that have the potential to lead to a mishap vice the blanket assessment of all failures. As the assessment process becomes more refined, it will be possible to isolate and eliminate failure modes that have no effect on the final safety of the system.

Additional process elements may be depicted using various symbols and graphics, according to the needs and preference of the analysts. Invariants and post–conditions of each process and of the system can be defined by activity limits, assuming the system remains within operating parameters. Limits can be used as one of the possible indicators for identifying potential failure. Depending on the system under investigation and the consequence of a limit–type failure, an un–handled limit violation may result in a hazardous event. Any graphic symbols used in the depiction should be referenced and defined in the graph body. Examples of graphic symbols include, but are not limited to:

IPO Activities, Modifiers, and Constraints	**Assessing Factors**	**Composite IAM**
Input $\xrightarrow{I_n}$	Failure Events ⟨F_n⟩	Conjunctive →⧖□
Process $\boxed{P_n}$	Current Activity (A_n)	Selective ⇉◇□
Output $\xrightarrow{O_n}$	Dependent Activity $\{\lvert DA \rvert\}$	Simultaneous ⇉○□
Limit /L_n/	Potential Malfunction ⟨M_n⟩	
Filter ‖⁞‖		

Figure 13 Essential Graphic Elements for IPO Block

Input: The basic IAM IPO activity that transports data and system process flow into a Process activity for computation, manipulation, and/or execution. The Input activity does not change the data value, serving only as a transport mechanism.

Process: The basic IAM IPO activity that executes actions within the system based on inputted data, system states, and process function. The Process activity has the ability to change data values, based on process functionality. The resulting data values are transported from the Process via the Output activity.

Output: The basic IAM IPO activity that transports data and system process flow out of a Process activity following computation, manipulation, and/or execution. The Output activity does not change the data value, serving only as a transport mechanism.

Limit: The basic IPO activity that bounds transported data values to within a specific window of limits, established in series with either an Input or Output activity. Limit activities have the ability to modify data values based on the logic statement of the Limit. No additional process action is taken other then to validate and bound the data values.

Filter: The basic IPO activity that filters transported data values to within a specific window of limits, established in series with either an Input or Output activity. The distinct difference between a Filter and a Limit is the ability for a Limit to change data values to fall within a predetermined set of values, while a Filter terminates or constrains the transportation of all values that do not meet the criteria established within said Filter.

Failure Events: The event within the system process flow that contains a failure element. One or more Failure Events can be contained within an IPO activity, while it may be possible for an IPO activity to contain no potential failure events.

Current Activity: The global descriptor or placeholder of IPO activities.

Dependent Activity: The series of activities for which the outcome of the primary activity is dependant upon to eventually result in a Malfunction event. In the case of a safety assessment, dependency runs linearly through the process from the current activity under assessment leading up to the Malfunction event under investigation.

Potential Malfunction: The resulting Malfunction event within a system as a consequence of the system process flow through a Failure event.

Conjunctive IAM: The composite IAM representative of two IPO blocks executing in series, one after the other, where as the previous block produces an Output activity that triggers the second block to be processed.

Selective IAM: The composite IAM representation of two or more IPO blocks that exclusively trigger a common Process activity. In the case of a Selective IAM, one, and only one of many inputs, triggers the subsequent Process activity.

Simultaneous IAM: The composite IAM representation of two or more IPO blocks that simultaneously trigger the execution of a common Process activity. In the case of a Simultaneous or Joint IAM, one to many Inputs activities triggers the subsequent Process activity.

By the nature of a safety assessment, it is critical to measure the probability of an action and its corresponding failure through all of its applicable series activities, cascading towards a malfunction. In such a case, the probability that one event will eventually result in a malfunction is dependant upon the actions of each of the elements downstream from the failing activity, up to the eventual malfunction. Each these elements Dependant Activities have the ability to influence the propagation of the failure consequence through the system process flow, potentially increasing or decreasing the probability that a malfunction will occur.

To better define the IAM and to provide a method for communicating its structure, it is imperative that elements be well defined and portrayed in examples. An *Activity* can be composed of any number of elements of *Inputs*, *Outputs*, *Limits (including Filters)*, *Processes*, and *Failures*. The result of the failure can then result in a *Malfunction* at some *Degree of Failure*. Taken together, all of the possible elements constitute a definable sample of the system, as denoted in Table 5:

$\underline{I} = I_1 \cup I_2 \ldots \cup I_n$ is all sets of *Input* activities in the system, where $I_1 = \{i1_1, i1_2, i1_3, \ldots, i1_m\}$ collects all of a specific Input activities for a given IPO block

$\underline{P} = P_1 \cup P_2 \ldots \cup P_n$ is all sets of *Process* activities in the system, where $P_1 = \{p1_1, p1_2, p1_3, \ldots, p1_m\}$ collects all of a specific Process activities for a given IPO block

$\underline{O} = O_1 \cup O_2 \ldots \cup O_n$ is all sets of *Output* activities in the system, where $O_1 = \{o1_1, o1_2, o1_3, \ldots, o1_m\}$ collects all of a specific Output activities for a given IPO block

$\underline{A} = \underline{I} \cup \underline{P} \cup \underline{O}$ is the set of all activities in the systems

$\underline{L} = L_1 \cup L_2 \ldots \cup L_n$ is all sets of *Limit Constraints* in the system, where $L_1 = \{l1_1, l1_2, l1_3, \ldots, l1_m\}$ collects all of a specific Limit Constraints on a specific system

$\underline{F} = F_1 \cup F_2 \ldots \cup F_n$ is all sets of *Failure Events* in the system directly relating to specific IPO Activities on a specific system where $F_1 = \{f1_1, f1_2, f1_3, \ldots, f1_m\}$ collects all of a specific Failure events for a given activity element.

$\underline{E} = \underline{L} \cup \underline{A} \cup \underline{F}$ is the set of Events in the system, where Failure, Activity, and Limits are all events in the system

$\underline{M} = M_1 \cup M_2 \ldots \cup M_n$ is all sets of *Malfunction* states in the system. Due to the interrelationships between Malfunctions, it is possible for the occurrence of one malfunction to overlap the occurrence of a second malfunction, or for one malfunction to preclude the occurrence of another.

$\underline{D}$ = {*intermittent, partial, complete, cataclysmic, et al*}, the enumeration of all possible degrees of failures

Table 5 IAM Safety System Objects

Because no standard arithmetic notation could be found to denote IPO flow of a software block through associated activities and failures, it becomes necessary to establish a set of formal notations to describe concepts using a rigorous math language, which is useful to quantitatively analyze safety and assess risk associated with the IAM. Such a mathematical notation makes it easier to develop proofs and algorithms that can be reused and reassessed, adding to the precision of the method under investigation. As this dissertation adds the concept of the IAM to the IPO, together with the concept of mathematically computing the safety of a software system, it is essential to establish an arithmetic foundation for which to base the subsequent safety calculations upon.

(1).	$\mathbf{P_e}$ **(a)**	Execution Probability Operator that transforms **a** activities to probability, where $\mathbf{a} \in \underline{\mathbf{A}}$
(2).	$\mathbf{P_f}$ **(f, d)**	Failure Probability Operator that transforms **f** failures at degree **d** to probability, where $\mathbf{f} \in \underline{\mathbf{F}}$, $\mathbf{d} \in \underline{\mathbf{D}}$
(3).	$\boldsymbol{f}$ **^** $\boldsymbol{a}$	Failure $\boldsymbol{f}$ of Activity $\boldsymbol{a}$ that is, $\boldsymbol{f}$ is associated with $\boldsymbol{a}$ where $\boldsymbol{f} \in \underline{\mathbf{F}}$, $\boldsymbol{a} \in \underline{\mathbf{A}}$**;** to denote the appearance of a specific Failure $\boldsymbol{f}$ when performing Activity $\boldsymbol{a}$.
(4).	$\boldsymbol{f_i}$**^** $\boldsymbol{a_j}$ **{[**$\mathbf{a_k}$**]}→ M**$_1$ $\boldsymbol{M_1}$ **depends on (**$\boldsymbol{f_1, f_2, \ldots f_n, a_1, a_2, \ldots a_n}$**)**	Failure $\boldsymbol{F_i}$ associated with Activity $\mathbf{a}_j$, through Dependent Activity $\mathbf{a}_k$**,** it can result in a failure leading to a hazardous situation and malfunction **M**, where $\boldsymbol{F_i} \in \underline{\mathbf{F}}$, $\boldsymbol{a_k} \in \underline{\mathbf{A}}$, $\mathbf{M}_l \in \underline{\mathbf{M}}$

Table 6 IAM Basic Notation Definitions

The third notation in Table 6 refers to the *Failure within a block,* which is a simplistic block with a single failure, while the fourth notation refers to the *Failure of a block with throughput to a Malfunction*. The addition of the *through block* represents the remainder of the process, including the malfunction. There may be several failure modes within a computational block that may not lead to a malfunction. Depending upon available resources, the assessment may need to concentrate on failure modes within the block that lead to hazardous events, disregarding benign failures.

1. Formal Safety Assessment of the IAM

The IAM example for a given IPO block deals with several aspects of failure combined to form the potential malfunction M_1, as illustrated in Figure 14.

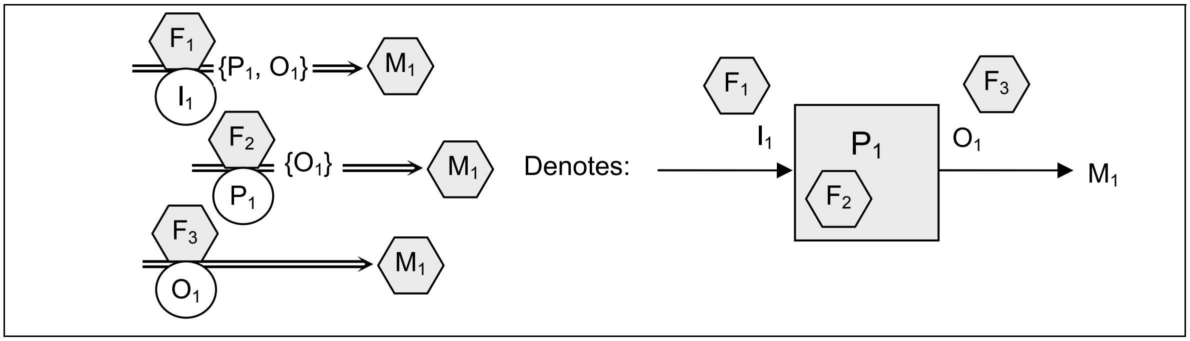


Figure 14 IAM Safety Analyses Notation

This diagram shows three different possible causes for malfunction M_1. The first emphasis is on the Input I_1 with the possible Failure F_1. The failure of input activity through dependent activities of process and output may result in a failure leading to a hazardous situation. Similarly, the other two failure aspects are in the process P_1 and output O_1, associated with possible failure F_2, F_3, respectively. Figure 14 illustrates the concept of multiple of activities combining to form the Malfunction M_1. Note that Example 1 is depicted as the left side of Figure 14. Using Table 6, we can represent this as:

$$(F_1 \wedge I_1 \{[P_1, O_1]\} \rightarrow M_1) \text{ or } (F_2 \wedge P_1 \{[O_1]\} \rightarrow M_1) \text{ or } (F_3 \wedge O_1 \rightarrow M_1)$$

Example 1 IAM Safety Analyses Mathematical Representation

Further, all of these portions combined will result in a failure leading to Malfunction M_1. In this way, the potential malfunction for the IAM can be formulated as follows:

$$\mathbf{M_1 \leq F_1 \wedge I_1 \{[\mathit{P_1, O_1}]\} \cup F_2 \wedge P_1 \{[\mathit{O_1}]\} \cup F_3 \wedge O_1}$$

Example 2 Malfunction Representation of the IAM Analyses

The assessment of the elements of the IAM results in the final potential occurrence of malfunction M_1. It utilizes either a qualitative and quantitative approach employing principles of statistics and probability to determine the level of safety risk, likelihood of hazardous events, and the economic cost–benefit of correcting the flaws through the lifecycle of a software system. It also reveals that pre–identification of potential hazards before the start of development balances the development against effect and cost.

2. Composite IAM

Beginning with the IAM for a given IPO block, we consider the more complex scenarios of a composite IAM. Fundamentally, there are three composing methods: *Conjunctive*, *Selective,* and *Simultaneous* composites, as shown in Figure 15. Other IAM representations exist, but are more complex and are beyond the scope of the introduction intended in this dissertation. The *Conjunctive* IAM represents two IPO blocks executing in series, one after the other. The previous block produces output O_1 that triggers the second block to be processed. The *Selective* IAM represents three IOP blocks working together (the ◊ representing *selection*). One of the two previous blocks produces output O_1 or O_2 that **exclusively** triggers the P_3 processing. The *Simultaneous* or *Joint* IAM represents three IOP blocks working together (the ○ representing *simultaneity*), and both previous blocks produce outputs O_1 and O_2 that jointly trigger the P_3 block.

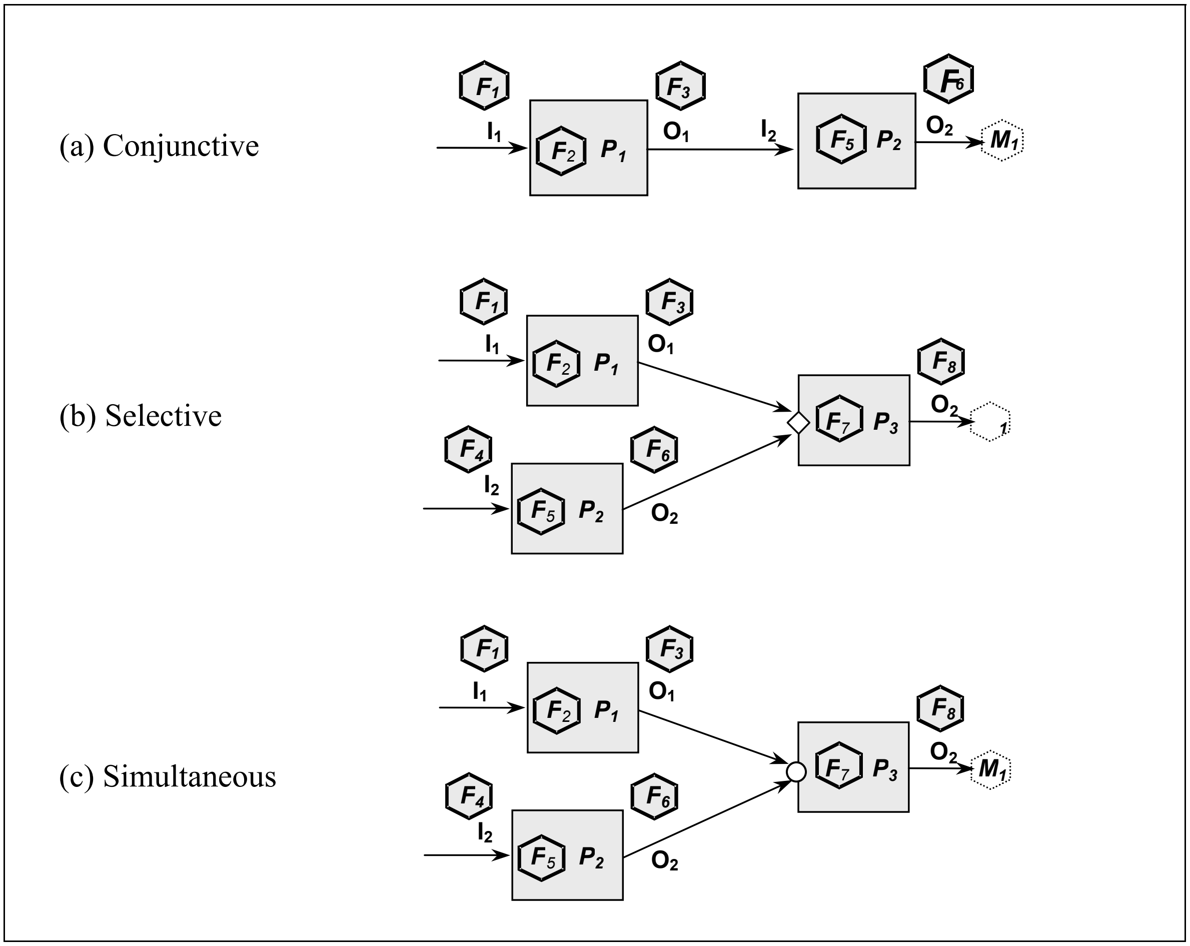


Figure 15 Composite IAM Representations

For the conjunctive IAM, Example 2 can be applied to get the intermediate Malfunction M_x produced by the previous block. The output O_1 of the previous block will be treated as the input for the second block, as depicted in Figure 16 as:

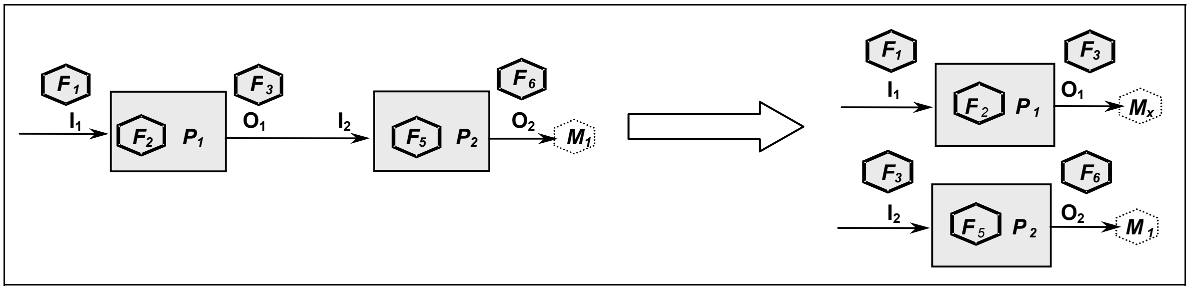


Figure 16 Conjunctive IAM split into Individual IAMs

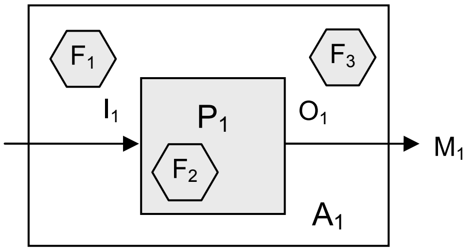
$$M_x = F_1\wedge I_1 \{[P_1, O_1]\}\cup F_2 \wedge P_1 \{[O_1]\}\cup F_3 \wedge O_1$$
$$M_1 = M_x \wedge I_2 \{[P_2, O_2]\}\cup F_5 \wedge P_2 \{[O_2]\}\cup F_6 \wedge O_2$$

Example 3 Conjunctive IAM Mathematical Representation

Therefore, the conjunctive IAM can be logically split into two individual IAMs. Once the factors of the individual IPO blocks are determined, such as input, process, and output and their associated failures, individual IAMs can be applied to analyze the safety, shown as Figure 16.

For the selective IAM, shown as Figure 15.b, there are three IPO blocks (I_1, P_1, O_1), (I_2, P_2, O_2), ([$O_1 \lozenge O_2$], P_3, O_3), each of which can be treated as an individual IAM. A new notation is introduced for the selective IAM: [$O_1 \lozenge O_2$]; meaning that one and only one of two inputs trigger the execution of process P_3. Hereby the combined effect of [$O_1 \lozenge O_2$] as inputs on the third IPO block, as $M_1\wedge O_1 \cap M_2\wedge O_2$, will produce the safety risk. This can be interpreted as a potential lower boundary assessment for the safety assessment. According to Example 2, the first two blocks may produce failures leading to malfunctions M_1 and M_2, respectively, while selective inputs may produce failure leading to M_3.

Quantitatively, applying the definitions of Table 6, the probability of failure can be formulated for the IAM. For the Basic IAM shown in Figure 12, the probability of failure for various types (failure degree) is the sum of the *probability of activity failure* by *probability of activity,* illustrated as follows:



As M_1 depends on (F_1, I_1, P_1, F_2, O_1, F_3) then

$$\boldsymbol{P_f(M_i, d) \le \Sigma(P_f(F_i, d) * P_e(A_i) * P_e(A_i \{DA_i\}))}$$

Where: $P_f(F_i, d)$ is Probability of Activity Failure,
$P_e(A_i)$ is Probability of Activity Execution,
$P_e(A_i\ \{\mathbf{DA_i}\})$ is Probability of Series Dependant Activity Execution.

$$P_f(M_1, A_1) \le (P_f(F_1, I_1) + P_f(F_2, P_1) + P_f(F_3, O_1)) * P_e(A_1)$$

Equation 3 IAM Summation

For the purpose of this dissertation, the Instantiated Activity Model is illustrated in terms of a notional aircraft weapon arming and control software system (WACSS). The weapons arming system is required to control the arming of specific weapons for deployment, store weapon's configurations and loadouts in a selectable menu, prevent inadvertent weapons release, prevent intentional release outside of permitted envelopes, and provide selectable fuse–arming delays to ensure sufficient separation of the weapon from the delivery unit. The WACSS would function as a subsystem of a greater stores controller and aircraft avionics system.[227, 228] The WACSS has a high potential for a hazardous event, as it controls explosive ordnance in a combat environment and interfaces with the avionics system of a high–performance military aircraft. Both ordnance and aircraft have the potential to cause significant property damage as well as take the lives of persons within their destructive radius. The destructive radius of a

[227] *DRAFT Joint CAF and USN Operational Requirements Document for Joint Direct Attack Munitions (JDAM) CAF 401-91-III-A*, Office of the Undersecretary for Defense (Acquisition & Technology); 16 December 1998.

[228] *8th Fighter Wing Weapons Attack Guide*, 8th Fighter Wing, U.S. Air Force; Kunsan Air Base, Korea; December 2000.

military weapon can range from a few dozen yards to over a half mile, depending on the specific weapon and method of employment.

We present an approach capable of improving the software process by increasing software safety and reducing the probability of hazardous events. This approach is compiled into a repetitive cycle of five phases, namely:

1. Hazard Identification
- System Task and Safety Requirement Analysis
- Investigation and Inspection
- Development of Consequence Severity Categories and Threshold

2. Software Safety Assessment
- Consequence Severity

3. Safety Decision Making and Development
- Process Flow Mapping
- Initial Failure Depiction
- Assessing Process
- Change Determination through Threshold Establishment

4. Implementation of Safety Controls
- Acceptance, Avoidance, Reduction, Spreading, and Transference
- Design and Development

5. Supervision of Safety Changes
- Implementation
- Assessments of Validity / Effectiveness
- Repeat

C. INITIAL IDENTIFICATION OF THE HAZARD

For each system, it must be determined whether hazards exist if the system were to experience any failure to meet project requirements. Specific hazards that exist must be identified and their consequences determined. Further analysis includes the review of potential hazards that may occur during the normal operation of the system within the parameters of system development requirements, and the review of potential hazards not constrained by system requirements. Such a review could be potentially overwhelming and devour precious resources if not well managed and constrained. The evaluation can be derived using system requirements and historical precedents. Hazards beyond the constraints of system requirements require a review of similar systems that may have hazards not considered in the development of the primary system. A review of system functionality should include the inspection for potential hazards that could be induced due to failed or missing system requirements. The initial identification could be an ad–hoc inspection at the system concept level to determine possible consequences of system failure. A more in–depth identification of system hazards can be accomplished with each progression in the development process, including revisions and supplements to the system requirements. Hazards should be investigated for their occurrence over the three possible states of the system:

- When the system fails to function properly – checking to see if an improper functionality of the system will result in a hazard,
- When the system fails to function – checking to see if the system is incapable of controlling them, and
- When the system functions properly – checking to see the existence of inherent hazards within the system.

Using the Spiral Development Concept, the initial examination would be strengthened and refined through each consecutive iteration of development and inspection. Subsequent cycles permit a more detailed examination of the development and potential consequences of failure.

Step 1. Action 1. - System Task / Safety Requirement Analysis – Identify the primary safety requirements of the system through a review of concept level requirements, including system objects, properties, tasks, and events. Identify system safety requirements as they pertain to system state and operating environment. Additional safety requirements may be identified using historical precedents and rationalization from similar systems. System requirements should be inspected for

completeness and the inclusion of system safety logic controls and interlocks, where applicable. Assessments should be made to evaluate size, time, effort, defects, and system complexity.

Step 1. Action 2. - Hazard Identification – Perform a hazard identification of the software system based on concept level system requirements, system tasks, and historical precedents. Identification includes identifying the Hazards, Consequences, and Malfunctions potentially occurring from the three states of hazard occurrence.

Hazards should be identified by their consequence, malfunction, system state, and failure required to generate the consequence. The Initial Hazard Identification is critical to system development as it establishes a foundation for the rest of the assessment. A system may have multiple potential hazards, based on the system design and the objects it controls. Likewise, each hazard may have multiple faults and triggers that set it in motion. This cursory inspection permits early identification and prioritization of potential hazards before the system begins to firmly take shape, as shown in the example of APPENDIX E.1 of this dissertation. Fault and trigger[229] controls and interlocks will be discussed later in this chapter.

During the Initial Hazard Identification Phase, faults, triggers, and specific failures may not be identified due to the infancy of the development process. The only resources available at this stage for hazard inspection and identification may be the System Concept Documents, Initial System Requirement Specifications, and other preliminary documents. As demonstrated in Table 20 and Table 22, malfunctions, hazards, and consequences may be grouped where similar in composition and content. Note, that while some categories may permit items to be consolidated, their root causes retain some value of independence. This root independence contributes to a unique series of safety assessments and failure probabilities for each branch of the failure. In some cases, multiple root failures may be set in motion by a single trigger. Each failure event

[229] Note: See Chapter II.C of this Dissertation for discussion and definitions of faults, triggers, and failures as they apply to software system safety.

may have its own distinct probability of occurrence before joining with other events further down the process line.

The inspection and object identification should consist of both forward and back–flow process inspections to determine all potential safety–related objects. The accomplishment of various "what–if" and "why" scenarios permits a review of the system from both ends of the process spectrum, from input to output. The actual testing method used by the assessment team depends on the system being tested, the ability to extract data from the tests, and the applicability of the tests to overall system safety. Inspections should attempt to identify the location of a potential failure with respect to the system flow, the degree of a failure and its potential propagation to other failures (snowball), the times or instances for which the failure might occur, and the repetition rate of the failure. Such properties make up what can be referred to as "failure exposure."[230]

Subsequent inspections will identify hazards and triggers to a greater detail, based on the level of development of the system and its relationship to potentially hazardous objects. The goal of making the IAM measurement on probability of failure is to identify potential hazards before the start of development, thereby providing the opportunity to balance development against effect. The degree of effort and detail in characterizing potential causes of a hazard should be commensurate with the severity of resulting consequences. The methods used to identify hazards and their causes, and to categorize severity should be well documented.

D. INITIAL SAFETY ASSESSMENT

The *Identification* and *Assessment* phases rely on multiple sources of evidence and contextual material to determine a level of safety for the system. Presenting these relationships, while preserving the flow and readability of the process depiction, is extremely difficult but essential to the success of the assessment. The more in depth an assessment is made of a system, the more accurate the evaluation will be. As more depth is added to the assessment, the product can become three and four–dimensional. The IAM provides a method for evaluating the system at one instance in state, but a system may have many states for which it must be evaluated. To ensure that the assessment is inclusive of all potential states without adding confusion, the assessment must be managed and cross–referenced in a logical manner. Appendix E demonstrates a potential method for logically depicting an assessment of a complex system across multiple states. The actual format of the software assessment process remains the prerogative of the development and assessment team, so long as the format provides information in an easy to discern fashion and does not detract from the safety of the system as a whole.

A *Safety Assessment* requires the balanced measurement of the probability of hazard occurrence (*P(H))*, and the severity of the hazard consequence (*C(H)*). The combination of these two values resolves the safety of the software system (*S*). It is possible that the probability of *Hazard Occurrence* cannot be accurately computed early in the development process due to a lack of system maturity. Some value of probability can be assumed based on similarities to existing/historic systems, taking into account lessons learned, improvements, and technological advances in related systems. Probabilities may be estimated across a field or ranges of values, depending on the fluidity and understanding of the system.

There exists a myriad of metrics and procedures capable of determining a degree of probability of the occurrence of a specific event in a software system.[231, 232, 233] The assessment of hazard probability should be based on the review of all pertinent information, as well as a subjective review of the system from the scrutiny of multiple

[230] *Operational Risk Management (ORM) Handbook, Subset to AF Instruction 91-213, 91-214, and 91-215 Operational Risk Management*, Air Force Civil Engineers, U. S. Air Force; 1991.

[231] See examples in Chapter II.E.2 – *Traditional Methods to Determine Software Safety*

[232] Pai, Ganesh J.; Donohue, Susan K.; and Dugan, Joanne Bechta; *Estimating Software Reliability From Process And Product Evidence*; Department of Electrical and Computer Engineering; and Systems and Information Engineering, The University of Virginia, Charlottesville, Virginia.

[233] Fischer, Rolf; Kirchgäßner, Bertold; *Reliability Analysis and Optimization in PERMAS*; *NAFEMS Seminar, Use of Stochastics in FEM Analysis,* INTES GmbH, Stuttgart, Germany, 08 May 2003.

developers. The degree of confidence in the assessment will increase in later stages of development as the system becomes more stable and the change decreases.

The severity of a specific consequence is related to the hazard density of the process, the relationship to other hazards (as one hazard may defeat or promote another), and the repeatability of such events leading to the hazard. Hazard density refers to the abundance of hazards that could occur over a set of system tasks.

Consequence Severity must first be assessed for its negative value or harm to the system, customer, or society. Additional consideration should be made of the economic or intrinsic costs of the hazard when determining Consequence Severity. The assessment of severity can be based against a predefined categorized table. Each category must be distinct from the previous to ensure no potential for overlap or confusion.[234] The table should range from the smallest discernable degree of *Severity* to the greatest degree possible. Various risk methodologies use a common set of Consequence Categories, as exemplified in Table 7.[235, 236] Additional levels and sub–levels may be introduced if the system assessment requires such granularity.

Definitions of specific categories are negotiable based on the intent of the system, resulting threat / consequence to the general public, threat to the system, and the resources of the operator / developer to compensate for the resulting action. Level definitions may be refined to fit the specific system. Definitions in Table 7 cover a

[234] Personal Comment: Establishing consequence severity threshold has traditionally been a difficult and politically charged task. In most cases, the levels are refined based on historical events and present observations of similar systems and hazards. In Naval aviation, evaluators developed two scales, one to measure the monetary damage of an event and a second scale to measure the personnel injury from an event. These scales omit an important measure of mission criticality, in that it determines how your mission making ability is influenced by a hazardous event occurrence. As a system matures and a safety assessment team becomes more experienced with dealing with specific hazards and consequences, they will realize a comfort level applicable to each scale of danger and the threshold for which the assessor and client will accept. Yes, this is a gray measure and will result in hours of debate between client, management, and developers. The scales used in Naval Aviation have matured over years of trial and error, and have shifted by promptings from economic and political voices.

[235] *Operational Risk Management (ORM) Handbook, Subset to AF Instruction 91-213, 91-214, and 91-215 Operational Risk Management*, Air Force Civil Engineers, U. S. Air Force; 1991.

[236] *MOD 00-56, The Procurement of Safety Critical Software in Defence Equipment Part 2: Requirements*, Ministry of Defence; Glasgow, United Kingdom; 1989.

system capable of physical injury and significant economical loss. Consequence Severity definitions may be significantly different for unique systems that may not result in physical injury or monetary loss, but may result in damage to the system or the environment. It may be necessary to further characterize terms used in severity definitions to eliminate confusion and provide distinct boundaries between severity levels. For example, in Table 7, definitions or examples may be provided for major, minor, and less then minor mission degradations, injuries, or system damages. Severity level ordinal values are introduced for brevity reference later in the assessment process.

For determination of a Safety Index, the severity definition is matched with a corresponding numeric value, ranging from 0 to 1.0. The severity value can then be used to calculate the final value of safety.

		LEVEL	DEFINITION
SEVERITY	**1.0**	I – CATASTROPHIC	Complete mission failure, loss of life, or loss of the system.
	0.6	II – CRITICAL	Major mission degradation, severe injury or occupational illness, or major system damage
	0.3	III – MARGINAL / MODERATE	Minor mission degradation, minor injury or occupational illness, or minor system damage
	0.0	IV – NEGLIGIBLE	Less then minor mission degradation, injury, illness, or minor system damage.

Table 7 Basic Consequence Severity Categories

Step 2. Action 1. - Development of Consequence Severity Categories – Develop a prioritized list of Consequence Severity Categories, ranging from the most severe to the least severe possible consequence. Severity categories should be well defined to eliminate confusion and provide distinct boundaries between.

Step 2. Action 2. - Initial Hazard Assessment – Perform an initial hazard assessment of the system by classifying hazards according to Consequence Severity, based on an agreed table of Consequence Severity Categories.

One military software system may consider a *Catastrophic* Consequence to be the death of three or more service members in a single incident, while a *Critical* Consequence might be the death of one or two service members. A commercial refrigeration software control system might consider a *Critical* Consequence to be the complete spoilage of a refrigerator's contents, while a *Catastrophic* Consequence could be the release of Freon refrigerant into the atmosphere and subsequent EPA fine. Naval Aviation uses a classification matrix based on the amount of monetary damage, personnel injury, disability, and death, as depicted in Table 8.

	LEVEL	DEFINITION
SEVERITY	A	Total damage cost if $1,000,000 or more and/or aircraft destroyed and/or fatal injury and/or permanent disability
	B	Total damage cost is $200,000 but less then $1,000,000 and/or permanent partial disability and/or hospitalization of three or more personnel.
	C	Total damage cost is $20,000 but less then $200,000 and/or five lost workdays.

Table 8 OPNAV Mishap Classification Matrix[237]

For the purpose of the WACSS example, Table 21 is included to demonstrate a probable Consequence Severity depiction. Optimally, each consequence should be evaluated, at a minimum, on:

- The importance / critically of the operation of the system to mission accomplishment,
- The consequence's effect on the continued operation of the system,
- The ability of the system to recover from the consequence,

[237] *OPNAV INSTRUCTION 3750.6R, Naval Aviation Safety Program*, Chief of Naval Operations, Department of the Navy; 01 March 2001.

- The ability of the owner / operator of the system to recover from the consequence,
- The ability of the owner / operator to afford the required compensation for the consequence (monetary damages, legal restitution, civil fines),
- The effect of the consequence on the general public, military, and governmental workers (each party graded separately),
- The resulting long term trust in the system, and
- The political / emotional effects of the consequence.

The above bulletized list serves as a generic sample of consequence assessments. A more specific list may be tailored to the actual product under development, taking into consideration the actual consequences that the system may experience. There is no specific ordering to the assessment, except that the review should encompass all potential aspects of consequences and applicable severity categorizations. For purposes of developing a system Consequence Severity table, as in Table 7:

1. Determine the types of consequences that apply to the specific system, using the above list or other applicable consequences relevant to the system under development.

2. Determine applicable break points that could be readably defined to segregate consequence severities for each type of consequence.

3. Determine applicable severity levels that apply to segregated consequence severities.

4. Match consequence severities levels to segregated consequences.

After constructing the system Consequence Severity table, it may be evident that some definitions could include elements that are tangible as well as intangible, depending on the elements of the evaluation.

During the assessment and development process, client and developers may realize that routine operation of the system may place operators or public at risk. Such risks must be evaluated in the same manner as other hazardous events and be an integral part of the final determination of the system's overall safety. The ultimate decision to continue production and employment of the system must judge if the risk and potential harm outweighs the benefit received from the operation of the system.

Subsequent assessments will identify additional hazard exposures, frequency, and probability based on the level of development and logic / functionality of the software system. One goal of the initial hazard assessment is to determine acceptable levels of failure based on hazard consequence severities. Potential results of the initial hazard assessment may include:

- A review of the budget assessed for the development, including additional budgetary requirements necessary to overcome, prevent, or mitigate identified consequences,
- A review of the proposed development schedule for the refined effort required to manage identified consequences,
- A review of system development requirements for applicability, taking into consideration newly and categorized consequences,
- A review of the capabilities of assigned developers and their abilities to overcome identified consequences using current methods, and
- The ultimate cost–benefit decision to continue or discontinue the development process.

These assessments will be used to direct the effort of the development process, optimally reducing the overall hazard potential through proper design. The methods used to assess consequences should be agreed upon before identification and should be well documented.

E. SOFTWARE DEVELOPMENT AND DECISION MAKING

Once hazards have been initially identified and assessed, it is then possible to develop the system using goal-oriented methods. The goal of the development should be to build a software system that produces as few hazards as possible, placing a greater emphasis on hazards with the most significant consequences.

The IAM, Instantiated Activity Model, is a typical IPO (Input–Process–Output) block schema dealing with a set of related activities such as *Input, Process, Output, Failure, Malfunction, etc*, as depicted in Figure 12. A shown, it is possible to associate a potential failure with each activity of the system. For instance, Input I_1 with potential failure F_1, through successive activities Process P_1 and Output O_1 would result in a failure leading to a Malfunction M_1. The IAM reveals the relationship between the essential IPO activities, the potential failures, and the hazardous situation or malfunction.

1. Process Flow Mapping

Software Engineering has a virtual cornucopia of graphic models to depict software logic process flow. Many of those models were previously reviewed in Chapter II.E. Additional models include the Stimulus–Response Structure and Spec Syntax.[238] Spec language is designed to define the environmental model of complex programs using logic based notation and pictorial representations. Regardless of the model selected, it must be capable of:

- Depicting the process flow of independent requirements
- Depicting the interdependencies of logic decisions
- Depicting the potential conflicts and recovery mechanisms of critical components
- Depicting the relationship and flow of function failure to hazard execution

[238] Berzins, Valdis Andris; Luqi; *Software Engineering with Abstractions*, Addison-Wesley Publishing; 1991.

After an investigation of available methods and models, it is determined that a pseudo form of Fault Tree Analysis[239] best suits the requirements of a Software Safety Process Flow, using additional graph elements to depict both the fan–out and fan–in characteristics of the process flow. Such a process graph analysis permits the depiction of decision–making and process structure where, like a tree, the process can split and branch from the trunk to cover all possible perturbations of the process, but include the additional ability for processes to merge back together or even flow backwards as feedback to preceding processes. Ideally, a software system would behave cyclically with a constant set of controlled inputs. Realistically, software system can have a near infinite set of possible inputs, depending on the declaration of the input variable. Process graph models are well suited to portraying such variable input to output systems.

Step 3. Action 1. - Choose a Process Depiction Model – Determine the optimal process depiction model to perform a safety assessment of the system. This process model should be capable of depicting requirement process flow, logic decisions, conflict and recovery, and the isolation of function failure to hazard execution.

The process flow mapping determines the initial set of blocks required to populate the Instantiated Activity Model using the identified system requirements. Once activity sets are identified, we populate sets with applicable high–level activity items and properties. Items and properties include, but are not limited to, process inputs, outputs, and connections. In accordance with the IAM and associated activities, we map the system process to include all high–level system processes, inputs, outputs, and limits.

[239] Hiller, Martin; Jhumka, Arshad; Suri Neeraj; *An Approach to Analyzing the Propagation of Data Errors in Software, (FTCS-31 and DCCA-9)*, The International Conference on Dependable Systems and Networks; 2001.

Ideally, each system would consist of a finite set of IPO blocks and elements. The terms *Process, Event, Function,* and *Module* can be assumed synonymous for depicting IPO block flow. In such three–object systems of inputs, processes, and outputs, errors can be introduced in the inputs and process objects, resulting in failed output objects. Basic IAM assumes that one input contributes to one or more errors. Realistically, the combination of one or more inputs may be required to generate a single error depending on the input value, limits of the system, and reliance or relation of one input to the next. In complex systems, a single process input becomes highly reliant on secondary inputs to meet the logic requirements of the system. Despite one input being out of bounds, its effect and action may be compensated for by a series of other inputs.

Once an instantiated activity model has been selected, the elements of the system can be identified and organized for later display in said model. The process graph model selected for this development includes the following elements:

- Independent IPO Block
- Failure Event
- Current Activity
- Dependability Activity

Step 3. Action 2. - Identify Objects Required to Populate the Process Model – Determine the initial set of objects required to populate the process model identified in Step 3.1., using system requirements identified in Step 1.1. Once object sets are identified, populate sets with applicable high–level object items and properties. Items and properties include, but are not limited to, process inputs, outputs, and connections. (See example Table 23 thru Table 26)

Object identification is accomplished by the ordinal identification of all major processes, functions, and properties of the software system in the following fashion:

(1) Identify Software System Processes and Title (Table 23)

(2) Designate Process Object Numbers

(3) Detail Process Descriptions

(4) Identify Software System Inputs to each Process (Table 24)

(5) Designate Input Object Numbers

(6) Detail Input Descriptions

(7) Assign Relations from Inputs to Processes

(8) Identify Software System Outputs to each Process (Table 25)

(9) Designate Output Object Numbers

(10) Detail Output Descriptions

(11) Assign Relations from Outputs to Processes and Inputs

(12) Identify Software System Limits to each Input and Output (Table 26)

(13) Designate Limit Object Numbers

(14) Detail Limit Descriptions

(15) Assign Relations from Limits to Processes, Inputs, and Outputs

(16) Depict / Map the System of Processes, Inputs, Outputs, Limits, and their Relations (Figure 21)

Steps 1 – 11 are similar to identifying the elements of a classic data flow diagram, with the additional element of process flow. Limits are defined as the anticipated bounds for which the system is expected to operate within, as per the development requirements. It could be expected that operation outside of those bounds might result in a failure in the system's operation. The term "limits" does not infer that actual objects, limits, controls, or interlocks exist that limit the inputs or outputs of the system to specific bounds, only that the system should operate within those bounds. It is possible that rejected inputs outside of acceptable limits will eliminate a safety–critical failure mode associated with the software process. The identification of such limits should be included in system development for the construction of applicable objects, limits, controls, and/or interlocks. The identification of limits is not restricted to one process or data flow, but can relate to multiple lines depending on the flow of the system.

Invariants and post–conditions of each process and of the system can be defined by object limits, assuming the system remains within operating parameters. Limits can be used as one of the possible indicators for identifying potential failure. Depending on the system under investigation and the consequence of a limit–type failure, that un–handled limit violation may result in a safety based hazardous event.

Step 3. Action 3. - Pictorially Map the System Process – In accordance with the process model identified in Step 3.1., and process objects identified in Step 3.2., map the system process, to include all high–level system processes, inputs, outputs, and limits. (See example Figure 21)

2. Initial Failure to Process Identification

The system process flow map relates system objects to potential failures and system operating errors. Through the use of a process graph, it becomes possible to identify the safety weaknesses within the system, matched with system processes, inputs, outputs, and limits following the flow of system operation. Such a depiction permits the observation of hypothetical process failure flow once a flaw is triggered. While malfunctions, hazards, consequences, and severity are identified early in the assessment process, a further assessment and assignment of failures to malfunctions and process objects completes the cycle of system failure identification.

Hypothetical failures can be identified early in the analysis and development process by reviewing the process flow graph, identifying the process line affected by specific system operations, the particular points at which a process line may start, where the process line may end, and which objects / relationships are required for performance of the particular process line. A process line can be defined as a microelement of the entire process graph with its own isolated branches and roots. A process line can include specific inputs, outputs, and processes that are isolated for a particular event and action, as depicted in Figure 24 thru Figure 28 (Pages 350 thru 374). Such branches and roots are observed in the greater process graph.

While a system may be plagued with scores of potential failures, for the purpose of a safety analysis, it is only essential to concentrate efforts on those failures that eventually relate to system hazards. Other failures, or even flaws, may result in less then optimal performance of the system, but do necessarily contribute to safety–related hazards. Their identification and analysis are accomplished in other forms of software development testing procedures not covered in this dissertation.

Step 4. Action 1. - Identify and Match corresponding Failures to Malfunctions. – In accordance with the malfunctions identified in Step 1.2., and process objects outlined in Step 3.2., identify the potential system failures that could eventually result in identified safety–related malfunctions. If identified failures relate to malfunctions not previously identified, return, and repeat the system assessment from Step 1, Action 2. Identified failures are then matched to specific process objects.

The identification of system failures and malfunctions should be composed in a table similar to that of the Initial Safety Assessment Table Example of Table 20 and further decomposed in Table 22 and Table 27. Failures, and their respective probabilities of execution, may be derived from research, analysis, and evaluation of historical data from similar systems. Once hypothetical failures have been identified and related to system objects, they may then be injected into the system process map as depicted in Figure 22. Failures can be identified by analyzing the malfunctions to determine which process objects are susceptible to failure for a given malfunction. One failure may propagate through the system as it follows the process flow. Such similar failures should be grouped and sub–noted for easy identification in the process map.

While a malfunction may answer the question of “What negative action might the system take if it was not to behave properly?”, a failure answers the *cause and effect* question of “Which process and how must that process fail, to cause the system to take such a negative action?” The initial evaluation is based completely on assumption and examination of the hypothetical system and not on actual system’s operation, assuming a worst–case scenario of system functionality.

Step 4. Action 2. - Add Identified Failures to the System Process Map – Using the process map completed in Step 3.3., and failures identified in Step 4.1., add identified failures to their corresponding locations on the process map using agreed process graph symbology.

Failure to Process Identification assumes that an element of the system will fail and result in a malfunction. The identification relies on the basic premise that the development is imperfect and will include flaws. Once safety critical functions are identified, additional emphasis can be placed on their development to reduce the probability of errors in the design and development. The identification of specific triggers and flaws is reserved for further investigation.

3. Assessing the System Process

To this point in the Software Safety Process, the analysis and investigation of the system has resulted in a series of products that both textually and graphically outline the flow and hypothetical failure possibilities of the system. The Safety Assessment will complete the initial investigation of the system by providing a numeric and textual result of the investigation, as it pertains to the system's safety and hazard avoidance. Once the events of the system process have been mapped as they pertain to safety, it is possible to determine the probability that a system event will occur, as well as the probability that that event will fail to occur properly. Consideration must be taken to the conditions mentioned in Chapter IV.B, namely the measured evaluation of *specific hazards*, *degrees of hazards*, *protections* and *redundancies*, *stability*, *cost*, *restoration*, and *repair.*

Probability is the basic study of the relative likelihood that a particular event will occur.[240] In the analysis of the software system, an assessment of Software Safety can only be made after determining the probability of execution of an event and if that event will function properly. Previous steps in the investigation have identified the potential hazardous outcome of such a failed event. In a safety assessment, each hazardous event

[240] Lindeburg, Michael R., P.E.; *Engineer in Training Reference Manual 7th Edition*, Professional Publications, Inc; Belmont, California; 1990.

has an independent probability of occurrence. The result of these calculations are use to make the final assessment and assignment of the Safety Index. For this investigation and assessment, this method will utilize principles in *Joint*, *Complementary*, and *Conditional Probability*, as well as principles in *Series* and *Parallel System Reliability*.

Assessing system process deals with such aspects as joint probability, complementary probability, conditional probability, failure severity, and so forth. *Joint Probability* specifies the probability of a combination of events. An event can be defined as the occurrence of objects (inputs, outputs, limits, processes, …) within the software system. The population for the assessment consists of all events that occur in the system that could potentially result in a hazardous event. Assuming that each failure could potentially lead to a hazardous event and that each failure is matched to a specific object, then it could be derived that the series of objects that contain a failure make up the population for the assessment.

Through the application of *Complementary Probability*, due to the size and complexity of some software systems, it may be more efficient to determine the probability that an event does not occur than to determine when it does occur. Given that P is the probability that an event will occur, 1 – P represents the probability that an event will not occur, the complement equals one minus the probability of occurrence.

Conditional Probability can be defined as the probability that one event will occur, given that another event would also occur. Such reliance permits the evaluation of one series to execute (P_e), as well as the evaluation of that series to fail to function properly (P_f), each series containing its own probability for occurrence. In a complete system, it cannot be assumed that all processes will occur continuously, nor can it be assumed that all events will occur flawlessly. Both probabilities must be evaluated, as P_f cannot occur without the occurrence of P_e.

a. Failure Severity

As reviewed previously in Chapter II.D, it was noted that failures have the probability of occurring, resulting in varying degrees of consequence severity. One object failure might occur undetected by the system as a whole, but the fact remains that a failure did occur; while another failure might propagate uncontrollably through the system, rendering the system incapable of further operation. An assessment of system safety must review the probability of object failure at varying degrees to determine the ultimate value of system safety.

Failures must be evaluated for their severity, probability of occurrence, and potential of that occurrence generating a malfunction. These three variables combine to determine the overall probability of the system failure. Table 9 lists probable Object Failure Severities ranging from least to greatest severity, as well as definitions of probable failure types. Additional types and definitions can be added at the prerogative of developers as well as those conducting the analysis. It should be noted that some failures may be so benign as to permit the system to continue operating; while a separate failure may cause the system to cease functioning and resulting in a hazardous event. As it is not necessary to conduct an analysis on object failures that do not result in a system malfunction or hazardous event, it is not necessary to take those objects into consideration. While, in many cases, failure severity may not directly contribute to the level of the hazard, it does serve as a characterization of system's ability to operate and its inability to limit program functionality and protection, and the potential to lead to additional hazards.

Failure Type	Definition
Invalid Failure **Disregarded**	Intentional design or secondary defect in parallel system, not resulting in a general system failure
Minor Flaw **Disregarded**	Flaw that does not cause a system failure or result in a malfunction
Latent Failure **Disregarded**	Failure that remains hidden in the background of the system, not resulting in a malfunction
Local Failure **Disregarded**	Failure local to an object, not contributing to a general system failure
Benign Failure **Disregarded**	Failure that propagates to a system failure with slight or insignificant consequences
Intermittent Failure	Failure that persists for a limited duration, followed by a system recovery, potentially, but not always resulting in a system malfunction
Partial Failure	Failure that results in the system ability to accomplish some, but not all requirements, potentially resulting in a malfunction
Complete Failure	Failure that results in the system's inability to perform any functions, resulting in a malfunction
Cataclysmic Failure	Sudden failure that results in a complete inability to perform any functions, resulting in a malfunction

Table 9 Failure Severity

Concretely, the assessment of the failure for various types can be represented as follows:

$$\begin{aligned}
P_{\mathrm{f}}(\mathrm{M}_1, \textit{intermittent}) \leq\; & P_{\mathrm{f}}(\mathrm{F}_1, \textit{intermittent})*P_{\mathrm{e}}(\mathrm{I}_1)*P_{\mathrm{e}}(\mathrm{I}_1\,\{[P_1, O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_2, \textit{intermittent})*P_{\mathrm{e}}(\mathrm{P}_1)*P_{\mathrm{e}}(\mathrm{P}_1\,\{[O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_3, \textit{intermittent})*P_{\mathrm{e}}(\mathrm{O}_1)
\end{aligned}$$

$$\begin{aligned}
P_{\mathrm{f}}(\mathrm{M}_1, \textit{partial}) \leq\; & P_{\mathrm{f}}(\mathrm{F}_1, \textit{partial})*P_{\mathrm{e}}(\mathrm{I}_1)*P_{\mathrm{e}}(\mathrm{I}_1\,\{[P_1, O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_2, \textit{partial})*P_{\mathrm{e}}(\mathrm{P}_1)*P_{\mathrm{e}}(\mathrm{P}_1\,\{[O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_3, \textit{partial})*P_{\mathrm{e}}(\mathrm{O}_1)
\end{aligned}$$

$$\begin{aligned}
P_{\mathrm{f}}(\mathrm{M}_1, \textit{complete}) \leq\; & P_{\mathrm{f}}(\mathrm{F}_1, \textit{complete})*P_{\mathrm{e}}(\mathrm{I}_1)*P_{\mathrm{e}}(\mathrm{I}_1\,\{[P_1, O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_2, \textit{complete})*P_{\mathrm{e}}(\mathrm{P}_1)*P_{\mathrm{e}}(\mathrm{P}_1\,\{[O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_3, \textit{complete})*P_{\mathrm{e}}(\mathrm{O}_1)
\end{aligned}$$

$$\begin{aligned}
P_{\mathrm{f}}(\mathrm{M}_1, \textit{cataclysmic}) \leq\; & P_{\mathrm{f}}(\mathrm{F}_1, \textit{cataclysmic})*P_{\mathrm{e}}(\mathrm{I}_1)*P_{\mathrm{e}}(\mathrm{I}_1\,\{[P_1, O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_2, \textit{cataclysmic})*P_{\mathrm{e}}(\mathrm{P}_1)*P_{\mathrm{e}}(\mathrm{P}_1\,\{[O_1]\}) + \\
& P_{\mathrm{f}}(\mathrm{F}_3, \textit{cataclysmic})*P_{\mathrm{e}}(\mathrm{O}_1)
\end{aligned}$$

In complex systems, it may be necessary to combine equations to represent composite failures with varying degrees of failure types; as if the system were to experience an intermittent failure on the input and a partial failure on the process.

Step 5. Action 1. - Development of Failure Severity Categories – Develop a prioritized list of Object Failure Severity Categories with applicable definitions. Using Failure Modes, Effects, and Criticality Analysis (FMECA) [241] ***techniques, severities shall define the types of failures that a specific object could potentially experience, ranging from the benign to the catastrophic, and the potential effect of that failure on the system as a whole. As the assessment is designed to evaluate system safety, it is possible to disregard object failure types that do not relate or result in hazardous events.***

[241] *NASA/SP—2000–6110, Failure Modes and Effects Analysis (FMEA), A Bibliography*, National Aeronautics and Space Administration; July 2000.

b. Application of Assessment

While the mathematical principles of a system assessment is straightforward and rooted in accepted engineering statistical practices, the initial determination of variable values requires some difficult assumptions based on historical precedents, trained observations, and theoretical postulation. As reviewed through this chapter, it is essential to determine:

1. The potential hazards of the system operation,

2. The process flow of the system,

3. The probability that the system will be executed as a whole,

4. The probability that an object within the system will be executed,

5. The probability that a failure related to an object will be executed,

6. The severity of that object failure, and

7. The probability that a failure will result in a hazardous event.

Potential system safety hazards have been identified using procedures in ***Step 1*** and ***Step 2*** of this assessment process. The process flow of the system has been reviewed and mapped in ***Step 3***. The probability of system execution is based on an evaluation of the system and its intended operation, in accordance with development requirements. Such an evaluation should be based on the ratio of system operation to a defined sample time. In a software system providing continuous operation, the $P_{\text{system execution (se)}}$ = 1.0, while in a software system providing operation for only half of the time, the P_{se} = .50. The sample time period may be a fixed period of time such as a 24–hour period, or a conditional time period based on the execution of a specific event such as the flight time of an aircraft. In the case of WACSS, the sample time period would consist of the time from aircraft power up to aircraft power down, conditional to flights that would employ a weapon. There is limited justification to conduct an analysis on flights where a weapon would not be employed or loaded, or on the time period while the aircraft sits idle on the flight line. Such a decision should be based on the intended function of the system during idle and power–up phases countered by the fact that that failure during these periods are only a small fraction of the total failures of the system.

The probability that an object will execute within the system depends, again, on the requirements and modes of operation of the system being evaluated. System objects can be evaluated independently or grouped as part of a process flow. The method for determining the actual probability of object occurrence is left to the prerogative of one making the analysis. It is not essential to determine the probability of objects within paths that do not relate to failures as their execution is not related to the safety assessment. To provide development continuity, it is beneficial to assign a standardized set of definitions to identify and classify occurrence probability, as previously constructed with the Consequence Severity example in Table 7. Such a probability definition table would include probability levels, frequency key words, and definitions, such as in Table 10. Other items may be included to add clarity to the definition.

Frequency	Definition	Probability
ALWAYS	Events will occur through the entire life of the system.	1.00
FREQUENT	Events are expected to occur often through the life of the system.	0.90
LIKELY	Events are expected to occur several times in the life of the system.	0.75
OCCASIONAL	Events are expected to occur in the life of the system.	0.50
SELDOM	Events are expected to occur seldom during the life of the system.	0.25
NEVER	Events will never occur during the life of the system.	0.00

Table 10 Example Probability Definition Table[242]

Step 5. Action 2. - Development of Execution Probability Definition Categories – Develop a prioritized list of Execution Probability Definition Categories with applicable probability levels, frequency keywords, and definitions.

The Example WACSS Evaluation may require a more complex and defined Probability Definition Table, as noted in Table 28.

Optimally, each event will occur within a given measure of probability. Each occurrence can be matched to, or closely to, a defined probability level, based on system inspection and the way in which the occurrence maps to the system process. Probability levels can either be computed using accepted prediction methods, historical precedents, process inspection, or other valid method of estimation. Such methods serve better for testing random input values to existing systems than to the generation of probability values. The more accurately system execution probability can be determined, the more accurately the eventual safety result will be.

[242] Note: The Example Probability Definition Table is intended for example purposes, and does not reflect the values required for an actual assessment. Actual values are determined through investigation and historical subject matter expertise, and are specific to the specific system under assessment.

Step 5. Action 3. - Assign Execution Probabilities to System Objects – Using the Process Map generated in Step 3.3., assign Execution Probabilities to all system objects that relate to system failures identified in Steps 4.1. and 4.2.. Execution Probabilities should be based on system inspection, historical precedents, and examination.

System Execution Probability can be determined on either the macro or micro level, from the execution of specific requirements or function to the entire system operation. Figure 23 serves as an example of a macro–level examination of the WACSS operation. The example depicts the operation of the WACSS units from aircraft launch to landing, while a micro–level examination could concentrate on the time sample of the actual launch sequence of the weapon. Hypothetically, on a 2.0 hour aircraft flight, the actual configuring, targeting, and launching of a weapon against a target may encompass less than 10 minutes of the entire flight. To generate a safety value for the system, it is very important to understand the macro as well as the micro level of system execution. The micro and macro level execution times will affect different mishaps and both are likely to affect the same mishap. For example, the risk of inadvertent weapon release (due to the WACSS malfunctioning) is present during the entire flight: therefore, there are both macro and micro issues to address. Another malfunction is the premature weapons release: this is likely affected only by the micro issues since the release of the weapon while not in the 10 minute weapons launching preparation would be an inadvertent release.

The process of Failure Probability Prediction is similar to the Object Execution Prediction, with the exception that failures occurs only when the object executes. Failure Probability is neither on the system macro or micro level as it directly relates only to one specific object. The probability that an object or event will fail in its execution depends on the manner in which the object was developed, its employment within the system, the resilience of the object, the timing of its operation, and the vulnerability of the object to failure. Failure instances are evaluated directly with the object for which they are related. As with object execution, the method for determining the probability of object failure is left to the analyzer. As with the Example Probability Definition Table in Table 10, a standardized set of definitions serves to identify and classify failures into comprehensible categories, as shown in Table 29. Failure Probability levels can be computed using standard failure prediction methods[243], historical precedents, process inspection, or other valid method of estimation including the object failure severity.[244]

A great body of research has been completed in the field of Reliability Modeling for Safety Critical Software Systems and the estimation of failure rates over time and operational events.[245] Most of this research assumes that a system will predictably fail to a set degree over a given period. While it is possible to mathematically model this concept, the method makes some general assumptions that do not accurately reflect the operation of a software system. Software does not behave in the same linear fashion that physical objects do. Their modes of operation or failure are dynamically related to the environment under which the system is placed. These states can change at such a rapid rate that the user may be completely unaware of their occurrence and imposition on the system's operation until it is too late. The developers can control, to some extent, the environment within the system but will have limited control on the external environment that can influence the system. There is no guarantee that the environment, internal or external to the system, will provide the same operational state for which the system was originally designed.

It is possible to give a mathematical representation for system reliability based on the evaluation of the system over time in a given environment, assuming that the system will experience the same inputs and operate in the same environment once it is deployed. In reality, every installation of the software system is unique. This uniqueness

[243] See methods in Section II.E.2 – *Traditional Methods to Determine Software Safety*

[244] Schneidewind, Norman F., *Reliability Modeling for Safety Critical Software*, IEEE Transactions on Reliability, Vol. 46, No. 1; March 1997.

[245] Schneidewind, Norman F., *Reliability Modeling for Safety Critical Software*, IEEE Transactions on Reliability, Vol. 46, No. 1, Institute of Electrical and Electronics Engineers, Inc., March 1997.

requires the developers to include robust levels of mitigation and control elements[246] to ensure that the system can continue to operate within the desired bounds for which it was designed. The derivation of any probability of operation, failure, or reliability should be based on the operation of the system elements as independent units that can be combined to generate a complete process assessment. Such an assessment and probability determination may be a combination of traditional reliability measures of operation over time, event, or states, the use of heuristic data gained from legacy systems of like design, or the use of subject matter assessments by experienced personnel familiar with system operation.

Any determination for probability of execution, failure, or operation should be based on a set environmental window. Should the system operate outside of that environmental criterion, then the assessment should be assumed void, necessitating a re-evaluation. Few systems will ever operate in a vacuum. It is imperative that requirements specify the controls and limits necessary to ensure that the system operates within the bounds for which the system was tested and that the system has the flexibility necessary to operate within the bounds required by the user. This delicate balance will tax the abilities of the developers to provide a flexible system that can be certified "safe."

Note: As failure probability may be relatively small for a given event, it is possible to depict Failure Probability with a multiplier extension. Table 29 and Table 30 each have a multiplier extension of x10^{-5}, i.e. a probability of 7.50 x10^{-5} means that the object has a probability of failure of 0.000075 for each time it is executed.

Step 5. Action 4. - Development of Object Failure Probability Definition Categories – Develop a prioritized list of Failure Probability Definition Categories with applicable probability levels, frequency keywords, and definitions as they apply to specific objects within the system.

[246] See Section V.E.4.b - Hazard Controls

In a perfect development process, each software system object would function flawlessly, much less without a failure (the difference previously discussed in this dissertation). As no system is ever without the slightest potential for failure, it is essential to measure when, how, and how frequently it will fail.

Step 5. Action 5. - Assign Failure Probabilities to System Objects – Using the Process Map generated in Step 3.3., Failure Process Map from Step 4.2, and Failure Severity Categories defined in Step 5.1., assign Failure Probabilities to all system objects that relate to system failures identified in Steps 4.1. and 4.2. for each severity of failure. Failure Probabilities should be based on system inspection, historical precedents, and examination.

As with System Execution Probability, System Failure Probability is determined on a variety of levels. The Initial Failure Probability Result is based on the failure of a specific object each time it executes. System Failure Probability is computed based on the results of the Object Failure Probability, Object Execution Probability, and System Process Flow Analysis. As each system executes, there is a probability that an internal object will execute, and then a probability that that object will fail in some degree of severity in its execution. The next logical process is to determine what the probability will be that a failure will be result in a system malfunction. Such a “what if” requires developing a scenario of operation for analyzing the system from the process start to malfunction. In the example WACSS, five primary malfunctions were identified with eighteen potential failure groups. Each of these malfunctions can be transformed into a potential failure scenario and process flow, as shown in Figure 24, Figure 25, Figure 26, Figure 27, and Figure 28.

Step 5. Action 6. Determine Possible System Hazard Flow – Using the Process Map generated in Step 3.3, the Failure Process Map from Step 4.2, and the Failure to Malfunction Identification of Step 4.1, determine the possible System to Hazard Process Flow. Such a Process Flow should include all system objects that could potentially result in a malfunction and eventually a failure.

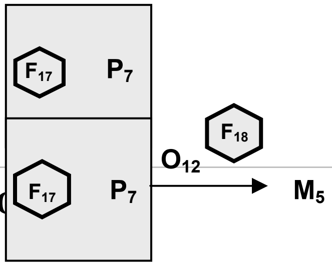
System process failure can be determined using any of a series of probability summation methods. The selected method should be agreed upon by all members of the assessment from the onset, taking into consideration the strengths and weaknesses of each of the various summation methods. The summation process must be capable of computing the probability of independent and dependent lines of system flow, including applicable presuppositions and post functional actions that contribute to the overall process probability of execution and failure. Previous steps in the Safety Assessment provided values for object execution and failure probability. These values, in conjunction with the Process Flow Map, provide the basic elements required to complete the Initial Safety Assessment.

No standard arithmetic notation could be found to denote the process of flow of a software system through associated objects and failures. To overcome this, the following notation examples of Example 4 and Example 5 are given with supplemental plain language definitions. Example 4 demonstrates a simplistic object with a single failure. Notationally, the unit can be represented by its failure and object, separated by bracketed character, as in the example – F_{17}^P_{7} {[O_{12}]} to denote Failure 17 of Process 7 through Output 12. In Example 5 the addition of *Through Objects* (objects which the process passes through but not necessarily including a failure) are included to represent the remainder of the process up to and including the Malfunction. Free formatted text presents an acceptable format for describing the safety assessment as a supplement to mathematical notation.[247]

[247] Kelly, Timothy Patrick; *Arguing Safety – A Systematic Approach to Managing Safety Cases, A Dissertation*, University of York, Department of Computer Science; September 1998.

F_{17}^P_7

Failure (F_{17}) of Process 7(P_7)



Example 4 Failure within an

F_{17}^P_7 $\{[O_{12}]\} \cup F_{18}$^$O_{12} \rightarrow M_5$

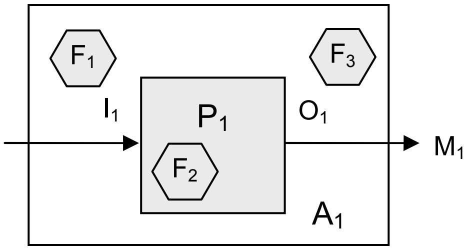
Failure (F_{17}) of Process (P_7), through Output O_{12}; with Failure (F_{18}) of Output O_{12} Resulting in Malfunction (M_5)

Example 5 Failure of an Object with throughput to a Malfunction

$\mathbf{M_1 \leq F_1 \wedge I_1 \{[\mathit{P_1, O_1}]\} \cup F_2 \wedge P_1 \{[\mathit{O_1}]\} \cup F_3 \wedge O_1}$ Example 2

$\boldsymbol{P_f(M_i, d) \leq \Sigma (P_f(F_i, d) * P_e(A_i) * P_e(A_i\ \{DA_i\}))}$ Equation 3

Where: $P_f(F_i, d)$ is Probability of Activity Failure for type,
$P_e(A_i)$ is Probability of Activity Execution,
$P_e(A_i\ \{\mathbf{DA_i}\}))$ is Probability of Series Dependant Activity Execution.



Assume:

$P_e\,(I_1) = 0.40$
$P_e\,(P_1) = 0.40$
$P_e\,(O_1) = 0.25$
$P_e\,(I_1\{[P_1, O_1]\}) = 0.8145$
$P_e\,(P_1\{[O_1]\}) = 0.7500$

$P_{f\ Intermittent}\ F_1 = 0.5000\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_2 = 0.6000\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_3 = 0.8200\text{x}10^{-5}$

$$P_{f\,Intermittent\ M1} \leq P_f(F_1, \mathit{intermittent})*P_e(I_1)*P_e(I_1\ \{[P_1, O_1]\}) + P_f(F_2, \mathit{intermittent})*P_e(P_1)*P_e(P_1\ \{[O_1]\}) + P_f(F_3, \mathit{intermittent})*P_e(O_1)$$

$$P_{f\,Intermittent\ M1} \leq (((0.5000\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.6000\text{x}10^{-5} * 0.40) * 0.7500) + (0.8200\text{x}10^{-5} * 0.25)) = 0.5479\text{x}10^{-5}$$

Example 6 Example Probability of Failure Equation

Example 6 demonstrates one potential method for determining the probability of failure for a given IAM. It can be assumed that each system may have a myriad of different process flows that ultimately may result in a malfunction. In the case of the above example, the process flow contains three *Failure* objects in series, with one *Through Object*, ultimately resulting in a *Malfunction*. Singular failure probabilities $F_{1\text{–}3}$ are determined using appropriate methods, as well as the determination of applicable process execution and related execution probabilities. Using probability methods discussed in this dissertation, it is possible to equate these values to derive a finite failure probability for the series. The summation of series probabilities can be combined to derive a final expression of probability that the system will execute a malfunction, as shown in Table 32.

Step 5. Action 7. - Determine the Probability for each Malfunction Occurrence. – Using the Object Failure Probabilities from Step 5.5. and the Hazard Flow generated in Step 5.6., determine the cause and effect failure probability of the system. System Probability should include consideration of all reliant or dependent objects to the system process.

Early in the Safety Assessment, it was possible to identify Malfunction Severity as it related to Malfunction Hazards and Consequences. Malfunction Severity, combined with the computed Probability of Malfunction Occurrence, can ultimately derive the Safety of the Software System. Relating malfunctions to consequences, it is possible to assign probabilities of occurrence to each consequence and finally a level of Safety to the system. This assignment of Safety requires the macro definition of a System Failure Probability Table, similar to the micro definition table generated in ***Step 5.4***., and Table 29. The table should include plain language descriptions and definitions of system failure with corresponding values of their frequency of occurrence, based on system operation. The frequency of occurrence references the probability that an event will occur for each operation of the system.

An operation of the system assumes the execution of any process series, including those series of operations that do not contain a failure or malfunction object. Based on the speed of some software system processors, it is possible for the system to execute scores of process per second. Table 11 shows a possible system failure definition table for a given system's operation.

Frequency	Definition	Probability $x10^{-5}$
ALWAYS	The system will fail each time it is executed.	> 100000.00
FREQUENT	The system will most likely fail when executed.	5000.00
LIKELY	The system will likely fail when executed.	250.00
PERIODICALLY	The system will periodically fail when executed.	10.00
OCCASIONAL	The system will occasionally fail when executed.	2.50
SELDOM	The system will seldom fail when executed.	0.75
SPORADICALLY	The system will fail sporadically when they are executed.	0.20
UNLIKELY	The system is unlikely to fail when executed.	0.05
NEVER	The system will never fail when executed.	0.00

Table 11 Example System Failure Definition Table[248]

Step 6. Action 1. - Development of System Failure Probability Definition Categories – Develop a prioritized list of Failure Probability Definition Categories with applicable probability levels, frequency keywords, and definitions as they apply to the system as a whole.

A measure of safety can now be determined by tabulating the probability of system failure against the criticality of a corresponding hazard. The probability versus criticality table has been applied successfully in numerous engineering and management safety assessments[249] to determine a level of safety of a system. As shown in Table 12,[250, 251, 252] it is possible to evaluate a system's probability of failure against the system's hazard severity to determine a value of safety.

[248] Note: The Example System Failure Definition Table is intended for example purposes only, and does not reflect the values required for an actual assessment. Actual values are determined through investigation and historical subject matter expertise.

[249] *OPNAV INSTRUCTION 3750.6R, Naval Aviation Safety Program*, Chief of Naval Operations, Department of the Navy; 01 March 2001.

[250] *Draft Reference Guide for Operational Risk Management*, Naval Safety Center; 09 September 1999.

[251] *Operational Risk Management (ORM) Handbook, Subset to AF Instruction 91-213, 91-214, and 91-215 Operational Risk Management*, Air Force Civil Engineers, U. S. Air Force; 1991.

[252] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; Washington, D.C.; 30 March 1984.

			PROBABILITY				
			ALWAYS	LIKELY	OCCASIONAL	SELDOM	UNLIKELY
			A	B	C	D	E
SEVERITY	CATASTROPHIC	I	Extreme	Extreme	High	High	Medium
	CRITICAL	II	Extreme	High	High	Medium	Low
	MODERATE	III	High	Medium	Medium	Low	Low
	NEGLIGIBLE	IV	Medium	Low	Low	Low	Low

Table 12 Example Probability vs. Severity Table

The horizontal axis is comprised of probability types identified in the System Failure Probability Definition Categories (or Malfunction Occurrence) of ***Step 6.1***, while the vertical axis consists of the Severity Categories defined in ***Step 2.1.*** The intersecting point of the two axes represents the safety of the system, or in the case of Table 12, represents how unsafe the system is for a given malfunction and hazard. Intersection values can be represented as either textual definitions or numeric values ranging from the most safe to the completely unsafe. The actual cell values are again based on historical analysis and rationalization from like systems, as well as the motivation and political atmosphere surrounding the system.

Step 6. Action 2. - Development of the Probability vs. Severity Table – Develop a two dimensional table representing System Failure Probability on the Horizontal Axis and Hazard Criticality on the Vertical Axis. Assign applicable safety values to table cell to represent the safety of the system based on each occurrence and corresponding safety level for a given intersection scenario.

The corresponding cell value of the Probability vs. Severity Table can be referred to as a Safety Assessment Index or SAI. Once the SAI has been calculated for a given Malfunction / Hazard or for the entire system, it is possible to judge the safety of the system in its current design, determine the necessary processes required for the next stage of development, and prioritize necessary resources required to improve the SAI's level if warranted.

The criticality of one hazard may seem insignificant when compared to the hazards of a separate system, as each system has its own potential set of consequences to hazards. A military system may suffer a catastrophic hazard resulting in the death of personnel while a food processing/grinding unit might suffer a catastrophic hazard resulting in the loss of a batch of food. Both hazards are catastrophic in their own measure, while comparatively one results in the loss of life and the other in the economic loss of bulk ingredients. It is essential that the evaluation take into account the mission and requirements of the system to determine appropriate levels of response to such SAI levels.

For the example WACSS Safety Assessment, Table 32 lists the mathematical summation of all probabilities of occurrence for each malfunction at each level. Table 33 represents the System Failure Definitions, outlining the bounds of applicable levels of failure. Using the results of these two tables, in conjunction with the Probability vs. Severity Table generated in ***Step 6.2.*** (Table 34), it is possible to identify probability letter designations, as shown in Table 35. This step, while not required, will assist later in classifying System Failures to Probability Categories.

The resulting SAI Product can take a variety of forms, ranging from a simple numeric value to denote the safety of the system to a textual description of the safety of the system, outlining the malfunctions, failures, hazards, consequences, and severities of the system with corresponding safety assessments. A summation safety value can be given for the product, assuming worst case and best case for hazard severity of the given system. The format of the product depends on the requirements of the assessment team, the manner in which the product may be used, and the format for which the team is most comfortable working with. Regardless of the ultimate format of the product, the logic and methodology behind the assessment remains the same. An example of a long form textual SAI result can be found in Section 0 of this dissertation.

Step 6. Action 3. - Determination of the Safety Assessment Index (SAI) – Using the Probability vs. Severity Table developed in Step 6.1., and Failure Summations from Step 5, determine the SAI for malfunctions and the summation of

the system by the intersection of event probability to hazard severity. SAI results should then be displayed using the method most practicable to the evaluation requirements.

4. Decision Making

Steps 1 through ***6*** of the Software Safety Assessment are based on the initial phases of the software development process, as depicted in Figure 11. As the software project is still in a stage of infancy, it is flexible enough to permit a refinement, remodeling, or redirection of efforts to improve the recently computed SAI value. The SAI should specify the relative level of safety of the system, based on a predefined safety index scale established during the evaluation. The limits of the scale may slide left or right, or may expand within its bounds to best represent the safety of the actual system. Once the SAI has been identified, it is essential to determine if the system's safety level meets the ultimate requirements of the system's development.

Assume that a development requirement stated that, "no portion of the system shall have a SAI level above *Moderately Unsafe*." The term *Moderately Unsafe* has been predefined to represent some level of safety in terms of malfunction/failure event probability against hazard severity. The *Moderately Unsafe* development goal specifies some quantitative level of safety that must be obtained prior to system release. This goal grants a level of assurance to developers and users that the product will function within some specified limit with a relative probability of a catastrophic event low enough to permit open integration and deployment. In the case of the example WACSS system, few events meet the hypothetical goal of a SAI no greater then *Moderately Unsafe*. A developer may review the intended methods and techniques for subsequent stages in a spiral development, to make necessary changes with the purpose to reduce the SAI to an acceptable level. Based on available resources, a decision may be made to address all unacceptable events, but prioritize resources so the *Unsafe* or *Extremely Unsafe* events are controlled first. If resources are limited, the developer may choose to address only those events whose SAI is *Unsafe* or *Extremely Unsafe*, and then reevaluate the software system to determine the new SAI level. Each development process poses unique scenarios and limiters that restrict the development and the ability to reduce the SAI towards *Safe*, assuming *Safe* to represent a system for which no unsafe incident will occur. Regardless of the limitations, the assessment permits a method that will help the developers assess the Software Safety.

a. Variables to Safety Decisions

The resulting safety assessment and SAI level in no way makes the system safer or reduces the quantity of failing objects. The safety assessment only presents a representation of the potential operation of the system, based on a review of system objects judged against a predetermined criterion for safety. The assessment can only benefit the system once decisions have been made on the proper course of action to improve software system safety. The ability for developers to make accurate safety decisions depends greatly on:

- The presentation of the safety assessment data,
- The resources available for the development/redevelopment, and
- The abilities and foresight of the developers.

The presentation of safety assessment data must be aesthetic in nature, as to permit an efficient and telling view of the information. Developers should not become tied up in the review and interoperation of the data but should be able to quickly discern the critical points that could jeopardize the success of the project. The outline textual format of safety assessment data (0) presents all of the required review information in a top down fashion that can be quickly referenced with other subordinate data elements. Pertinent safety–related system objects and their properties can be displayed as sub categories to relevant headers and primary objects. This format gives the assessment and development teams the ability to include or omit data elements that are not applicable to the particular investigation and process.

Additional safety presentation formats include the creation of a Hazard to Safety or Malfunction to Safety Table as depicted in Table 13. For ease of reference in Table 13, the Severity and Probability axis reference codes from Table 12 are included.

Depending on the scope of the assessment and investigation, additional columns can be inserted to add depth and clarity to the table. In the case of the example WACSS assessment, an extended safety assessment table including columns representing object failure, malfunctions, and multi–dimensional phases of safety can be used to represent the depiction requirements, as shown in Table 36.

HAZARD	SEVERITY	PROBABILITY	SAFETY
H_1	CATASTROPHIC	LIKELY	I B – Extremely Unsafe
H_2	CRITICAL	OCCASIONAL	II C – Significantly Unsafe
H_3	MARGINAL / MODERATE	SELDOM	III D – Minor Unsafe Issues
H_4	CRITICAL	LIKELY	II B – Highly Unsafe

Table 13 Example Hazard to Safety Table

The Hazard to Safety Table can serve as a guide for future safety improvement and decision–making. Based on the safety measure from the assessment, the developers and project managers can prioritize hazards by safety levels, based on predefined goals and objectives of the development and remaining resources available for the improvements. A requirement of the project might be that no "Significantly Unsafe" incidents or greater will be accepted in the development. From the assessment and threshold evaluation, the developers can determine the most viable method of control or mitigation for a particular hazard.

Once developers are able to review and evaluate the results of the safety assessment, a decision can be made on the goals for improvement. The goals for software system improvement are based on five principles of hazard control, namely:[253]

- **Acceptance** Accept the identified hazard and resulting consequence with no changes.

[253] *Operational Risk Management (ORM) Handbook, Subset to AF Instruction 91-213, 91-214, and 91-215 Operational Risk Management*, Air Force Civil Engineers, U. S. Air Force; 1991.

- **Avoidance** Avoid the Failure. Canceling or delaying operations of the system that could potentially result in an object's failure.

- **Reduction** Plan or design the system with minimized potential for system failure using mitigation, prevention, and error handling.

- **Spreading** Increase the exposure of the system to positive processes while reducing the exposure of the system to negative processes, consequently reducing the potential for object failure over time.

- **Transference** Shift the possible losses or cost of the failure to other systems, or transfer vulnerable requirements to more reliable system.

The decision to implement any one of the five methods of process improvement requires an understanding and review of the resources required to make the required improvement. Even *acceptance* of a hazard requires the expense of some amount of resources as the hazard has been investigated and assessed, documentation and training is designed to inform others of the hazard, and the hazard is isolated to prevent additional change. It is understood that some level of resources have been expended to develop the system to its present level, even if the system is only in its conceptual phase. Resources may include, but not be limited to, the time schedule of development, staff, budget, facilities, personnel, software, and development and testing tools. Any changes to the system may require some reallocation of resources beyond that already planned. In the case of some changes, specifically *Avoidance* or *Transference* where system operation is reduced to improve system reliability, the level of system development effort might be correspondingly reduced. In a worst case, without proper management, oversight, and functionality, such action could cause development efforts to increase. Regardless of the method chosen to reduce the probability of a hazardous event, a limiting factor of the method execution will be the resources available.

As referenced in Chapter III of this dissertation, many software systems fail due to the limited abilities and lack of foresight of the developing team. When developers are incapable of properly designing a system, errors will inevitably surface during system's inspection and operation. Despite the best of development practices, a lack of safety foresight and ability to plan for potential failures will result in a failed oversight to safe system operation. The decision process must evaluate the abilities of the developers as well as the foresight for the developers to prevent the addition of further errors.

Assuming that a maximum SAI level has been established in the requirements of the development process, the software system can be reviewed to determine which hazards must be controlled to comply with the established standard. Once hazards are identified, resources and controls can be prioritized in an appropriate fashion to improve system safety. Using the previously defined example of Table 36 and the hypothetical SAI requirement for no object to result in greater then a Moderately Unsafe action, objects and properties of Table 36 are shaded to indicate which require improvement and control.

b. Hazard Controls

Of the five classes of hazard control; *Acceptance, Avoidance*, *Reduction*, *Spreading*, and *Transference*, each must be reviewed and understood for their impact on system requirements, required resources, ability to implement, and potential benefit, as shown in Table 14.

The decision of which control is appropriate depends greatly on the circumstances the control is attempting to manipulate. Controls must be judged for their ability and manner for which they eliminate hazards, the efficiency in execution, overhead, expected improvement mission success, enhanced capabilities, and reduced risks. It may be possible for more than one control type to prevent a failure, yet the selection must be made on the level of effort required to implement the control and the expectations gained from its inclusion.

Acceptance has absolutely no effect on software system safety hazards, but may be optimal in cases where resources are limited, the probability of failure is small, and/or the hazard consequence is minimal. Some resources may be required to isolate the hazard from further development, and to documentation and training customers and developers of the hazard.

The ***Avoidance*** or “elimination” control does not solve a failure but rather removes the failure by removing system functionality essentially avoiding the triggers that induce the failure. Such a control has a direct impact on the requirements of the software system because it removes functionality that may be required by the system to operate “completely.” A decision must be made on the functionality, necessity, or aesthetic value of system operations that have been removed to avoid failures. Avoidance must be done in conjunction with a critical review of system requirements for the elimination of unnecessary overhead while conserving essential operations. Such a removal of functionality requires a review of the importance of the specific process and the impact and reliance issues generated by other objects. If such a function is trivial in nature, then it can be removed with little impact on the primary operation of the system. Few software–based functions related to system safety are trivial and can be removed to improve a system’s SAI level. Some safety–related software systems are designed solely to prevent a hazardous event; therefore, their avoidance or removal would decrease the safety of the system and promote a hazardous event.

Spreading implies the act of spreading or diluting the exposure potential of identified failure points out over the system terms of operating time or locality to other failure points. *Spreading* does not necessarily reduce the number of failures, but increases the number of non–failure points, thereby mathematically reducing the ratio of failure to non–failure objects and the overall potential for failure for a given set. In laymen’s speak, a tablespoon of poison will kill a rat, but if you diluted the poison in a pool of water the rat will have to drink quite a bit of the solution to get the same result. *Spreading*, while mathematically sound, is not always advantageous, as the rat may drown from the water before he ever is affected by the poison, so will the software system be affected by the introduction of superfluous objects and actions not intended in the functional requirements. The act of spreading is more soundly integrated in non–

hazardous software systems where the act of hazard control is not one of the prime requirements of system operation.

Optimally, failure or hazard ***Reduction*** is the most productive method of safety trigger management, as it actually works to reduce the potential for a hazardous event. *Reduction* stands as the foundation of contemporary Software Systems Safety Efforts. Depending on established system requirements, the potential for a hazardous event can be reduced by removing the flaw from the system before it could ever occur. For the sake of terminology, not developing the flaw from the onset can be assumed the same as removing a potential flaw from the concept. If a flaw cannot be removed and the failure not prevented, failure mitigation can be used to lessen the severity of the failure or even prevent the development of the action into a hazard. Mitigation can include the transference of failed processes to other systems for redundant operation, the ability for the system to recover and prevent subsequent failures, and the in–line addition of failure preventers that can sense the hazardous event and control its propagation and consequence to an acceptable level. Mitigation, while it does not remove the failure directly, controls the probability of the hazardous event, thereby increasing safety. Error handling is the ability to sense the fact that an error has occurred, react to it, and prevent its continual propagation. An error handler might cease operation of the failed object until it can reset itself and provide a positive output, might provide a supplemental output that is within the bounds of system requirements, or might revert to a redundant system object capable of providing a reliable output.

If the potential hazard cannot be reduced, spread out, or avoided, it may be possible to transfer the effects of the failure to other portions of the system or transfer the most vulnerable requirements to a more reliable or robust system. ***Transference*** can be accomplished similar to error handling, as a reactionary process that transfers control of the system and associated failure to another unit to prevent or control the occurrence of the hazard. *Transference* also may imply a preventive measure by recommending the transfer of potentially hazardous requirements and unstable objects to other systems to isolate and better control their failed occurrence. *Transference* reduces the burden of the system to handle failure by shifting the responsibility onto a secondary component. The ultimate reduction is dependent upon the methods of transference and the effort required to make this transition. In some cases, the overall gain to system burden could be minimal. In cases of *Transference*, the failure does not disappear, but is simply moved to a system better suited to react to its occurrence.

	Effect on Hazardous Event	***Level of Effort***	***Effect on System Functionality***	***Effect on System Safety***
Acceptance	None	Minimal	None	None
Avoidance	Significant	Medium	Significant	Minimal
Reduction	Significant	Significant	Minimal	Significant
Spreading	Medium	Medium	Significant	Minimal
Transference	Significant	Significant	Significant	Medium

Table 14 Hazard Control Effect on System Safety

c. Making the Difficult Decisions

Given the five primary hazard controls previously referenced as well as the introduction of variables to software improvement decisions, it is possible to make specific goals and methods for the improvement of the identified software system. Using the shaded example of Table 36 as a basis, thirteen hazards and nineteen consequences (some duplicated for given malfunctions) were identified as beyond the acceptable SAI limits established in the hypothetical system requirements. The optimal goal of the safety decision process would be to develop/redevelop the system such that the summation of SAI levels of each potentially failing object would result equal to or that required in the specifications documents.

Reviewing the steps required to generate the assessment, it is only possible to increase the SAI Safety Level of the system by:

1. Lowering the criteria for which the system is evaluated against,

2. Reducing the probability that a failure/hazardous event will occur, or by

3. Reducing the consequence of the hazardous event.

Lowering the criteria for which the system is evaluated against would produce an immediate and linear increase in the "*safety*" of the system in terms of the quantitative value, but will not necessarily result in a reduction in the number of unsafe incidents that may occur. Such an adjustment of the criteria must only be executed if the criteria was flawed in its assumptions, a more accurate criterion was discovered, or the criteria was refined to add granularity and clarity to the assessment. Special care should be taken to preclude undue influence or pressure to adjust the criteria to a level that would mask the actual failure and resulting hazard.

The consequence of some hazardous events is static for a given software system. In a case where the software system completely fails to control a specific event, the event will then occur in an unacceptable and hazardous manner. Further control of the hazardous event must be accomplished by an external system, either a mechanical or software system isolated from the original failure laden system. While the hazardous consequence could not be controlled by the given system, its effect may be mitigated by additional systems that can act upon it. In cases where the system retains some control of the hazardous event and corresponding consequence, it may be possible to affect or reduce the consequence of the failure. The ability to control the consequence of any hazard must be based on the type of consequence, the remaining controls of a potentially failing system and the redundant or parallel systems tasked with mitigating the potential event.

The most plausible method of increasing the safety of the software system is to reduce the probability that a hazardous event will occur at all. Procedurally stated, reducing the probability of a hazardous event could be accomplished by removing the existence of possible flaws, reducing the probability that the failure will occur, reducing the likelihood that a failure could propagate through the system, and the reducing the potential that a failure could result in a hazardous event. It is most advantageous to destroy the chain of failure before it ever has a chance to root into the system. If not possible to interrupt the chain, it may be possible to break the links of the chain once they are identified by the safety assessment. Removing the existence of flaws can be accomplished through the use of proper design techniques, requirements review, development verification, and testing with the aspects of safety in mind.

The probability of failure can be reduced by:

- Methods of design,
- The ability of the system to control inputs, objects, and processes,
- The redundancy of the system to compensate for failed operation (if redundancy is designed for safety), and
- Reducing the exposure of system to potential failure objects.

As previously stated, vulnerable objects may be required for the operation of the system despite their potential for failure. In such cases, it may be possible to isolate system operation through error handling, failure mitigation, or through the use of secondary systems that can isolate the hazardous burden from the primary system. In cases where a safety–related system hazard could not be eliminated from the system, the next objective must be to minimize the occurrence and potential severity of the hazard. Such controls can be inserted into the software to limit the probability of occurrence of the hazard to some appreciable limit or permit the system to quickly recover, preventing a further occurrence of the hazard. Beyond the software control system, it may be possible to incorporate mechanical interlocks and safety breaks that can prevent a hazardous event should the system fail.

Mitigation measures designed to improve the safety of a system could quickly detract from mission effectiveness by limiting the operational environment, responsiveness, reliability, or other desirable attributes, and overall lethality of the system. Each decision will have trade offs that must be evaluated for their impact on the safety, mission effectiveness, and operational capabilities of the system. In some systems, it may be beneficial to operate on "the edge of criticality" to obtain optimal system performance; understanding and accepting the potential for a hazardous event should the system cross over that edge. In other cases, where the failure criticality of the system would pose unacceptable risk should it fail, operating with sufficient control would be essential. Striking that balance between operational risk and system safety risk is essential to the successful deployment of the software in the system context.

Despite the method selected to decrease the SAI level of the system after a safety assessment, it is imperative to identify the necessary changes and take appropriate action as early in the development process as possible. It should be noted that the cost and time for system repair and modification increases with each recurrent phase of development. The increased expense of such modifications may serve to jeopardize system safety as much as the act of a single system failure.

Using the SAI improvement goal as a guide, it is then possible to review the failure, hazard, and consequence lists to determine which elements must be improved to decrease the SAI value below an acceptable threshold. Elements can be evaluated for their ease of developmental change and improvement, the degree for which they must be improved to meet the system, and the methods and resources required to implement the change. Additional consideration must be given to the effect that any change may have on the system characteristics, their requirements, or functionality. Changes must be documented, testable, and not contribute to additional failure probabilities. Some changes may result in increased overhead, expense, or decreased system performance to counter the threat of a potential hazard.

Step 7. Action 1. - Determine Required Improvements – Determine the system improvements required to decrease independent and system SAI values to an acceptable level, identifying appropriate controls of Avoidance, Reduction, Spreading, and/or Transference to each element. Identify quantitative improvement goals for each object that is to be improved, countered by required resources, and cost vs. benefits of the actual improvement.

The format for any goal improvement depiction should include the object to be improved, the selected control type(s), the control specifications of the improvement, resources required, any measurable change goal expected in object failure probability, and any severity change goal in respective hazard consequences. Where possible, the anticipated change to object/system SAI levels for each object improvement should be computed and noted. Finally, it would be beneficial to outline the anticipated effects of the change improvements on system requirements, functionality, and performance. System developers will require adequate justification for incorporating additional design requirements into the system. The table should be formatted in the expected order of object improvement execution, taking into account resources required/available, effect, and complexity of the improvement. As resources may be limited, it would be possible to budget improvements to get the maximum SAI change level before resources are exhausted.

Using the improved Spiral Model example of Figure 11, working in the lower right fourth quadrant of *Software Decision Making and Development* and *Validation*, it is then possible to determine the best method for modifying requirements specifications (if necessary), and for developing the actual project. Assuming this to be the first iteration of development, safety changes and process improvements to the software system may be nothing more than changes in requirement specifications, anticipated process development methodologies, and resource reallocations. In subsequent stages of development, improvements may include the costly decomposition and redesign/development of software code. Dramatic software redesigns can be prevented through prior planning and adherence to proper techniques. Where possible, the safety assessment and decision process should be accomplished as early as possible to benefit the system while minimizing the changes to completed portions of the system.

5. Development

The development/redevelopment of a system using the new safety directed improvements requires no significant changes to existing development practices. Nonetheless, the safety improvements will require a greater adherence to the principles of safety within those practices. The earlier that safety precautions can be executed in the development process, the smaller the negative impacts the system will experience (rework, lost resources, potential hazard execution), as well as the greater the positive impact on software system safety. While requirements are in review, the demand for safety controls should be incorporated into the software system documentation. To ensure that system changes can be tracked and traced, once objects are in development, changes and additions of controls should be documented in their respective fashion.

Step 7. Action 2. - Incorporate Safety Controls – Incorporate the Safety Controls identified in Step 7.1. into the Software System. Changes should be well documented in requirement specifications and code development specifications. Any refinements and improvements should take into consideration their effect on present objects as well as any related or reliant objects within the system.

Safety–Critical Software Systems can be highly fragile, depending on the criticality of the hazardous event it is attempting to prevent. It is possible to strengthen the fragility of a system by adding specific design features that are robust, proven, and serve to mitigate, prevent, or reduce the potential occurrence a hazardous event, sometimes referred to as "Defensive Programming". Example design features can include, but are not limited to:

- ***Firewalls*** that isolate safety–critical code from the rest of the system.
- ***Redundancy*** of critical systems, granting the ability to continue operation with a secondary system should the primary fail.
- ***Screening*** and ***Filtering*** of system inputs to prevent triggering potential failures.
- ***Timed Replacements*** of critical code and system operation to refresh system functionality should it become unstable.
- ***Data Diversity*** to sequence various inputs to generate output results that are either exactly the same or semantically equivalent in some way.
- ***Error Trapping*** to halt the propagation of system failures through the system.

- ***Error Handling*** to correct system's operation should the system fail to function properly.
- ***Checkpoints*** to monitor system operation and take corrective action should the system fail to pass checkpoint tests.

The use of proven System Object Modeling, CASE tools, and other system prototyping design techniques assist in the pre–coding phases of system development and provide an opportunity for integrating and testing of various features.

Firewalls provide isolation of critical components from the remainder of the system. This isolation prevents the flow of potential failures out of critical components into the rest of the system, as well as failure flow from the system back into the critical component. Firewalls can also prevent the introduction of known triggers to failure prone objects. The function of a safety firewall may be as a barrier, a filter, or as channel to data and process transfer, controlling the dissemination of information through a predetermined field of logic. In cases where the firewall may serve as a barrier, no information or process flow will be transferred through to other components not critical to the current process. Firewall filters will only permit the transfer of information or process flow that meets a specific criterion, while a channel will permit the flow only through a directed path, omitting flow to undesired portions of the system. Depending on the logic within the firewall control, the flow of information or process may flow one way or bi–directional, as shown in Figure 17. F_1 represents the use of a barrier firewall, preventing the flow of any information from the Alpha Process to Bravo. F_2 represents a filtering firewall that checks the flow of information between the two process flows using a series of discriminators and proofs. F_3 represents a channel that can logically redirect or inhibit information through to various points within the Bravo Process. Improvements to the SAI level are based on the type of failure that each firewall is designed to prevent, as well as the functional resilience of the firewall.

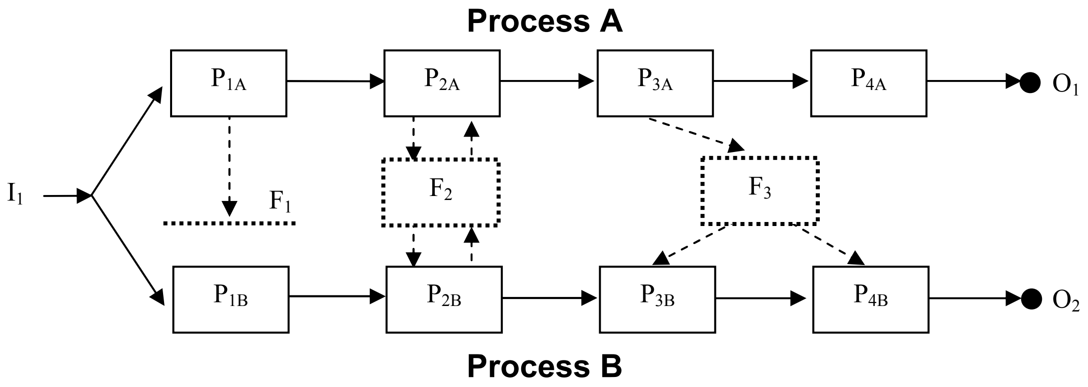


Figure 17 Firewall Control Example Figure

Redundancy involves the integration of parallel components or processes to backup the operation of critical processes. Redundancy can be accomplished using either two or more identical components operating in parallel, or by the use of dissimilar system capable of accomplishing like tasks, shown in Figure 18. In the case of identical components, the system would be capable of reverting to a back up process in the event that the primary process failed to operate. In cases where the environment causes a failure of the system, a duplicate redundant system might also experience the same failure. Redundant systems must be capable of robust operation in environments conversely that of its "twin" or they fail to serve as viable alternatives. Additional dilemmas exist in cases where the input to the primary process resulted in the failure of the primary component. If no change is made to the input and it is subsequently rerouted to the secondary process, the same failure will likely result. Identical components are useful in cases where components are susceptible to failure from sources other than input values such as operating resources (power failure, storage space, output devices, processor failures…), or are susceptible to destruction during the course of operation (catastrophic impact, frozen components, combat casualty…). As an alternative, it may be ideal to develop dissimilar redundant components that are capable of providing a complementary level of functionality using an alternative method of logic and resources. Dissimilarity permits the flexibility to attempt continued operation using the same potentially flawed input and generate a functional output. In cases of dissimilar component development, additional resources must be allocated that would otherwise not be required in redundantly similar systems. System SAI level improvement is based on the type of redundant process implemented in the system. In redundantly similar systems, the probability of failure will only improve to the degree that a failure from operational resource or catastrophic casualties could be eliminated. In redundantly independent systems, the system's probability of failure is directly related to the multiplication of the two components' independent probability of failure[254], i.e. $F_1 = 2.5\text{x}10^{-3}$, $F_2 = 4.3\text{x}10^{-3}$, $\therefore\ F_{1,2} = 1.075\text{x}10^{-5}$. Of note, such an example only applies to detectable failures in a statistically independent process.

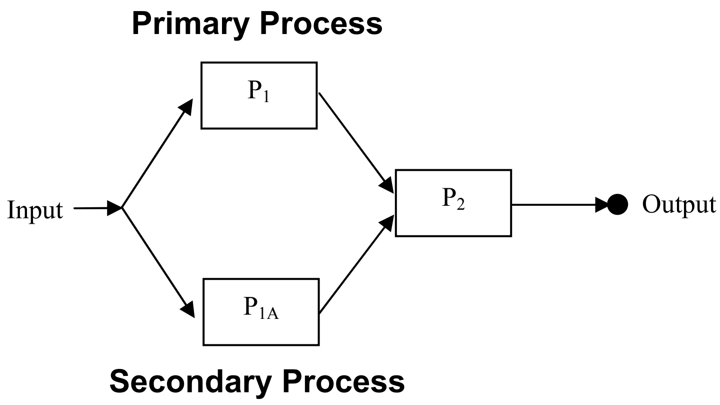


Figure 18 Redundant Control Example Figure

Screening and ***Filtering*** permits the trapping of process inputs and outputs to ensure that only acceptable values are permitted to flow through the system. Filters are designed to function in series with the system process flow and react according to the limits of the data and screen type. Filters may continually function to prevent the flow of unacceptable values – *Active Filter*; while other filter controls react to generate alternative input / output values to ensure continuous operation – *Reactive Filter*. The filter can be physically placed before the input of a component it is designed to protect, or directly after the component whose output is suspect, as shown in Figure 19. In addition

[254] Littlewood, Bev; *The Impact of Diversity Upon Common Mode Failures*, The Centre for Software Reliability, City University, Northampton Square; London, England.

to the straight line Active Filter example, the Reactive Filter contains additional processes (P_{R1} and P_{R2}) that are triggered by filter logic to generate alternative data values to support the primary process (P_1). System SAI level improvement is based on the type of filter used in series with the system, the strength of the filter, and the reactive logic to flawed values.

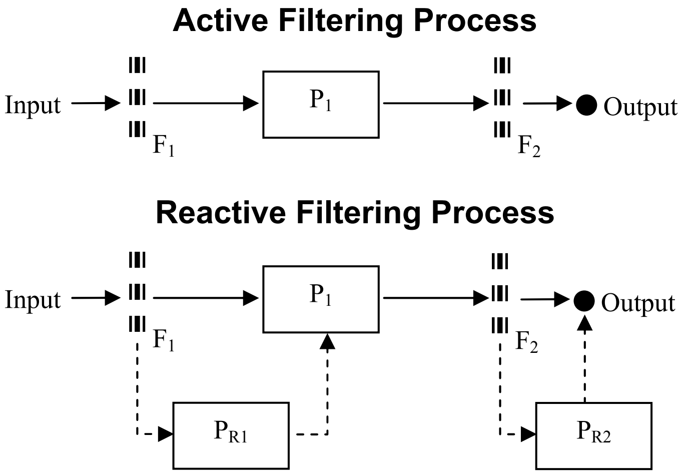


Figure 19 Filter Control Example Figure

Timed Replacements involved the refreshing of system code, components, or operational states to ensure compliance with some established standard. A timed replacement does not prevent a failure, but rather prevents the continued operation of the system in a failed state if:

1. The failure can be countered by the refreshing of the system,

2. The system can survive up to the timed replacement gate, and

3. The failure has not disabled the ability of the system to refresh itself.

The replacement is designed to trigger at regular intervals to ensure stability of the system, but could be triggered to execute should a separate component of the system so command. *Timed Replacement* does not reduce the failure probability of a system, but may reduce the Consequence Severity by refreshing or restarting operation in a safe state. The resulting reduction in Consequence Severity would potentially correspond to a reduction in system SAI values.

Data Diversity serves to generate alternative input values for a process should the initial input be outside some prescribed limit.[255] Supplemental values may be completely dissimilar to the initial input, but should result in essentially the same or semantically equivalent values. Diversity may be reactive or active in its execution, depending on the nature of its design. Data Diversity is similar in nature to the Filtering Control with the additional requirement to ensure that the final result is equal to the expected result while using different input values. Such a control would benefit safety–critical software systems where inputs may be generated from various external components in diverse formats. The Data Diversity component may generate conversion values to convert data formats or related values that generate near identical values. In the case of a division function, a denominator value of zero would result in a "divide by zero" error. Such an error could be resolved through Data Diversity by changing the input to a near infinitely small value. A Filter may restrict values, while Data Diversity will change failed values.

Error Trapping halts the propagation of failures through the system by the use of data and system status inspection. When values fall outside of prescribed limits, the error trapping logic shuts down or isolates the active process flow to prevent the error from

[255] Torres-Pomales, Wilfredo; *NASA/TM-2000-210616, Software Fault Tolerance: A Tutorial*, National Aeronautics and Space Administration, Langley Research Center; Hampton, Virginia; October 2000.

infecting additional components. *Error Trapping* does not prevent a failure but rather prevents the propagation of the failure down through the system and optimally to halting a hazardous event. In come cases, the execution of an error trapping function may result in additional hazards as system operation and control is halted to prevent propagation.

Error Handling builds on the concept of *Error Trapping* by halting the propagation of failure once it is identified, with the additional act of error correction. While *Error Trapping* halts the process flow on error detection, *Error Handling* attempts to continue process flow with a subsequent correction. Similar to the *Reactive Filtering Control,* as system functionality falls outside of predetermined limits, the control arrests the process flow, inserts an accepted response, and then continues the operation. At the system code level, *Error Handling* can be accomplished through the use of the **ON ERROR** or other like syntax statement. *Error Handling* relies on the ability of the program to

1. Sense the fact that an error has occurred,

2. Recognize of the type of error,

3. Recognize the failed input if required,

4. Have knowledge of a potential resolution,

5. Have the ability to take corrective action.

The below code example in Example 7 demonstrates a plausible *Error Handler* using *Data Diversity* for a "divide by zero" error. The user has the ability to enter any desired value for the Numerator and Denominator in lines 7 and 8. In the event that a zero value is entered in the Denominator, the Error Handler will be triggered in line 9. The error handler case statement logic would select error #6, which in turn would change the Denominator variable to a value approaching near zero. Line 17 would restart the system at the division statement with the new Denominator value for the given error, giving nearly the same result. For other errors, the Error Handler would not be able to come up with a respective solution and would halt system's operation.

Error Number 6 is the case return value for Overflow or Divide by Zero errors. In the below code example, the procedure inquires of the operator for Numerator and Denominator values. If the division results in an Overflow or Divide by Zero error, then the procedure will execute its Error Handler. By select case, should the return error number = 6 then the procedure will handle the error by replacing the denominator with a near infinitely small value, thereby permitting the execution of the division. In all other error cases, the procedure will alert the user of the failure for further troubleshooting.

```
Private Sub Do_Division
Dim Dnum as Double                                          'Double Variable Numerator
Dim Dden as Double                                          'Double Variable Denominator
Dim Dres as Double                                          'Double Variable Result
Dim Response as String
On Error Goto Error Handler                                 'Define the Error Handler
        Dnum = Val(InputBox("Enter the Numerator"))
        Dden = Val(InputBox("Enter the Denominator"))
        Dres = Dnum / Dden
        Response = Msgbox(Dnum & " divided by " & Dden & " = " & Dres)
Exit Sub

Error Handler:
Select Case Err.Number
        Case 6                                              'Overflow or Divide by Zero Error
                Dden = 1.0e–32   'Make denominator near infinitely small
                Resume
        Case Else
                Msg = "Error # " & Str(Err.Number) & " generated by " _
                & Err.Source & Chr(13) & Err.Description
                MsgBox Msg, , "Error", Err.Helpfile, Err.HelpContext
                Exit Sub
        End Select
End Sub
```

MS Basic Example

Example 7 Error Handler Example

Checkpoints are designed to monitor system operation and status at various flow points to ensure that a specific criterion is met. If the criterion were not met at the *Checkpoint*, the system would take some effort to correct the status. *Checkpoint* controls do not prevent an error, but attempt to prevent the propagation of an error past a specific point of the system process. *Checkpoints* may function in kind with a replacement or refreshing function that can either replace unacceptable values or refresh system code and status during inspection. The success of the control, like the *Timed Replacement*, assumes that (1) the failure can be countered by the refreshing of the system, (2) the system can survive up to the checkpoint gate, and (3) the failure has not disabled the ability of the system to refresh itself. *Checkpoints* may trigger the use of redundant components, data diversity, or refreshing system states. The *Checkpoint* may halt, redirect, or correct process flow, depending on the checkpoint process logic. The *Checkpoint* control does not reduce the failure probability of a specific object, but may reduce the probability that a failure will propagate through the system. The resulting reduction in system failure probability could potentially correspond to a reduction in system SAI values.

The ability of Failure Prevention Controls to prevent the occurrence of a potential hazard depends on the tactic of the development, the error/failure to be prevented or handled, and the properties of the control, as shown in Table 15. No single control is capable of preventing the occurrence of every hazard. Depending on the complexity of the system and potential failure, it may be necessary to use multiple controls through the system to prevent the occurrence of the hazard. The positioning of hazard controls in the system also is dependent on the properties of the control and the intended method of employment. It is essential to position controls in close proximity to the intended event to prevent the spreading of unwanted system flow.

Control	**Trigger Prevention**	**Failure Prevention**	**Failure Propagation**	**System Restoration**
Firewall	Y	Y	Y	N
Redundancy	N	Y	Y	N
Filtering	Y	Y	Y	N
Timed Replacement	N	N	Y	Y
Data Diversity	Y	Y	N	N
Error Trapping	N	Y	Y	N
Error Handling	N	Y	Y	N
Checkpoint	N	N	Y	Y

Table 15 Failure Control Properties

6. Subjective Factors to Safety

Putnam and Mah were quoted in Chapter IV.B of this dissertation, that the four core measures of a software development include *size*, *time*, *effort*, and *defects*. In Chapter III of this dissertation, a discussion was made of the potential developmental factors that contribute to the safety or failure of a software system. It may be possible to extrapolate that Software Safety would increase or decrease for the modified action of a specific set of element variables, without providing a quantifiable result, as follows:

Development Element	Developmental Action	Effect on Safety
Core Components[256]		
System Size	Increase Size	Decrease Safety
Time to Develop	Increase Time	Increase Safety / Decrease Safety
Effort to Develop	Increase Effort	Increase Safety / Decrease Safety
System Defects	Increase Defects	Decrease Safety
System Complexity	Increase Complexity	Decrease Safety
Implementation Induced Failures[257]		
Software Used Outside of its Limits	Increased use outside of Limits	Decrease Safety
Over Reliance on the Software System	Increased Reliance	Decrease Safety
Software Developed Incorrectly[258]		
Effects of Political Pressure on Development	Increased Political Pressure	Decrease Safety
The Lack of System Understanding	Increased Lack of System Understanding	Decrease Safety
The Inability to Develop	Increased Inability to Develop	Decrease Safety
Failures in Leadership in Development	Increased Lack of Leadership	Decrease Safety
Development with a Lack of Resources	Increased lack of Resources	Decrease Safety
Software Not Properly Tested[259]		
Limited Testing Due to a Lack of Resources	Increased Resource Limits to Testing	Decrease Safety
Software Not Fully Tested Due to Developmental Knowledge	Increased Failure to Test due to Developmental Knowledge	Decrease Safety
Software Not Tested and Assumed to be Safe	Increased Failure to Test due to Assumed Safety	Decrease Safety

Table 16 Developmental Effects to Safety

The trend of safety effects in Table 16 can be logically derived through various software subject matter sources, while the particular level of safety change may require a significant effort and examination of the effect of a particular element to the action of

[256] See Chapter IV.B – METRIC DEVELOPMENT.

[257] See Chapter III.C – IMPLEMENTATION INDUCED FAILURES.

[258] See Chapter III.B – SOFTWARE DEVELOPED INCORRECTLY.

[259] See Chapter III.D –SOFTWARE NOT PROPERLY TESTED

system safety. Additional research and metric development may later be possible to determine the quantitative effect of the element on safety. The level of element application should be done with the full knowledge of its effect on the system and the intended result on the action. The metric may consist of three or more element dimensions against safety, or may be consist of an additional metric stage that can provide some factor to the probability of a hazardous event. For example, the effect of *discovered system defects* vs. the *limited testing due to resources* may generate a factor of *probability of a hazardous event*, assuming that each defect could have potentially resulted in a hazardous event and the limited resource was related to the discovery of a possible defect. In other cases, the element may simply apply to a particular defect resolution.

A detailed review of system requirements will identify and permit isolation of many potentially hazardous events that may occur during system operation. Through an analysis of the system requirements, it may be possible to identify and calculate the complexity of the software system, based on historical precedents.

While no concrete measure may exist to determine subjective elemental effects on system safety, each element should be reviewed and assessed for their effects in successive iterations of development. The combined effect of some element actions may be measured against the safety assessment during redevelopment by computing the *delta* (Δ) of the safety index. Each of the elements should be evaluated before, during, and after each cycle of development to determine if their action should be modified or regulated to continue or prevent further changes to the safety index. Some acceptable and measurable level of testing must be established at the onset of development, resulting in a testing *delta*. The ability to link that testing delta to some potential safety hazard depends on the testing not completed, the system being developed, and how the untested portion may react to cause an unsafe event. Such a review can be accomplished through the use of historical failure events and development decompositions, or through the use of identified development taxonomies, as shown in Table 17.

1. Product engineering

1.1 Requirements (stability, completeness, clarity, validity, feasibility, precedent, and scale).
1.2 Design (functionality, interfaces, performance, testability, hardware constraints, and non–developmental software).
1.3 Code and unit test (feasibility, testing, coding/implementation).
1.4 Integration and test (environment, product, system).
1.5 Engineering specialties (maintainability, reliability, safety, security, human factors, and specifications).

2. Development environment

2.1 Development process (formality, suitability, process control, familiarity, and product control).
2.2 Development system (capacity, suitability, usability, familiarity, reliability, system support, and deliverability).
2.3 Management process (planning, project organization, management experience, program interfaces).
2.4 Management methods (monitoring, personnel management, quality assurance, and configuration management).
2.5 Work environment (quality attitude, cooperation, communication, and morale).

3. Program constraints

3.1 Resources (schedule, staff, budget, and facilities).
3.2 Contract (type of contract, restrictions, and dependencies).
3.3 Program interfaces (customer, associate contractors, subcontractors, prime contractor, corporate management, vendors, and politics).

Table 17 SEI's Taxonomy of Risks[260]

A taxonomy may take the form of a survey with Yes/No or scaled responses. The subjective taxonomies may include some method of scoring or weighting the evaluated elements to produce a score or scale of development safety. For example, a score a 0 through 10 or grade of "*F*" through "*A+*" could be given to evaluate the system requirements, with sub–scores assessing the products of requirement stability, completeness, clarity, and so on. Scores or grades could be determined by defined criteria with an associated scale. The subjective measure could be used in tandem with the SAI evaluation to generate a more complete picture of system safety.

Step 8. Action 1 – Determine the Subjective Elements to System Safety Development. Determine the subjective elements to system development that relate to

[260] *Software Risk Management, Technical Report CMU / SEI-96-012*, Software Engineering Institute; June 1996.

safety and the prevention of a hazardous event. Determine applicable measures and definitions to classify and assess elements for their potential effect to the system.

Step 8. Action 2. – Evaluate System Subjective Elements. Evaluate the software system for elements identified in Step 8.1.. Assign a grade or measure to system elements indicating their compliance to assigned definitions, *derived from Step 2 Action 1 and Step 5, Actions 1 through 7.* ***Summarize evaluated elements to determine the overall effect of subjective elements on software system safety.***

F. SUPERVISION OF SAFETY CHANGES

A Software Safety Assessment is not viable unless it can be measured, implemented, redeveloped, and then re–measured. It is not realistic to imagine that Software Safety techniques can have any effect without proper management and supervision of their execution. Development without oversight is essentially hazardous and significantly adds to developmental risk.

Safety development / redevelopment using the identified hazard controls and safety elements and techniques serve no benefit unless they are integrated correctly, monitored, and reassessed for their effect on the system SAI level. The monitoring of development and change improvement require a consolidated effort of all members of the development team as well the leadership to ensure that changes contribute to the system, rather then harm. After the first iteration of development, it is necessary to review subsequent stages to determine what level of improvement was gained versus the intended SAI goal. The foundation and success of supervision requires:

- An understanding of the practices of Software Safety,
- Authority to make change decisions,
- The aptitude to identify potential change tactics,
- An understanding of the current system, requirements, and development goals,
- An understanding of the intended change product,

- The aptitude to make interim safety assessments during development, and
- The leadership to control the development process and meet the required SAI levels.

It is critical to safety development success to supervise and manage the application of safety principles, to monitor for benefit, and intervene or prevent additional hazard executions. Safety Supervision strongly relies on a knowledge base of trained subject matter experts with experience in system development with an emphasis towards safety. These experts may or may not have experience in the development of software, but have an understanding of the principles of system safety and their managed implementation. Supervision consists of:

- Determining a realistic safety index goal,
- Authoring the development plan to obtain the goal,
- Managing the development to meet the goal, and
- And measuring to determine if the goal is met.

The steps of safety supervision may not be completed in a single cycle, but across a series of cycles, through the completion of development. The management technique selected should be based on the proven methods and standards such as Software Configuration Management (SCM) or Capability Maturity Model Management (CMM). The supervision should be well documented and provide methods for assessment and peer review. Various military and civil standards have been reviewed in Chapter II.E.1 of this dissertation that includes methods of supervision.

Step 9. – Supervise the Safety Development – Using accepted methods of supervision and software management, supervise the development of the software system to ensure compliance with the principles of safety development. Ensure compliance with applicable development methods, system requirements, and safety assessments. Ensure that system developmental failures are identified and remedied as soon as possible in the current or next development cycle, or are acknowledged for their fragility to customers. At the completion of the current developmental cycle,

commence where applicable, the next successive cycle and Step 1.1 of the Safety Assessment.

G. ASSESSMENT OF VALIDITY / EFFECTIVENESS OF THE MODEL

It would be beyond the scope of this dissertation and model to create a metric capable of measuring all aspects of the development process and system functionality, and further capable of accurately generating an all–encompassing safety measure. The number of elements that contribute to the safe development and execution of a software–based system can reach near infinite. The validity of this model can be assured through the establishment of realistic measured goals and objectives.

The primary goals of this model are to:

1. Determine a quantitative value for the number of failures during a period of system operation, and

2. Determine a qualitative value for the safety of system operation. The terms *failure* and *safety* have been previously defined, as they apply to this dissertation study.

The number of failures that may occur during a system's element operational period can be identified through any of a series of previously discussed methods. Each of these methods contains their own failure probability that can be affected by a variety of triggers or external stimuli, potentially inhibiting the proper operation of the element. Presented is a method for incorporating the success and failure of individual elements into a combined system failure probability using accepted methods of probability and statistics.

The quantitative product is validated through the use of existing failure rate methods commonly used and accepted within the state of the art. Due to the limits of this study, I make no attempt to justify one failure rate method over the next. The decision to use a particular failure rate method is determined by the individual developer, based on personal preference, appropriate relationship to the element/system being evaluated, and amount of effort/resources required to determine the failure rate. The summation of elemental failure rates is accomplished through the use of accepted mathematical methods. The validation of any failure rate method can be justified or evaluated against actual failure rates after project completion or during system testing. These validations would compel the selection of specific measures during subsequent assessments.

The qualitative value of safety is more difficult to validate, as there lacks any comparable form of determining a value for safety. Many of the existing safety evaluation methods are subjective or qualitative in nature and are directly related to the failure rate of a system, taking into consideration the effects of controls and filters, the various operating conditions of the system, and the significance of potential hazards. Other evaluation methodologies, such as those proposed in MIL-STD-882D, the JSSSSH, the NASA Software Safety Standard, and IEC 61508, assume that the requirements are imperfect (from a safety perspective). From that imperfection, the failure rate of a system becomes a reliability issue that may or may not influence safety. Many mishaps can potentially result from software functioning without a failure, but as the requirements specified it to execute. Imperfect requirements may not bind the software sufficiently to prevent a hazardous event. Most of the controls and filters are at the micro–level and are designed to handle specific failure modes or other causal factors. Their beneficial effect affects only the failure mode (causal factor) for the hazard being addressed. At the system level, the system safety analysts address all hazards and their causal factors as well as the mitigation built into the system to reduce the overall risk. The method developed and presented in this dissertation use some subjective basis for determining safety thresholds. These thresholds can be standardized for all similar systems within the state of the art of high–assurance Software Engineering.

As there lacks any existing safety method for basing the dissertation against, it is only possible to validate the process through which the method evolves. As previously introduced in Chapter I.E of this dissertation, safety was determined through the evaluation of the following factors in Table 18.

- Complexity
- Veritability of Inputs
    - Cleanliness of Inputs (*Quality*)
        - Dependability / Reliability Factor of Inputs
    - Ability to Sanitize Inputs (*Correction*)
        - Consequences of Sanitization
    - Ability to Filter Inputs (*Prevention*)
        - Consequences of Filtering
- Permeability of the Requirements
- Permeability of the Outputs
- Veritability of Outputs
    - Ability to Verify Outputs (*Quality*)
        - System quality control
    - Ability to Sanitize Outputs (*Correction*)
        - Consequences of Sanitization
    - Ability to Filter Outputs (*Prevention*)
        - Consequences of Filtering
- Probability of a Fault
- Consequence of Fault
- Probability of Failure
- Consequence of Failure
- Product Safety or Dependability Index.

Table 18 Quantitative and Qualitative Factors of Safety

Chapters IV and V of this dissertation address the validation and computation of each of these values independently. The evaluation of these results against a developed threshold demonstrates the benefit of the presented method. I further define the methods required to create acceptable threshold standards for the evaluation. The effectiveness of the method can be judged by the following factors:

- By the level / extent for which a system must be evaluated to generate quantitative values – increased investigation increases the probability that weaknesses will be discovered and corrected, thereby improving safety.

- By the use of a repeatable method for determining the safety of a system – increasing user proficiency through the repeated use of a standardized procedure, thereby assuring a more stable performance in the evaluation process.

- By the use of reusable safety threshold gates – increasing the depth of the model by the use of standardized evaluation practices, thereby increasing the acceptance of the safety evaluation method.

- By the use of customizable bounds, limits, and definitions that can be tailored to meet the specific needs of the developers – increasing the adaptability of the metric to the particular requirements and methodologies necessary for efficient development.

- By the ability to catalog measured system element performance in various systems – increasing the ability to compare and relate the system performance and safety of one system against the historical performance of a second associated system, increasing the ease of use and efficiency of the system.

- By the incorporation of effective correction methods – increasing the safety of the system by the inclusion of logical processes to strengthen and protect the system, thereby increasing safety.

The primary function of this method is the ability to place a value of safety upon a software–based system. The validity of that method is still based on the ability of the evaluator to employ the principles of the metric, recognize the potential faults and hazards from within the system, and to make the appropriate corrections required to increase the safety level to an acceptable level.

H. COMPARISON TO PREVIOUS WORKS

Chapter II.E.1 of this dissertation outlined the state of the art of Software Safety standards, while Chapter II.E.2 reviewed the state of the art of safety evaluation methods. While evaluating the relatively small field of software based safety–related methods, it is evident that there exists no safety evaluation method that can assist developers in accurately determining a true value of a software system's safety. Many of the observed metrics detail methods for identifying faults and hazards within a system, while other metrics detail how to make a system safer, some as simplistic as to imply that a system safety is directly related to faults. APPENDIX D.1 of this dissertation consists of a review of predominant Software Safety Standards and Techniques.

The method introduced in this study presents a unique approach to Software Safety Assessments beyond that offered by existing methods. While the methods investigated for this study provide some benefit to Software Safety through process improvement, [261] the presented method introduces a complete lifecycle philosophy towards the development and employment process of high–assurance systems with new or refined definitions, a methodical assessment process, customizable thresholds, methods for limiting failure severity, and process improvement. Due to the infant nature of software development and the field of Software Safety, and the new methods introduced within this dissertation, there exists little similarity to current works of the same field.

I. CONCLUSIONS

Software development contains an inherent level of risk that could potentially jeopardize the completion and success of a software system project. It may be possible to develop a metric to measure the risks to software development using elements and properties that assess the size, complexity, and fluidness of a system.[262] The concept and

[261] See Chapter II.E – *STANDARDIZED FOUNDATION OF SOFTWARE SAFETY*

[262] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

rationale for determining Software Safety is well rooted in mathematics and procedural methodologies, while the application of such an assessment remains to be completed. This chapter has presented a plausible format for developing such a metric, based on accepted and proven methods of system safety, tailored to configure to the demands of software based systems. The ultimate goal of a safety assessment would be to solve for [$S = \Sigma P(H) * C(H)$]. The stepwise process introduced in this chapter and demonstrated in APPENDIX E offers a plausible method to determine the safety of the system. While the study of Software Safety and Risk Management contains methods of preventing an unsafe occurrence, the use of a mathematically based metric provides a tangible measure for determining how safe a system may be.

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VI. APPLICATION OF THE FORMAL METHOD FOR EVALUATION OF SOFTWARE SYSTEMS

"Engineers should recognize that reducing risk is not an impossible task, even under financial and time constraints. All it takes in many cases is a different perspective on the design problem."

– Mike Martin and Roland Schinzinger, Ethics in Engineering[263]

While many disciplines of engineering rely on adherence to the laws of nature (i.e., aerospace, civil, and mechanical engineering), Software Engineering relies on man to determine the laws and bounds based on which the software system is constructed. The independent developer is capable of determining and assigning new laws that bound and controls the software system. This fluid structure grants great liberty to the developer, while adding a significant degree of risk and failure probability to system development and operation.

Software Safety Assurance requires the combination of various disciplines to ensure a successful and acceptable[264] development product, including:

- The ability to develop safer software,
- The ability to measure the development of the software system, as well as system functionality, and
- The ability to take system measurements and apply them to generate a measure of system safety.

The ability to develop safer software is well documented. The concepts and practices of Software Safety Assurance range from the obvious "To make software safer, prevent the occurrence of hazards"; to the more complex concepts of software

[263] Martin, Mike; Schnizinger, Roland, *Ethics in Engineering*, McGraw-Hill Science/Engineering/Math Division, 3rd edition; 01 February 1996.

[264] Note: The term "acceptable" denotes the fact that no safety critical system can be considered absolutely without the potential for a hazardous event. It is possible though, to determine a level of hazardous events that would be acceptable to system operation.

development management, methodology, and practices. Many of the current standards of Software Safety Assurance are included in Chapter II.E of this dissertation. The limitations and ability of a development team to actually create a system at some actual or arbitrary[265] level is reviewed in Chapter III. The ability to make a system under safe conditions does not necessarily infer safety; it only implies that the system was designed under such safe conditions. A sound assertion of safety can only be accomplished through a measurement of the product by an accepted metric.

The capacity to measure the development of a software system is varied, depending on the intended product of the measurement, the software system in question, and the resources available to make such measurements. Lines of code[266], complexity, temperature[267], volatility[268], and required resources all provide some type of measurement that can be used to determine the ability of a team to actually develop a software system. Chapter II.E included a discussion of the potential measures that could contribute to an assessment of the software development, while their applicability toward Software Safety was reviewed throughout this study. Mean time to failure, hazard occurrence probability, and Consequence Severity are all acceptable measures that contribute to determining the safety of the software system. The more difficult task is to find a way to take the resulting measurement and logically apply it towards some resulting Software Safety value.

A Measure of System Safety is one the *Holy Grails* of Software Engineering. Many organizations and private corporations have touted its existence, while its foundation is based largely on hearsay and loose theoretical assumptions. Each safety–critical software system may have one or more potentially hazardous events, each with

[265] Note: The term “arbitrary” denotes the fact that many software professionals have no concept of how safe they desire the system to be. Many developers and customers fail to understand the mechanics of software failure and thereby desire an absolute value of safety without perception of the consequence.

[266] Note: Lines of code or any count of modules, function points, or other acceptable elements of the software system.

[267] Saboe, Michael S.; *Software Technology Transition, Entropy Based Engineering Model*, Software Physics, Naval Postgraduate School; Monterey, California; March 2002.

[268] Nogueira de Leon, Juan Carlos; *A Formal Model for Risk Assessment in Software Projects*, Naval Postgraduate School; Monterey, California; September 2000.

their own potential for occurrence and operation, and each with an independent measure of acceptance. The statement that a system is safe must take into account each of the independent elements of system operation and failure only in so much as they apply to Software Safety. Any review of software system operation beyond those that could potentially result in a hazardous event is not required.

A. A SAFETY KIVIAT MODEL

After all of the assessments and testing has been completed, it still falls upon the developers and clients to determine if the system is actually safe enough for employment. Multiple criterions have been established from the requirement's specification documents that spell out the thresholds for the system's safety. In the end, the level of safety hinges upon a series of factors that combine to generate a confidence, and ultimately, a level of safety. Such factors would including, but not be limited to:

- Logic, including the use of Controls and Mitigators,
- Process and Methodologies,
- Experience of the Requirement's Authors, Designers, Developers, and Integration Teams,
- Reuse of Trusted Systems, and
- Testing and Assessment Methods

In the development process, as the performance, competence, or proficiency of each of the elements – *Logic, Process, Experience, Reuse, and Testing* – increases, the ultimate confidence in the system increases, directly resulting in an improvement in Safety. Each of these elements has a direct relationship upon the other elements within the group, essentially complimenting their performance. As Logic increases, the Effort required to implement the Process and Methodologies decreases, increasing the level of performance of the Process. As the Reuse of proven elements increases, then the effort of Testing decreases, permitting greater resources to be expended on other critical testing elements. Experience has a direct effect on the performance on all of the elements.

Using the Kiviat graph technique, it is possible to depict the levels of performance of each of the elements as they relate to Software Safety Engineering to demonstrate a measure of confidence for the development process. Figure 20 demonstrated a potential method for depicting the elements with each gradient representing the level of performance of the element. The center gradient would represent a non-existent level of proficiency for the vector, increasing out the highest level of proficiency at the end of the vector. Connecting each point on the vectors creates a bounded area representing the total proficiency of the development process. The Kiviat graph can represent a visual depiction of the development process when concentrating on Software Safety, vice the traditional measurements of the software components. Encouraging a strong emphasis on the system safety process during development, the greater the area, the greater the confidence an engineer may gain in the system's development, thereby implying greater system safety.

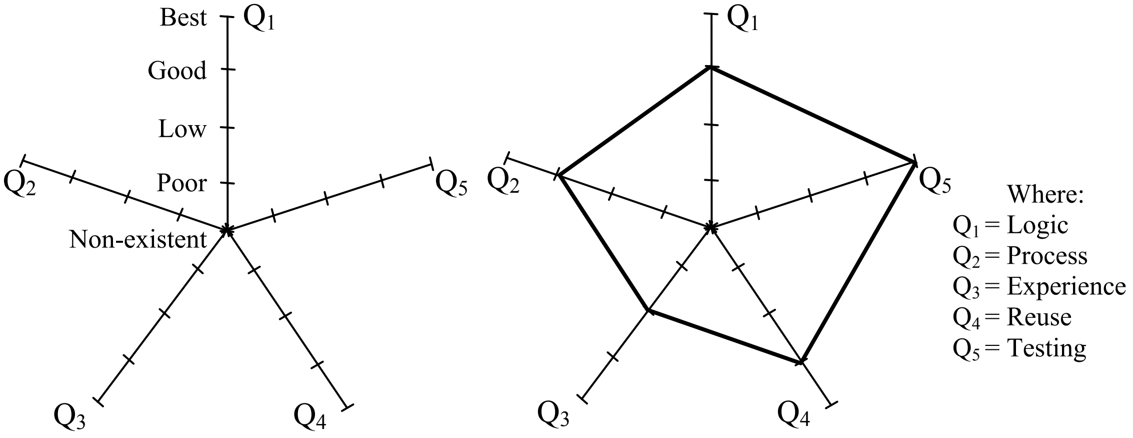

Figure 20 Kiviat Depictions of Safety Related Elements

Through continued refinement, the ultimate Kiviat graph may contain any number of elements that contribute to the safety of the system through development. Using the Kiviat graphic, it is possible to visually depict the elements of the development process, demonstrating balance within the apportionment of resources and tasking, relating a value of confidence, and implying a level of effort necessary to complete the construction of the system in the early stages of development. Rather then existing as a static product, the resultant Kiviat graph would serve as a dynamic representation of safety elements throughout the lifecycle of development. This depiction can be reassessed at periodic stages of development and then compared at the end process for validity. Once refined, such a model could be used to associate safety to each of the elements and to the associated bounded area.

B. EFFECTIVENESS OF THE METHOD

The goal of the Software Safety Assessment is to determine a level of safety for the software system. The effectiveness of the method is based on the evaluator's ability to investigate the system requirements; identify potential hazards, failures, and malfunctions; and determine probabilities of event activities. From that assessment, it is then possible to evaluate the system against established thresholds. System thresholds are established based on criteria from the development requirements, historical precedents, and subject matter expertise.

The effectiveness of the assessment can be judged by the comparison of identified failures, malfunctions, and hazards; probabilities; and consequence severities against actual results observed after system employment. It would be perilous and foolish to leave known hazards in the software system to observe their result in a real–world environment. Depending on the system and identified hazards, it might be possible to simulate the real–world operating environment, but the simulation could mask events otherwise occurring in an uncontrolled environment.

If it were possible to identify and control unacceptable hazards, the system could be deployed and observed in the real–world environment. In this state, the system could be evaluated and compared against the development assessment. The difference between observed and predicted actions result in a measurement of the effectiveness of the assessment.

In cases where it would be impracticable to permit the system to operate to its failure; either due to limited resources (time, capital, testing mechanisms…), the infrequency of unidentified failures, or desire to have a real time measure of assessment effectiveness; it would be possible to compare the findings of the Software Safety Assessment against the findings of similar system assessments. Such a comparison could only be accomplished where there exists an archive of software systems and their safety assessment results. Such a library would not be unlike that of today's software code libraries or COTS / GOTS repositories.

C. AUTOMATION

As stated in Chapter IV.B, the success of a Software Safety Metric relies on robustness, repeatability, simplicity, ease of calculation, and the potential for automatic collection. As previously presented, the Software Safety Metric meets all of the requirements for metric acceptability, with the exception of automatic collection. The concept of a mathematical approach to determining the safety of the system is very robust to change, with the exception of the additional burden on the developer to assure that the results are part of the new computation. The mathematical principles supporting the computation do not change for each iteration of development and are actually stable from project to project. Within a well defined system, the ability to independently repeat and arrive at like conclusions should be assured, as long as each evaluator completely understands the practices of software evaluation and probability computation. By the use of standardized practices, the metric is intended to be simplistic and require little training to perform. Through the use of accepted probability and statistics equations, and the ability of developers to limit the metric to fit their specific requirements, the complexity of calculation is greatly reduced.

While the use of such a metric standard may be possible to some degree, the ultimate trial comes from the ability to automate the collection and computation process, thereby ensuring compliance and standardization to the metric fundamentals. The results of each assessment can then be archived and reevaluated for conformance of metric predictions of safety levels to measured failure rated after the system has been implemented. With the repeated appraisal of the assessment process and metric computations, modifications and enhancements can be made to this research to continue the improvement of the state of the art. Safety Assessment Automation would reduce or eliminate the need for human intervention in the collection and evaluation process, assuring repeatability and ease of use. Such automation must be unidirectional, from the system to the automated metric, ensuring that the metric automation system does not inadvertently introduce a potential flaw or failure to the system under investigation.

Currently, there exist numerous commercial code–level software test and development tools that can evaluate and control the robustness of a system. Such automated design level tools, like the Ada–based compiler *Spark*[269], intend to prevent software-induced failures during code development, while they lack the ability to prevent design deficiencies in specifications and implementation. Test level tools, such as the Ada–analysis tool *AdaSTAT*[270], attempt to evaluate the finished product code for completeness and violations of project–specific language restrictions. Pre–code level design tools, fabricated to develop the elements of the system before coding commences attempt to determine system elements and their operating parameters before the scripting of actual code. Tools such as *CAPS*[271] or *PSDL* automate the design process through prototyping and object creation. Some prototype tools are capable of automated base level code creation from the trial product. For example, CAPS is based on a prototyping language with module specifications for modeling real-time systems and combining reusable software. Such tools make it possible for prototypes to be designed quickly and executed to validate requirements.[272] The addition of an automated safety assessment module to such a prototyping system would increase the efficiency of system development by permitting near simultaneous development in conjunction with a safety evaluation in the initial stages of development. It must be assumed that each system development tool and compiler is free of defect and that the product that is produced contains no logic based failures beyond those defined in development.

[269] Barnes, John; High Integrity Ada, *The SPARK Approach – Spark 1.00 for Windows*, Addison-Wesley, Praxis Critical System Limited; 1997.

[270] *AdaSTAT – Ada Static Analysis Tool*, DCS IP, LLC; Alexandria, Virginia; 2002.

[271] *CAPS – Computer Aided Prototyping Systems*, Naval Postgraduate School; Monterey, California.

[272] *Faculty Research Catalog of the Department of Computer Science*, Naval Postgraduate School, Monterey, California; April 2003.

Despite the abundance of code-related design tools, I have noted that flaws and errors in code methodology are only one of a chain of potential elements that leads to determining the safety of a software system. Invariably, the most likely source of safety–related failures is in the requirements specification. They are generally incomplete, inaccurate, ambiguous, and subject to interpretation. Ultimately, an automated tool must include the tracking of software system development from requirements to the test product with some integration to system operation. Currently, many developers rely on a menagerie of different management tools including *Microsoft Project*[273], *DOORS*[274], or other homegrown databases and documents. Within the flexibility of these tools, is the ability to tailor the product to meet the explicit needs of the organization. Each of these management tools, while highly flexible, detracts from standardization while adding functionality.

It is possible to develop a software–based system on two levels:

- Capable of taking user inputs to manage the development of the software system and generate a possible Software Safety Index, and

- Capable of taking user inputs, coupled with third party automated software tools, to manage the development of the software system and generate a possible Software Safety Index.

The development of the first system is highly plausible, assuming that a standardized methodology of software management and documentation can be agreed upon. It would be possible to gather and present system requirements, establish system safety limit tables, manage system development and tasking, prompt user assessments at the base level, and produce an automated SAI output. The development of the second system, while increasing the level of assessment automation, would be more difficult as it must rely on the functionality of third party development tool. The Software Safety tool must assume the static development of the third party tool (no improvements), and the

[273] *Microsoft Project 2000*, Microsoft Corporation; Redmond, Washington; 2001.

continuous use of the current software language and format (assuring use of the third party tool). It would be more applicable to tie the concept of Software Safety Assurance and management directly into the development of future software development tools.

The presentation format of assessed data can be as critical as the data itself. Properly presented, the data can be easily translated and understood by members of the development team. The data presentation format could be tailored to meet the needs and preferences of the developers and the clientele. Various software development tools have automated modules that can present assessed data in preformatted report formats including Gantt charts, object flow charts, and stop light depictions.

Until such time that an automated safety development tool is created, the Software Safety metric can be semi–automated using any of a number of spreadsheets, database, or development management tools.

D. METRIC

The stepwise format of the Software Safety Assessment permits a structured flow for implementing the metric. Despite lacking automation, the structure flow of the metric could be manually blended into the existing development process by overlaying metric procedures into accepted spiral development models. It is not essential that metric steps be accomplished uninterrupted, rather efficiency dictates that steps be incorporated in order throughout the development and implementation process to provide real–time opportunities to alter and correct potentially unsafe processes.

[274] *DOORS*, Telelogic AB; Malmö, Sweden; Irvine, California; 2001.

The success of the Software Safety Assessment metric depends on the following factors:

- An understanding of the consequences of potential failures.[275]
- The ability to use hazard awareness and identification in a mitigation process that reduces the potential for hazardous events.[276]
- The integrity to identify weaknesses in the software process without fear of negative consequences or reprisals.[277]
- The repeated use of the metric to build confidence, proficiency, and adaptability to the development process.[278]
- Access to industry and field library resources to gain broad–based situational awareness to the state of the art of Software Engineering.[279]
- Standardization in the design and nomenclature of hazard and severity tables tailored to the field of high–assurance systems.[280]

Despite any lack or availability of resources necessary to make safety changes discovered in the assessment process, it is essential that individuals make the required assessments to gain awareness of the potential for the system. Should the system fail in the future and result in a hazardous event, it may be possible for the developer / owner of the system to prepare reactionary processes to compensate or mitigate for the event.

[275] See Chapter V.C. - INITIAL IDENTIFICATION OF THE HAZARD

[276] See Chapter V.E.4. - Decision Making.

[277] See Chapter III.B.1. - Political Pressure

[278] See Chapter V.F. - SUPERVISION OF SAFETY CHANGES

[279] See Chapter VI.C. - AUTOMATION

[280] See Chapter II.G.1. - Comparisons of Safety Definitions

E. MANAGEMENT

1. System Managers

The success of Software Safety relies on the management of and proper adherence to the principles of software development and employment. Managers must be well aware of the requirements of a Software Safety Assessment, as well as the tools, methods, and practices required for such a development. The use of an automated tool would greatly increase the efficiency of the Software Safety Assessment process, decreasing the burden on the development manager. It is imperative that management discovers and provides the tools and resources required for an efficient development process that encourages complete development, compliance to accepted requirements, and the reduction of potentially unsafe events.

Management is ultimately responsible for the successful integration of the safety assessment into the Software Engineering process.

Managers must present an atmosphere that encourages a realistic assessment of the product, does not discourage members for discovering faults, and rewards members for the discovery of potentially unsafe faults that can be corrected. Management is not deterred from punishing members who create a potentially unsafe element, as long as the reprimand does not detract from the overall success of the engineering process.

The atmosphere that management presents to the development and implementation process, and the emphasis for which they put on safety assessments, directly affects the success or failure of a program. If a manager places little concern for safety and project completeness, then engineers may potentially disregard required process steps as burdensome and without merit. If a manager establishes accountability and training towards a goal of increased Software Safety, then engineers will potentially incorporate those traits into the software process. It becomes the manager’s duty to discover a balance between efficient development of a high–assurance software system (efficiency measures including the reduction of potentially unsafe events) and the over–burdensome requirement of safety verification beyond that which would create a diminishing return.

2. Metric Management

It is my opinion that the success of any process relies on three basic principles:

(1) Its acceptance among the professional body for which it represents,

(2) Its ability to provide a usable product, and

(3) Its ability to adapt and be customized for changing environments and improvements in the state of the art for which it represents.

The safety assessment process introduced presents a refreshing view to the field of Software Development and Engineering. The introduction of these concepts and methods to the body of Software Engineers should be accomplished in three distinct phases:

(1) The introduction of safety, failure, and hazard definitions as they apply to the field of Software Engineering,

(2) The introduction of hazard and severity tables, as demonstrated in this dissertation, and

(3) The incorporation of the stepwise safety assessment process, utilizing definitions and tables introduced in the first two phases.

The introduction of the dissertation subject matter would be accomplished through its published incorporation in various professional journals and periodicals, as well as at lectures and gatherings where new methods can be openly introduced, discussed, and reviewed by contemporaries of the Software Engineering field.

Managing the extended life of the safety assessment process requires some acceptance by the professional field of Software Engineers. *The professional field is not limited solely to organizations such as System Safety Society, the American Society of*

Safety Engineers or IEEE[281], but to include specialized organizations such as *ASCE[282], ASME[283], NSPE[284],* DISA[285], DARPA[286], NUREG[287], and BSI[288]. Academic organizations and symposiums, such as the Monterey Workshop, sponsored by the Software Engineering Department of the Naval Postgraduate School, provides a valuable opportunity for introducing the method of safety assessments to a wide body of Software Engineers as well as governmental and private organizations interested in increasing the safety of high–assurance systems.

The software assessment presented in this study is designed to provide two products to the Software Engineer – The quantitative measurement of software failures through the software lifecycle; and the qualitative measurement of Software Safety. The ability to accomplish both goals requires some level of training and instruction to industry professionals, to ensure proper implementation and compliance to the established principles. Failure to provide such training could result in the breakdown of the software assessment method and eventually its disregard as an industry tool. Training could be easily accomplished through the use of periodical literature, published instruction, and academic incorporation.

The process previously introduced in this study is still in its infancy; no more mature then the field of Software Engineering itself. Such infancy encourages review and improvements to approach maturity. The success of the assessment process demands the continued maturity of the method to ensure that a usable product can be generated across the widest variance of Software Engineering circumstances.

The ability to customize and adapt the safety assessment is essential to guarantee the widest incorporation into the engineering field. The concept of a safety assessment is

[281] Institute of Electrical and Electronic Engineers.
[282] American Society of Civil Engineers.
[283] American Society of Mechanical Engineers.
[284] National Society of Professional Engineers.
[285] Defense Information Systems Agency.
[286] Defense Advanced Research Projects Agency.
[287] U.S. Nuclear Regulatory Commission.
[288] British Standards Institute.

not new to the engineering discipline, but additional emphasis is needed to incorporate the process into the field of Software Engineering. Customization and adaptations can be accomplished so long as they do not detract from the functionality and ability of the assessment to provide a viable product. The use of safety/failure libraries and archives would provide users with resources for generating usable thresholds and controls to better manage the engineering process and ensure a usable result. Libraries could be exclusive to private organizations that have a sufficiently large development base to ensure some variety, or can be public in nature, fed by governmental, private, or academic entities with a common interest in increasing Software Safety and reducing the risk of hazardous events.

Each of these topics is a viable subject for additional research and discussion beyond the scope of this dissertation.

F. COMPLETENESS

Completeness, in the form of a software assessment assumes that all of the potential roots of the system have been investigated and evaluated. It is not necessarily implied that each root will be free of a defect, but that each root has been assigned a value of probability, and that probability and consequence are well understood. Previous software development projects have revealed that poor granularity of metrics and measures did not reveal problems until they had already occurred. A Software Safety Assessment is fruitless if a failure occurs that was not previously discovered or anticipated. Each assessment and investigation must be thorough enough to completely discover every potential failure, in so much as resources permit.

When resources limit the investigation of potential failures, emphasis can be put on roots of the system that hold the greatest consequence should a failure occur. Where consequences are equal, emphasis can be put on roots where the probability of occurrence cannot be mitigated by the use of some control. Completeness does not imply an absolute investigative coverage of the entire system, but rather the assurance that the system has been protected completely, as so far as resource and development permits. If one black box element of the system can be controlled and isolated, should an unknown error occur within its operation, and then isolation and control does not affect the continuous operation of the system as a whole, then the element can be considered safe. It should be cautioned that even a minor change to the system, especially the software, could result in a change to the system context that invalidates that assessment.

Risks are not always identified or reported. Even when metrics and measures are reported that showed risks, there may be no action by government or contractor to correct incipient problems. The success of a Software Safety Assessment relies on a mechanism for feedback that affects the system product, the development / redevelopment process, and the extent to which system requirements were effected.

The safety development process must be evaluated for the economic requirement and potential benefits of the application change. The safety development process must be looked at as a change to the system, as it is designed to improve upon existing requirements and development shortfalls. If the system requirements were correct and complete (from a safety perspective) at the onset of development, then safety changes would not be required. Various metrics and scales have been developed to measure the required resources and effort necessary to make development changes.[289] Those estimations can then be verified at the completion of development. Safety benefits are hypothetically based on an assumption of system functionality that can only be verified at the completion of an established goal, either in time or action.

Controls must be evaluated for their potential benefit to Software Safety and failure prevention, as well as their effect on system performance and ability to meet developmental requirements. The implementation of safety controls requires an evaluation of potential resource economics, the level of effort required to include the control, and the potential effect of the control upon the overall operation of the system.

[289] Boehm, Barry; Clark, Bradford; Horowitz, Ellis; Madachy, Ray; Shelby, Richard; Westland, Chris; *Cost Models for Future Software Lifecycle Processes: COCOMO 2.0*, Annals of Software Engineering; 1995.

Completeness of the system must consider the effects of specific elements upon single requirements as well as upon the system as a whole.

G. PERSPECTIVE CLIENTELE

The safety assessment method introduced in this dissertation is applicable to a variety of Software Engineering ventures. Primarily, the safety assessment would benefit the development and implementation of high–assurance software systems. The extent of the safety assessment is not solely limited to high–assurance systems, but can serve to benefit the development of all systems that have the potential for a hazardous event. Predominately, resources are expended for safety assessments only on systems that require a high assumption of safety. This particular method of safety assessing can be applied to any scale of Software Safety Engineering, from the most benign to the most precarious. The potential client for such an assessment process spans a myriad of distinctions from private, to educational, to governmental organizations.

The power generation field relies greatly upon high–assurance software systems to manage, control, and provide power to the general public. The failure of a power generating system can potentially result in any of a number of hazardous events external to the power generator – to clients who rely on the power system. The inability to control the power generating system could result in a catastrophic event internal to and external to the power generator – such as in the control systems to a nuclear power facility. Clients such as the public power generation field would greatly benefit from such a method and its ability to provide:

- A valid safety assessment of the potential hazards of the system.
- The ability to identify weaknesses and cost of potential mitigation controls.
- The ability to inform and protect from potential hazards through the inspection and identification of safety–related system operation.

The world's military superpowers insist on highly effective and technologically advanced weapons and defense systems capable of meeting the national objectives of their respective leaders. The failure of such a technological weapon could result in the inability to meet expected goals and combative milestones. The failure of a defensive system could leave allied forces vulnerable to attack and eventually susceptible to considerable troop losses. With the reliance on technologically complex weapons to bring order and victory to the battlefield, it would be prudent for defense contractors and developers to utilize such a safety assessment process. The results of such a process would provide military commanders with a realistic expectation of the success or failure of their weapons and defenses as well as the foresight to make compensatory alterations to their battle plans.

The chemical industry has automated a considerable portion of their manufacturing process, using various high–assurance systems to ensure a superior quality of chemicals, biological agents, and pharmaceuticals. Should the production of these chemicals fall outside of the delicate balance permitted in their nature, then the hazardous event could have cataclysmic results with worldwide consequences. One could only imagine the impact of an inadvertent release of a biological agent or the tragic result of a chemical spill into a national waterway. Private industry has an economic and moral interest in the success of their product. Such a safety assessment would permit industry to protect, mitigate, and prepare for a hazardous event. The ability to assess and measure the safety of a product gives industry the capacity best serve its clients and further guarantee the continued viability of their organization.

Educational institutions serve as the bedrock for future development practices and standards introduction. From this foundation, new engineers are instructed on the techniques and talents that will provide tomorrow's solutions. If the concept of Software Safety Assessments is established early in the educational process of future Software Engineers, then in the long term, the trend towards reviewing and measuring software for its ability to prevent or participate in a hazardous event can be recognized. Formal education is paramount towards the future success of Software Safety. Assessment and measurement is the first in a series of process steps necessary for the security of software evolution.

H. CONCLUSIONS

The application of a Software Safety Assessment has been justified by its ability:

- To support critical development and implementation decisions at milestone or other decision points.

- To find the reasons for major problems such as cost overrun, schedule slip, inability to meet development requirements, the inclusion of potential faults, or a failure to pass a technical milestone such as testing.

- To baseline the program status, identify and prioritize risks, and plan for improvements and risk management.

  - This kind of assessment is not in reaction to a crisis. Its objective is to prevent problems by early recognition of risks and to identify opportunities to make improvements.

- To investigate specific technical issues or evaluate technical products for their ability to control and prevent the occurrence of a hazardous event.

- To determine how well successive series of development are capable of implementing a safe development.[290]

The assessment process introduced in this dissertation is capable of establishing a basis for qualitative Software Safety. The application of this assessment process can be accomplished with minimal overhead to existing spiral or repeating development processes. The process does not limit itself to the development of a software system alone, but includes the installation and employment processes as well. From its inception, this stage-wise process was intended to meet each of the basis practices of a valid assessment. As a first generation assessment process is will continue to grow and mature, compounded upon and refined by additional research and application.

The use of this metric will require some changes to the methods for which software is designed and implemented. These changes will include a greater obligation by management to ensure compliance to the assessment requirements. Developers will be required to pay greater attention to potential mitigation controls necessary to reduce identified hazards. Product customers will need to pay greater attention to the potential hazards of the product that they are about to implement and be prepared to take responsibility for those hazards that cannot be mitigated. The burden for these requirements to management, developers, and customers should be minimal when compared effort required for the entire software system process.

The process can be readily incorporated into existing software development projects or be adapted as necessary to be included into future ventures. Benefits from the safety assessment can attained by both private, commercial, governmental and educational users. Where possible; information, mechanics, and findings of the safety assessment process can be shared by various users to establish a baseline of safety data, ultimately improving the development and implementation of high–assurance systems.

[290] Attributed to Clapp, Judith; *The Best Practices - Forum on Independent Program Assessments*, The MITRE Corporation; Bedford, Massachusetts; 05 December 2000.

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VII. SOFTWARE DEVELOPMENT DECISIONS

A. SOFTWARE NEGLIGENCE

Software producers have an inherent responsibility to their customer to provide a product that is, to a reasonable degree; safe, free of defects, and meets the requirements agreed upon at the time of production.

Under negligence law, software developers must not release a product that poses an unreasonable risk of personal injury or property damage to the customers or the general public.[291] Negligence is defined as the "failure to exercise the degree of care expected of a person of ordinary prudence in like circumstances in protecting others from a foreseeable and unreasonable risk of harm in a particular situation."[292] To a great extent, most lawsuits over defective software are for breach of contract or fraud, partially because they did not involve or were caught before they could result in personal injury or property damage. In the most unfortunate of circumstances, software's failure causes such harm. Personal injury could run the gambit from actual to presumed harm, be it physical or mental.

It is possible for a customer or member of the general public injured by a software related event to sue a software provider or the developers for not taking reasonable measures to ensure the product was safe. Reasonable measures are those actions that a reasonable, cautious provider or developer would take to protect the safety of its customers or the general public. The common approach to determining the financial responsibility of the developer can be expressed legally by the cost–benefit equation expressed in Equation 4, from the formula by Judge Learned Hand in the case of *United States v. Carroll Towing Co.*[293, 294]

[291] Kaner, C.; *Software Negligence & Testing Coverage*, Software QA Quarterly, Vol. 2, #2, p. 18; 1995.

[292] *Negligence, Merriam-Webster's Dictionary of Law*, Merriam-Webster, Incorporated; 1996.

[293] *Federal Reporter, Second Series*, vol. 159, pg. 169, United States Court of Appeals, 2nd Circuit; 1947.

[294] Landes, W.; Posner, R.; *The Economic Structure of Tort Law*, Harvard University Press; 1987.

$$\boldsymbol{B} = P \times L$$

Where ***B*** = The Burden or Expense of preventing the hazardous event.
L = The Severity of the Loss if the event were to occur.
P = The Probability of the Occurrence of an event.

Equation 4 Legal Definition of the Cost–Benefit Equation

It would be considered unreasonable for a software producer to develop a software product where the burden of production exceeds the severity and probability of a hazardous event.[295] In a recent and highly publicized case, GTE Corp. mistakenly printed 40,000–50,000 unlisted residential phone numbers and addresses in 19 directories that were leased to telemarketers in communities between Santa Barbara and Huntington Beach. GTE blames the problem on a software failure. The company faced fines of up to $1.5 billion, if found guilty of gross negligence. The case was resolved in 1998 in an undisclosed settlement.[296] Such a settlement would question if it would have been reasonable to expect GTE to pay $1.5 billion to compensate for such an incident, considering the fact that the injury to customers was an invasion of privacy and that a nuisance was created by telemarketers contacting their private phone numbers, or if it would have been more economical (or possible) to afford a lesser sum to mitigate the incident before it would have occurred through the development of a better software system. In May of 2000, Pacific Bell published the names, numbers, and addresses of more than 11,400 unlisted Cox Communications telephone subscribers in San Diego. Cox Communications admits that it erroneously forwarded Pacific Bell the numbers, citing a software error. Cox has since paid over $4.5 million to replace approximately 440,000 phone books, as well as an undisclosed expense for new unlisted numbers and other compensation.[297]

[295] Kaner, C; *Quality Cost Analysis: Benefits and Risks*, Software QA, vol. 3, num. 1, pg. 23; 1996.

[296] *X Telecom Digest*, Volume 18, Issue 60; 27 April 1998.

[297] Hammerman, Ted; Sparapani, Tim; *"If I were them…"*, Office.com; 26 July 2000.

The safety assessment method addressed in this dissertation would serve to compute the possible burden for such a hazard, either by identifying the effort to mitigate the hazard or the potential cost for such hazard to occur. It would be reasonably expected that a prudent developer would make such an assessment to:

1. Determine / Identify the functionality of his system,

2. Identify the weaknesses within the operation of the system,

3. Determine the potential occurrences of hazardous events within the system's operation,

4. Justify the efforts required to mitigate such events,

5. Determine if additional efforts are required to meet product functional and safety requirements, and

6. Legally protect the developer from potential suit should a hazardous event arise by demonstrating sufficient precaution and investigation of system operation.

Should an unexpected hazard occur, a properly executed safety assessment with the appropriate documentation would protect the investment by demonstrating that sufficient effort was expended to find all reasonable hazards.

B. SOFTWARE MALPRACTICE

Malpractice infers that an individual has provided a service below that which would have been reasonably expected by a respective member of the professional community, resulting in injury or loss.[298] Article 2B of the Uniform Commercial Code defines the requirements for malpractice within the software field.[299], [300] The expectation

[298] *Malpractice, Merriam-Webster's Dictionary of Law*, Merriam-Webster, Incorporated; 1996.

[299] *Uniform Commercial Code Article 2B Revision Home Page*; http://www.law.uh.edu/ucc2b.

[300] Kaner, C; *Quality Cost Analysis: Benefits and Risks*, Software QA, vol. 3, num. 1, pg. 23; 1996.

of quality of a production of software is no different than the threshold that may be held for a medical device, legal service, or building construction. Instead of a hard medium of production, the software industry generates a soft product that can still have catastrophic results if improperly developed, employed, or terminated. Should a developer promise working code and deliver garbage, the developer may be liable for breach of contract. Should the developer convey that he is capable of delivering a specific type of application but have no real experience, then the developer could be liable for misrepresentation.

In a malpractice case, the level of care provided would be compared against that expected from a comparable professional software developer. Software developers may be judged against a standard agreed upon within the contract, requirements, or by the assumption given to the type of work under development. If the product does not meet the requirements and it would be reasonably expected for a professional to follow standards required to guarantee such results, then a measure of liability would be in force. Software development does not have a general standard that covers the measurement and assessment of high–assurance systems. Numerous safety standards exist which are proprietary to specific companies, development groups, and governmental organizations. Malpractice requires some level basis of standard to assess liability.

There currently exists no standardized format for reviewing, evaluating, and rating a software system for its potential harm to society. Through this study, I introduce a possible format for certifying a software product to some accepted threshold of safety, based on an established criteria.[301]

C. NEGLIGENT CERTIFICATION

It is intended that the Software Safety Assessment process introduced in this dissertation be used as a basis for the accreditation and certification of future high–assurance systems. Should this or any safety assessment process be deemed as a viable method to meet the demands of safety engineering, the chosen method may be legally

[301] See Chapter V.E.3 – *Assessing the System Process.*

challenged and found potentially liable should an evaluated system fail. The general public might expect that an assessment process would identify all potential failure method and hazards, as well as provide alternatives for their mitigation and control. In reality, the assessment process can only identify faults that fall within the scope of the assessment and in particular, within the ability for the assessor to identify.

The assessment process in this dissertation does not imply endorsement to any product, nor does it state absolutely that the product will not experience a hazardous event. What the assessment process does is provide a method for developers and managers to view a product with an eye towards potential failures, introducing methods for their mitigation and control. The assessment process is designed to be straightforward and as stepwise as possible, easily integrating into existing development practices. The burden still remains with the developer to ensure that proper practices are in place to ensure a viable assessment product and that assessment recommendations are acted upon.

An extensive search of legal papers and industry press releases have revealed no history of filings against software developers for the violation or manipulation of software certifications. Despite the fact, there remains the potential for future systems to be challenged for misrepresenting their results against any such certification, or outright pose a legal challenge against the certification method itself for failing to prevent *any* hazardous event.

D. SAFETY ECONOMICS

As noted in Chapter I of this dissertation, over $250 Billion is spent on software development annually. A sizeable percentage of that investment is lost due to failures in software design, process engineering, and cancelled projects. There is no accurate value for the amount of money lost due to software related failure but, again, experts put the value into the billions of dollars annually. Many of the failures result in the mere “nickel and dime” incidents, but the breadth of these failures results in a compounded sum that should force others to take notice. News accounts publicize only the most spectacular incidents that result in significant losses and dramatic effects. Tragically, the failure of some systems results in the harm to, or loss of life of, another human being. It is the combination of these three (Compounded sum of failures; Poor industry publicity of software failures; The potential injury to or loss of human life) that must justify the efforts of a Software Safety Assessment.

Customers are a highly impressionable public.

Customers are quickly affected by bad publicity and implied confidence. They can be swayed by colorful advertisement, statistics, and personalized attention. Customers will shy away from events or products that could place them in a bad light, be labeled "politically incorrect," or place them in a perceived jeopardy of offending their own customer base. Should a software product or developer demonstrate a history or pattern of failures over a given period of time or be related to a single high–profile failure event, customers may withdraw their interest until such time as a stable product becomes available. In the meantime, customers would turn to alternative in–house solutions, to a third party provider, or discontinue the requirement for such product altogether. In some cases, customers may turn to a competitor's product with sufficient investment as to not economically justify reverting back when a stable product is finally offered. Software systems are optimally updated about every twelve to eighteen months, making the window for change or reinvestment ripe for transition to alternative products. The failure of any one system today could result in the loss of business tomorrow.

From a legal standpoint, should the cost of potential litigation, compensatory damage, and punitive damage for a specific hazardous occurrence exceed the cost for which it would take to fix the known failure, then it would be justified to resolve the problem. The failure to sufficiently test the product could place the developer in jeopardy of a negligence lawsuit for not reasonably testing the system. The failure to repair an identified failure could place the developer in jeopardy of a negligence lawsuit for not reasonably making the system safe. Should it not be cost effective (the potential burden of a hazardous event is less that the cost of preventing the event) then the developer may justify not mitigating a specific hazardous event. It should be emphasized, that intentionally leaving a known hazard in the system could make the developer liable under malicious circumstances, possibly compounding legal judgments.

From a moral standpoint, software developers have an ethical requirement to provide the most reliable software product to the consumer with the least potential for a hazardous event. Various software development standard bodies, such as IEEE, and the British and Australian Computer Societies have agreed on independent sets of bylaws outlying the moral and ethical requirements for software development, namely that:

- Members will approve software only if they have a well–founded belief that it is safe, meets specifications, passes appropriate tests, and does not diminish quality of life, diminish privacy, or harm the environment. The ultimate effect of the work should be to the public good,[302]

- Members shall in their professional practice safeguard public health and safety and have regard to protection of the environment,[303] and

- Members must protect and promote the health and safety of those affected by the product provided. [304]

The adherence to and acceptance of these basic principles of ethics places a potential economic burden upon the software provider. While this burden of training and adherence may be significant, the potential rewards of producing a product that provides for the "safety and welfare of the public" [305] could be the increased revenue from additional contracts and devoted customer base.

[302] *Software Engineering Code of Ethics and Professional Practice*, IEEE-CS/ACM Joint Task Force on Software Engineering Ethics and Professional Practices, SEEPP Executive Committee; 1998.

[303] *British Computer Society Code of Conduct*, The British Computer Society, London, England; 22 April 1992.

[304] *Australian Computer Society Code of Ethics*, Australian Computer Society; 1999.

[305] *Software Engineering Code of Ethics and Professional Practice*, IEEE-CS/ACM Joint Task Force on Software Engineering Ethics and Professional Practices, SEEPP Executive Committee; 1998.

E. CONCLUSION

There can be little doubt that the hazardous failure of a software system would result in an expensive penalty to the developer, the client, and potentially the general public. The legal ramifications of a software failure could range from the civil penalty to incarceration. It is imperative that software systems be designed with the consequential understanding that failure could result in the downfall of the developers who were tasked with the construction of the system. To this end, the inclusion of a Software Safety Assessment demonstrates an additional level of competence and security, limiting the potential for legal action in cases of negligence or malpractice in software development.

It is possible to estimate the cost of development through any of a myriad of development assessment tools, while the incorporation of a Software Safety Assessment would add an additional layer of change assessment, should change be warranted, or to hazard cost, should a hazardous event be identified. The economic ramifications of such an event could be determined throughout the development process, leading to the ability to redirect assets and efforts to ensure beneficial product. The benefits of a Software Safety Assessment can be measured in terms of the hazards for which it identifies or prevents, or for the financial assets that it saves through the prevention of such events.

VIII. SUMMARY AND CONCLUSIONS

Software Safety is not based on a new development method, but rather the refinement and application of existing methods of development.

As industry and governments increasingly place the management of critical operations under the control of software–based systems, the potential and severity for a hazardous event increases. Software based systems exercise a predominant automated control over the United States military command and control network and defense systems, as well the control and functionality of today's sophisticated weaponry. Software is used to control and manage civil utilities, public communications, industry trading, and the commercial food supply. Medicine, transportation, and the public food supply are all manipulated to some degree by software automation. The extensive reliance upon such systems consequently results in an increased probability for significant economic loss or physical injury to those in contact with the system should they fail.

While it is difficult to render a software system completely devoid of any potential failure, it is possible to identify, classify, and potentially mitigate failures and hazardous events within a software system. From that effort, it is possible to establish a safety index to gauge the safety of a system against unwanted events. Through this study, I introduce a formal Software Safety Assessment method for deriving a quantitative and qualitative safety value for system operation. This approach utilizes a series of accepted development methods for determining equitable values of system's operations and management, combined to generate a unique perspective of high–assurance software operation.

There currently exists no publicly accepted method for determining a safety index of software systems. While a variety of private methods may exist, the proprietary and specific nature of these methods makes them unacceptable for use as a general safety assessment method. The method introduced in this dissertation builds upon the philosophical foundation of legacy methods to establish a generalized method that can be tailored to meet the specific need of each development scenario.

There is no "Silver Bullet"[306] to prevent the occurrence of all failures and hazardous events within a software system, but the identification of the potential occurrence increases system safety through awareness and recognition. The primary benefit of this dissertation is the introduction of a method of system safety awareness through operational analysis. Many systems sputter and hesitate under the burden of excessive development review – essentially "Paralysis by Analysis." Through the presentation of this study, I provide a method for reviewing and assessing the operation of the system with minimal encumbrance, essentially taking place in series with the existing development process.

<u>QUESTION:</u> Is it possible to develop a common assessment criterion that can determine if software is safe?

<u>ANSWER:</u> YES. Through the stepwise process introduced in this dissertation,[307] it is possible to make an assessment of the developed product to determine the level of safety of a software system.[308] The stepwise process is broken down into incremental stages that guide the evaluation through the establishment of safety thresholds, the identification of malfunctions and hazards, and ultimately the assessment of the system. From that assessment, it is possible to assign a safety measure to the software development.

[306] Brooks, Frederick P., Jr.; *No Silver Bullet, Essence and Accidents of Software Engineering*, Computer Magazine; April 1987.

[307] See Chapter 0 – *11. PROCESS* PROCEDURES.

[308] See Chapter V – *DEVELOPING THE MODEL.*

A. CONTRIBUTIONS

The primary contribution of this dissertation to the state of the art of Software Engineering is the formalization of a method and metric to incorporate Software Safety into the development process.[309] A significant contribution of this dissertation is the formal study and research in the under–represented field of Software Safety. This formal model directly impacts and improves the state of the art by refining current methods of development to better identify unsafe practices and methodologies through the software lifecycle that could lead to failure. The success of this software development methodology is the increased awareness of safety in high–assurance software systems, the reduction of risk through the software lifecycle, with corresponding increases in efficiency, decreases in overall software system costs, and a decrease in occurrence of hazards in a software system. The introduced method builds upon the established practices of the MOD 00–56 UK Safety Standard and MIL–STD–882D, combined with the principles of risk / safety assessments, the principles of statistics and mathematics, and the design flow aspects of the Boehm Spiral Method. Specific contributions within this dissertation include safety definitions, the Software Safety metric, and additional process improvements.

1. Six Factors of Safety Failure

This study and dissertation is based on correcting the six inhibiting factors to Software Safety success, introduced in Chapter II.C, namely:

- A failure to realize that there is a problem with the current state of Software Safety,
- A failure to recognize potentially unsafe circumstances in software systems,
- A failure to identify the flaws of the Software Development Process,
- An inability to quantify flaws, faults, and failures into a measurable value,

[309] See Chapter V – *DEVELOPING THE MODEL* and Chapter VI - *APPLICATION OF THE FORMAL METHOD FOR EVALUATION OF SOFTWARE SYSTEMS.*

- An inability to qualify the solutions to potential flaws for evaluation and efficient rectification, and
- A failure to comprehend the solution to Software Failure.

These six factors are derived from a review of prominent and available literature regarding the failures of past products and systems, as well as a commonsensical approach to failure in general.

2. Definitions

The current state of the art of software development is littered with proprietary terminology that limits the establishment of an engineering standard. To provide a benchmark for safety standards terminology which I have introduced:

- An improved series of definitions to delineate failure types,
- New definitions for degrees of software failure semantics, and
- New definitions to delineate the severity of failure.

These series of definitions describe the aspects of Software Engineering with an emphasized view towards Software Safety and process improvement. A consolidated list of applicable safety definitions are included in APPENDIX A of this dissertation, including second and third party definitions related to this dissertation. Where possible and appropriate, a comparison and contrast of existing definitions is included throughout this dissertation to demonstrate the improvement process within this document over existing state of the art definitions.[310] This series is in no way complete and affords itself to continued improvement and refinement in future research.

[310] See Chapter II.G.1 – *Comparisons of Safety Definitions*.

3. Metric

Key contributions of this dissertation to the state of the art of Software Engineering are the introduction of a common metric for evaluating software and the development process to qualitatively and quantitatively determine a safety index of a particular software system. The ability of the developer to create a baseline scale to judge the software system against permits a degree of flexibility and adaptability beyond that found in legacy assessments. The resulting assessment value can then be evaluated against potential hazards and faults to determine the cost–benefit ratio of efforts to remedy or prevent the hazard. The introduced metric is defined and demonstrated throughout Chapter V of this dissertation. A synopsis of the process procedures is reviewed in 0 at the conclusion of this dissertation.

The introduction in this dissertation of the Safety Assessment Index (SAI)[311] gives Software Engineers a snap shot result of a software system's safety based on a tailored assessment process. The ability to evaluate and relate system hazard probability and hazard severity to system operation increases the capacity of software developers to make decisions beneficial to system safety. No such index was discovered during the investigation phase of this dissertation, and the inclusion of one such would markedly increase development comprehension and efficiency.

4. Process Improvement

The incorporation of the preceding Software Safety Assessment method results in an improved efficiency to the software development process. This process improvement includes a review of Software Safety economics and the cost / benefits of safety development over existing methods. The introduction of a Safety Element to Requirement Level Assignment provides a common foundation for software developers to build a requirement specification upon. From this foundation, developers can produce a system with safety as the intent, prepared for the incorporation of a cyclical safety assessment. Proper safety assessments can reduce repetitive design and developments through the early identification of hazardous and unwanted modules. Malicious portions of the system can be removed or repaired to ensure an optimal operation of the system through the use of limited resources and time. The safety assessment, designed to be incorporated in parallel with the development process, can provide timely updates to the development, tracking each change, empowering the developer with better decision making abilities. The economic impact of the assessment is dependent on the level of process improvement, the failures prevented and hazards averted, and the legal protections received through the use of a standardized safety assessment process.

5. Contributing Benefits

No assessment process will directly make a software system safer. That is not the intention of an assessment process. An assessment process is designed to evaluate and present a measure of a system's operation and design based on established criteria for further decision–making. It is with this data that the user can then determine if or what actions he should take to meet respective goals for system safety. It is intended that, with the assessment process, developers can evaluate a software system, identify potential weaknesses, measure the required assets necessary to compensate for the weakness, and then determine the potential benefit from the compensation. If the compensation is cost–worthy, then the determination can be made to enact the change, thereby making the system "safer." A determination to make a system safe must be based on a sound assessment of the system against an accepted threshold, a review of the costs and benefits, and the ability to make the required changes.

This dissertation, its study, and introduced methods are intended to improve the process of Software Engineering to provide a quantitative and qualitative assessment of a software product's operation. When applied, this software process has the potential of increasing the efficiency of software development by eliminating repetitive development efforts and flaws that can be identified early in the software process. Where possible, the software assessment can increase productivity through the use of standardized processes that can be related to existing methods and projects.

[311] See Chapter V.B. – THE INSTANTIATED ACTIVITY MODEL

B. CHANGES TO LEGAL PROTECTIONS

As quoted earlier in this dissertation, "Doing software risk management makes good sense, but talking about it can expose you to legal liabilities. If a software product fails, the existence of a formal risk plan that acknowledges the possibility of such a failure could complicate and even compromise the producer's legal position."[312] The atmosphere in which software is developed is ripe for legal challenges when events occur that jeopardize public safety or economics. Software Engineers must feel protected within their development to create a system that has the potential to cause a hazardous event, but accredited to be safe through the use of an accepted assessment method. A failure to protect software developers from legal challenges could result in the stifling of creative knowledge. Developers need the freedom to develop with the assurance of some level of protection, as long as they follow a standardized process, openly identify the potential for hazardous events, and permit peer review of the final product. Should the process and concepts brought forward in this dissertation be accepted as a standardized process for assessing the safety of a software system, it would afford some level of protection to developers against malpractice and negligence.

C. MANAGEMENT

Improvements to Software Safety require a definitive change to management and business practices. The current state of development does not properly assure the identification, assessment, and rectification of software hazards. The proprietary nature of the art does not permit broad based acceptance of assessment results, nor does it permit the transfer of lessons learned from Software Safety improvement methods. The success of Software Safety requires management to create an atmosphere where safety is not an end goal of development, but rather an integral part of the development and integration process. Each phase of development must be tailored towards improving the system's performance with periodic assessments that can quickly identify hazards, propose

[312] Boehm, B; De Marco, T; *Software Risk Management*, IEEE Software, Institute of Electrical and Electronics Engineers, Inc.; May – June, 1997.

corrective measures and controls, and increase the understanding of system capabilities, while not inhibiting the overall development process, possibly increasing the efficiency of the development.

The methods proposed within this dissertation will directly impact the fashion in which software is developed. Every practice must be scrutinized for completeness and compliance with safe development practices. The concept of Software Safety Assurance can be offensive to some, as it will criticize and critique previously accepted methods of software development. Software development managers must be prepared to amend their development philosophies to better integrate the principles of safety development.

D. HANDLING FRAGILITY

Software is fragile. Its logic is derived from a Boolean decision process in which every event must be placed into a true or false statement. If a statement can be written with sufficient detail, it becomes possible to articulate compound thought. As events become more complex and the systems for which they control become unstable, the possibility for failure increases. It is these measures of intricacy, instability, failure probability, control, and mitigation that form a root of Software Safety. The identification, control, and improvement of these values are paramount to improving the quality of a software system. To assess these values developers and managers need a standardized assessment process, tailored to meet the needs of specific needs of a varied range of systems.

Software Safety is not the removal of all unsafe events within a system. It is not the counting of code to determine safety verses length. Complexity is not an isolated measure of safety, nor is change, nor is risk a measure of safety. Safety is the measure of a system's ability to prevent a hazardous event. Where a system is unable to prevent such an event, it is the measure of the mitigation of that event.

The metric and methods in this dissertation and study are designed to improve the state of the art of software development without imposing an overwhelming burden on existing development efforts. Software, in its fragility necessitates an assessment process capable of identifying, categorizing, measuring, and improving its operation and establishing some factor of safety. That measure and vocabulary are the intention of this dissertation.

E. SUGGESTIONS FOR FUTURE WORK

This dissertation serves as an introduction to a possible standardized method for assessing the safety of a software system. The methods and procedures introduced in this dissertation are based on the theoretical combination of existing methods and procedures, tailored to meet the specific needs of software based systems. Examples presented in this dissertation are theoretical applications of the method against a hypothetical system. Future work could include the application of the assessment process against an actual software system, judged for its ability to accurately depict the fragilities of a system, to assist in the decision making process to correct identified events, and the potential efficiency savings through the use of the assessment process.

Once an assessment has identified specific elements of a system that warrant improvement, the developers must determine the methods that would most optimally enhance the process. In this dissertation, I introduce a method for assessing the existing development. Due to the scope of this dissertation, I have omitted specific methods for modifying corresponding requirements, designs, and code to mitigate identified hazards. Research and development into methods of process improvement would benefit the field of Software Safety and Software Engineering.

One key to the success of the Software Safety Assessment is the ability to identify potential hazards. Additional research is necessary to aid in the development of methods for eliciting safety requirements and system safety constraints. Eliciting safety requirements and constraints is predicated on being able to identify the potential hazards and the related causal factors. The success of the assessment is found in the ability to prevent a hazardous event, consequently saving valuable resources. If the assessment relies on impractical or inefficient methods for identifying requirement and hazards, then it could become uneconomical to investigate and identify extremely rare events.

Research should include methods for estimating reliability and boundaries of historical events that might indicate the existence of unforeseen events not identified thorough traditional methods.

In the perfect system, the Probability of Failure would be Zero ($P_f = 0$), to say that the system would never fail. In a realistic system, there most likely exists some probability that the system will fail in one form or another ($0 \leq P_f \leq 1$). Unanticipated states frequently result in failures that the developers did not anticipate. A benefit to the state of the art and the Software Engineering community would be the development of a method for characterizing the distribution of expected inputs to the software and their effect. The measure should be designed to encompass the bounds of each input and the variations and potential states of the system.

The tradeoff between financial cost and human injury will always be controversial. In its complexity, a software system has the potential to result in hazardous consequences in terms of both economic and personal injury. The current process combines the two factors into a single assessment. Future research and process improvement can foster changes to the safety assessment to include a partially ordered two–dimensional scale for consequences of a Hazard based on cost and injury.

It is essential that archived assessment results be compared against the actual performance of deployed systems. Research and development should be accomplished to foster an empirical measurement or comparison of predicted failure data to actual failures. The comparison of predicted versus actual performance can be used to calibrate the model and method to provide a more accurate future assessment. Based on these performance and evaluation trends, it would also be possible to specify an expected loss for a specific failure rate and safety index.

As the assessment process is refined and incorporated, it should be submitted for critical review through field literature and accrediting organizations. The submission process requires a significant degree of preparation and "suitcasing." Future efforts can be placed at validating the assessment process, refining it for submission, and then putting forward a proposal for accreditation as a standard in national, international, and governmental organizations.

Definitions proposed within this dissertation are intended as a guide for properly understanding the intricate facets of software development and safety. Future efforts can be concentrated at refining proposed definitions for submission as accepted characterization of a Software Safety Assurance Process.

The ability to automate the software development process has greatly increased Software Engineering efficiency and reduced the overall management burden. Future efforts can be placed at developing an automated process that would integrate the concepts of Software Safety, tailored measurement baselines, and assessments. Reports and presentations could be standardized within the automated process using actual and forecasted data.

This dissertation makes a brief approach at addressing safety design requirements and their incorporation into the software development process. Specifically addressed topics included **Software Requirements Hazard Analysis** in Chapter II.E.2.c and **Requirements Trends Toward Failure** in Chapter III.C. There exists a need to conduct greater research and formalization of safety design requirements and their incorporation into the software development process. The incorporation of a standardized formal language for specifying safety attributes would have an immediate impact on the state of the art of Software Safety.

Briefly discussed in this dissertation are methods for determining the probability of a specific action, be it the probability of execution or the probability of failure of an event. Existing software reliability metrics do not provide a verifiable or consistent means for quantifying the probability of failure of a specific process within a software system. To this end, there exists a need to conduct greater research and formalization of methods for determining the probability of software event failure. Such research should be based on an analysis of elements as identified in Table 1 (*Quantitative and Qualitative Factors of Safety*) of this dissertation.

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APPENDIX A. DEFINITION OF TERMS

Acceptable Level of Risk: (a) A judicious and carefully considered assessment by the appropriate authority that a computing activity or network meets the minimum requirements of applicable security directives. The assessment should take into account the value of assets; threats and vulnerabilities; counter measures and operational requirements. [DISA/D2, 1999], [AFSEC]

(b) As it applies to safety, threshold determination of exposure to the chance of injury or loss. It is a threshold of the function of the possible frequency of occurrence of the undesired event, of the potential severity of resulting consequences, and of the uncertainties associated with the frequency and severity. [NASA, 1996]

Action Based Failures: Failures associated with an internal fault and associated triggering actions. Action Based Failures contain logic or software–based faults that can remain dormant until initiated by a single or series of triggering actions or events. [Williamson – Page 49]

Active Software Safety System: A software system that directly controls some hazardous function or safety–critical system operation, to ensure that the operation of that system remains within some acceptable bound. [Williamson – Page 121]

Benign Failure: A failure whose severity is slights enough to be outweighed by the advantages to be gained by normal use of the system. [Nesi, 1999]

Capability maturity model, CMM: A five–layer model against which an industry can evaluate its organizational maturity with respect to software development. The levels are 1: Initial, 2: Repeatable, 3: Defined, 4: Managed and 5: Optimizing. [SEI-93-TR-24]

Cataclysmic Failure: A sudden failure that results in a complete inability to perform all required functions of an item, referring both to the rate in which the system failed, and to the severity degree of the Mishap that resulted from the failure. [Williamson – Page 60]

Code and fix: A simple approach for program developing based on which of the programmers write the code, test and fix the found errors without following a formalized development life–cycle. [Nesi, 1999]

Complete Failure: A failure that results in the system's inability to perform any required functions. [Williamson – Page 60], [Nesi, 1999]

Complexity: A measure of how complicated an element (typically of code or design) is. It represents how complex it is to understand (although this also involves cognitive features of the person doing the understanding) and/or how complex is to execute the code (for instance, the computational complexity). The complexity evaluation can be performed by considering the computational complexity of the functional part of the system — i.e., the dominant instructions in the most iterative parts of the system. The complexity may be also a measure of the amount of memory used or the time spent in execution an algorithm. [Nesi, 1999]

Compliance: The capability of the software product to adhere to standards, conventions or regulations in laws, and similar prescriptions. It is a sub–feature of functionality. [Nesi, 1999]

Comprehensibility: Synonymous of understandability. The capability of a software system to include a set of functionalities. [Nesi, 1999]

Concept/Conceptual: The period of time in the software development cycle during which the user needs are described and evaluated through documentation (for example, statement of needs, advance planning report, project initiation memo, feasibility studies, system definition, documentation, regulations, procedures, or policies relevant to the project). [IEEE 1991]

Consequence Severity: The magnitude of severity related to the consequence of a hazardous event. Consequence Severity can be defined as a graduated list of terms and expressions, as an ordinal list of increasing magnitude, or as pure values representing the monetary cost of the hazard. [Williamson – Page 150]

Constructive Cost Model, COCOMO: A method for evaluating the cost of a software package proposed by Dr. Barry Boehm. There are a number of different types: The Basic COCOMO Model estimates the effort required to develop software in three modes of development (Organic Mode, Semidetached Mode, or Embedded Mode). The Intermediate COCOMO Model an extension of the Basic COCOMO model. The Intermediate model uses an Effort Adjustment Factor (EAF) and slightly different coefficients for the effort equation than the Basic model. The Intermediate model also allows the system to be divided and estimated in components. The Detailed COCOMO Model differs from the Intermediate COCOMO model in that it uses effort multipliers for each phase of the project. [Nesi, 1999]

Continuous Improvement: The process of tuning the software development process in order to achieve better results in the future versions. The improvement is based on the assessment of the systems development and in performing corresponding actions for correcting problems and improving the general process behavior. [Nesi, 1999]

Control: System objects capable of preventing or mitigating the effects of a system malfunction should a failure occur. Controls may consist of any of a number of filters, redundant operators, or other hardware or software objects depending on the architecture of the system and control that is to be employed. A control may be able to filter unacceptable values and triggers before contacting a fault, preventing the occurrence of a failure. [Williamson – Page 211]

Cost Estimation: In the early stages of a software project, some estimate of the total cost, overall effort required and, hence, personnel requirement (and other resources) is needed. Cost estimation describes a suite of techniques that take early artifacts of the software development process and, from these, calculate a first estimate of overall cost. COCOMO and Function Points are two cost estimation models used in a traditional development. [Nesi, 1999]

Cost Of Failure: A measure of the severity of the consequences of failure. Depending on the type of system, different scales may be used e.g., duration of down time, consequential cash loss, number of lives lost, etc. Cost of failure to user must be distinguished from cost of maintenance to vendor. [Nesi, 1999]

Cost/benefit analysis: The analysis of benefits and costs related to the implementation of a product. [Nesi, 1999]

Critical Design Review (CDR): A review conducted to verify that the detailed design of one or more configuration items satisfy specified requirements; to establish the compatibility among configuration items and other items of equipment, facilities, software, and personnel; to assess risk areas for each configuration item; and, as applicable, to assess the results of the producibility analyses, review preliminary hardware product specifications, evaluate preliminary test planning, and evaluate the adequacy of preliminary operation and support documents. (IEEE Standard 610.12–1990) For Computer Software Configuration Items (CSCIs), this review will focus on the determination of the acceptability of the detailed design, performance, and test characteristics of the design solution, and on the adequacy of the operation and support documents. [IEEE 1991]

Critical Path: The set of activities that must be completed in sequence and on time to have the entire project being completed on time. Related to PERT charts. [Nesi, 1999]

Critical Software: A software for which the safety is strongly relevant and its failure could produce damages for the users. See real time system, critical task, and critical system. [Nesi, 1999]

Critical System: A system that possesses a critical (or safety–critical) mode of failure that could have impact on safety or on economic aspects. For example, critical on–board avionics systems are defined as those that, if they fail, will prevent the continued safe flight and landing of the aircraft (e.g., those responsible for pitch control). [Nesi, 1999]

Criticality: Classification of the consequences, or likely consequences, of a failure mode, or classification of the importance of a component for the required service of an item. See severity. [Nesi, 1999]

Deadlock: A situation in which computer processing is suspended because two or more devices or processes are each awaiting resources assigned to the other. (IEEE Standard 610.12–1990)

Decomposition: The process of creating a program in terms of its components by starting from a high–level description and defining components and their relationships. The process start from the highest level to reach the definition of the smallest system components and their relationships, passing through several intermediate structural abstractions. [Nesi, 1999]

Defect: Non–fulfillment of an intended usage requirement, or reasonable expectation, including one concerned with safety. A non–conformance between the input products and the output products of a system development phase. The main purpose of verification activities (e.g., inspection) is to detect defects so that they can be corrected before subsequent development phases. If not detected and corrected during development, defects may give rise to one or more faults in the delivered system, and hence to failure in operation. Some defects (e.g., inappropriate comments in source code) cannot give rise to faults, but may adversely affect maintainability or other quality characteristics. [Nesi, 1999]

Effort to Develop: A measure of the effort required to build the software system, measured in man–hours, man–months, or processor–hours. *Effort* is a factor of the *time* to develop verses the number of persons/assets required for the development period, compounded by the complexity of the system and aptitude of the resources. Safety is directly affected by the complexity of the system and aptitude of the resources, and indirectly affected by the *time* required to develop. [Williamson – Page 138]

External Failure: An undesirable event in the environment that adversely affects the operation of an item. [Nesi, 1999]

Failsafe: An item is said failsafe when, following detection of a hazardous state, a mishap can be avoided despite a possible loss of service. The possibility of designing an item to "failsafe" obviously depends on its having a safe mode of failure. [Nesi, 1999]

Fail Soft: The condition of a system that continue to provide main functionalities even in the presence of some failure. [Nesi, 1999]

Failure: **(a)** The inability of a computer system to perform its functional requirements, or the departure of software from its intended behavior as specified in the requirements. A failure is an event in time. A failure may be due to a physical failure of a hardware component, to activation of a latent design fault, or to an external failure. Following a failure, an item may recover and resume its required service after a break, partially recover and continue to provide some of its required functions (fail degraded) or it may remain down (complete failure) until repaired. [Nesi, 1999]

(b) The inability of a system or component to perform its required functions within specified performance requirements. (IEEE Standard 610.12–1990)

Failure Tolerance: The ability of a system or subsystem to perform its function(s) or maintain control of a hazard in the presence of failures within its hardware, firmware, or software. [IEEE 1991]

Firmware: Computer programs and data loaded in a class of memory that cannot be dynamically modified by the computer during processing. [IEEE 1991]

Fault: A system object that contains an error in logic, that when triggered, could induce a failure in system operation. A fault can potentially reside in the system indefinitely without ever inducing a failure, lacking the existence of an appropriate trigger. [Williamson – Page 44]

Fault Detection: A process that discovers or is designed to discover faults; the process of determining that a fault has occurred. [IEEE 1991]

Fault Isolation: The process of determining the location or source of a fault. [IEEE 1991]

Fault Masking: A condition in which the occurrence of a fault is masked. [Nesi, 1999]

Fault Recovery: A process of elimination of a fault without permanent reconfiguration. [IEEE 1991]

Fault Tolerance: The capability of the software product to maintain a specified level of performance in cases of software faults or of infringement of its specified interface. The specified level of performance may include failsafe capability. This is often provided by the use of diverse redundant software modules. [Nesi, 1999]

Flaw: A specific item that detracts from the operation or effectiveness of the software system without resulting in a failure or loss of operability. [Williamson – Page 42]

Formal Method: A software specification and production method, based on a precise mathematical syntax and semantics, that comprises: a collection of mathematical notations addressing the specification, design and development phases of software production; a well–founded logical inference system in which formal verification proofs and proofs of other properties can be formulated; and a methodological framework within which software may be developed from the specification in a formally verifiable manner. Formal methods can be operational denotational or dual (hybrid). [Nesi, 1999]

Handling Type Fault: A fault characterized by an inability of the system's logic to handle erroneous entries or parameters out of the normal bounds of the system. [Williamson – Page 46]

Hazard Analysis: the evaluation and documentation of hazards and formulation of a control mechanism that can affect a facility, system, subsystem, or component. [NHAG]

Hazard Probability: The likelihood, expressed in qualitative or quantitative terms, that a hazardous event will occur as:

- Frequent – likely to occur frequently
- Probable – will occur several times in the life of an item
- Occasional – likely to occur at sometime in the life of an item
- Remote – unlikely but possible to occur in the life of an item
- Improbable – so unlikely that it can be assumed occurrence may not be experienced.

[NHAG]

Hazard Severity Categories: A qualitative measurement of the worst potential consequence resulting from personnel error, environmental conditions, design inadequacies, procedural deficiencies, and system, subsystem, and component failure or malfunction. These categories are as follows:

- Catastrophic – a hazardous occurrence in which the worst–case effects will cause death, disabling personnel injury, or facility or system loss
- Critical – a hazardous occurrence in which the worst–case effects will cause severe (non-disabling) personnel injury, severe occupational illness, or major property or system damage
- Marginal – a hazardous occurrence in which the worst–case effects could cause minor injury, minor occupational illness, or minor system damage
- Negligible – a hazardous occurrence in which the worst–case effects could cause less than minor injury, occupational illness, or system damage.

[NHAG]

Independent Verification and Validation (IV&V): A process whereby the products of the software development lifecycle phases are independently reviewed, verified, and validated by an organization that represents the acquirer of the software and is completely independent of the provider. [NASA, 1997]

Inhibit: A design feature that provides a physical interruption between an energy source and a function (e.g., a relay or transistor between a battery and a pyrotechnic initiator, a latch valve between a propellant tank and a thruster, etc.). [IEEE 1991]

Interlock: Hardware or software function that prevents succeeding operations when specific conditions exist. [IEEE 1991]

Intermittent Failure: The failure of an item that persists for a limited duration of time following which the system recovers its ability to perform a required function without being subjected to any action of corrective maintenance, possibly recurrent. [Williamson – Page 60], [Nesi, 1999]

Invalid Failure: "A failure that is, but isn't"

(a) An apparent operation of the primary system that appears as a failure or defect to the user but is actually an intentional design or limitation.

(b) A developmental shortcoming resulting from the developer not designing the system to the expectations of the user.

(c) The operation of the system in an environment for which the system was not designed or certified to function. [Williamson – Page 60]

Latent Failure: A failure that has occurred and is present in a part of a system but has not yet contributed to a system failure. [Williamson – Page 60]

Lifecycle: The period that starts when a software product is conceived and ends when the software is no longer available for use. The software lifecycle traditionally has eight phases: Concept and Initiation; Requirements; Architectural Design; Detailed Design; Implementation; Integration and Test; Acceptance and Delivery; and Sustaining Engineering and Operations. [IEEE 1991]

Life–Cycle Management (LCM): Life–cycle management means the management of an item or system from inception/Pre–Milestone 0 through program termination. The term is also used in relation to Supply Management as management of an item from the time it first comes into the government inventory until it is disposed of at the end of its service life. The Services/Agencies have organizations to perform this level of management, but it can also be done under contract. LCM includes the procurement of initial and sustainment spare and repair parts; item management of those parts; oversight of the maintenance process (government or contractor); configuration control; planning for product improvements; the collection of failure and demand data, analysis and appropriate support process modification; and proper disposal action at the end of the lifecycle. [DISA/D4]

Lines–of–code metrics, LOC: A software metric that counts the lines of code of a source, in order to evaluate its size. [Nesi, 1999]

Local Failure: A failure that is present in one part of the system but has not yet contributed to a complete system failure. [Williamson – Page 60]

Locking Up: The state in which a software system fails to respond or execute any action for all commands, analogous to a Type 4 Failure. [Williamson – Page 40]

Loss: An expression of the unrecoverable expenses related to correcting system failures, software defects, management oversights, and other compensatory costs. [Williamson – Page 23]

Millennium problem: Y2K Bug; The problem due to the definition of the date in software system by means of a couple of characters for storing the last two digit of the years. This causes problems when dates varying also for the hundreds of years are manipulated. It has been called millennium problem since it has been mainly highlighted around the year 2000. [Nesi, 1999]

Minor Flaw: A flaw does not cause a failure, does not impair usability, and the desired requirements are easily obtained by working around the defect. [Williamson – Page 60], [Nesi, 1999]

Mishap: An accident; The occurrence of an unplanned event or series of events and actions that results in death, injury, occupational illness, or damage to or loss of equipment, property, damage to the environment, or otherwise reducing the worth of the system; an accident. [IEEE 1991], [NASA, 1997], [NHAG]

Mongolian Horde Technique: Analogous to the Mongolian Horde technique of warfare in which the armies of Genghis Khan would amass an overwhelming force of untrained warriors against a smaller enemy and conquer them through disproportional numbers. In the field of Software Engineering, the technique implies the use of an overwhelming number of intermediate level programmers and developers to generate an event that would be better managed using fewer and better skilled developers. [Williamson – Page 35]

Negative Testing: Software Safety Testing to ensure that the software will not go to a hazardous state or generate outputs that will create a hazard in the system in response to out of bound or illegal inputs. [IEEE 1991]

No–Go Testing: Software Safety Testing to ensure that the software performs known processing and will go to a known safe state in response to specific hazardous situations. [IEEE 1991]

Partial Failure: The failure of one or more modules of the system, or the system's inability to accomplish one or more system requirements while the rest of the system remains operable. [Williamson – Page 60]

Performance Requirements: Requirements imposing specific constraints on the final performance of the system. This is typical of real–time and critical systems. [Nesi, 1999]

Performance Specification: A document that specifies the performance that the final system has to provide. This is typical of real–time and critical systems. [Nesi, 1999]

Physical Failure: A failure that is solely due to physical causes, e.g., heat, chemical corrosion, mechanical stress, etc. [Nesi, 1999]

Preliminary Design Review (PDR): A review conducted to evaluate the progress, technical adequacy, and risk resolution of the selected design approach for one or more configuration items; to determine each design's compatibility with the requirements for the configuration item; to evaluate the degree of definition and assess the technical risk associated with the selected manufacturing methods and processes; to establish the existence and compatibility of the physical and functional interfaces among the configuration items and other items of equipment, facilities, software, and personnel; and as appropriate, to evaluate the preliminary operation and support documents. For CSCIs, the review will focus on: (1) the evaluation of the progress, consistency, and technical adequacy of the selected architectural design and test approach, (2) compatibility between software requirements and architectural design, and (3) the preliminary version of the operation and support documents. [IEEE 1991]

Preliminary Hazard Analysis (PHA): Analysis performed at the system level to identify safety–critical areas, to provide an initial assessment of hazards, and to identify requisite hazard controls and follow–on actions. [IEEE 1991]

Quality: The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs. Not to be exchanged with the "degree of excellence" or "fitness for use" that meet only partially the definition. Software quality is defined in the ISO 9126 norm series. Software quality includes: functionality, reliability, usability, efficiency, maintainability, and portability. The quality of a system is the evaluation of the extent to which the system meets the above mentioned features. The response of the system to these features is called the estimated quality profile. Quality should not be used as a single term to express a degree of excellence in a comparative sense nor should it be used in a quantitative sense for technical evaluations. To express these meanings, a qualifying adjective shall be used. For example, use can be made of the following terms: "relative quality" where entities are ranked on a relative basis in the "degree of excellence" or " comparative sense" (not to be confused with grade); "quality level" in a "quantitative sense" (as used in acceptance sampling) and "quality measure" where precise technical evaluations are carried out. [Nesi, 1999]

Quality Control: Operational techniques and activities that are used to fulfill requirements for quality. Quality control involves operational techniques and activities aimed at both monitoring a process and at eliminating causes of unsatisfactory performance at all stages of the quality loop in order to result in economic effectiveness. [Nesi, 1999]

Random Failure: Failures that result from a variety of degradation mechanisms in the hardware. Unlike failures arising from systematic failures, system failure rates arising from random hardware failures can be quantified with reasonable accuracy. [Nesi, 1999]

Reactionary Type Fault: A fault characterized by an inability of the system's logic to react to acceptable values of inputs, as defined in the system requirements. [Williamson – Page 60]

Reactive Software Safety System: A software system that reacts to the operation of a hazardous function or safety–critical system, to react when the operation falls outside of some predetermined and acceptable bounds. [Williamson – Page 121]

Reliability: The probability that a system will perform its required function(s) in a specified manner over a given period of time and under specified or assumed conditions. [Hughes, 1999]

Resource Based Failures: Failures associated with the uncommanded lack of external resources and assets. Resource Based Failures are generally externally based to the logic of the system and may or may not be software based. [Williamson – Page 60]

Risk: **(a)** Chance of hazard or bad consequences; exposure to chance of injury or loss. Risk level is expressed in terms of hazard probability or severity. [CALL, 2000]

(b) As it applies to safety, exposure to the chance of injury or loss. It is a function of the possible frequency of occurrence of the undesired event, of the potential severity of resulting consequences, and of the uncertainties associated with the frequency and severity. [IEEE 1991]

Risk Management: **(a)** Risk management is divided into the following tasks: Risk assessment, Risk identification, Risk analysis and prioritization, Risk control, Risk management planning, Risk resolution and monitoring. [Nesi, 1999]

(b) The process of detecting, assessing, and controlling risk arising from operational factors and making decisions that balance risk costs with mission benefits. Includes five steps: (identify the hazards; assess the hazards; develop controls and make risk decision; implement controls; and supervise and evaluate). [CALL, 2000]

Risk Prioritization: The assessment of the loss probability and loss magnitude for each identified risk item. Prioritization involves producing a ranked and relative ordering of the risk items identified and analyzed. [Nesi, 1999]

Robustness: The degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions. [Nesi, 1999]

Safe: A magnitude of software success and reliability in which the probability of hazardous events has been reduced to an acceptable predefined level. [Williamson – Page 30]

Safety: **(a)** The ability of a system to operate without unacceptable risk in accordance with its requirements in a consistent and predictable manner for a given time in a given environment without mishap. For system safety, all causes of failures which lead to an unsafe state shall be included; hardware failures, Software Failures, failures due to electrical interference, due to human interaction and failures in the controlled object. The system safety also depends on many factors that cannot be quantified but can only be considered qualitatively. [Nesi, 1999]

(b) Freedom from the occurrence or risk of injury or loss; the quality of averting or not causing injury or loss. [RHCD, 1980].

Safety Analysis. A systematic and orderly process for the acquisition and evaluation of specific information pertaining to the safety of a system. [IEEE 1991]

Safety Architectural Design Analysis (SADA). Analysis performed on the high–level design to verify the correct incorporation of safety requirements and to analyze the Safety Critical Computer Software Components (SCCSCs). [IEEE 1991]

Safety Assessment Index: The relationship derived from the probability of a hazardous event or events against the severity of such events. A Safety Assessment Index can be defined as a graduated list of terms and expressions, or as an ordinal list of increasing magnitude. [Williamson]

Safety–Critical: **(a)** Those software operations that, if not performed, performed out–of sequence, or performed incorrectly could result in improper control functions (or lack of control functions required for proper system operation) that could directly or indirectly cause or allow a hazardous condition to exist. [IEEE 1991]

(b) A system whose failure may cause injury or death to human beings, e.g., an aircraft or nuclear power station control system. Common tools used in the design of safety–critical systems are redundancy and formal methods. [Nesi, 1999]

Safety–Critical Computer Software Component (SCCSC): Those computer software components (processes, modules, functions, values or computer program states) whose errors (inadvertent or unauthorized occurrence, failure to occur when required, occurrence out of sequence, occurrence in combination with other functions, or erroneous value) can result in a potential hazard, or loss of predictability or control of a system. [MIL-STD-882B, 1986]

Safety–Critical Software: Software that: (1) Exercises direct command and control over the condition or state of hardware components; and, if not performed, performed out–of–sequence, or performed incorrectly could result in improper control functions (or lack of control functions required for proper system operation), which could cause a hazard or allow a hazardous condition to exist. (2) Monitors the state of hardware components; and, if not performed, performed out–of–sequence, or performed incorrectly could provide data that results in erroneous decisions by human operators or companion systems that could cause a hazard or allow a hazardous condition to exist. (3) Exercises direct command and control over the condition or state of hardware components; and, if performed inadvertently, out–of–sequence, or if not performed, could, in conjunction with other human, hardware, or environmental failure, cause a hazard or allow a hazardous condition to exist. [MIL-STD-882B, 1986]

Safety Detailed Design Analysis (SDDA): Analysis performed on Safety–Critical Computer Software Components to verify the correct incorporation of safety requirements and to identify additional hazardous conditions. [NASA – 1997]

Software Economics: The study of the economic effects of software development, integration, management, and operation. In terms of Software Safety, Software Economics includes the study of the economic effects of software failure, hazardous operation, mitigation, and control integration. [Williamson – Page 265]

Software Engineering: **(a)** The discipline of promoting the establishment of theoretical foundations and practical disciplines for software, similar to those found in the established branches of engineering. [NATO, 1967]

(b) The establishment and use of sound engineering principles in order to obtain economically software that is reliable and works efficiently on real machines. [NATO, 1969]

(c) The application of a systematic, disciplined, quantifiable approach to the development, operation, and maintenance of software. [IEEE, 1991]

Software Defect: A software defect is a perceived departure in a software product from its intended properties, which if not rectified, would under certain conditions contribute to a software system failure (departure from required system behavior during operational use). [Nesi, 1999]

Software Development Risk: The risks to successful software development, as quantified by the ability to meet project requirements and goals within acceptable limits regardless of the potential for or incident of hazardous events during the operation of the software. [Nogueira, 2000]

Software Failure: **(a)** The inability of a system or component to perform its required functions within specified performance requirements. [IEEE 610]

(b) The state in which a system has failed to execute or function per the defined requirements due to a design fault. Failure is usually the result of an inability to control the triggering of a system fault. Faults can be categorized in one or more of four types, depending on the circumstances leading to the failure and the resulting action. Failures can be further divided into one of two categories based on the source of the failure. [Williamson – Page 47]

Software Fault: **(a)** A design fault located in a software component. See fault. [Nesi, 1999]

(b) An imperfection or impairment in the software system that, when triggered, will result in a failure of the system to meet design requirements. A fault is stationary and does not travel through the system. [Williamson – Page 44]

Software Flaw: A specific item that detracts from the operation or effectiveness of the software system without resulting in a failure or loss of operability. A software flaw does not result in a failure. A flaw may reduce the aesthetic value of a product, but does not reduce the system's ability to meet development requirements. [Williamson – Page 42]

Software Hazards: The potential occurrence of an undesirable action or event that the software based system may execute due to a malfunction or instance of failure. [Williamson – Page 52]

Software Malfunctions: A malfunction is the condition wherein the system functions imperfectly or fails to function at all. A malfunction is not defined by the failure itself, but rather by the fact that the system now fails to operate. The term malfunction is a very general term, referring to the operability of the entire system and not to a specific component. [Williamson – Page 50]

Software Management: The act of managing software development, integration, operation, and termination. Software Safety requires additional management emphasis in safety assessments, decision–making, economics, and development atmosphere. [Williamson – Page 251]

Software Requirements Review (SRR): A review of the requirements specified for one or more software configuration items to evaluate their responsiveness to and interpretation of system requirements and to determine whether they form a satisfactory basis for proceeding into a preliminary (architectural) design of configuration items. [IEEE Standard 610.12–1990]

Software Requirements Specification (SRS): Documentation of the essential requirements (functions, performance, design constraints, and attributes) of the software and its external interfaces. [IEEE 1991]

Software Reliability: The ability of a software system to meet defined requirements over a specified measure of time or through a defined set of events. Reliability can be defined as the ratio of the time of proper operation against total operation time, the ratio of proper operational events versus total operational events. [Williamson – Page 101]

Software Safety Requirements Analysis (SSRA): Analysis performed to examine system and software requirements and the conceptual design in order to identify unsafe modes for resolution, such as out–of–sequence, wrong event, deadlocking, and failure–to–command modes. [IEEE 1991]

Software Safety: The application of the disciplines of system safety engineering techniques throughout the software lifecycle to ensure that the software takes positive measures to enhance system safety and that errors that could reduce system safety have been eliminated or controlled to an acceptable level of risk. [IEEE 1991]

Specification Fault: A design fault of an item that results from its required function having been incorrectly or incompletely defined. Specification faults often give rise to usability problems in operation, but can lead to other types of incident also. They can only be detected by validation, not verification. [Nesi, 1999]

System Safety: Application of engineering and management principles, criteria, and techniques to optimize safety and reduce risks within the constraints of operational effectiveness, time, and cost throughout all phases of the system lifecycle. [IEEE 1991]

System Size: A measure of the requirements, functions (function points), processes, scripts, frames, methods, objects, classes, or lines of code used to determine the size of the system. Specific *size* does not necessarily cause a system to be safe or unsafe, rather *size* denotes the volume of the system. [Williamson – Page 134]

System Task: The action requirements, goals, and objectives of the software system specified in requirements documentation. [Williamson – Page 172]

Test Readiness Review (TRR): A review conducted to evaluate preliminary test results for one or more configuration items; to verify that the test procedures for each configuration item are complete, comply with test plans and descriptions, and satisfy test requirements; and to verify that a project is prepared to proceed to formal test of the configuration items. [IEEE 1991]

Time to Develop: A measurement of the time to develop the software system in terms of hours, months, or years. *Time* is a factor of the system's size, complexity, method of development, and personnel actually executing the development. While *time* does not directly apply to System Safety, its sub–components do have an affect. *Time* affects minor safety when assessing personnel turnover, system oversight and understanding of early generation against optimized components, and in the context of time critical development projects where a delay could fail to prevent a hazardous event. [Williamson – Page 135]

Trap: Software feature that monitors program execution and critical signals to provide additional checks over and above normal program logic. Traps provide protection against undetected software errors, hardware faults, and unexpected hazardous conditions. [IEEE 1991]

Trigger: An event, value, or system state that reacts with a system fault to initiate a failure. The effects of a trigger can be controlled through the use of filters, controls, or error handlers. [Williamson – Page 39]

Type 1 Failure: One of the four subsets of the Type Failure List – A failure type that occurs when a system executes an uncommanded action. This failure type can occur when the system is not in operation, as it would be expected that the system would not receive any commands when not in operation. This type of failure is not related to any command or provocation, and occurs outside of the system requirements. This failure may be triggered by the state of the system or by an input not related to a command. [Williamson – Page 40]

Type 2 Failure: One of the four subsets of the Type Failure List – A failure type that occurs when a system executes an inappropriate action for a specific command during system operation. When a user or procedure generates a command to the system, it should be expected that the system would respond with a predetermined series of actions or responses. In the case of a Type 2 Failure, the system executed a false response to a system command. It should be noted that the system attempted to execute a response to the command, though be it incorrect. [Williamson – Page 40]

Type 3 Failure: One of the four subsets of the Type Failure List – A failure type that occurs when a system fails to execute a required action for a specific command during system operation. [Williamson – Page 40]

Type 4 Failure: One of the four subsets of the Type Failure List – A failure type that occurs when a system fails to respond or execute any action for all commands, essentially with the system *"locking up."* [Williamson – Page 40]

Usability: The capability of the software product to be understood, learned, used and attractive to the user, when used under specified conditions. Some aspects of functionality, reliability and efficiency will also affect usability, but for the proposes of ISO/IEC 9126 they are not classified as usability. Usability should address all of the different user environments that the software may affect, which may include preparation for usage and evaluation of results. [Nesi, 1999]

User–friendly: The typical definition for user interface presenting a set of appealing features that are perceived by users as easy systems to interact with. [Nesi, 1999]

Validation: (1) An evaluation technique to support or corroborate safety requirements to ensure necessary functions is complete and traceable. (2) The process of evaluating software at the end of the software development process to ensure compliance with software requirements. [IEEE 1991]

Verification: (1) The process of determining whether the products of a given phase of the software development cycle fulfill the requirements established during the previous phase (see also validation). (2) Formal proof of program correctness. (3) The act of reviewing, inspecting, testing, checking, auditing, or otherwise establishing and documenting whether items, processes, services, or documents conform to specified requirements. [IEEE 1991]

WACSS: A factious weapons arming and control software system derived for demonstration purposes within this dissertation. [Williamson – Page 171]

Waiver: A variance that authorizes departure from a particular safety requirement where alternate methods are employed to mitigate risk or where an increased level of risk has been accepted by management. [NASA, 1997]

Attributed to

[AFSEC] *Security Taxonomy and Glossary*, Albuquerque Full-Scale Experimental Complex, Sandia National Laboratories, Albuquerque, New Mexico; 1997.

[CALL, 2000] *CALL Dictionary and Thesaurus*, Center for Army Lessons Learned, U.S. Army; 23 May 2000, http://call.army.smil.mil/call/thesaur/index.htm

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[Williamson] From Dissertation. A portion of the definitions introduced in this dissertation may be widely accepted in the field of Software Engineering as slang or part of the common vernacular. The author takes no credit for the introduction of those terms but takes acknowledgment for refining the definitions as stated in this appendix.

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APPENDIX B. INCIDENTS AND MISHAPS[313]

1. ARIANE 5 FLIGHT 501 FAILURE

On the morning of 04 June 1996, on the maiden flight of the Ariane 5 launcher and rocket, the launcher's flight control system and the primary and secondary Inertial Reference Systems failed 36.7 seconds after lift off.[314] The failure of the Inertial Reference System (IRS) resulted in the instantaneous swiveling of the two solid rock booster and Vulcain cryogenic engine nozzles to full deflection. As the craft passed an altitude of 12,000 feet, the launcher veered from its flight path, broke up, and exploded. The explosion was trigger by a system commanded self–destruct sequence responding to the aerodynamic loading and breaking up of the solid rocket boosters from the main vehicle.

The Ariane 5 was equipped with two IRSs operating in parallel, with identical hardware and software. One IRS was active and the second was in "hot" stand–by, and if the On–Board Computer (OBC) detected that the active IRS has failed it would have immediately switches to the other second, provided that this unit was functioning properly. The Ariane 5 was also equipped with two OBCs and other redundant flight control systems. The supporting IRS software was nearly identical to the IRS software of the Ariane 4 Launcher.

During the final seconds of the flight, the vehicle's solid booster and Vulcain main engine nozzles were commanded to full deflection by the OBC Software, based on data transmitted from the active IRS. The IRS system had become corrupted, and was transmitting a diagnostic bit pattern, mistaken by the OBC for flight data. The Primary IRS system failed due to an internal IRS software exception caused by the conversion of a larger 64–bit floating point value to a smaller 16–bit signed integer value. Simply, the 64–bit value was too large for the 16–bit value (limited at 32,768), resulting in an

[313] Various syndicated news services and press wires.

[314] Lions, J. L., Prof., Chairman; *ARIANE 5 Flight 501 Failure, Report by the Inquiry Board*, ESA; Paris, France; 19 July 1996.

Operand Error Failure of the Primary IRS, and subsequent failure of the Secondary IRS when it attempted the conversion 72 milliseconds prior. The Ada System Code was not programmed to protect against an Operand Error within that particular portion of logic. The specific logic module was designed to perform final alignment prior to lift off and served no purpose once the vehicle left the launch pad. The alignment module was designed to continue to operate for approximately 40 seconds after lift off, based on requirements of the Ariane 4 vehicle, and was not required for the Ariane 5. The Operand Error was a result of an extremely high Horizontal Bias related to the horizontal velocity of the vehicle as it continued through its flight acceleration. The Horizontal Bias was higher then expected by the alignment module because the Ariane 5 vehicle accelerated faster then the Ariane 4. While the values were consistent with design parameters for the Ariane 5, the IRS logic was not modified to compensate for the difference.

A review of the recovered material, memory readouts, software code, and post flight simulation and reconstruction showed to be consistent with a single failure scenario. The mishap investigation board determined that the failure Ariane 501 was the result of the complete loss of guidance and attitude information 37 seconds after start of the main engine ignition sequence. This loss of information was due to specification and design errors in the software of the inertial reference system resulting from an attempt to convert a 64–bit floating point value into a 16–bit integer. Along with the loss of the Ariane rocket, four uninsured satellites worth over $500 million were destroyed.

2. THERAC–25 RADIATION EXPOSURE INCIDENT

Between June 1985 and January 1987, the Therac–25 Computerized Radiation Therapy Machine administered overdoses of radiation to six known patients, three of them resulting in deaths.[315]

[315] Leveson, Nancy, U. of Washington; Turner, Clark S., U of California, Irvine; *An Investigation of the Therac-25 Accidents*, IEEE Computer, vol. 26, num. 7, pg. 18-41, Institute of Electrical and Electronics Engineers, Inc.; July 1993.

The Therac–25 was a medical–grade linear accelerator designed to accelerate electrons to create high–energy beams that can destroy tumors with minimal impact on the surrounding healthy tissue with energy similar to X–ray photons. The Therac–25 was designed on the foundation of the Therac–20 and Therac–6, originally designed in collaboration with the Canadian Governmental Company Atomic Energy Commission Limited (AECL) and a French company called CGR. Subsequent to the falling out of their joint relationship, AECL designed the Therac–25 unit as a solo venture. In comparison to early version of the Therac unit, the Therac–25 was capable of producing 25 million electron volts (25–MeV) of X–ray energy through a more compact and efficient double–pass accelerator technology developed by AECL. The Therac–25 was more versatile and easier to use then its predecessors. The increased energy could be better aimed at the target tumor, taking advantage of the phenomenon of "depth dose": “As the energy increases, the depth in the body at which maximum dose buildup occurs also increases, sparing the tissue above the target area.” Eleven Therac–25 units were manufactured and distributed, five to the United States and six to Canada.

The Therac–25 was designed to control safety interlocks and system operations through the use of software, to a greater extent then the Therac–20 and Therac–6 units. The Therac–6 and Therac–20 were designed with mechanical interlocks to protect and police the machine, as well as independent protective circuits for monitoring electron–beam scanning. These functions were automated in the Therac–25. Post–mishap investigation revealed that the Therac–6 and Therac–20 software package was used as a baseline for the development of the Therac–25 code. Investigators and quality assurance managers were previously unaware of the baseline code issue.

In six separate incidents, patients received excessively high doses of X–ray energy, at times exceeding 20,000–rad (radiation absorbed dose). A typical single therapeutic dose would be in the 200–rad range. It should be noted that doses of 1,000 rads could be fatal if delivered to the whole body, and that a 500 rads dose will cause death in 50 percent of the population. Patients were administered doses as per the unit’s procedures, but the system’s safety interlocks failed to prevent the excessive radiation. In some cases, the machine administrated a lethal dose only to indicate that no dose had been administered, prompting the technician to administer a second dose. In one particular case, a patient was received five successive lethal doses because the unit fell off line after administering each successive dose. The patient later died. Other patients received such extreme doses of energy as to leave burn marks on the opposite side of their torsos. The experience could be equated to cooking the body from the inside out, only revealing surface damage when the underlying tissue was already destroyed.

Due to potential liability and legal issues, coupled with the fear of business losses, it was difficult to immediately find out details behind the incidents. Post–mishap investigation revealed that the unit had the potential for generating excessive doses of radiation that would go undetected and prevented by the Software Safety Interlocks due to race conditions in the data entry system. Many of the faults that caused the radiation overdoses were also found in the Therac–20 software, but were never detected until after the Therac–25 accidents because the Therac–20 included hardware mechanical safety interlocks that prevented the excessive doses and subsequent injuries. Many of the incidents went immediately unreported to the FDA due to a lack of understanding of the incident, or even the realization that an incident had even happened. Additionally, reporting regulations for medical device incidents at that time applied only to equipment manufacturers and importers, and not users, and health–care professionals and institutions were not required to report incidents to manufacturers. The law has since been amended.

3. TITAN–4 CENTAUR/MILSTAR FAILURE

On April 30, 1999, the United States Air Force was scheduled to launch a Titan–4 Centaur rocket from the Cape Canaveral Air Station on Florida's East Coast.[316] The rocket's mission was to place a MILSTAR Military Communication Satellite into a 22,300 mile Earth orbit. During the post launch flight, the rocket processed erroneous flight data computed from the Centaur's upper stage software system. The erroneous

[316] *MILSTAR Accident Board Releases Results*, Air Force Press News (AFPN); Peterson Air Force Base, Colorado; 22 July 1999.

flight data resulted in the Titan rocket repeatedly attempting to reorient itself, in contradiction with opposing data to continue on its present flight path. The conflict between flight data and erroneous computations resulted in the upper stage prematurely depleting itself of all usable hydrazine fuel. Without sufficient fuel and a proper navigation solution, the Titan rocket fell into a low Earth orbit, and deployed the MILSTAR satellite in a useless position with respect to the rest of its constellation.

The MILSTAR Satellite was to be part of an array of the Joint MILSTAR (Military Strategic Tactical and Relay) Satellite Communications System. Once operational, the system would provide a worldwide, secure, jam resistant, strategic, and tactical communications capability for Joint Military use.

The mishap investigation board found the primary cause of the mishap to be a failure within the Centaur upper stage software, which failed to detect and correct a human error made during manual entry of data values in the Centaur's flight software file. Loaded with the incorrect software values, the Centaur lost all attitude control, and rendered itself incapable of flight. The mishap review specifically faulted the development, testing and quality assurance process of the upper stage software module for the mishap.

The Air Force Space Command attempted to salvage the MILSTAR Satellite with no success. On May 4th, 1999, the Air Force declared the MILSTAR Satellite a complete loss and permitted it to drift in low Earth orbit as space–junk. It has been estimated that it would cost the U. S. Military over $1 billion to replace the failed satellite. Without it, the existing $3.8 billion satellite network would be useless.

4. PATRIOT MISSILE FAILS TO ENGAGE SCUD MISSILES IN DHAHRAN

On the night of February 25, 1991, an Iraqi Scud Missile penetrated the Patriot Missile Defense Shield surrounding Dhahran, Saudi Arabia, and struck a warehouse used by U.S. Forces as a barracks, killing 28 and wounding 98 U.S. Army soldiers.[317] U.S. and Allied Soldiers were in Saudi Arabia as part of coalition forces in support of Operation Desert Storm and Desert Watch to push Iraqi forces out of Kuwait. The Patriot Missile Battery was setup to provide ballistic missile intercept protection for theater forces, and prevent an escalation of provoked hostilities against Israel.

The Raytheon Company initially developed the Patriot Missile as a Surface to Air Missile (SAM) intended to intercept and destroy sub and super–sonic aircraft. During the Gulf War of 1991, the U.S. Army was in need of a high–altitude intercept weapon to counter the ballistic missile threat of the Iraqi Scud Missile. The Patriot Missile was reintroduced as a suitable COTS weapon to engage the threat. No modifications were made to the weapon, despite the fact that the Scud missile was capable of flying at over Mach 6, well above the design requirements for the Patriot Fire Control System.[318]

On the evening of February 25th, six Patriot batteries were located in the Al Jubayl–Dhahran– Bahrain area. Two batteries were assigned to engage the Dhahran bound missile. Of the two assigned batteries, one was out of commission for repair of a radar receiver. The remaining battery was manned and operational, and capable of engaging the incoming Scud missile. The assigned battery had been on–line continuously for four days due to a high concentration of Scud activity in the local area. During the four days of operation, due to software designed mathematical truncating and rounding flaw, the fire control system's clock had compounded a drift of .36 seconds. The Patriot system was designed and tested for only 14 hours of continuous performance, making the clock drift negligible against slower flying aircraft. Against a Mach 6 target,

[317] Falatko, Frank; *Report Issues on Scud Missile Attack, Memorandum for Correspondents*, Department of Defense News, Department of Defense; 05 June 1991.

a clock error of .36 seconds would equate to a missed firing control solution of 2407.68 feet, well outside the kill envelope of the Patriot Missile. All known procedures were followed, and the weapon was employed as directed.

The post–mishap investigation concluded that the software generated clock drift was the most likely explanation as to why the battery did not effectively detect or engage the incoming Scud. The clock drift was not felt to be a significant problem when Patriot was employed against slower flying aircraft and the system cycle times were kept to a minimum. Against a highflying, fast moving, ballistic target, with long system cycle times, the clock drift error was an unacceptable factor. Shutdown and reboots would have reset the clock and removed any drift. That procedure was not released to the field units. A similar error was noted on February 20th after the analysis of another failed Scud engagement. The Raytheon Company had previously detected the error and had already shipping a software update to field units. The software patch arrived on the morning after the Scud impacted the barracks compound.

The Patriot was heralded as the hero of the Gulf War and was initially credited with a 90% kill ration. The US General Accounting Office's post war analysis determined that the Patriot was only credited with killing less then 9% of its targets. The Congressional Research Service revised its figures, stating that there was conclusive proof of only one Scud warhead destroyed by the Patriot System. Israeli analysts reached similar conclusions. The Patriot contract has since been transferred to the Lockheed–Martin Corp.[319, 320]

[318] Note: Mach 6 = Apx. 4,560 MPH, under standard conditions. Mach 1 = Apx. 760 MPH at sea level, with an atmospheric pressure = 29.92 in Hg, and temperature of 70° F.

[319] Farrell, John A., Globe Staff Writer; *The Patriot Gulf Missile 'Didn't Work'*, Boston Globe, pg. 1, 13; January 2001.

[320] Rogers, David, Staff Reporter; *Flaw In Patriot Missiles Leads the U.S. to Replace Hundreds*, Wall Street Journal; 23 March 2000.

5. USS YORKTOWN FAILURE

In an attempt to reduce manpower, workloads, maintenance and the costs of operating future ships in the United States Navy, the Department of Defense attempted to design and deploy a series of so–called "Smart Ships" equipped with the latest in COTS software and hardware technology. On one particular voyage in September 1997, the Aegis Guided Missile Cruiser U.S.S. Yorktown (CG–48) was left drifting dead in the water due to a Software Failure as simplistic as a "division by zero" error.[321]

During maneuvers off the coast of Cape Charles, VA., a Yorktown crewmember manually entered a test value into the ship's computer system. Due to a failure to trap the erroneous value or even to isolate and handle the potential error, the system went into an infinite loop while it attempted to divide by zero, and subsequently brought the entire ship to a halt. The ship's control system was managed on a Windows NT architecture, and the error occurred within a Microsoft NT provided application. The Navy confirms that the ship remained adrift for about two hours and forty–five minutes before personnel were able to restart the system and bring navigation and propulsion support back on–line. Investigation has revealed that a previous loss of propulsion also occurred on May 2nd, 1997, directly related to the ship's software. It should be noted that the cruisers Hue City and Vicksburg also were sidelined by Windows designed bugs within their ship support and control systems.[322]

Despite the numerous faults and errors, the Navy has considered the ship and its program a success due to the amount of information and lessons learned from the integration of Smart Technology with a deploying vessel. The potential consequences of a vessel dead in the water could have been catastrophic, had there been a physical hazard to avoid or enemy to combat. With a loss of ship's systems, comes the potential loss of weapons control, further jeopardizing the crew and those within the range of the weapons.

6. MV–22 OSPREY CRASH AND SOFTWARE FAILURE

After an embarrassing and catastrophic flight history, plagued with accidents, deaths, falsified maintenance records, and political pork–bellying the V–22 Osprey program was put on infinite suspension following the December 11, 2000 accident that killed four marines.[323] The Osprey was noted for its ability to fly like a plane with its two oversized propellers at speeds in excess of 300 knots, but could tilt its wings and transition into a helicopter like mode for landing and hovering.

The V–22 was developed by Boeing's to support the militaries desire to incorporate a tilt–rotor type–wing in its future inventory. The U. S. Navy lost interest early in the program due to mechanical problems and early system failures. The U. S. Marines and U. S. Air Force remained dedicated the project, due to the need to replace its existing fleet of aging transport and logistics aircraft. The recent series of accidents and revelations about maintenance irregularities have cost the Boeing Company one of its back–pocket supporters – the U.S. Air Force Special Operations Command, and resulting in the scrapping of a 50 aircraft order by the USAF.

U. S. Senate Investigations discovered that the Marine V–22 Training Squadron, VMMT–204, was falsifying maintenance records by the order of the squadron's commanding officer, LCOL O. Fred Leberman. The CO had ordered the doctoring of maintenance data and operations reports to improve the aircraft's poor reliability rate. The information surfaced from an anonymous tip from a squadron mechanic.

On 11 December 2000, Crossbow–8 was on its final approach into Marine Corps Air Station New River, N.C., about 7 mi. from the airfield, when the aircraft suffered a leak in its No. 1 hydraulic system that drives flight–critical systems. At the time of the hydraulic leak, the pilot was attempting to transition from forward flight fixed–wing

[321] Slabodkin, Gregory; *Software Glitches Leave Navy Smart Ship Dead In The Water*, Government Computer News; 13 July 1998.

[322] Said, Carolyn; *Floating Test Pad For High Tech*, San Francisco Chronicle, pg. 1, 07 October 2000.

[323] Wall, Robert; *V-22 Support Fades Amid Accidents, Accusations, Probes, Aviation Week and Space Technology*, Washington, D.C., pg 28; 29 January 2001.

mode to helicopter mode. When the leak was detected by the onboard flight control computers, a triple–redundant set of leak isolation and switching valves attempted to isolate and contain the leak, while preserving flight control. Without hydraulic control, the pilot was dead stick and no ability to manipulate any control surface. Due to a failure within the software logic the leak was not isolated properly and the aircraft departed controlled flight and impacted the ground, killing all four crewmembers.

The Crossbow–8 had logged less then 160 flight hours before its fatal mishap. There have been three previous fatal mishaps with the V–22; one in 1991, killing four persons, attributed to faulty wiring; a second in June 1992, killing seven persons aboard, attributed to an oil leak and subsequent fire; and a third in April 2000, killing nineteen crewmembers and passengers, attributed to vortex ring state.[324] It should be noted that the April 2000 mishap of Nighthawk–72 had suffered a navigational computer failure earlier in the flight and was relying on its wingman's computers for system navigation. The computer failure was not "directly" attributed to the mishap. Additionally, prior to the suspension of flight operations, the Marines had recorded no less then one dozen uncommanded flight event in which the aircraft flew without command and control of the pilot. Other faults have been detected in various software modules including the modules controlling gyroscope systems. The actual cost of the V–22 aircraft is not disclosed, but industry experts expect the price to be well in excess of the originally estimated $66 Million stated by Boeing Aircraft. There is no schedule to resume flight operations with the remaining seven Osprey aircraft.

7. FAA – AIR TRAFFIC CONTROL FAILURE

During the fall of 2000, the Federal Aviation Administration (FAA) performed a nationwide scheduled upgrade of its host software to its air traffic control system.[325] This system was designed to provide a visual representation of an aircraft's identity, altitude,

[324] Richmond, Peter, *Crash Of The Osprey*, GQ, pg. 138; January 2001.

[325] Lefevre, Greg; Richer, Susan; Afflerbach, Chuck; *FAA Suspends Software Upgrades Following California Computer Glitches*, Cable News Network, San Francisco, California Bureau; 24 October 2000.

speed and direction to air traffic controllers from the FAA's new high–speed computers. The upgrade had been ongoing since the beginning of the year. During a period of five days, two of the newly upgraded Air Route Traffic Control Stations, one in Freemont, CA and a second in Los Angeles, CA completely shutdown, rendering the most of the state of California and western Nevada essentially blind to air traffic. The shutdown caused flight delays nationwide and overseas. The total losses in productivity, excess manpower and expenses, and lost revenue range in the tens of millions of dollars. The actual figure is still under debate.

Investigators attempted to isolate the failure to hardware, software, and/or human error. After a detailed review, the FAA isolated the failure to the software upgrade package and its inability to receive data from some incoming aircraft. Immediately, the FAA ordered a moratorium on all Air Route Traffic Control Centers nationwide not to install or test any more software upgrades until further notice. At that time, 18 of the 21 centers had received and installed the upgrade. Three centers had not received the upgrade.

8. WINDOWS 98 CRASH DURING THE COMDEX 1998 CONVENTION

During a highly publicized demonstration of the newest Microsoft Operating System (OS) at COMDEX Spring 1998, Microsoft Chairman Bill Gates was left standing in front of blank screen after a full system crash.[326] The public failure occurred while Bill Gates was addressing some 85,000–computer professionals at the annual technology conference. Mr. Gates was the features speaker for the annual conference.

The operating system crashed when a Microsoft technician attempted to plug an external scanner into the demonstration computer. The demonstration moved to another computer to complete the presentation. Mr. Gates smiled and noted that, "I guess we still have some bugs to work out. That must be why we're not shipping Windows 98 yet." Windows 98 was designed to replace the 150 million copies of Windows 95, and was

[326] Various Cable News Network and Associated Press Wire Reports; 20 April 1998.

supposed to make computers easier to use and accept additional peripherals through the use of plug and play technology. Mr. Gates noted that "while we're all very dependent on technology, it doesn't always work."

The product was supposed to be released on January 1st, 1998, but fell behind deadlines due to numerous failures and bugs. The Windows 98 OS was further tested and later distributed to the public in the summer of 1998. Windows 98 was later replaced by Windows 2000, only after Microsoft was forced to issue numerous service packs and system advisories to overcome publicly noted faults and failures.

9. DENVER AIRPORT BAGGAGE SYSTEM

An example of poor software design is the Denver International Airport luggage controller. In this case, Jones says that the senior executives did not have a sufficient background in software systems and as a result accepted "nonsensical software claims at face value." The airport boasted about its new "…automated baggage handling system, with a contract price of $193 million, will be one of the largest and most sophisticated systems of its type in the world. It was designed to provide the high–speed transfer of baggage to and from aircraft, thereby facilitating quick turnaround times for aircraft and improved services to passengers." The baggage system, which came into operation in October 1995, included "over 17 miles of track; 5.5 miles of conveyors; 4,000 telecarts; 5,000 electric motors; 2,700 photocells; 59 laser bar code reader arrays; 311 radio frequency readers; and over 150 computers, workstations, and communication servers. The automated luggage handling system (ALHS) was originally designed to carry up to 70 bags per minute to and from the baggage check–in."[327]

However there were fundamental flaws identified but not addressed in the development and testing stage. ABC news later reported that "In tests, bags were being misloaded, misrouted or fell out of telecarts, causing the system to jam." The Dr. Dobbs Journal (January 1997) also carried an article in which the author claims that his software

[327] Jones, Carpers; *Patterns of Software Systems Failure and Success*; Thomson Computer Press; 1996

simulation of the automatic baggage handling system of the Denver airport mimicked the real–life situation. He concluded that the consultants did perform a similar simulation and, as a result, had recommended against the installation of the system. However, the city overruled the consultant's report and gave the go–ahead (the contractors who were building the system never saw the report).[328]

The report into the failure of the Denver ALHS says that the Federal Aviation Authority had required the designers (BAE Automated Systems Incorporated) to properly test the system before the opening date on 28th February 1995. Problems with the ALHS had already caused the airport’s opening date to be postponed and no further delays could be tolerated by the city. The report speculates that delays had already cost the airport $360 million by February 1995.

The lack of testing inevitably led to problems with the ALHS. One problem occurred when the photo eye at a particular location could not detect the pile of bags on the belt and hence could not signal the system to stop. The baggage system loaded bags into telecarts that were already full, resulting in some bags falling onto the tracks, again causing the telecarts to jam. This problem caused another problem. This one occurred because the system had lost track of which telecarts were loaded or unloaded during a previous jam. When the system came back on–line, it failed to show that the telecars were loaded. Also the timing between the conveyor belts and the moving telecarts were not properly synchronized, causing bags to fall between the conveyor belt and the telecarts. The bags then became wedged under the telecarts. This eventually caused so many problems that there was a need for a major overhaul of the system.

The government report concluded that the ALHS at the new airport was afflicted by "serious mechanical and software problems.” However, you cannot help thinking how much the city was blamed for their part in a lack of demand for proper testing. Denver International Airport had to install a $51 million alternative system to get around the problem. However, United Airlines still continue to use the ALHS.

[328] Dr. Dobbs Journal; January 1997.

Approved in 1989. Planned to be operational by end of 1993. 53 sq. miles. 5 runways, with possibly 12 in the future. 3 landings simultaneously in all weather conditions. 20 major airlines. Cost $4.2B. Needed large–scale baggage handling system. $193 million. 4000 telecars carry luggage across 21 miles of track. Laser scanners read barcodes on luggage tags. Photocells tracked telecars movement. Controlled by 300 computers. Software bugs galore! Telecars were misrouted and crashed. Baggage was lost and damaged. Without baggage handling, the airport could not open, costing $1.1M per day. Airport opened in February 1995. Baggage system had extra $88M spent on it. 1 airline used it. Others used an alternative carbon–based neural network system. How can the software be tested and validated before it is put in charge of a system of this complexity?

10. THE LONDON AMBULANCE SERVICE

The failure of the London Ambulance Service (LAS) on Monday and Tuesday 26 and 27 November 1992, was, like all major failures, blamed on a number of factors. These include inadequate training given to the operators, commercial pressures, no backup procedure, no consideration was given to system overload, poor user interface, not a proper fit between software and hardware and not enough system testing being carried out before hand. Claims were later made in the press that up to 20–30 people might have died as a result of ambulances arriving too late on the scene. According to Flowers, "The major objective of the London Ambulance Service Computer Aided Dispatch (LASCAD) project was to automate many of the human–intensive processes of manual dispatch systems associated with ambulance services in the UK. Such a manual system would typically consist of, among others, the following functions: Call taking. Emergency calls are received by ambulance control. Control assistants write down details of incidents on pre–printed forms."[329]

The LAS offered a contract for this system and wanted it to be up and running by 8th January 1992. All the contractors raised concerns about the short amount of time

[329] Flowers, Stephen; *Software Failure: Management Failure*; Chichester: John Wiley and Sons; 1996.

available but the LAS said that this was non–negotiable. A consortium consisting of Apricot, Systems Options and Datatrak won the contract. Questions were later asked about why their contract was significantly cheaper than their competitors. (They asked for £1.1 million to carry out the project while their competitors asked for somewhere in the region of £8 million.)

The system was lightly loaded at start–up on 26 October 1992. Staff could manually correct any problems, caused particularly by the communications systems such as ambulance crews pressing the wrong buttons. However, as the number of calls increased, a build up of emergencies accumulated. This had a knock–on effect in that the system made incorrect allocations on the basis of the information it had. This led to more than one ambulance being sent to the same incident, or the closest vehicle was not chosen for the emergency. As a consequence, the system had fewer ambulance resources to use. With so many problems, the LASCAD generated exception messages for those incidents for which it had received incorrect status information. The number of exception messages appears to have increased to such an extent the staff were not able to clear the queues. Operators later said this was because the messages scrolled of the screen and there was no way to scroll back through the list of calls to ensure that a vehicle had been dispatched. This all resulted in a viscous circle with the waiting times for ambulances increasing. The operators also became bogged down in calls from frustrated patients who started to fill the lines. This led to the operators becoming frustrated, which in turn led to an increased number of instances where crews failed to press the right buttons, or took a different vehicle to an incident than that suggested by the system. Crew frustration also seems to have contributed to a greater volume of voice radio traffic. This in turn contributed to the rising radio communications bottleneck, which caused a general slowing down in radio communications that, in turn, fed back into increasing crew frustration. The system therefore appears to have been in a vicious circle of cause and effect. One distraught ambulance driver was interviewed and recounted that the police are saying "Nice of you to turn up" and other things. At 23:00 on October 28, the LAS eventually instigated a backup procedure, after the death of at least 20 patients.

An inquiry was carried out into this disaster at the LAS and a report was released in February 1993. Here is what the main summary of the report said: "What is clear from the Inquiry Team's investigations is that neither the Computer Aided Dispatch (CAD) system itself, nor its users, were ready for full implementation on 26 October 1992. The CAD software was not complete, not properly tuned, and not fully tested. The resilience of the hardware under a full load had not been tested. The fall back option to the second file server had certainly not been tested. There were outstanding problems with data transmission to and from the mobile data terminals. … Staff, both within Central Ambulance Control (CAC) and ambulance crews, had no confidence in the system and was not all fully trained and there was no paper backup. There had been no attempt to foresee fully the effect of inaccurate or incomplete data available to the system (late status reporting/vehicle locations etc.). These imperfections led to an increase in the number of exception messages that would have to be dealt with and which in turn would lead to more callbacks and enquiries. In particular the decision on that day to use only the computer generated resource allocations (which were proven to be less than 100% reliable) was a high–risk move."

In a 1994 report by Simpson, she claimed that the software for the system was written in Visual Basic and was run in a Windows operating system. This decision itself was a fundamental flaw in the design. "The result was an interface that was so slow in operation that users attempted to speed up the system by opening every application they would need at the start of their shift, and then using the Windows multi–tasking environment to move between them as required. This highly memory–intensive method of working would have had the effect of reducing system performance still further."[330]

The system was never tested properly and nor was their any feedback gathered from the operators before hand. The report refers to the software as being incomplete and unstable, with the back up system being totally untested. The report does say that there was "functional and maximum load testing" throughout the project. However, it raised

[330] Simpson, Moira; *999!: My Computers Stopped Breathing*!; The Computer Law and Security Report, pg. 76-81, March – April 1995.

doubts over the "completeness and quality of the systems testing.” It also questions the suitability of the operating system chosen.

This along with the poor staff training was identified to be the main root of the problem. The management staff was highly criticized in the report for their part in the organization of staff training. The ambulance crew and the central control crew staff were, among other things, trained in separate rooms, which did not lead to a proper working relationship between the pair. Here is what the report said about staff training:

"Much of the training was carried out well in advance of the originally planned implementation date and hence there was a significant "skills decay" between then and when staff were eventually required to use the system. There were also doubts over the quality of training provided, whether by Systems Options or by LAS's own Work Based Trainers (WBTs). … This training was not always comprehensive and was often inconsistent. The problems were exacerbated by the constant changes being made to the system."[331]

[331] *Inquiry into the London Ambulance Service*; February 1993.

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APPENDIX C. ABBREVIATIONS AND ACRONYMS

ABF	Action Based Failure
AECL	Atomic Energy of Canada Limited
Attr	Attributed
BIT	Built–In Test
BIT	Built In Test
BITE	Built–In Test Equipment
BSI	British Standards Institute
C(H)	The Consequence Severity of a Hazardous Event
C2	Command and Control
C3	Command, Control, and Communications
C4I	Command, Control, Computers, Communications, and Intelligence
CASE	Computer Aided Software Engineering Tool
CDR	Critical Design Review
CIA	Central Intelligence Agency
CMM	Capability Maturity Model Management
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
CSA	Code Safety Analysis
CSCI	Computer Software Configuration Item
CSHA	Code Level Software Hazard Analysis
CT	Coverage Testing
DARPA	Defense Advanced Research Projects Agency
DID	Data Item Description
DISA	Defense Information Systems Agency
DoD	Department of Defense
DODD	Department of Defense Directive
DoT	Department of Transportation
E	The set of all Events in the system, where the set of Events contains Inputs, Outputs, Limits, and / or Processes.
EPA	Environmental Protection Agency
EST	Eastern Standard Time
FBC	Faster, Better, Cheaper
FDIR	Fault Detection, Isolation, and Recovery
FMECA	Failure Modes Effect and Criticality Analysis
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GFE	Government Furnished Equipment
GMT	Greenwich Mean Time, see also UTC
GOTS	Government Off The Shelf
GUI	Graphical User Interface
(H)	Hazardous Event
HAZOP	Hazardous Operation

I	The set of all Inputs in the System
IAM	Instantiated Activity Model
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IRS	Internal Reference System
IT	Information Technology
IV&V	Independent Verification and Validation
IW	Information Warfare
L	The set of all Limits in the System
JPL	Jet Propulsion Laboratory
JSSSH	Joint Software System Safety Handbook
JTO	Joint Technology Office
KISS	Keep It Simple, Stupid
MCO	Mars Climate Orbiter
MIB	Mishap Investigation Board
MIL–STD	Military Standard
MUD	Multiple User Dimension, Multiple User Dungeon, Multiple User Dialogue
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NHB	NASA Handbook
NMI	NASA Management Instruction
NSA	National Security Agency
NUREG	U.S. Nuclear Regulatory Commission
O	The set of all Outputs in the System
OBC	On–Board Computer
ORM	Operational Risk Management
P	The set of all Processes in the System
P(H)	The probability that a Hazardous Event (H) will occur
PDR	Preliminary Design Review
PHA	Preliminary Hazard Analysis
PSDL	Prototype System Description Language
P_{se}	Probability of System Execution
QA	Quality Assurance
RBF	Resource Based Failure
RBT	Requirements Based Testing
SADA	Safety Architectural Design Analysis
S	The Safety of the Software System
SAI	Safety Assessment Index
SAM	Surface to Air Missile
SARA	Safety Analysis and Risk Assessment
SCCSC	Safety–Critical Computer Software Component
SCM	Software Configuration Management
SDDA	Safety Detailed Design Analysis
SDHA	Software Design Hazard Analysis

SE	Software Engineers, Software Engineering
SFTA	Software Fault Tree Analysis
SRB	Solid Rocket Booster
SRHA	Software Requirements Hazard Analysis
SRR	Software Requirements Review
SRS	Software Requirements Specification
SSR	Software Specification Review
SSRA	Software Safety Requirements Analysis
SSSH	Software System Safety Handbook
STD	Standard
THAAS	Theater High Altitude Area Defense System
TRR	Test Readiness Review
UPS	Uninterrupted Power Supply
UTC	Coordinated Universal Time, see also GMT
WACSS	Weapon Arming and Control Software System

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APPENDIX D. DISSERTATION SUPPLEMENTS

1. SOFTWARE SAFETY STANDARD TECHNIQUES REVIEW[332]

STANDARD	TECHNIQUE(S)
AFISC – "Software System Safety"[333]	• Nuclear Safety Cross–Check Analysis • Petri Nets • Software Fault Tree (soft Tree) – Uses of Fault Trees: Cutset, Quantitative, Common Cause Analysis • Software Sneak Circuit Analysis (Desk Checking, Code Walk–Through, Structural Analysis, Proof of Correctness) • Preliminary Software Hazard Analysis • Follow–on Software Hazard Analysis
FDA – (DRAFT) Reviewer Guidance for Computer–Controlled Devices[334]	• Code Walk–Through • Failure Mode, Effects, and Criticality Analysis • Fault Tree Analysis
FDA – "Reviewer Guidance for Computer–Controlled Medical Devices Undergoing 510(k) Review"[335]	• Failure Mode, Effects and Criticality Analysis
IECWG9 – "Software for Computers in the Application of Industrial Safety–Related Systems"[336]	• Cause Consequence Diagrams • Event Tree Analysis • Failure Mode, Effects, and Criticality Analysis • Fault Tree Analysis • Hazard and Operability Study • Monte–Carlo Simulation

[332] *NISTIR 5589, A Study on Hazard Analysis in High Integrity Software Standards and Guidelines*, U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, Computer Systems Laboratory, Gaithersburg, Maryland; January 1995.

[333] *AFISC SSH 1-1, Software System Safety*, Headquarters Air Force Inspection and Safety Center; 05 September 1985.

[334] *(DRAFT) Reviewer Guidance for Computer-Controlled Devices*, Medical Device Industry Computer Software Committee; January 1989.

[335] *Reviewer Guidance for Computer-Controlled Medical Devices Undergoing 510(k) Review*, Office of Device Evaluation, Center for Devices and Radiological Health, Food and Drug Administration.

[336] *IEC/TC65A WG9, IEC 65A(Secretariat)122, Software for Computers in the Application of Industrial Safety-Related Systems, ver. 1.0*, British Standards Institution; 26 September 1991.

IEEEP1228–C[337], IEEEP1228–D[338], IEEEP1228–E[339] – "Draft Standard for Software safety Plans"[340]	• Event Tree Analysis • Failure Modes and Effects Analysis • Fault Tree Analysis • Petri Nets • Sneak Circuit Analysis • Software Safety Requirements Analysis • Software Safety Design Analysis • Software Safety Code Analysis • Software Safety Test Analysis • Software Safety Change Analysis
"Joint Software System Safety Handbook"[341]	• Joint Vision of Software Safety based Best Practices of DOD, USCG, FAA, NASA, Contractors, and Academia • How–To Handbook for Implementation of Software System Safety. • Review of Current and Antiquated Governmental, Commercial, and International Standards • Introduction of Risk Management and System Safety, and Software Safety Engineering • Management of COTS • Sample Documentation
JPL – "Software Systems Safety Handbook" [342]	• Petri Nets • Software Fault Tree Analysis • Software Requirements Hazard Analysis • Software Top–Level and Detailed Design Hazard Analysis • Code–Level Hazard Analysis • Interface Hazard Analysis • Software Change Hazard Analysis

[337] *IEEEP1228-C P1228, (DRAFT C) Draft Standard for Software Safety Plans*, Institute of Electrical and Electronics Engineers; 13 November 1990.

[338] *IEEEP1228-D P1228, (DRAFT D) Standard for Software Safety Plans*, Institute of Electrical and Electronics Engineers, Inc.; 06 March 1991.

[339] *IEEEP1228-E P1228, (DRAFT E) Standard for Software Safety Plans*, Institute of Electrical and Electronics Engineers, Inc.; 19 July 1991.

[340] Note: The Draft IEEEP 1228 Series has recently been formalized as *IEEE 1228-1994, IEEE Standard for Software Safety Plans*, Institute of Electrical and Electronics Engineers, Inc.; 2002.

[341] *Software System Safety Handbook, A Technical & Managerial Team Approach*, Joint Software System Safety Committee, Joint Services System Safety Panel; December 1999.

[342] *JPL D-10058, Software Systems Safety Handbook*, prepared by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration; 10 May 1993.

MIL–STD–882B – " System Safety Program Requirements" [343]	• Code Walk–Through • Cross Reference Listing Analysis • Design Walk–Through • Nuclear Safety Cross–Check Analysis • Petri Net Analysis • Software Fault Tree Analysis • Software/Hardware Integrated Critical Path Analysis • Software Sneak Analysis • Software Requirements Hazard Analysis • Top–Level Design Hazard Analysis • Detailed Design Hazard Analysis • Code–Level Software Hazard Analysis • Software Safety Testing • Software/User Interface Analysis • Software Change Hazard Analysis
UK STAN 0055 – "Requirements For Safety Related Software In Defence Equipment"[344]	• Common Cause Failure Analysis • Event Tree Analysis • Software Hazard Analysis • Software Classification • Software Functional Analysis • Failure Modes and Effects Analysis • Fault Tree Analysis
Ontario Hydro – "Standard for Software Engineering of Safety Critical Software"[345]	• Code Hazards Analysis
NASA–I1740 – "(Interim) NASA Software Safety Standard" [346, 347]	• Software Safety Requirements Analysis • Software Safety Architectural Design Analysis • Software Safety Detailed Design Analysis • Code Safety Analysis • Software Test Safety Analysis • Software Change Analysis

Table 19 Software Safety Standard Techniques Review

[343] *MIL-STD-882B, System Safety Program Requirements*, Department of Defense; 30 March 1984.

[344] *Defence Standard 00-55, Requirements For Safety Related Software In Defence Equipment*, Ministry of Defence, United Kingdom; 01 August 1997.

[345] Standard for Software Engineering of Safety Critical Software*, Rev. 0,* Ontario Hydro; Ontario, Canada; December 1990.

[346] *NSS 1740.13, (Interim) NASA Software Safety Standard*, National Aeronautics and Space Administration; February 1996.

[347] Note: NSS 1740.13 has been formalized as *NASA-STD-8719.13A, NASA Technical Standard for Software Safety*, National Aeronautics and Space Administration; 15 September 1997.

2. COVERAGE TESTING MEASURES[348]

The following is a list of coverage testing measures for determining the completeness and functionality of a Software System. The intent of coverage testing is to find faults and triggers within the system or its independent modules. The level of C*overage* is measured by the amount of testing completed within each field of testing, determined by the level of effort and completeness of each testing field. For example, 100% line coverage is not interpreted to mean that every line of code was executed, but to mean that every line of code was tested for every possible fault and trigger that could occur from the simple execution of a line of code.

1. ***Line coverage.*** Test every line of code (Or ***Statement coverage:*** test every statement).

2. ***Branch coverage.*** Test every line, and every branch on multi–branch lines.

3. ***N–length sub–path coverage.*** Test every sub–path through the program of length N. For example, in a 10,000 line program, test every possible 10–line sequence of execution.

4. ***Path coverage.*** Test every path through the program, from entry to exit. The number of paths may be exponentially large to test, compared to lines of code.

5. ***Multicondition or predicate coverage***. Force every logical operand to take every possible value. Two different conditions within the same test may result in the same branch, and so branch coverage would only require the testing of one of them.

6. ***Trigger every assertion check in the program.*** Initiate and test the response of all triggers within a system using real and impossible data where able.

7. ***Loop coverage.*** Test the execution of all loops to detect bugs that exhibit themselves only when a loop is executed more than once.

8. ***Every module, object, component, tool, subsystem, etc.*** This includes the testing of COTS / GOTS systems with which the developer has no access to code level testing methods. The programming staff does not have the source code to these components, so measuring line coverage is impossible. At a minimum, testers

[348] Kaner, Cem; *Software Negligence and Testing Coverage*, Software QA Quarterly, vol. 2, num. 2, pg. 18; 1995/1996.

need a list of all these components and test cases that exercise each one at least once.

9. ***Fuzzy decision coverage.*** If the program makes heuristically–based or similarity–based decisions, and uses comparison rules or data sets that evolve over time, check every rule several times over the course of training.

10. ***Relational coverage.*** Checks whether the subsystem has been exercised in a way that tends to detect off–by–one errors such as errors caused by using < instead of <=. This coverage includes:

    - Every boundary on every input variable.
    - Every boundary on every output variable.
    - Every boundary on every variable used in intermediate calculations.

11. ***Data coverage.*** At least one test case for each data item / variable / field in the program.

12. ***Constraints among variables: (Reliance)*** Let **X** and **Y** be two variables in the program. **X** and **Y** constrain each other if the value of one restricts the values the other can take. For example, if **X** is a transaction date and **Y** is the transaction's confirmation date, **Y** cannot occur before **X**.

13. ***Each appearance of a variable.*** Suppose that you can enter a value for **X** on three different data entry screens, the value of **X** is displayed on another two screens, and it is printed in five reports. Change **X** at each data entry screen and check the effect everywhere else **X** appears.

14. ***Every type of data sent to every object.*** A key characteristic of object–oriented programming is that each object can handle any type of data (integer, real, string, etc.) that you pass to it. So, pass every conceivable type of data to every object.

15. ***Handling of every potential data conflict.*** Check for the entry of inconsistent or incompatible data from dissimilar points of the system to induce a conflict, testing for reaction and handling. For example, in an appointment–calendaring program, what happens if the user tries to schedule two appointments at the same date and time?

16. ***Handling of every error state.*** Verifying the ability of a program to handle induced errors, including all possible error states, effects on the stack, available memory, handling of keyboard input, etc.

17. ***Every complexity / maintainability metric against every module, object, subsystem, etc.*** Mathematical and logic checks for completeness and validity.

18. ***Conformity of every module, subsystem, etc. against every corporate coding standard.*** Several organizations believe that it is useful to measure characteristics

of the code, such as total lines per module, ratio of lines of comments to lines of code, frequency of occurrence of certain types of statements, etc. A module that does not fall within the "normal" range might be summarily rejected (bad idea) or re–examined to see if there is a better way to design this part of the program.

19. ***Table–driven code.*** The table is a list of addresses or pointers or names of modules. In a traditional CASE statement, the program branches to one of several places depending on the value of an expression. In the table–driven equivalent, the program would branch to the place specified in, say, location 23 of the table. The table is probably in a separate data file that can vary from day to day or from installation to installation. By modifying the table, you can radically change the control flow of the program without recompiling or relinking the code. Some programs drive a great deal of their control flow this way, using several tables. Examples include:

    - Check that every expression selects the correct table element
    - Check that the program correctly jumps or calls through every table element
    - Check that every address or pointer that is available to be loaded into these tables is valid (no jumps to impossible places in memory, or to a routine whose starting address has changed)
    - Check the validity of every table that is loaded at any customer site.

20. ***Every interrupt.*** An interrupt is a special signal that causes the computer to stop the program in progress and branch to an interrupt handling routine. Later, the program restarts from where it was interrupted. Interrupts might be triggered by hardware events (I/O or signals from the clock that a specified interval has elapsed) or software (such as error traps). Generate every type of interrupt in every way possible to trigger that interrupt.

21. ***Every interrupt at every task, module, object, or even every line.*** The interrupt handling routine might change state variables, load data, use or shut down a peripheral device, or affect memory in ways that could be visible to the rest of the program. The interrupt can happen at any time–between any two lines, or when any module is being executed. The program may fail if the interrupt is handled at a specific time. Example: what if the program branches to handle an interrupt while it is in the middle of writing to the disk drive?

22. ***Every anticipated or potential race.*** Imagine two events, **A** and **B**. Both will occur, but the program is designed under the assumption that **A** will always precede **B**. This sets up a race between **A** and **B** –if **B** ever precedes **A**, the program will probably fail. To achieve race coverage, you must identify every potential race condition and then find ways, using random data or systematic test case selection, to attempt to drive **B** to precede **A** in each case. Races can be

subtle. Suppose that you can enter a value for a data item on two different data entry screens. User 1 begins to edit a record, through the first screen. In the process, the program locks the record in Table 1. User 2 opens the second screen, which calls up a record in a different table, Table 2. The program is written to automatically update the corresponding record in the Table 1 when User 2 finishes data entry. Now, suppose that User 2 finishes before User 1. Table 2 has been updated, but the attempt to synchronize Table 1 and Table 2 fails. What happens at the time of failure, or later if the corresponding records in Table 1 and 2 stay out of synch?

23. ***Every time–slice setting.*** Users can control the grain of switching between tasks or processes. The size of the time quantum that is chosen can make race bugs, time–outs, interrupt–related problems, and other time–related problems more or less likely. Complete coverage is a difficult problem in this instance because testers are not just varying time–slice settings through every possible value. Testers also have to decide which tests to run under each setting. Given a planned set of test cases per setting, the coverage measure looks at the number of settings you have covered.

24. ***Varied levels of background activity.*** In a multiprocessing system, tie up the processor with competing, irrelevant background tasks. Look for effects on races and interrupt handling. Similar to time–slices, your coverage analysis must specify categories of levels of background activity (figure out something that makes sense) and all timing–sensitive testing opportunities (races, interrupts, etc.).

25. ***Each processor type and speed***. Which processor chips do you test under? What tests do you run under each processor? Testers are looking for:

- Speed effects, like the ones you look for with background activity testing, and

- Consequences of processors' different memory management rules, and

- Floating point operations, and

- Any processor–version–dependent problems that you can learn about.

26. ***Every opportunity for file / record / field locking***.

27. ***Every dependency on the locked (or unlocked) state of a file, record or field.***

28. ***Every opportunity for contention for devices or resources.***

29. ***Performance of every module / task / object.*** Test the performance of a module then retest it during the next cycle of testing. If the performance has changed significantly, you are either looking at the effect of a performance–significant redesign or at a symptom of a new bug.

30. ***Free memory / available resources / available stack space at every line or on entry into and exit out of every module or object.***

31. ***Execute every line (branch, etc.) under the debug version of the operating system.*** This shows illegal or problematic calls to the operating system.

32. ***Vary the location of every file.*** What happens if the user installs or moves one of the program's components, controls, initialization, or data files to a different directory or drive or to another computer on the network?

33. ***Check the release disks for the presence of every file.***

34. ***Every embedded string in the program.*** Use a utility to locate embedded strings. Then find a way to make the program display each string.

35. ***Operation of every function / feature / data handling operation under every program preference setting.***

36. ***Operation of every function / feature / data handling operation under every character set, code page setting, or country code setting.***

37. ***Operation of every function / feature / data handling operation under the presence of every memory resident utility (inits, TSRs).***

38. ***Operation of every function / feature / data handling operation under each operating system version.***

39. ***Operation of every function / feature / data handling operation under each distinct level of multi–user operation.***

40. ***Operation of every function / feature / data handling operation under each network type and version.***

41. ***Operation of every function / feature / data handling operation under each level of available RAM.***

42. ***Operation of every function / feature / data handling operation under each type / setting of virtual memory management.***

43. ***Compatibility with every previous version of the program.***

44. ***Ability to read every type of data available in every readable input file format.*** If a file format is subject to subtle variations (e.g. CGM) or has several sub–types (e.g. TIFF) or versions (e.g. dBASE), ***test each one.***

45. ***Write every type of data to every available output file format.*** Testing includes writing to every potential format as well as testing the readability of that format by appropriate secondary programs.

46. ***Every typeface supplied with the product.*** Check all characters in all sizes and styles. If your program adds typefaces to a collection of fonts that are available to several other programs, check compatibility with the other programs (nonstandard typefaces will crash some programs).

47. ***Every type of typeface compatible with the program.*** Testing includes the use of different TrueType and Postscript typefaces, and fixed–sized bitmap fonts.

48. ***Every piece of clip art in the product***. Test each with this program. Test each with other programs that should be able to read this type of art.

49. ***Every sound / animation provided with the product.*** Play them all under different device (e.g. sound) drivers / devices. Check compatibility with other programs that should be able to play this clip–content.

50. ***Every supplied (or constructible) script*** to drive other machines / software (e.g. macros) / BBS's and information services (communications scripts).

51. ***All commands available in a supplied communications protocol.***

52. ***Recognized characteristics.*** For example, every speaker's voice characteristics (for voice recognition software) or writer's handwriting characteristics (handwriting recognition software) or every typeface (OCR software).

53. ***Every type of keyboard and keyboard driver.***

54. ***Every type of pointing device and driver at every resolution level and ballistic setting.***

55. ***Every output feature with every sound card and associated drivers.***

56. ***Every output feature with every type of printer and associated drivers at every resolution level.***

57. ***Every output feature with every type of video card and associated drivers at every resolution level.***

58. ***Every output feature with every type of terminal and associated protocols.***

59. ***Every output feature with every type of video monitor and monitor–specific drivers at every resolution level.***

60. ***Every color shade displayed or printed to every color output device (video card / monitor / printer / etc.) and associated drivers at every resolution level. In addition, check the conversion to grey scale or black and white.***

61. ***Every color shade readable or scannable from each type of color input device at every resolution level.***

62. ***Every possible feature interaction between video card type and resolution, pointing device type and resolution, printer type and resolution, and memory level.***

63. ***Every type of CD–ROM drive connected to every type of port (serial / parallel / SCSI) and associated drivers.***

64. ***Every type of writable disk drive / port / associated driver.***

65. ***Compatibility with every type of disk compression software.*** Check error handling for every type of disk error, such as full disk.

66. ***Every voltage level from analog input devices.***

67. ***Every voltage level to analog output devices.***

68. ***Every type of modem and associated drivers.***

69. ***Every FAX command (send and receive operations) for every type of FAX card under every protocol and driver.***

70. ***Every type of connection of the computer to the telephone line (direct, via PBX, etc.; digital vs. analog connection and signaling); test every phone control command under every telephone control driver.***

71. ***Tolerance of every type of telephone line noise and regional variation (including variations that are out of spec) in telephone signaling (intensity, frequency, timing, other characteristics of ring / busy / etc. tones).***

72. ***Every variation in telephone dialing plans.***

73. ***Every possible keyboard combination.*** Keyboard combinations include tester hotkeys designed by debugging tools. These hotkeys may crash a debuggerless program. Other times, these combinations may reveal an Easter Egg (an undocumented, probably unauthorized, and possibly embarrassing feature). ***The broader coverage measure is every possible keyboard combination at every error message and every data entry point.***

74. ***Recovery from every potential type of equipment failure.*** Full coverage includes each type of equipment, each driver, and each error state. For example, test the program's ability to recover from full disk errors on writable disks. Include floppies, hard drives, cartridge drives, optical drives, etc. Include the various connections to the drive, such as IDE, SCSI, MFM, parallel port, and serial connections, because these will probably involve different drivers.

75. ***Function equivalence.*** For each mathematical function, check the output against a known good implementation of the function in a different program. Complete coverage involves equivalence testing of all testable functions across all possible input values.

76. ***Zero handling.*** For each mathematical function, test when every input value, intermediate variable, or output variable is zero or near zero. Look for severe rounding errors or divide–by–zero errors.

77. ***Accuracy of every graph,*** across the full range of graphable values. Include values that force shifts in the scale.

78. ***Accuracy of every report.*** Look at the correctness of every value, the formatting of every page, and the correctness of the selection of records used in each report.

79. ***Accuracy of every message***.

80. ***Accuracy of every screen.***

81. ***Accuracy of every word and illustration in the manual.***

82. ***Accuracy of every fact or statement in every data file provided with the product.***

83. ***Accuracy of every word and illustration in the on–line help.***

84. ***Every jump, search term, or other means of navigation through the on–line help.***

85. ***Check for every type of virus / worm that could ship with the program.***

86. ***Every possible kind of security violation of the program, or of the system while using the program.***

87. ***Check for copyright permissions for every statement, picture, sound clip, or other creation provided with the program.***

88. ***Verification of the program against every program requirement and published specification.***

89. ***Verification of the program against user scenarios.*** Use the program to do real tasks that are challenging and well specified. For example, create key reports, pictures, page layouts, or other documents events to match ones that have been featured by competitive programs as interesting output or applications.

90. ***Verification against every regulation (IRS, SEC, FDA, etc.) that applies to the data or procedures of the program.***

91. ***Usability tests of every feature / function of the program.***

92. ***Usability tests of every part of the manual.***

93. ***Usability tests of every error message.***

94. ***Usability tests of every on–line help topic.***

95. ***Usability tests of every graph or report provided by the program.***

96. ***Localizability / localization tests every string.*** Check program's ability to display and use this string if it is modified by changing the length, using high or low ASCII characters, different capitalization rules, etc.

97. ***Compatibility with text handling algorithms under other languages (sorting, spell checking, hyphenating, etc.)***

98. ***Every date, number, and measure in the program.***

99. ***Hardware and drivers, operating system versions, and memory–resident programs that are popular in other countries.***

100. ***Every input format, import format, output format, or export format that would be commonly used in programs that are popular in other countries.***

101. ***Cross–cultural appraisal of the meaning and propriety of every string and graphic shipped with the program.***

3. DEFINITION OF SOFTWARE ENGINEERING

In 1967, the NATO Science Committee referred to the state of the art of Software Engineering as the discipline of "...promoting the establishment of theoretical foundations and practical disciplines for software, similar to those found in the established branches of engineering."[349] Two years later, NATO refined its definition of Software Engineering as "the establishment and use of sound engineering principles in order to obtain economically software that is reliable and works efficiently on real machines." [350] The IEEE Standard simply defined Software Engineering as "the application of a systematic, disciplined, quantifiable approach to the development, operation, and maintenance of software."[351]

[349] *Software Engineering, Report on a conference by the NATO Science Committee*, NATO Science Committee; 1967.

[350] Naur, Peter; Randall, Brian; Editors, *Software Engineering, Report on a conference by the NATO Science Committee*, NATO Science Committee, January 1969.

[351] def: *Software Engineering, IEEE Standard Glossary of Software Engineering Terminology, IEEE Standard 610.12,* Institute of Electrical and Electronics Engineers, Inc.; 1990, 1991.

APPENDIX E. DISSERTATION METRIC

1. INITIAL HAZARD IDENTIFICATION

Fault	Trigger	Failure	Malfunction	Hazard	Consequence
U/K at present evaluation	U/K at present evaluation	U/K at present evaluation	Drop incorrect weapon from pylon	Loss of weapon due to incorrect targeting and delivery parameters	Cost of Weapon
				Danger to the airframe when deploying a weapon out of proper delivery parameters	Loss of Airframe, Loss of Aircrew.
				Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage
				Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty
				Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
			Loss of weapon’s configuration data	Deployment of weapon without configuration or improper configuration data	Cost of Weapon
				Danger to the airframe when deploying an improperly configured weapon	Loss of Airframe, Loss of Aircrew.
				Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage
				Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty
				Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
				Inability of the weapon to properly arm, fuse, and target	
			Inability to prevent weapons release outside of the weapon’s envelope	Weapon incapable of acquiring and striking the target	Cost of Weapon
				Danger to the airframe when deploying a weapon out of proper delivery parameters	Loss of Airframe, Loss of Aircrew.
				Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage
				Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty
				Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
			Inability to fuse weapon – Dead Fuse	Weapon not detonating on target	Cost of Weapon
					Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
			Weapon fusing to detonate too early after weapon’s release	Weapon could inadvertently detonate close to delivery aircraft	Loss of Airframe, Loss of Aircrew
					Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
				Weapon not detonating on target	Cost of Weapon
					Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
			Signal incompatibility / feedback to the Aircraft Data–Bus	Aviation Data–Bus unable to process flight data	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
					Inability to control aircraft – Loss of Airframe, Loss of Aircrew
					Damage to vulnerable aviation software systems on the data–bus

Table 20 WACSS Initial Hazard Identification Table

The example Initial Hazard Identification Table demonstrated in Table 20 serves as an illustration to the dissertation model in Chapter V.E.2 and process Step 4. Action 1.

INITIAL SAFETY ASSESSMENT

For the purpose of the WACSS, the following Consequence Severity Categories are agreed upon.

			DEFINITION
SEVERITY	I	CATASTROPHIC	Complete military mission failure, loss of Blue Force life, or loss of the aircraft.
	II	CRITICAL	Major military mission degradation, loss if White Force life, severe injury to Blue Force, significant damage to the aircraft, or complete system damage.
	III	MARGINAL / MODERATE	Minor military mission degradation, complete loss of the weapon, minor damage to the aircraft, or major system damage
	IV	NEGLIGIBLE	Less then minor military mission degradation or minor system damage.

Table 21 WACSS Consequence Severity Categories

The example Consequence Severity Category Table demonstrated in Table 21 serves as an illustration to the dissertation model in Chapter V.D and process Steps 2.1 and 2.2.. The Example numeric definition can be derived from the dissertation example in Table 7.

Malfunction	**Hazard**	**Consequence**	Severity
Drop incorrect weapon from pylon	Loss of weapon due to incorrect targeting and delivery parameters	Cost of Weapon	III – Marginal / Moderate
	Danger to the airframe when deploying a weapon out of proper delivery parameters	Loss of Airframe, Loss of Aircrew	I – Catastrophic
	Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage	II – Critical
	Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty	I – Catastrophic
	Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
Loss of weapon's configuration data	Deployment of weapon without configuration or improper configuration data	Cost of Weapon	III – Marginal / Moderate
	Danger to the airframe when deploying an improperly configured weapon	Loss of Airframe, Loss of Aircrew.	I – Catastrophic
	Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage	II – Critical
	Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty	I – Catastrophic
	Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
	Inability of the weapon to properly arm, fuse, and target		II – Critical
Inability to prevent weapons release outside of the weapon's envelope	Weapon incapable of acquiring and striking the target	Cost of Weapon	III – Marginal / Moderate
	Danger to the airframe when deploying a weapon out of proper delivery parameters	Loss of Airframe, Loss of Aircrew.	I – Catastrophic
	Weapon could possibly fall on undesired target	Blue on White (Neutral) Collateral Damage	II – Critical
	Weapon could possibly fall on friendly forces	Blue on Blue (Friendly Fire) Casualty	I – Catastrophic
	Resulting lack of sufficient weapons to complete mission	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
Inability to fuse weapon – Dead Fuse	Weapon not detonating on target	Cost of Weapon	III – Marginal / Moderate
		Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
Weapon fusing to detonate too early after weapon's release	Weapon could inadvertently detonate close to delivery aircraft	Loss of Airframe, Loss of Aircrew	I – Catastrophic
		Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
	Weapon not detonating on target	Cost of Weapon	III – Marginal / Moderate
		Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
Signal incompatibility / feedback to the Aircraft Data–Bus	Aviation Data–Bus unable to process flight data	Inability to complete mission tasking, risk to friendly force protection, risk to own protection.	II – Critical
		Inability to control aircraft – Loss of Airframe, Loss of Aircrew	I – Catastrophic
		Significant damage to vulnerable aviation software systems on the data–bus	III – Marginal / Moderate
		Minor damage to vulnerable aviation software systems on the data–bus	IV – Negligible

Table 22 WACSS Initial Safety Assessment Table

The example Initial Safety Assessment Table demonstrated in Table 22 serves as an illustration to the dissertation model in Chapter V.E.2 and process Step 4. Action 1., and refinement to Table 20.

2. INITIAL PROCESS IDENTIFICATION

ID	Title	Description	Relations
P_1	Weapon Data Processor	Process of raw Weapons status and configuration data for use on the WACSS.	From I_1, I_2, I_3; to O_1,
P_2	Aircraft Data Processor	Process of Aircraft status and configuration data for use on the WACSS.	From I_4, I_5; to O_2
P_3	System Data Processor	Process of refined aircraft / weapon status and configuration data for use on the WACSS and Aircraft Data–Bus.	From I_6, $I_{7,}$ I_{10}; to O_3, O_4
P_4	User Input / System Feedback Processor	Process of user inputs for menu selection, configuration changes, and launch commands.	From I_8, I_9, I_{14}; to O_5, O_6, O_7, O_8
P_5	Weapon Configuration Change Processor	Process of Configuration Command Changes; verify that changes are in compliance and within limits of the weapon and aircraft	From I_{11}; to O_9, O_{10}
P_6	System Display Processor	Process of data for display, as per user and system requests / requirements.	From I_{12}; to O_{11}
P_7	Weapon Launch / Deployment Processor	Process of Launch Command; verify that weapon and aircraft are within parameters.	From I_{13}; to O_{12}, O_{13}

Table 23 WACSS Initial Process Identification

The example Initial Process Identification Table demonstrated in Table 23 serves as an illustration to the dissertation model in Chapter V.E.1 and process Step 3. Action 2.

ID	Description	Relations
I_1	Raw input from the Weapon regarding type and configuration. Input includes data on the specific type and model of the weapon as well as configuration modifications and additions to the weapon. Values are static for the weapon once loaded.	From Weapon; to P_1
I_2	Raw input from the Weapon regarding status. Input includes feedback of weapons arming, targeting, and detonation data.	From Weapon; to P_1
I_3	Raw input from the Weapon's Rack regarding rack configuration. Input includes feedback from the weapon	From Weapon's Rack; to P_1
I_4	Raw input from Aircraft regarding status and configuration (non–flight)	From Aircraft; to P_2
I_5	Raw input from Aircraft regarding flight parameters and orientation	From Aircraft; to P_2
I_6	Processed input of Weapons status and configuration	From $O_{1;}$ to P_3
I_7	Processed input from Aircraft regarding flight parameters	From $O_{2;}$ to P_3
I_8	Consolidated aircraft / weapon status and configuration data for use on the WACSS	From O_4; to P_4
I_9	User inputs, menu selections, configuration changes, and launch commands	From User to System Input; to P_4
I_{10}	Processed user inputs, weapons and aircraft data, resulting in changes to weapon and aircraft data	From O_5; to P_3
I_{11}	Processed user input commands reflecting changes in the weapon's configuration	From O_6; to P_5
I_{12}	Processed user input and system commands reflecting changes in the WACSS and aircraft display systems	From O_7; to P_6
I_{13}	Processed user input commands to launch or deploy the weapon	From O_8; to P_7
I_{14}	Data feedback from command to launch the weapon	From O_{13}; to P_4
I_{15}	Data feedback from requested changes to the weapon configuration	From O_9; to P_4

Table 24 WACSS Initial Input Identification

ID	Description	Relations
O_1	Processed output of Weapon's status and configuration	From P_1; to I_6
O_2	Processed output of Aircraft's status and configuration	From P_2; to I_7
O_3	Consolidated output of Aircraft / Weapon status and configuration for the aircraft / weapon status and configuration data for use on the Aircraft Data–Bus.	From P_3; to Aircraft Data–Bus
O_4	Consolidated output of Aircraft / Weapon status and configuration for the aircraft / weapon status and configuration data for use on the WACSS.	From P_3; to I_8
O_5	Processed user inputs, weapons and aircraft data, resulting in changes to weapon and aircraft data	From P_4; to I_{10}
O_6	Processed user input commands reflecting changes in the weapon's configuration	From P_4; to I_{11}
O_7	Processed user input and system commands reflecting changes in the WACSS and aircraft display systems	From P_4; to I_{12}
O_8	Processed user input commands to launch or deploy the weapon	From P_4; to I_{13}
O_9	Data feedback from requested changes to the weapon configuration	From P_5; to I_{15}
O_{10}	Weapon change configuration commands	From P_5; to Weapon
O_{11}	Processed WACSS display commands	From P_6; to Display System
O_{12}	Weapon launch or deployment commands	From P_7; to Command Launch
O_{13}	Data feedback from weapon launch or deployment commands	From P_7; to I_{14}

Table 25 WACSS Initial Output Identification

ID	Description	Relations
L_1	Limit value to Open / Closed	In line with I_3

Table 26 WACSS Initial Limit Identification

The example Initial Input, Output, and Limit Identification Table demonstrated in Table 24, Table 25, and Table 26 serve as an illustration to the dissertation model in Chapter V.E.1 and process Step 3. Action 2.

3. INITIAL PROCESS MAP

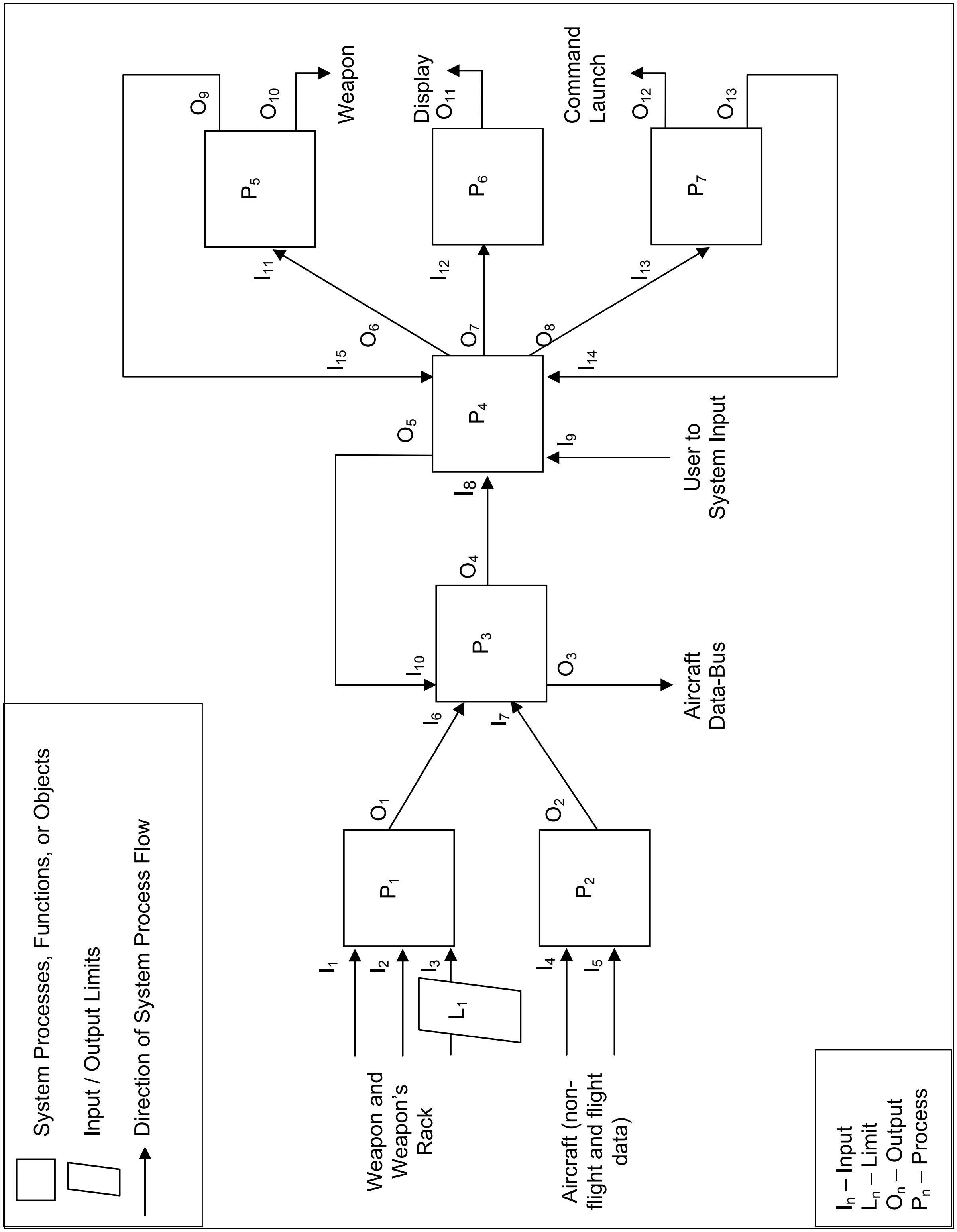

Figure 21 WACSS Initial Process Flow Depiction

The example WACSS Initial Process Flow Depiction demonstrated in Figure 21 serves as an illustration to the dissertation model in Chapter V.E.1 and process Step 3. Action 3.

ID	Failure	ID	Malfunction
F_1	Failure in the Aircraft Data–Bus Output – O_3	M_1	Signal incompatibility / feedback to the Aircraft Data–Bus
F_2	Failure in the processing of system data in P_3		
F_3	Failure in weapon's configuration change logic – P_{5f}	M_2	Weapon fusing to detonate too early after weapon's release
F_4	Failure in weapon's signals regarding current status of the weapon – I_2, P_1, O_1, I_6, P_3		
F_5	Failure in weapon's signals regarding the configuration of the weapon – I_1, P_1, O_1, I_6, P_3		
F_6	Failure in system data signals / transfer – O_4, I_8, P_4, O_6, I_{11}		
F_7	Failure / incompatibility in Weapon's configuration signals in O_{10}		
F_8	Failure in weapon's configuration change logic – P_5	M_3	Inability to fuse weapon – Dead Fuse
F_9	Failure / incompatibility in Weapon's configuration signals in O_{10}		
F_{10}	Failure in launch logic to deploy weapon with fusing. – P_7		
F_{11}	Failure in Weapon's signal regarding weapon's configuration and status – I_1, I_2, P_1, O_1, I_6, P_3		
F_{12}	Failure in Weapon's data signal regarding weapon's configuration and status – I_1, I_2, P_1, O_1, I_6, P_3	M_4	Inability to prevent weapons release outside of the weapon's envelope
F_{13}	Failure in Aircraft data signal regarding flight and non–flight data – I_4, I_5, P_2, O_2, I_7, P_3		
F_{14}	Failure in weapons launch / deployment logic to validate weapon's envelope – P_7		
F_{15}	Failure in the weapons launch signal – P_7, O_{12}		
F_{16}	Failure in system data signals / transfer – O_4, I_8, P_4, O_8, I_{13}		
F_{17}	Failure in weapons launch / deployment logic to select the proper weapon – P_7	M_5	Drop incorrect weapon from pylon
F_{18}	Failure in the system to comprehend which weapon was selected – P_4, I_9, O_8, I_{13}, P_7		

Table 27 WACSS Initial Failures to Malfunction Identification

The example Initial Failure to Malfunction Identification Table demonstrated in Table 27 serves as an illustration to the dissertation model in Chapter V.E.2 and process Step 4. Action 1., and refinement to Table 20 and Table 22.

4. INITIAL FAILURE PROCESS MAP

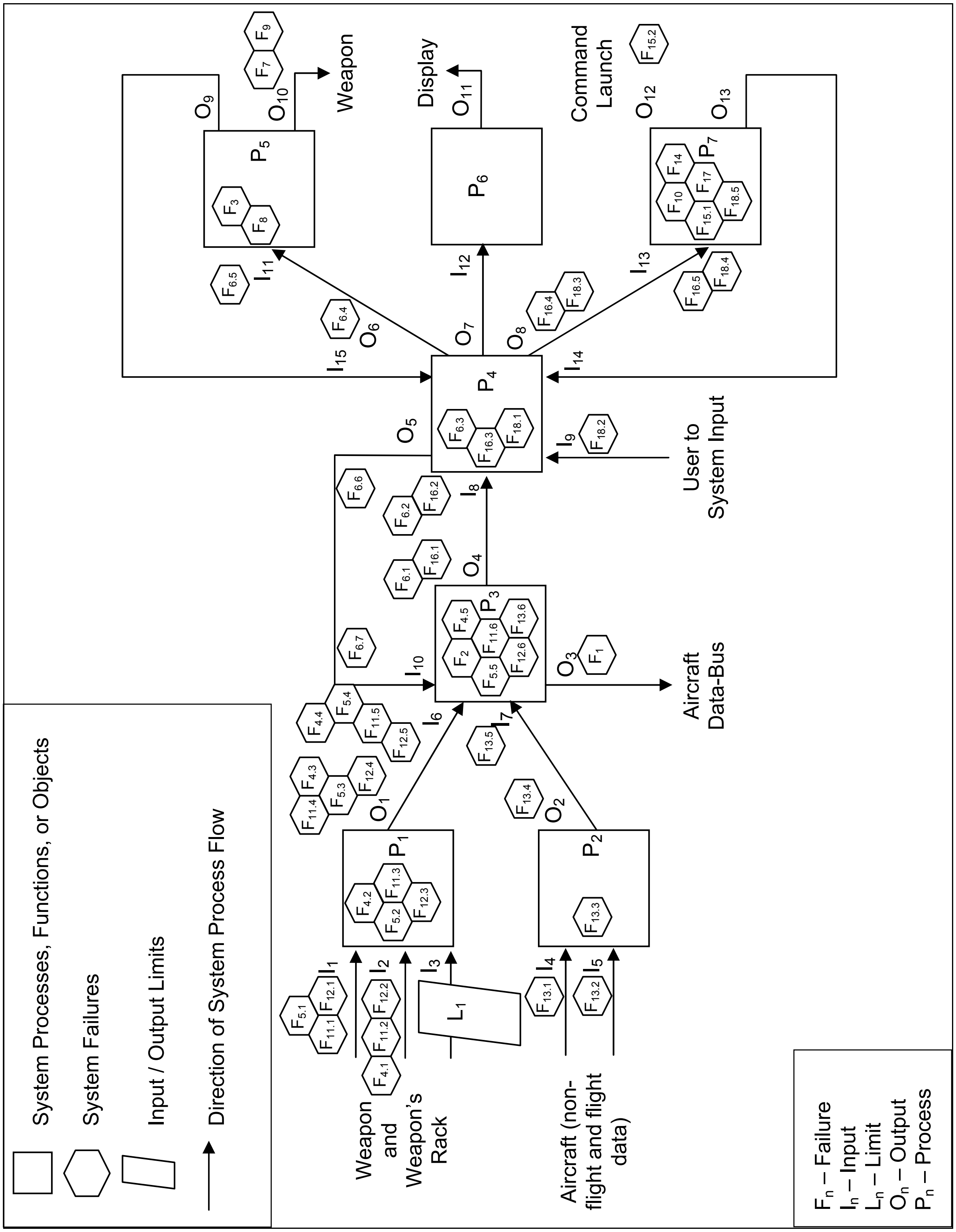

Figure 22 WACSS Initial Failure Depiction

The example WACSS Initial Failure Depiction demonstrated in Figure 22 serves as an illustration to the dissertation model in Chapter V.E.2 and process Step 4. Action 2.

5. PROCESS ASSESSMENT

Probability of System Execution

Let P_{se} = 1.0 or 100%. The system will execute 100% of the time.

Where:

- The time sample = the total flight time of the aircraft, from launch to land.
- The flight mission consists of weapons employment

Frequency of Execution

Frequency	Definition	Probability
ALWAYS	Objects are executed constantly during the sample time life of the system.	1.00
FREQUENT	Objects are executed often in the sample time life of the system.	0.90
LIKELY	Objects are executed several times in the sample time life of the system.	0.75
PERIODICALLY	Objects are executed at regular intervals in the sample time life of the system.	0.66
OCCASIONAL	Objects are executed in the sample time life of the system.	0.50
SELDOM	Objects are executed seldom in the sample time life of the system.	0.25
SPORADICALLY	Objects are executed infrequently or at scattered instances within the sample time life of the system.	0.15
UNLIKELY	Objects are so unlikely to execute it can be assumed that it will not occur in the sample time life of the system.	0.05
NEVER	Objects are assured never to execute during the sample time life of the system.	0.00

Table 28 WACSS Execution Probability Definition Table

The example Execution Probability Definitions demonstrated in Table 28 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 2.

Frequency of Failure

Frequency	Definition	Probability $x10^{-5}$
ALWAYS	Objects will fail each time they are executed.	1.00
FREQUENT	Objects will most likely fail when executed.	0.90
LIKELY	Objects will likely fail when executed.	0.75
PERIODICALLY	Objects will periodically fail when executed.	0.66
OCCASIONAL	Objects will occasionally fail when executed.	0.50
SELDOM	Objects will seldom fail when executed.	0.25
SPORADICALLY	Objects will fail sporadically when they are executed.	0.15
UNLIKELY	Objects are unlikely to fail when executed.	0.05
NEVER	Objects will never fail when executed.	0.00

Table 29 WACSS Object Failure Probability Definition Table

The example Object Failure Probability Definition Table demonstrated in Table 29 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 4.

6. OBJECT EXECUTION PROBABILITY

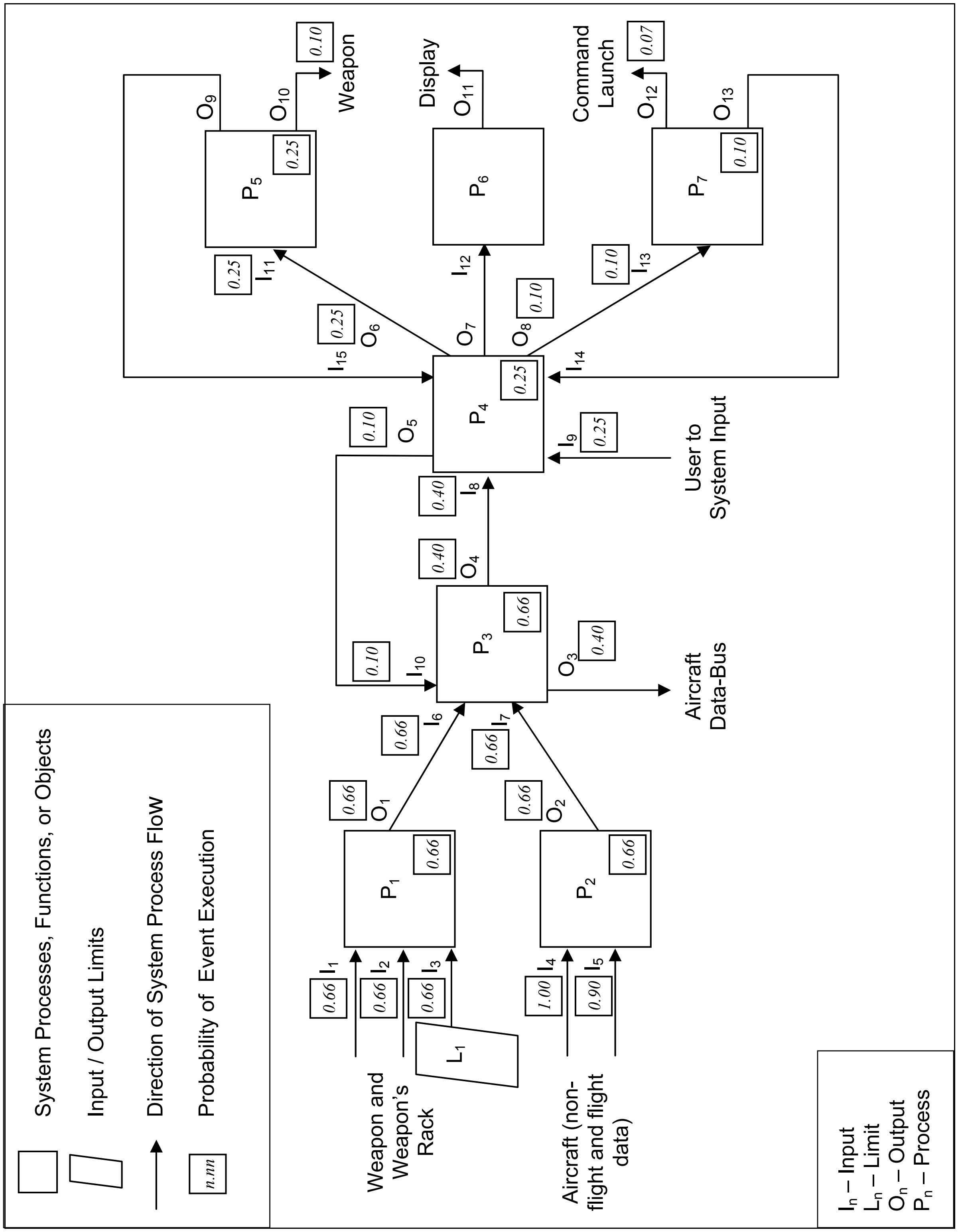

Figure 23 WACSS Object Execution Probability Map

The example Object Execution Probability Map demonstrated in Figure 23 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 3.

7. OBJECT FAILURE PROBABILITY

Failure ID	Intermittent Failure Prob $P_f\ x10^{-5}$	Partial Failure Prob $P_f\ x10^{-5}$	Complete Failure Prob $P_f\ x10^{-5}$	Cataclysmic Failure Prob $P_f\ x10^{-5}$	Object ID	Execution Prob P_e	Malfunction ID
F_1	2.5000	1.2500	0.6250	0.3125	O_3	0.40	M_1
F_2	2.0000	1.0000	0.5000	0.2500	P_3	0.66	M_1
F_3	0.8000	0.4000	0.2000	0.1000	P_5	0.25	M_2
$F_{4.1}$	1.5000	0.7500	0.3750	0.1875	I_2	0.66	M_2
$F_{4.2}$	1.0000	0.5000	0.2500	0.1250	P_1	0.66	M_2
$F_{4.3}$	0.5000	0.2500	0.1250	0.0625	O_1	0.66	M_2
$F_{4.4}$	0.5000	0.2500	0.1250	0.0625	I_6	0.25	M_2
$F_{4.5}$	1.2000	0.6000	0.3000	0.1500	P_3	0.66	M_2
$F_{5.1}$	1.8000	0.9000	0.4500	0.2250	I_1	0.66	M_2
$F_{5.2}$	1.0000	0.5000	0.2500	0.1250	P_1	0.66	M_2
$F_{5.3}$	0.5000	0.2500	0.1250	0.0625	O_1	0.66	M_2
$F_{5.4}$	0.5000	0.2500	0.1250	0.0625	I_6	0.25	M_2
$F_{5.5}$	1.2000	0.6000	0.3000	0.1500	P_3	0.66	M_2
$F_{6.1}$	0.5000	0.2500	0.1250	0.0625	O_4	0.40	M_2
$F_{6.2}$	0.5000	0.2500	0.1250	0.0625	I_8	0.40	M_2
$F_{6.3}$	0.5000	0.2500	0.1250	0.0625	P_4	0.25	M_2
$F_{6.4}$	0.5000	0.2500	0.1250	0.0625	O_6	0.25	M_2
$F_{6.5}$	0.5000	0.2500	0.1250	0.0625	I_{11}	0.25	M_2
$F_{6.6}$	0.2000	0.1000	0.0500	0.0250	O_5	0.10	M_2
$F_{6.7}$	0.2000	0.1000	0.0500	0.0250	I_{10}	0.10	M_2
F_7	0.8000	0.4000	0.2000	0.1000	O_{10}	0.10	M_2
F_8	1.0000	0.5000	0.2500	0.1250	P_5	0.25	M_3
F_9	0.8000	0.4000	0.2000	0.1000	O_{10}	0.10	M_3
F_{10}	1.2000	0.6000	0.3000	0.1500	P_7	0.10	M_3
$F_{11.1}$	1.8000	0.9000	0.4500	0.2250	I_1	0.66	M_3
$F_{11.2}$	1.5000	0.7500	0.3750	0.1875	I_2	0.66	M_3
$F_{11.3}$	1.4000	0.7000	0.3500	0.1750	P_1	0.66	M_3
$F_{11.4}$	0.5000	0.2500	0.1250	0.0625	O_1	0.66	M_3
$F_{11.5}$	0.5000	0.2500	0.1250	0.0625	I_6	0.66	M_3
$F_{11.6}$	1.2000	0.6000	0.3000	0.1500	P_3	0.66	M_3
$F_{12.1}$	1.8000	0.9000	0.4500	0.2250	I_1	0.66	M_4
$F_{12.2}$	1.5000	0.7500	0.3750	0.1875	I_2	0.66	M_4
$F_{12.3}$	1.4000	0.7000	0.3500	0.1750	P_1	0.66	M_4
$F_{12.4}$	0.5000	0.2500	0.1250	0.0625	O_1	0.66	M_4
$F_{12.5}$	0.5000	0.2500	0.1250	0.0625	I_6	0.66	M_4
$F_{12.6}$	1.4000	0.7000	0.3500	0.1750	P_3	0.66	M_4
$F_{13.1}$	1.5000	0.7500	0.3750	0.1875	I_4	0.90	M_4
$F_{13.2}$	1.5000	0.7500	0.3750	0.1875	I_5	0.90	M_4
$F_{13.3}$	1.0000	0.5000	0.2500	0.1250	P_2	0.66	M_4
$F_{13.4}$	0.5000	0.2500	0.1250	0.0625	O_2	0.66	M_4
$F_{13.5}$	0.5000	0.2500	0.1250	0.0625	I_7	0.66	M_4
$F_{13.6}$	1.4000	0.7000	0.3500	0.1750	P_3	0.66	M_4
F_{14}	1.2000	0.6000	0.3000	0.1500	P_7	0.10	M_4
$F_{15.1}$	0.5000	0.2500	0.1250	0.0625	P_7	0.10	M_4
$F_{15.2}$	0.8000	0.4000	0.2000	0.1000	O_{12}	0.07	M_4
$F_{16.1}$	0.5000	0.2500	0.1250	0.0625	O_4	0.40	M_4
$F_{16.2}$	0.5000	0.2500	0.1250	0.0625	I_8	0.40	M_4
$F_{16.3}$	0.8000	0.4000	0.2000	0.1000	P_4	0.25	M_4
$F_{16.4}$	0.6000	0.3000	0.1500	0.0750	O_8	0.10	M_4
$F_{16.5}$	0.6000	0.3000	0.1500	0.0750	I_{13}	0.10	M_4
F_{17}	1.0000	0.5000	0.2500	0.1250	P_7	0.10	M_5
$F_{18.1}$	0.8000	0.4000	0.2000	0.1000	P_4	0.25	M_5
$F_{18.2}$	1.9000	0.9500	0.4750	0.2375	I_9	0.25	M_5
$F_{18.3}$	0.5000	0.2500	0.1250	0.0625	O_8	0.10	M_5
$F_{18.4}$	0.5000	0.2500	0.1250	0.0625	I_{13}	0.10	M_5
$F_{18.5}$	1.5000	0.7500	0.3750	0.1875	P_7	0.10	M_5

Table 30 WACSS Failure Probability Table

The example Failure Probability Table demonstrated in Table 30 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 5.

Failure ID	**Object ID**	**Execution Prob P_e**	**Conditional Intermittent Failure Prob P_f $x10^{-5}$**	**Conditional Partial Failure Prob P_f $x10^{-5}$**	**Conditional Complete Failure Prob P_f $x10^{-5}$**	**Conditional Cataclysmic Failure Prob P_f $x10^{-5}$**	**Malfunction ID**
F_1	O_3	0.40	1.0000	0.5000	0.2500	0.1250	M_1
F_2	P_3	0.66	1.3200	0.6600	0.3300	0.1650	M_1
F_3	P_5	0.25	0.2000	0.1000	0.0500	0.0250	M_2
$F_{4.1}$	I_2	0.66	0.9900	0.4950	0.2475	0.1238	M_2
$F_{4.2}$	P_1	0.66	0.6600	0.3300	0.1650	0.0825	M_2
$F_{4.3}$	O_1	0.66	0.3300	0.1650	0.0825	0.0413	M_2
$F_{4.4}$	I_6	0.25	0.1250	0.0625	0.0313	0.0156	M_2
$F_{4.5}$	P_3	0.66	0.7920	0.3960	0.1980	0.0990	M_2
$F_{5.1}$	I_1	0.66	1.1880	0.5940	0.2970	0.1485	M_2
$F_{5.2}$	P_1	0.66	0.6600	0.3300	0.1650	0.0825	M_2
$F_{5.3}$	O_1	0.66	0.3300	0.1650	0.0825	0.0413	M_2
$F_{5.4}$	I_6	0.25	0.1250	0.0625	0.0313	0.0156	M_2
$F_{5.5}$	P_3	0.66	0.7920	0.3960	0.1980	0.0990	M_2
$F_{6.1}$	O_4	0.40	0.2000	0.1000	0.0500	0.0250	M_2
$F_{6.2}$	I_8	0.40	0.2000	0.1000	0.0500	0.0250	M_2
$F_{6.3}$	P_4	0.25	0.1250	0.0625	0.0313	0.0156	M_2
$F_{6.4}$	O_6	0.25	0.1250	0.0625	0.0313	0.0156	M_2
$F_{6.5}$	I_{11}	0.25	0.1250	0.0625	0.0313	0.0156	M_2
$F_{6.6}$	O_5	0.10	0.0500	0.0250	0.0125	0.0063	M_2
$F_{6.7}$	I_{10}	0.10	0.0500	0.0250	0.0125	0.0063	M_2
F_7	O_{10}	0.10	0.0800	0.0400	0.0200	0.0100	M_2
F_8	P_5	0.25	0.2500	0.1250	0.0625	0.0313	M_3
F_9	O_{10}	0.10	0.0800	0.0400	0.0200	0.0100	M_3
F_{10}	P_7	0.10	0.1200	0.0600	0.0300	0.0150	M_3
$F_{11.1}$	I_1	0.66	1.1880	0.5940	0.2970	0.1485	M_3
$F_{11.2}$	I_2	0.66	0.9900	0.4950	0.2475	0.1238	M_3
$F_{11.3}$	P_1	0.66	0.9240	0.4620	0.2310	0.1155	M_3
$F_{11.4}$	O_1	0.66	0.3300	0.1650	0.0825	0.0413	M_3
$F_{11.5}$	I_6	0.66	0.3300	0.1650	0.0825	0.0413	M_3
$F_{11.6}$	P_3	0.66	0.7920	0.3960	0.1980	0.0990	M_3
$F_{12.1}$	I_1	0.66	1.1880	0.5940	0.2970	0.1485	M_4
$F_{12.2}$	I_2	0.66	0.9900	0.4950	0.2475	0.1238	M_4
$F_{12.3}$	P_1	0.66	0.9240	0.4620	0.2310	0.1155	M_4
$F_{12.4}$	O_1	0.66	0.3300	0.1650	0.0825	0.0413	M_4
$F_{12.5}$	I_6	0.66	0.3300	0.1650	0.0825	0.0413	M_4
$F_{12.6}$	P_3	0.66	0.9240	0.4620	0.2310	0.1155	M_4
$F_{13.1}$	I_4	0.90	1.3500	0.6750	0.3375	0.1688	M_4
$F_{13.2}$	I_5	0.90	1.3500	0.6750	0.3375	0.1688	M_4
$F_{13.3}$	P_2	0.66	0.6600	0.3300	0.1650	0.0825	M_4
$F_{13.4}$	O_2	0.66	0.3300	0.1650	0.0825	0.0413	M_4
$F_{13.5}$	I_7	0.66	0.3300	0.1650	0.0825	0.0413	M_4
$F_{13.6}$	P_3	0.66	0.9240	0.4620	0.2310	0.1155	M_4
F_{14}	P_7	0.10	0.1200	0.0600	0.0300	0.0150	M_4
$F_{15.1}$	P_7	0.10	0.0500	0.0250	0.0125	0.0063	M_4
$F_{15.2}$	O_{12}	0.07	0.0560	0.0280	0.0140	0.0070	M_4
$F_{16.1}$	O_4	0.40	0.2000	0.1000	0.0500	0.0250	M_4
$F_{16.2}$	I_8	0.40	0.2000	0.1000	0.0500	0.0250	M_4
$F_{16.3}$	P_4	0.25	0.2000	0.1000	0.0500	0.0250	M_4
$F_{16.4}$	O_8	0.10	0.0600	0.0300	0.0150	0.0075	M_4
$F_{16.5}$	I_{13}	0.10	0.0600	0.0300	0.0150	0.0075	M_4
F_{17}	P_7	0.10	0.1000	0.0500	0.0250	0.0125	M_5
$F_{18.1}$	P_4	0.25	0.2000	0.1000	0.0500	0.0250	M_5
$F_{18.2}$	I_9	0.25	0.4750	0.2375	0.1188	0.0594	M_5
$F_{18.3}$	O_8	0.10	0.0500	0.0250	0.0125	0.0063	M_5
$F_{18.4}$	I_{13}	0.10	0.0500	0.0250	0.0125	0.0063	M_5
$F_{18.5}$	P_7	0.10	0.1500	0.0750	0.0375	0.0188	M_5

Table 31 WACSS Conditional Failure Probability Table

The example Conditional Failure Probability demonstrated in Table 31 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 4.

8. SYSTEM HAZARD FLOW AND PROBABILITY

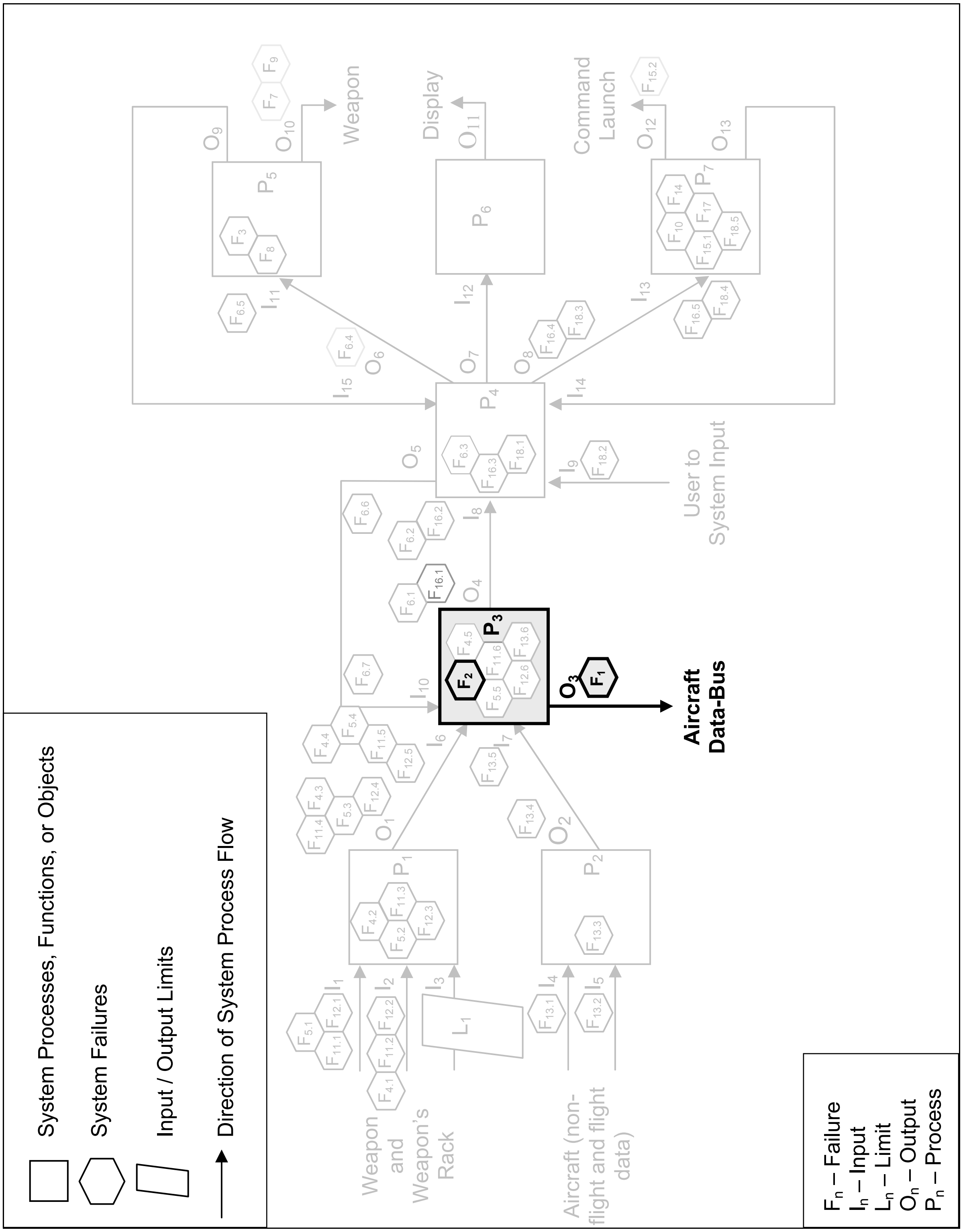

Figure 24 WACSS M_1 Malfunction Process Flow

M_1 – Single Incompatibility / feedback to the Aircraft Data–Bus

Case 1:

Failure (F_1) of Output 3 (O_3), resulting in a failure of the Aircraft Data–Bus and Malfunction 1 (M_1)

$F_1 \wedge O_3 \rightarrow M_1$

Assume:

$P_e\ O_3$	0.40
$P_{f\ Intermittent}\ F_1$	$2.5000\text{x}10^{-5}$
$P_{f\ Partial}\ F_1$	$1.2500\text{x}10^{-5}$
$P_{f\ Complete}\ F_1$	$0.6250\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_1$	$0.3125\text{x}10^{-5}$

Intermittent $(2.5000\text{x}10^{-5} * 0.40) = 1.0000\text{x}10^{-5} \therefore$

Partial $(1.2500\text{x}10^{-5} * .40) = 0.5000\text{x}10^{-5} \therefore$

Complete $(0.6250\text{x}10^{-5} * .40) = 0.2500\text{x}10^{-5} \therefore$

Cataclysmic $(0.3125\text{x}10^{-5} * .40) = 0.1250\text{x}10^{-5} \therefore$

There is a $1.0000\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.5000\text{x}10^{-5}$ probability of a partial failure, $0.2500\text{x}10^{-5}$ probability of complete failure, and a $0.1250\text{x}10^{-5}$ probability of a cataclysmic failure during the output operation of O_3, generating a signal incompatibility or feedback error to the Aircraft Data–Bus.

Case 2:

Failure (F_2) of Process 3 (P_3), through to O_3, resulting in a failure of the Aircraft Data–Bus and Malfunction 1 (M_1)

$F_2 \wedge P_3\ \{[O_3]\} \rightarrow M_1$

Assume:

$P_e\ P_3$	0.66
$P_e\ O_3 \cup P_3$	0.95
$P_{f\ Intermittent}\ F_2$	$2.0000\text{x}10^{-5}$
$P_{f\ Partial}\ F_2$	$1.0000\text{x}10^{-5}$
$P_{f\ Complete}\ F_2$	$0.5000\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_2$	$0.2500\text{x}10^{-5}$

Intermittent $(2.0000\text{x}10^{-5} * 0.66) * (0.95) = 1.2540\text{x}10^{-5} \therefore$

Partial $(1.0000\text{x}10^{-5} * .66) * (0.95) = 0.6270\text{x}10^{-5}$ ∴

Complete $(0.5000\text{x}10^{-5} * .66) * (0.95) = 0.3135\text{x}10^{-5}$ ∴

Cataclysmic $(0.2500\text{x}10^{-5} * .66) * (0.95) = 0.1568\text{x}10^{-5}$ ∴

There is a $1.2540\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.6270\text{x}10^{-5}$ probability of a partial failure, a $0.3135\text{x}10^{-5}$ probability of complete failure, and a $0.1568\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of P_3, generating a signal incompatibility or feedback error to the Aircraft Data–Bus.

Summary:

Failure in Case 1 or Failure in Case 2, resulting in a failure of the Aircraft Data–Bus and Malfunction 1 (M_1)

$P_{M1} = \{P_{Case\ 1}\ or\ P_{Case\ 2}\}$
Intermittent $P_{M1} = 1.0000\text{x}10^{-5} + 1.2540\text{x}10^{-5} = 2.2540\text{x}10^{-5}$
Partial $P_{M1} = 0.5000\text{x}10^{-5} + 0.6270\text{x}10^{-5} = 1.1270\text{x}10^{-5}$
Complete $P_{M1} = 0.2500\text{x}10^{-5} + 0.3135\text{x}10^{-5} = 0.5635\text{x}10^{-5}$
Cataclysmic $P_{M1} = 0.1250\text{x}10^{-5} + 0.1568\text{x}10^{-5} = 0.2818\text{x}10^{-5}$

$P_{M1\ Total} = P_{M1\ Intermittent} + P_{M1\ Partial} + P_{M1\ Complete} + P_{M1\ Cataclysmic}$

$P_{M1\ Total} = 2.2540\text{x}10^{-5} + 1.1270\text{x}10^{-5} + 0.5635\text{x}10^{-5} + 0.2818\text{x}10^{-5}$
$P_{M1\ Total} = 4.2263\text{x}10^{-5}$

There is a $4.2263\text{x}10^{-5}$ probability that the WACSS will experience a safety–related malfunction and hazardous event during system operation, associated with a signal incompatibility or feedback error to the Aircraft Data–Bus.

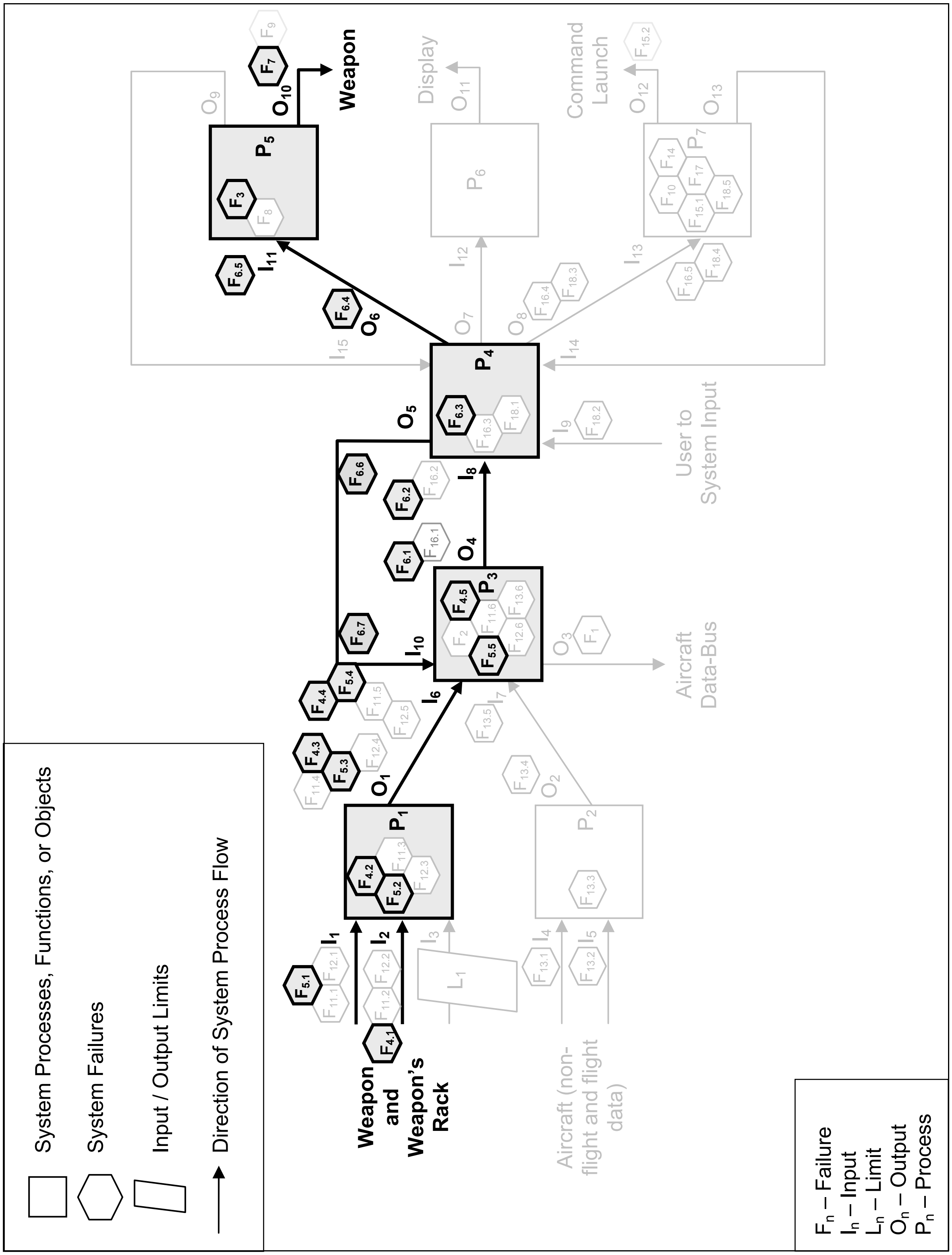

Figure 25 WACSS M_2 Malfunction Process Flow

M_2 – Weapon fusing to detonate too early after weapon's release

Case 1:

Failure (F_3) of Process 5 (P_5), through O_{10}, resulting in a failure of weapon fusing and Malfunction 2 (M_2)

F_3^P_5 {[O_{10}]} → M_2

Assume:

P_e P_5	0.25
P_e $O_{10} \cup P_5$	0.95
$P_{f\ Intermittent}$ F_3	$0.8000\text{x}10^{-5}$
$P_{f\ Partial}$ F_3	$0.4000\text{x}10^{-5}$
$P_{f\ Complete}$ F_3	$0.2000\text{x}10^{-5}$
$P_{f\ Cataclysmic}$ F_3	$0.1000\text{x}10^{-5}$

Intermittent ($0.8000\text{x}10^{-5}$ * 0.25) * (0.95) = $0.1900\text{x}10^{-5}$ $\therefore$

Partial ($0.4000\text{x}10^{-5}$ * .25) * (0.95) = $0.0950\text{x}10^{-5}$ $\therefore$

Complete ($0.2000\text{x}10^{-5}$ * .25) * (0.95) = $0.0475\text{x}10^{-5}$ $\therefore$

Cataclysmic ($0.1000\text{x}10^{-5}$ * .25) * (0.95) = $0.0238\text{x}10^{-5}$ $\therefore$

There is a $0.1900\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0950\text{x}10^{-5}$ probability of a partial failure, $0.0475\text{x}10^{-5}$ probability of complete failure, and a $0.0238\text{x}10^{-5}$ probability of a cataclysmic failure during the output operation of P_5 (The Weapon Configuration Change Processor), causing the weapon to fuse and detonate too early after weapon release

Case 2:

Failure ($F_{4.1}$) of Input 2 (I_2), and/or Failure ($F_{4.2}$) of Process 1 (P_1), and/or Failure ($F_{4.3}$) of Output 1 (O_1), and/or Failure ($F_{4.4}$) of Input 6 (I_6), and/or Failure ($F_{4.5}$) of Process 3 (P_3), through to O_4, I_8, P_4, O_6, I_{11}, P_5, and O_{10}, resulting in a failure of weapon fusing and Malfunction 2 (M_2)

($F_{4.1}$^I_2 {[P_1, O_1, I_6, P_3]} or $F_{4.2}$^P_1 {[O_1, I_6, P_3]} or $F_{4.3}$^O_1 {[I_6, P_3]} or $F_{4.4}$^I_6 {[P_3]} or $F_{4.5}$^P_3) {[O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}]} → M_2

Assume:

$P_e\ I_2$	0.66
$P_e\ P_1$	0.66
$P_e\ O_1$	0.66
$P_e\ I_6$	0.25
$P_e\ P_3$	0.66
$\sum P_e\ \{O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}\} \cup (I_2, P_1, O_1, I_6, P_3)$	0.6983
$\sum P_e\ \{P_1, O_1, I_6, P_3\} \cup I_2$	0.8145
$\sum P_e\ \{O_1, I_6, P_3\} \cup P_1$	0.8574
$\sum P_e\ \{I_6, P_3\} \cup O_1$	0.9025
$P_e\ P_3 \cup I_6$	0.95
$P_{f\ Intermittent}\ F_{4.1}$	1.5000x10^{-5}
$P_{f\ Partial}\ F_{4.1}$	0.7500x10^{-5}
$P_{f\ Complete}\ F_{4.1}$	0.3750x10^{-5}
$P_{f\ Cataclysmic}\ F_{4.1}$	0.1875x10^{-5}
$P_{f\ Intermittent}\ F_{4.2}$	1.0000x10^{-5}
$P_{f\ Partial}\ F_{4.2}$	0.5000x10^{-5}
$P_{f\ Complete}\ F_{4.2}$	0.2500x10^{-5}
$P_{f\ Cataclysmic}\ F_{4.2}$	0.1250x10^{-5}
$P_{f\ Intermittent}\ F_{4.3}$	0.5000x10^{-5}
$P_{f\ Partial}\ F_{4.3}$	0.2500x10^{-5}
$P_{f\ Complete}\ F_{4.3}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}\ F_{4.3}$	0.0625x10^{-5}
$P_{f\ Intermittent}\ F_{4.4}$	0.5000x10^{-5}
$P_{f\ Partial}\ F_{4.4}$	0.2500x10^{-5}
$P_{f\ Complete}\ F_{4.4}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}\ F_{4.4}$	0.0625x10^{-5}
$P_{f\ Intermittent}\ F_{4.5}$	1.2000x10^{-5}
$P_{f\ Partial}\ F_{4.5}$	0.6000x10^{-5}
$P_{f\ Complete}\ F_{4.5}$	0.3000x10^{-5}
$P_{f\ Cataclysmic}\ F_{4.5}$	0.1500x10^{-5}

Intermittent (((1.5000x10^{-5} * 0.66) * (0.8145)) + ((1.0000x10^{-5} * 0.66) * (0.8574)) + ((0.5000x10^{-5} * 0.66) * (0.9025)) + ((0.5000x10^{-5} * 0.25) * (0.95)) + (1.2000x10^{-5} * 0.66)) * (0.6983) =

(0.8064x10^{-5} + 0.5659x10^{-5} + 0.2978x10^{-5} + 0.1188x10^{-5} + 0.7920x10^{-5}) * (0.6983) = 1.8022x10^{-5} ∴

Partial (((0.7500x10^{-5} * 0.66) * (0.8145)) + ((0.5000x10^{-5} * 0.66) * (0.8574)) + ((0.2500x10^{-5} * 0.66) * (0.9025)) + ((0.2500x10^{-5} * 0.25) * (0.95)) + (0.6000x10^{-5} * 0.66)) * (0.6983) =

(0.4032x10^{-5} + 0.2821x10^{-5} + 0.1489x10^{-5} + 0.0594x10^{-5} + 0.3960x10^{-5}) * (0.6983) = 0.9005x10^{-5} ∴

Complete (((0.3750x10^{-5} * 0.66) * (0.8145)) + ((0.2500x10^{-5} * 0.66) * (0.8574)) + ((0.1250x10^{-5} * 0.66) * (0.9025)) + ((0.1250x10^{-5} * 0.25) * (0.95)) + (0.3000x10^{-5} * 0.66)) * (0.6983) =

(0.2016x10^{-5} + 0.1415x10^{-5} + 0.0745x10^{-5} + 0.0297x10^{-5} + 0.1980x10^{-5}) * (0.6983) = 0.4506x10^{-5} ∴

Cataclysmic (((0.1875x10^{-5} * 0.66) * (0.8145)) + ((0.1250x10^{-5} * 0.66) * (0.8574)) + ((0.0625x10^{-5} * 0.66) * (0.9025)) + ((0.0625x10^{-5} * 0.25) * (0.95)) + (0.1500x10^{-5} * 0.66)) * (0.6983) =

(0.1008x10^{-5} + 0.0707x10^{-5} + 0.0372x10^{-5} + 0.0148x10^{-5} + 0.0990x10^{-5}) * (0.6983) = 0.2252x10^{-5} ∴

There is a $1.8022x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.9005x10^{-5}$ probability of a partial failure, a $0.4506x10^{-5}$ probability of complete failure, and a $0.2252x10^{-5}$ probability of a cataclysmic failure during the operation of I_2, P_1, O_1, I_6, and/or P_3 as a failure in the weapon's signals regarding the current status of the weapon, causing the weapon to fuse and detonate too early after weapon release

Case 3:

Failure ($F_{5.1}$) of Input 1 (I_1), and/or Failure ($F_{5.2}$) of Process 1 (P_1), and/or Failure ($F_{5.3}$) of Output 1 (O_1), and/or Failure ($F_{5.4}$) of Input 6 (I_6), and/or Failure ($F_{5.5}$) of Process 3 (P_3), through to O_4, I_8, P_4, O_6, I_{11}, P_5, and O_{10}, resulting in a failure of weapon fusing and Malfunction 2 (M_2)

$(F_{5.1}\hat{}I_1 \{[P_1, O_1, I_6, P_3]\}$ or $F_{5.2}\hat{}P_1 \{[O_1, I_6, P_3]\}$ or $F_{5.3}\hat{}O_1 \{[I_6, P_3]\}$ or $F_{5.4}\hat{}I_6 \{[P_3]\}$ or $F_{5.5}\hat{}P_3) \{[O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}]\} \rightarrow M_2$

Assume:

P_e I_1	0.66	$P_{f\ Partial}$ $F_{5.2}$	$0.5000x10^{-5}$
P_e P_1	0.66	$P_{f\ Complete}$ $F_{5.2}$	$0.2500x10^{-5}$
P_e O_1	0.66	$P_{f\ Cataclysmic}$ $F_{5.2}$	$0.1250x10^{-5}$
P_e I_6	0.25	$P_{f\ Intermittent}$ $F_{5.3}$	$0.5000x10^{-5}$
P_e P_3	0.66	$P_{f\ Partial}$ $F_{5.3}$	$0.2500x10^{-5}$
$\sum P_e$ $\{O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}\} \cup (I_1, P_1, O_1, I_6, P_3)$	0.6983	$P_{f\ Complete}$ $F_{5.3}$	$0.1250x10^{-5}$
$\sum P_e$ $\{P_1, O_1, I_6, P_3\} \cup I_2$	0.8145	$P_{f\ Cataclysmic}$ $F_{5.3}$	$0.0625x10^{-5}$
$\sum P_e$ $\{O_1, I_6, P_3\} \cup P_1$	0.8574	$P_{f\ Intermittent}$ $F_{5.4}$	$0.5000x10^{-5}$
$\sum P_e$ $\{I_6, P_3\} \cup O_1$	0.9025	$P_{f\ Partial}$ $F_{5.4}$	$0.2500x10^{-5}$
P_e $P_3 \cup I_6$	0.95	$P_{f\ Complete}$ $F_{5.4}$	$0.1250x10^{-5}$
$P_{f\ Intermittent}$ $F_{5.1}$	$1.5000x10^{-5}$	$P_{f\ Cataclysmic}$ $F_{5.4}$	$0.0625x10^{-5}$
$P_{f\ Partial}$ $F_{5.1}$	$0.7500x10^{-5}$	$P_{f\ Intermittent}$ $F_{5.5}$	$1.2000x10^{-5}$
$P_{f\ Complete}$ $F_{5.1}$	$0.3750x10^{-5}$	$P_{f\ Partial}$ $F_{5.5}$	$0.6000x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{5.1}$	$0.1875x10^{-5}$	$P_{f\ Complete}$ $F_{5.5}$	$0.3000x10^{-5}$
$P_{f\ Intermittent}$ $F_{5.2}$	$1.0000x10^{-5}$	$P_{f\ Cataclysmic}$ $F_{5.5}$	$0.1500x10^{-5}$

Intermittent $(((1.5000x10^{-5} * 0.66) * (0.8145)) + ((1.0000x10^{-5} * 0.66) * (0.8574)) + ((0.5000x10^{-5} * 0.66) * (0.9025)) + ((0.5000x10^{-5} * 0.25) * (0.95)) + (1.2000x10^{-5} * 0.66)) * (0.6983) =$

$(0.8064x10^{-5} + 0.5659x10^{-5} + 0.2978x10^{-5} + 0.1188x10^{-5} + 0.7920x10^{-5}) * (0.6983) = 1.8022x10^{-5}$ ∴

Partial $(((0.7500x10^{-5} * 0.66) * (0.8145)) + ((0.5000x10^{-5} * 0.66) * (0.8574)) + ((0.2500x10^{-5} * 0.66) * (0.9025)) + ((0.2500x10^{-5} * 0.25) * (0.95)) + (0.6000x10^{-5} * 0.66)) * (0.6983) =$

$(0.4032x10^{-5} + 0.2821x10^{-5} + 0.1489x10^{-5} + 0.0594x10^{-5} + 0.3960x10^{-5}) * (0.6983) = 0.9005x10^{-5} \therefore$

Complete $(((0.3750x10^{-5} * 0.66) * (0.8145)) + ((0.2500x10^{-5} * 0.66) * (0.8574)) + ((0.1250x10^{-5} * 0.66) * (0.9025)) + ((0.1250x10^{-5} * 0.25) * (0.95)) + (0.3000x10^{-5} * 0.66)) * (0.6983) =$

$(0.2016x10^{-5} + 0.1415x10^{-5} + 0.0745x10^{-5} + 0.0297x10^{-5} + 0.1980x10^{-5}) * (0.6983) = 0.4506x10^{-5} \therefore$

Cataclysmic $(((0.1875x10^{-5} * 0.66) * (0.8145)) + ((0.1250x10^{-5} * 0.66) * (0.8574)) + ((0.0625x10^{-5} * 0.66) * (0.9025)) + ((0.0625x10^{-5} * 0.25) * (0.95)) + (0.1500x10^{-5} * 0.66)) * (0.6983) =$

$(0.1008x10^{-5} + 0.0707x10^{-5} + 0.0372x10^{-5} + 0.0148x10^{-5} + 0.0990x10^{-5}) * (0.6983) = 0.2252x10^{-5} \therefore$

There is a $1.8022x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.9005x10^{-5}$ probability of a partial failure, a $0.4506x10^{-5}$ probability of complete failure, and a $0.2252x10^{-5}$ probability of a cataclysmic failure during the operation of I_1, P_1, O_1, I_6, and/or P_3 as a failure in the weapon's signals regarding the configuration of the weapon, causing the weapon to fuse and detonate too early after weapon release

Case 4:

Failure ($F_{6.1}$) of Output 4 (O_4), and/or Failure ($F_{6.2}$) of Input 8 (I_8), and/or Failure ($F_{6.3}$) of Process 4 (P_4), and/or Failure ($F_{6.4}$) of Output 6 (O_6), and/or Failure ($F_{6.5}$) of Input 11 (I_{11}), through to P_5, and O_{10}, resulting in a failure of weapon fusing and Malfunction 2 (M_2)

$(F_{6.1}\hat{}O_4 \{[I_8, P_4, O_6, I_{11}]\}$ or $F_{6.2}\hat{}I_8 \{[P_4, O_6, I_{11}]\}$ or $F_{6.3}\hat{}P_4 \{[O_6, I_{11}]\}$ or $F_{6.4}\hat{}O_6 \{[I_{11}]\}$ or $F_{6.5}\hat{}I_{11}) \{[P_5, O_{10}]\} \rightarrow M_2$

Note P_4 includes the Loop Process Flow from O_5 through I_{10} and back into P_3, triggered by failure type 6. For the purpose of this example, it shall be assumed that the loop cycle shall occur 100 times during the examination period.

Assume:

P_e O_4	0.40
P_e I_8	0.40
P_e P_4	0.25
P_e O_6	0.25
P_e I_{11}	0.25
$\sum P_e$ $\{O_5, I_{10}\}$ Loop Case	0.10
$\sum P_e$ $\{P_5, O_{10}\} \cup (O_4, I_8, P_4, O_6, I_{11})$	0.9025
$\sum P_e$ $\{I_8, P_4, O_6, I_{11}\} \cup O_4$	0.8145
$\sum P_e$ $\{P_4, O_6, I_{11}\} \cup I_8$	0.8574
$\sum P_e$ $\{O_6, I_{11}\} \cup P_4$	0.9025
P_e $I_{11} \cup O_6$	0.95
$P_{f\ Intermittent}$ $F_{6.1}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.1}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.1}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.1}$	$0.0625x10^{-5}$
$P_{f\ Intermittent}$ $F_{6.2}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.2}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.2}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.2}$	$0.0625x10^{-5}$

$P_{f\ Intermittent}$ $F_{6.3}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.3}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.3}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.3}$	$0.0625x10^{-5}$
$P_{f\ Intermittent}$ $F_{6.4}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.4}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.4}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.4}$	$0.0625x10^{-5}$
$P_{f\ Intermittent}$ $F_{6.5}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.5}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.5}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.5}$	$0.0625x10^{-5}$
$P_{f\ Intermittent}$ $F_{6.6}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.6}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.6}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.6}$	$0.0625x10^{-5}$
$P_{f\ Intermittent}$ $F_{6.7}$	$0.5000x10^{-5}$
$P_{f\ Partial}$ $F_{6.7}$	$0.2500x10^{-5}$
$P_{f\ Complete}$ $F_{6.7}$	$0.1250x10^{-5}$
$P_{f\ Cataclysmic}$ $F_{6.7}$	$0.0625x10^{-5}$

$Loop\ Case_{\ Intermittent} = 1 - (1 - ((0.5000x10^{-5} * 0.10) + (0.5000x10^{-5} * 0.10)))^{100} =$
$1.0000 \text{ x } 10^{-5}$

$Loop\ Case_{\ Partial} = 1 - (1 - ((0.5000x10^{-5} * 0.10) + (0.5000x10^{-5} * 0.10)))^{100} =$
$0.5000 \text{ x } 10^{-5}$

$Loop\ Case_{\ Complete} = 1 - (1 - ((0.5000x10^{-5} * 0.10) + (0.5000x10^{-5} * 0.10)))^{100} =$
$0.2500 \text{ x } 10^{-5}$

$Loop\ Case_{\ Cataclysmic} = 1 - (1 - ((0.5000x10^{-5} * 0.10) + (0.5000x10^{-5} * 0.10)))^{100} =$
$0.1250 \text{ x } 10^{-5}$

Intermittent $(((0.5000x10^{-5} * 0.40) * (0.8145)) + ((0.5000x10^{-5} * 0.40) * (0.8574)) + ((0.5000x10^{-5} * 0.25) * (0.9025)) + ((0.5000x10^{-5} * 0.25) * (0.95)) + (0.5000x10^{-5} * 0.25)) * (0.9025) + 1.0000 \text{ x } 10^{-5} =$

$(0.1629x10^{-5} + 0.1715x10^{-5} + 0.1128x10^{-5} + 0.1188x10^{-5} + 0.1250x10^{-5}) * (0.9025) = 1.6236x10^{-5}$ ∴

Partial $(((0.2500x10^{-5} * 0.40) * (0.8145)) + ((0.2500x10^{-5} * 0.40) * (0.8574)) + ((0.2500x10^{-5} * 0.25) * (0.9025)) + ((0.2500x10^{-5} * 0.25) * (0.95)) + (0.2500x10^{-5} * 0.25)) * (0.9025) + 0.5000 \text{ x } 10^{-5} =$

$(0.0815\text{x}10^{-5} + 0.0857\text{x}10^{-5} + 0.0564\text{x}10^{-5} + 0.0594\text{x}10^{-5} + 0.0625\text{x}10^{-5}) * (0.9025) = 0.8118\text{x}10^{-5} \therefore$

Complete $(((0.1250\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.1250\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.1250\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.1250\text{x}10^{-5} * 0.25) * (0.95)) + (0.1250\text{x}10^{-5} * 0.25)) * (0.9025) + 0.2500 \text{ x } 10^{-5}=$

$(0.0407\text{x}10^{-5} + 0.0429\text{x}10^{-5} + 0.0282\text{x}10^{-5} + 0.0297\text{x}10^{-5} + 0.0313\text{x}10^{-5}) * (0.9025) = 0.4060\text{x}10^{-5} \therefore$

Cataclysmic $(((0.0625\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.0625\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.0625\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.0625\text{x}10^{-5} * 0.25) * (0.95)) + (0.0625\text{x}10^{-5} * 0.25)) * (0.9025) + 0.1250 \text{ x } 10^{-5}=$

$(0.0204\text{x}10^{-5} + 0.0214\text{x}10^{-5} + 0.0141\text{x}10^{-5} + 0.0148\text{x}10^{-5} + 0.0156\text{x}10^{-5}) * (0.9025) = 0.2029\text{x}10^{-5} \therefore$

There is a $1.6236\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.8118\text{x}10^{-5}$ probability of a partial failure, a $0.4060\text{x}10^{-5}$ probability of complete failure, and a $0.2029\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of O_4, I_8, P_4, O_6, and/or I_{11} as a failure in system data signals transfer, causing the weapon to fuse and detonate too early after weapon release

Case 5:

Failure (F_7) of Output 10 (O_{10}) resulting in a failure of weapon fusing and Malfunction 2 (M_2)

F_7^$O_{10} \rightarrow M_2$

Assume:

$P_e\, O_{10}$	0.10
$P_{f\ Intermittent}\, F_7$	$0.8000\text{x}10^{-5}$
$P_{f\ Partial}\, F_7$	$0.4000\text{x}10^{-5}$
$P_{f\ Complete}\, F_7$	$0.2000\text{x}10^{-5}$
$P_{f\ Cataclysmic}\, F_7$	$0.1000\text{x}10^{-5}$

Intermittent $(0.8000\text{x}10^{-5} * 0.10) = 0.0800\text{x}10^{-5} \therefore$

Partial $(0.4000\text{x}10^{-5} * 0.10) = 0.0400\text{x}10^{-5} \therefore$

Complete $(0.2000\text{x}10^{-5} * 0.10) = 0.0200\text{x}10^{-5} \therefore$

Cataclysmic $(0.1000\text{x}10^{-5} * 0.10) = 0.0100\text{x}10^{-5} \therefore$

There is a $0.0800\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0400\text{x}10^{-5}$ probability of a partial failure, a $0.0200\text{x}10^{-5}$ probability of complete failure, and a $0.0100\text{x}10^{-5}$ probability of a cataclysmic failure during the output operation of O_{10} as a failure / incompatibility in Weapon's configuration signals, causing the weapon to fuse and detonate too early after weapon release

Summary:

Failure in Case 1, Case 2, Case 3, Case 4, or Case 5, resulting in the weapon fusing to detonate too early after weapon's release and Malfunction 2 (M_2)

$P_{M2} = \{P_{Case\ 1}$ or $P_{Case\ 2}$ or $P_{Case\ 3}$ or $P_{Case\ 4}$ or $P_{Case\ 5}\}$

Intermittent $P_{M2} = 0.1900\text{x}10^{-5} + 1.8022\text{x}10^{-5} + 1.8022\text{x}10^{-5} + 1.6236\text{x}10^{-5}\ 0.0800\text{x}10^{-5} = 5.4980\text{x}10^{-5}$
Partial $P_{M2} = 0.0950\text{x}10^{-5} + 0.9055\text{x}10^{-5} + 0.9055\text{x}10^{-5} + 0.5118\text{x}10^{-5} + 0.0400\text{x}10^{-5} = 2.7578\text{x}10^{-5}$
Complete $P_{M2} = 0.0475\text{x}10^{-5} + 0.4506\text{x}10^{-5} + 0.4506\text{x}10^{-5} + 0.4060\text{x}10^{-5} + 0.0200\text{x}10^{-5} = 1.3847\text{x}10^{-5}$
Cataclysmic $P_{M2} = 0.0238\text{x}10^{-5} + 0.2252\text{x}10^{-5} + 0.2252\text{x}10^{-5} + 0.2029\text{x}10^{-5} + 0.0100\text{x}10^{-5} = 0.6871\text{x}10^{-5}$

$P_{M2\ Total} = P_{M2\ Intermittent} + P_{M2\ Partial} + P_{M2\ Complete} + P_{M2\ Cataclysmic}$

$P_{M2\ Total} = 5.4980\text{x}10^{-5} + 2.7578\text{x}10^{-5} + 1.3847\text{x}10^{-5} + 0.6871\text{x}10^{-5}$
$P_{M2\ Total} = 10.3276\text{x}10^{-5}$

There is an $10.3276\text{x}10^{-5}$ probability that the WACSS will experience a safety–related malfunction and hazardous event during system operation, causing the weapon to fuse and detonate too early after weapon release

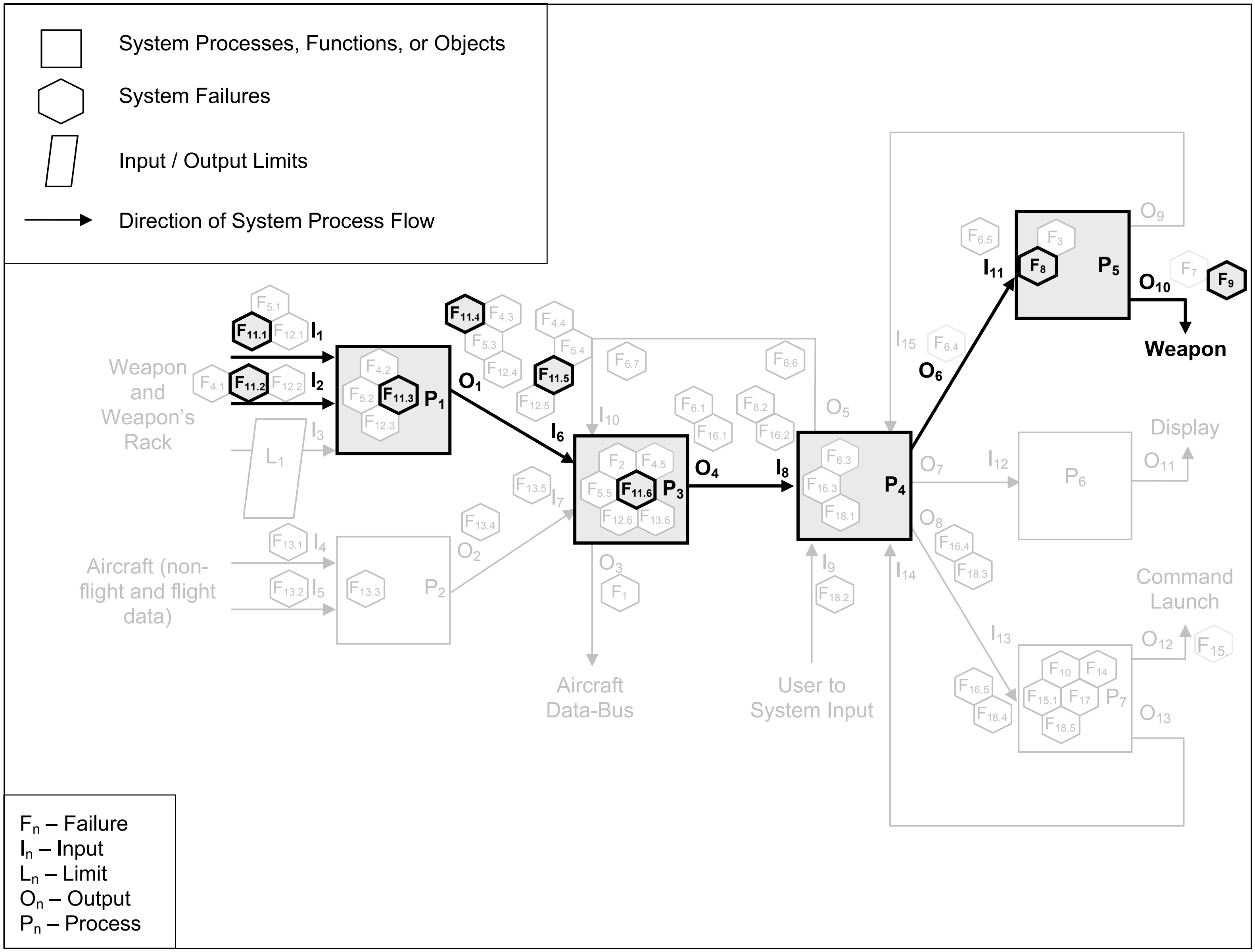

Figure 26 WACSS M_3 Malfunction Process Flow

M_3 – Inability to fuse weapon – Dead Fuse

Case 1:

Failure (F_8) of Process 5 (P_5), through O_{10}, resulting in an inability to fuse the weapon – Dead Fuse, and Malfunction 3 (M_3)

F_8^P_5 {[O_{10}]} → M_3

Assume:

P_e P_5	0.25
P_e $O_{10} \cup P_5$	0.95
$P_{f\ Intermittent}$ F_8	$1.0000\text{x}10^{-5}$
$P_{f\ Partial}$ F_8	$0.5000\text{x}10^{-5}$
$P_{f\ Complete}$ F_8	$0.2500\text{x}10^{-5}$
$P_{f\ Cataclysmic}$ F_8	$0.1250\text{x}10^{-5}$

Intermittent $(1.0000\text{x}10^{-5} * 0.25) * (0.95) = 0.2375\text{x}10^{-5}$ $\therefore$

Partial $(0.5000\text{x}10^{-5} * .25) * (0.95) = 0.1188\text{x}10^{-5}$ $\therefore$

Complete $(0.2500\text{x}10^{-5} * .25) * (0.95) = 0.0594\text{x}10^{-5}$ $\therefore$

Cataclysmic $(0.1250\text{x}10^{-5} * .25) * (0.95) = 0.0297\text{x}10^{-5}$ $\therefore$

There is a $0.2375\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.1188\text{x}10^{-5}$ probability of a partial failure, $0.0594\text{x}10^{-5}$ probability of complete failure, and a $0.0297\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of P_5 (The Weapon Configuration Change Processor), resulting in an inability to fuse the weapon – Dead Fuse

Case 2:

Failure (F_9) of Output 10 (O_{10}) resulting in an inability to fuse the weapon – Dead Fuse, and Malfunction 3 (M_3)

F_9^O_{10} → M_3

Assume:

P_e O_{10}	0.10
$P_{f\ Intermittent}$ F_9	$0.8000\text{x}10^{-5}$
$P_{f\ Partial}$ F_9	$0.4000\text{x}10^{-5}$
$P_{f\ Complete}$ F_9	$0.2000\text{x}10^{-5}$
$P_{f\ Cataclysmic}$ F_9	$0.1000\text{x}10^{-5}$

Intermittent ($0.8000x10^{-5}$ * 0.10) = $0.0800x10^{-5}$ $\therefore$

Partial ($0.4000x10^{-5}$ * .10) = $0.0400x10^{-5}$ $\therefore$

Complete ($0.2000x10^{-5}$ * .10) = $0.0200x10^{-5}$ $\therefore$

Cataclysmic ($0.1000x10^{-5}$ * .10) = $0.0100x10^{-5}$ $\therefore$

There is a $0.0800x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0400x10^{-5}$ probability of a partial failure, $0.0200x10^{-5}$ probability of complete failure, and a $0.0100x10^{-5}$ probability of a cataclysmic failure during the output operation of O_{10}, resulting in an inability to fuse the weapon – Dead Fuse

Case 3:

Failure (F_{10}) of Process 7 (P_7) resulting in an inability to fuse the weapon – Dead Fuse, and Malfunction 3 (M_3)

F_{10}^$P_7 \rightarrow M_3$

Assume:

P_e P_7	0.10
$P_{f\ Intermittent}$ F_{10}	$1.2000x10^{-5}$
$P_{f\ Partial}$ F_{10}	$0.6000x10^{-5}$
$P_{f\ Complete}$ F_{10}	$0.3000x10^{-5}$
$P_{f\ Cataclysmic}$ F_{10}	$0.1500x10^{-5}$

Intermittent ($1.2000x10^{-5}$ * 0.10) = $0.1200x10^{-5}$ $\therefore$

Partial ($0.6000x10^{-5}$ * .10) = $0.0600x10^{-5}$ $\therefore$

Complete ($0.3000x10^{-5}$ * .10) = $0.0300x10^{-5}$ $\therefore$

Cataclysmic ($0.1500x10^{-5}$ * .10) = $0.0150x10^{-5}$ $\therefore$

There is a $0.1200x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0600x10^{-5}$ probability of a partial failure, $0.0300x10^{-5}$ probability of complete failure, and a $0.0150x10^{-5}$ probability of a cataclysmic failure during the operation of P_7, resulting in an inability to fuse the weapon – Dead Fuse

Case 4:

Failure ($F_{11.1}$) of Input 1 (I_1), and/or Failure ($F_{11.2}$) of Input 2 (I_2), and/or Failure ($F_{11.3}$) of Process 1 (P_1), and/or Failure ($F_{11.4}$) of Output 1 (O_1), and/or Failure ($F_{11.5}$) of Input 6 (I_6), and/or Failure ($F_{11.6}$) of Process 3 (P_3), through O_4, I_8, P_4, O_6, I_{11}, P_5, and O_{10}, resulting in an inability to fuse the weapon – Dead Fuse, and Malfunction 3 (M_3)

($F_{11.1}$^I_1 {[P_1, O_1, I_6, P_3]} or $F_{11.2}$^I_2 {[P_1, O_1, I_6, P_3]} or $F_{11.3}$^P_1 {[O_1, I_6, P_3]} or $F_{11.4}$^O_1 {[I_6, P_3]} or $F_{11.5}$^I_6 {[P_3]} or $F_{11.6}$^P_3) {[O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}]} → M_3

Assume:

$P_e\ I_1$	0.66
$P_e\ I_2$	0.66
$P_e\ P_1$	0.66
$P_e\ O_1$	0.66
$P_e\ I_6$	0.66
$P_e\ P_3$	0.66
$\sum P_e\ \{O_4, I_8, P_4, O_6, I_{11}, P_5, O_{10}\} \cup (I_1, I_2, P_1, O_1, I_6, P_3)$	0.6983
$\sum P_e\ \{P_1, O_1, I_6, P_3\} \cup I_1$	0.8145
$\sum P_e\ \{P_1, O_1, I_6, P_3\} \cup I_2$	0.8145
$\sum P_e\ \{O_1, I_6, P_3\} \cup P_1$	0.8574
$\sum P_e\ \{I_6, P_3\} \cup O_1$	0.9025
$P_e\ I_6 \cup P_3$	0.95
$P_{f\ \textit{Intermittent}}\ F_{11.1}$	$1.8000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.1}$	$0.9000\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.1}$	$0.4500\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.1}$	$0.2250\text{x}10^{-5}$
$P_{f\ \textit{Intermittent}}\ F_{11.2}$	$1.5000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.2}$	$0.7500\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.2}$	$0.3750\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.2}$	$0.1875\text{x}10^{-5}$
$P_{f\ \textit{Intermittent}}\ F_{11.3}$	$1.4000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.3}$	$0.7000\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.3}$	$0.3500\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.3}$	$0.1750\text{x}10^{-5}$
$P_{f\ \textit{Intermittent}}\ F_{11.4}$	$0.5000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.4}$	$0.2500\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.4}$	$0.1250\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.4}$	$0.0625\text{x}10^{-5}$
$P_{f\ \textit{Intermittent}}\ F_{11.5}$	$0.5000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.5}$	$0.2500\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.5}$	$0.1250\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.5}$	$0.0625\text{x}10^{-5}$
$P_{f\ \textit{Intermittent}}\ F_{11.6}$	$1.2000\text{x}10^{-5}$
$P_{f\ \textit{Partial}}\ F_{11.6}$	$0.6000\text{x}10^{-5}$
$P_{f\ \textit{Complete}}\ F_{11.6}$	$0.3000\text{x}10^{-5}$
$P_{f\ \textit{Cataclysmic}}\ F_{11.6}$	$0.1500\text{x}10^{-5}$

Intermittent (((1.8000x10^{-5} * 0.66) * (0.8145)) + ((1.5000x10^{-5} * 0.66) * (0.8145)) + ((1.4000x10^{-5} * 0.66) * (0.8574)) + ((0.5000x10^{-5} * 0.66) * (0.9025)) + (0.5000x10^{-5} * 0.66) * (0.95)) + (1.2000x10^{-5} * 0.66)) * (0.6983) =

(0.9676x10^{-5} + 0.8064x10^{-5} + 0.7922x10^{-5} + 0.2978x10^{-5} + 0.3135x10^{-5} + 0.7920x10^{-5}) * (0.6983) = 2.7719x10^{-5} ∴

Partial (((0.9000x10^{-5} * 0.66) * (0.8145)) + ((0.7500x10^{-5} * 0.66) * (0.8145)) + ((0.7000x10^{-5} * 0.66) * (0.8574)) + ((0.2500x10^{-5} * 0.66) * (0.9025)) + (0.2500x10^{-5} * 0.66) * (0.95)) + (0.6000x10^{-5} * 0.66)) * (0.6983) =

(0.4838x10^{-5} + 0.4032x10^{-5} + 0.3961x10^{-5} + 0.1489x10^{-5} + 0.1568x10^{-5} + 0.3960x10^{-5}) * (0.6983) = 1.3860x10^{-5} ∴

Complete (((0.4500x10^{-5} * 0.66) * (0.8145)) + ((0.3750x10^{-5} * 0.66) * (0.8145)) + ((0.3500x10^{-5} * 0.66) * (0.8574)) + ((0.1250x10^{-5} * 0.66) * (0.9025)) + (0.1250x10^{-5} * 0.66) * (0.95)) + (0.3000x10^{-5} * 0.66)) * (0.6983) =

$(0.2419x10^{-5} + 0.2016x10^{-5} + 0.1981x10^{-5} + 0.0745x10^{-5} + 0.0784x10^{-5} + 0.1980x10^{-5})$
$* (0.6983) = 0.6930x10^{-5}$ $\therefore$
Cataclysmic $(((0.2250x10^{-5} * 0.66) * (0.8145)) + ((0.1875x10^{-5} * 0.66) * (0.8145)) + ((0.1750x10^{-5} * 0.66) * (0.8574)) + ((0.0625x10^{-5} * 0.66) * (0.9025)) + (0.0625x10^{-5} * 0.66) * (0.95)) + (0.1500x10^{-5} * 0.66)) * (0.6983) =$

$(0.1210x10^{-5} + 0.1008x10^{-5} + 0.0990x10^{-5} + 0.0372x10^{-5} + 0.0392x10^{-5} + 0.0990x10^{-5})$
$* (0.6983) = 0.3465x10^{-5}$ $\therefore$

There is a $2.7719x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $1.3860x10^{-5}$ probability of a partial failure, a $0.6930x10^{-5}$ probability of complete failure, and a $0.3465x10^{-5}$ probability of a cataclysmic failure during the operation of I_1, I_2, P_1, O_1, I_6, and/or P_3 as a failure in weapon's signal regarding weapon's configuration and status, resulting in an inability to fuse the weapon – Dead Fuse

Summary:

Failure in Case 1, Case 2, Case 3, or Case 4, resulting in the weapon fusing to detonate too early after weapon's release and Malfunction 3 (M_3)

$P_{M3} = \{P_{Case\ 1}$ or $P_{Case\ 2}$ or $P_{Case\ 3}$ or $P_{Case\ 4}\}$

Intermittent $P_{M3} = 0.2375x10^{-5} + 0.0800x10^{-5} + 0.1200x10^{-5} + 2.7719x10^{-5} = 3.2094x10^{-5}$

Partial $P_{M3} = 0.1188x10^{-5} + 0.0400x10^{-5} + 0.0600x10^{-5} + 1.3860x10^{-5} = 1.6048x10^{-5}$
Complete $P_{M3} = 0.0594x10^{-5} + 0.0200x10^{-5} + 0.0300x10^{-5} + 0.6930x10^{-5} = 0.8024x10^{-5}$
Cataclysmic $P_{M3} = 0.0297x10^{-5} + 0.0100x10^{-5} + 0.0150x10^{-5} + 0.3465x10^{-5} = 0.4012x10^{-5}$

$P_{M3\ Total} = P_{M3\ Intermittent} + P_{M3\ Partial} + P_{M3\ Complete} + P_{M3\ Cataclysmic}$

$P_{M3\ Total} = 3.2094x10^{-5} + 1.6048x10^{-5} + 0.8024x10^{-5} + 0.4012x10^{-5}$
$P_{M3\ Total} = 6.0178x10^{-5}$

There is a $6.0178x10^{-5}$ probability that the WACSS will experience a safety–related malfunction and hazardous event during system operation, resulting in an inability to fuse the weapon – Dead Fuse

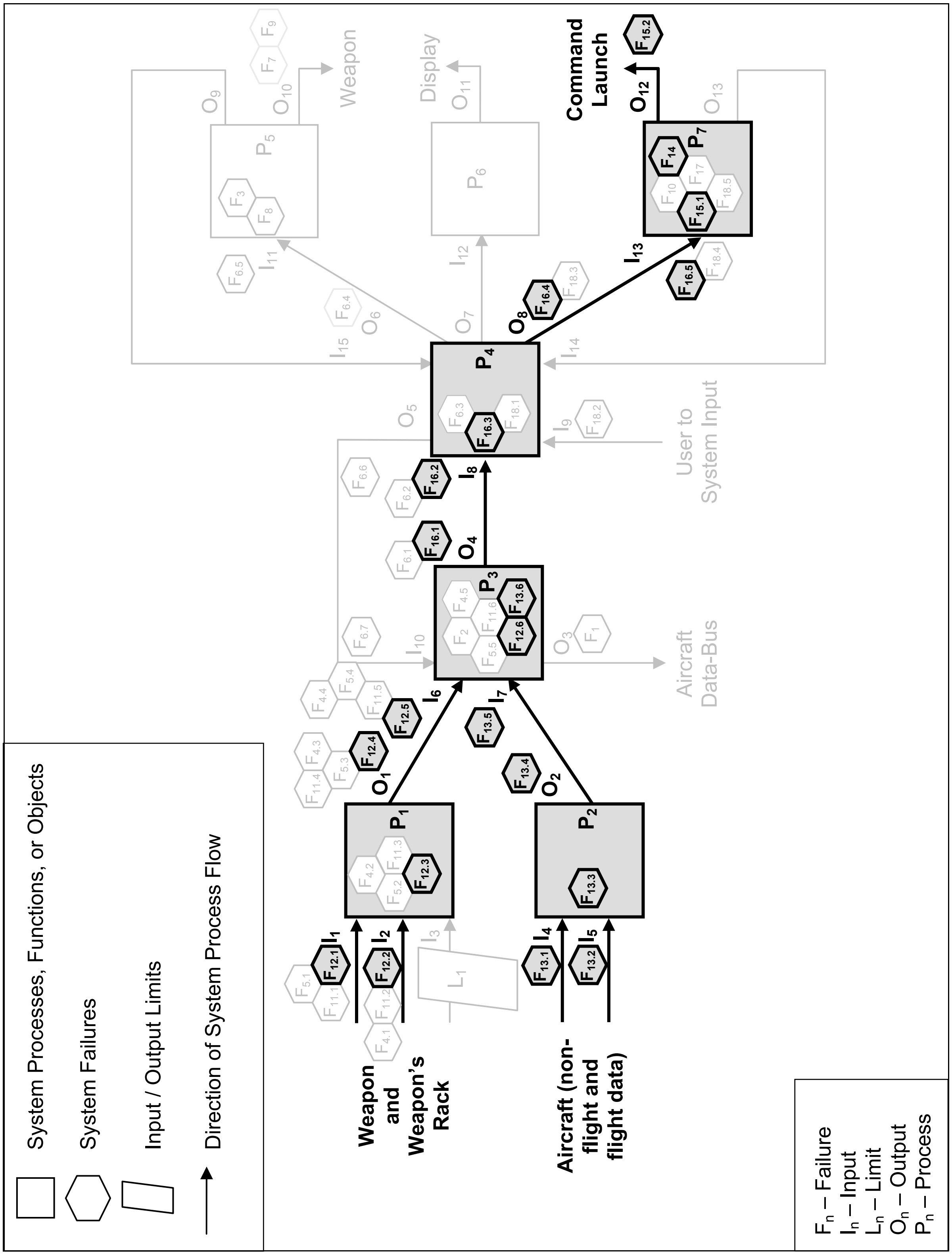

Figure 27 WACSS M_4 Malfunction Process Flow

M_4 – Inability to prevent weapons release outside of weapon's envelopes

Case 1:

Failure in Weapon's data signal regarding weapon's configuration and status – I_1, I_2, P_1, O_1, I_6, P_3

Failure ($F_{12.1}$) of Input 1 (I_1), and/or Failure ($F_{12.2}$) of Input 2 (I_2), and/or Failure ($F_{12.3}$) of Process 1 (P_1), and/or Failure ($F_{12.4}$) of Output 1 (O_1), and/or Failure ($F_{12.5}$) of Input 6 (I_6), and/or Failure ($F_{12.6}$) of Process 3 (P_3), through O_4, I_8, P_4, O_8, I_{13}, P_7, and O_{12}, resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

$(F_{12.1}\text{^}I_1 \{[P_1, O_1, I_6, P_3]\} \text{ or } F_{12.2}\text{^}I_2 \{[P_1, O_1, I_6, P_3]\} \text{ or } F_{12.3}\text{^}P_1 \{[O_1, I_6, P_3]\} \text{ or } F_{12.4}\text{^}O_1 \{[I_6, P_3]\} \text{ or } F_{12.5}\text{^}I_6 \{[P_3]\} \text{ or } F_{12.6}\text{^}P_3) \{[O_4, I_8, P_4, O_8, I_{13}, P_7, O_{12}]\} \rightarrow M_4$

Assume:

$P_e\ I_1$	0.66
$P_e\ I_2$	0.66
$P_e\ P_1$	0.66
$P_e\ O_1$	0.66
$P_e\ I_6$	0.66
$P_e\ P_3$	0.66
$\sum P_e \{O_4, I_8, P_4, O_6, I_{13}, P_7, O_{12}\} \cup (I_1, I_2, P_1, O_1, I_6, P_3)$	0.6983
$\sum P_e \{P_1, O_1, I_6, P_3\} \cup I_1$	0.8145
$\sum P_e \{P_1, O_1, I_6, P_3\} \cup I_2$	0.8145
$\sum P_e \{O_1, I_6, P_3\} \cup P_1$	0.8574
$\sum P_e \{I_6, P_3\} \cup O_1$	0.9025
$P_e\ I_6 \cup P_3$	0.95
$P_{f\ Intermittent}\ F_{12.1}$	$1.8000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.1}$	$0.9000\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.1}$	$0.4500\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.1}$	$0.2250\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_{12.2}$	$1.5000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.2}$	$0.7500\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.2}$	$0.3750\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.2}$	$0.1875\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_{12.3}$	$1.4000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.3}$	$0.7000\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.3}$	$0.3500\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.3}$	$0.1750\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_{12.4}$	$0.5000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.4}$	$0.2500\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.4}$	$0.1250\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.4}$	$0.0625\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_{12.5}$	$0.5000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.5}$	$0.2500\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.5}$	$0.1250\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.5}$	$0.0625\text{x}10^{-5}$
$P_{f\ Intermittent}\ F_{12.6}$	$1.4000\text{x}10^{-5}$
$P_{f\ Partial}\ F_{12.6}$	$0.7000\text{x}10^{-5}$
$P_{f\ Complete}\ F_{12.6}$	$0.3500\text{x}10^{-5}$
$P_{f\ Cataclysmic}\ F_{12.6}$	$0.1750\text{x}10^{-5}$

Intermittent $(((1.8000\text{x}10^{-5} * 0.66) * (0.8145)) + ((1.5000\text{x}10^{-5} * 0.66) * (0.8145)) + ((1.4000\text{x}10^{-5} * 0.66) * (0.8574)) + ((0.5000\text{x}10^{-5} * 0.66) * (0.9025)) + (0.5000\text{x}10^{-5} * 0.66) * (0.95)) + (1.4000\text{x}10^{-5} * 0.66)) * (0.6983) =$

$(0.9676\text{x}10^{-5} + 0.8064\text{x}10^{-5} + 0.7922\text{x}10^{-5} + 0.2978\text{x}10^{-5} + 0.3135\text{x}10^{-5} + 0.9240\text{x}10^{-5}) * (0.6983) = 2.8641\text{x}10^{-5} \therefore$

Partial (((0.9000x10^{-5} * 0.66) * (0.8145)) + ((0.7500x10^{-5} * 0.66) * (0.8145)) + ((0.7000x10^{-5} * 0.66) * (0.8574)) + ((0.2500x10^{-5} * 0.66) * (0.9025)) + (0.2500x10^{-5} * 0.66) * (0.95)) + (0.7000x10^{-5} * 0.66)) * (0.6983) =

(0.4838x10^{-5} + 0.4032x10^{-5} + 0.3961x10^{-5} + 0.1489x10^{-5} + 0.1568x10^{-5} + 0.4620x10^{-5}) * (0.6983) = 1.4321x10^{-5} $\therefore$

Complete (((0.4500x10^{-5} * 0.66) * (0.8145)) + ((0.3750x10^{-5} * 0.66) * (0.8145)) + ((0.3500x10^{-5} * 0.66) * (0.8574)) + ((0.1250x10^{-5} * 0.66) * (0.9025)) + (0.1250x10^{-5} * 0.66) * (0.95)) + (0.3500x10^{-5} * 0.66)) * (0.6983) =

(0.2419x10^{-5} + 0.2016x10^{-5} + 0.1981x10^{-5} + 0.0745x10^{-5} + 0.0784x10^{-5} + 0.2310x10^{-5}) * (0.6983) = 0.7161x10^{-5} $\therefore$

Cataclysmic (((0.2250x10^{-5} * 0.66) * (0.8145)) + ((0.1875x10^{-5} * 0.66) * (0.8145)) + ((0.1750x10^{-5} * 0.66) * (0.8574)) + ((0.0625x10^{-5} * 0.66) * (0.9025)) + (0.0625x10^{-5} * 0.66) * (0.95)) + (0.1750x10^{-5} * 0.66)) * (0.6983) =

(0.1210x10^{-5} + 0.1008x10^{-5} + 0.0990x10^{-5} + 0.0372x10^{-5} + 0.0392x10^{-5} + 0.1155x10^{-5}) * (0.6983) = 0.3580x10^{-5} $\therefore$

There is a 2.8641x10^{-5} probability of the WACSS experiencing an intermittent failure, a 1.4321x10^{-5} probability of a partial failure, a 0.7161x10^{-5} probability of complete failure, and a 0.3580x10^{-5} probability of a cataclysmic failure during the operation of I_1, I_2, P_1, O_1, I_6, and/or P_3 as a resulting in an inability to prevent weapons release outside of the weapon's envelope

Case 2:

Failure ($F_{13.1}$) of Input 4 (I_4), and/or Failure ($F_{13.2}$) of Input 5 (I_5), and/or Failure ($F_{13.3}$) of Process 2 (P_2), and/or Failure ($F_{13.4}$) of Output 2 (O_1), and/or Failure ($F_{13.5}$) of Input 7 (I_7), and/or Failure ($F_{13.6}$) of Process 3 (P_3), through O_4, I_8, P_4, O_8, I_{13}, P_7, and O_{12}, resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

($F_{13.1}$^I_4 {[P_2, O_2, I_7, P_3]} or $F_{13.2}$^I_5 {[P_2, O_2, I_7, P_3]} or $F_{13.3}$^P_2 {[O_2, I_7, P_3]} or $F_{13.4}$^O_2 {[I_7, P_3]} or $F_{13.5}$^I_7 {[P_3]} or $F_{13.6}$^P_3) {[O_4, I_8, P_4, O_8, I_{13}, P_7, O_{12}]} $\rightarrow$ M_4

Assume:

P_e I_4	0.90
P_e I_5	0.90
P_e P_2	0.66
P_e O_2	0.66
P_e I_7	0.66
P_e P_3	0.66
$\sum P_e$ $\{O_4, I_8, P_4, O_6, I_{13}, P_7, O_{12}\} \cup (I_{4,}\ I_5, P_2, O_2, I_7, P_3)$	0.6983
$\sum P_e$ $\{P_2, O_2, I_7, P_3\} \cup I_4$	0.8145
$\sum P_e$ $\{P_2, O_2, I_7, P_3\} \cup I_5$	0.8145
$\sum P_e$ $\{O_2, I_7, P_3\} \cup P_2$	0.8574
$\sum P_e$ $\{I_7, P_3\} \cup O_2$	0.9025
P_e $I_7 \cup P_3$	0.95
$P_{f\ Intermittent}$ $F_{13.1}$	1.5000x10^{-5}
$P_{f\ Partial}$ $F_{13.1}$	0.7500x10^{-5}
$P_{f\ Complete}$ $F_{13.1}$	0.3750x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.1}$	0.1875x10^{-5}
$P_{f\ Intermittent}$ $F_{13.2}$	1.5000x10^{-5}
$P_{f\ Partial}$ $F_{13.2}$	0.7500x10^{-5}
$P_{f\ Complete}$ $F_{13.2}$	0.3750x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.2}$	0.1875x10^{-5}
$P_{f\ Intermittent}$ $F_{13.3}$	1.0000x10^{-5}
$P_{f\ Partial}$ $F_{13.3}$	0.5000x10^{-5}
$P_{f\ Complete}$ $F_{13.3}$	0.2500x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.3}$	0.1250x10^{-5}
$P_{f\ Intermittent}$ $F_{13.4}$	0.5000x10^{-5}
$P_{f\ Partial}$ $F_{13.4}$	0.2500x10^{-5}
$P_{f\ Complete}$ $F_{13.4}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.4}$	0.0625x10^{-5}
$P_{f\ Intermittent}$ $F_{13.5}$	0.5000x10^{-5}
$P_{f\ Partial}$ $F_{13.5}$	0.2500x10^{-5}
$P_{f\ Complete}$ $F_{13.5}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.5}$	0.0625x10^{-5}
$P_{f\ Intermittent}$ $F_{13.6}$	1.4000x10^{-5}
$P_{f\ Partial}$ $F_{13.6}$	0.7000x10^{-5}
$P_{f\ Complete}$ $F_{13.6}$	0.3500x10^{-5}
$P_{f\ Cataclysmic}$ $F_{13.6}$	0.1750x10^{-5}

Intermittent (((1.5000x10^{-5} * 0.90) * (0.8145)) + ((1.5000x10^{-5} * 0.90) * (0.8145)) + ((1.0000x10^{-5} * 0.66) * (0.8574)) + ((0.5000x10^{-5} * 0.66) * (0.9025)) + (0.5000x10^{-5} * 0.66) * (0.95)) + (1.4000x10^{-5} * 0.66)) * (0.6983) =

(1.0996x10^{-5} + 1.0996x10^{-5} + 0.5659x10^{-5} + 0.2978x10^{-5} + 0.3135x10^{-5} + 0.9240x10^{-5}) * (0.6983) = 3.0030x10^{-5} $\therefore$

Partial (((0.7500x10^{-5} * 0.90) * (0.8145)) + ((0.7500x10^{-5} * 0.90) * (0.8145)) + ((0.5000x10^{-5} * 0.66) * (0.8574)) + ((0.2500x10^{-5} * 0.66) * (0.9025)) + (0.2500x10^{-5} * 0.66) * (0.95)) + (0.7000x10^{-5} * 0.66)) * (0.6983) =

(0.5498x10^{-5} + 0.5498x10^{-5} + 0.2829x10^{-5} + 0.1489x10^{-5} + 0.1568x10^{-5} + 0.4620x10^{-5}) * (0.6983) = 1.5015x10^{-5} $\therefore$

Complete (((0.3750x10^{-5} * 0.90) * (0.8145)) + ((0.3750x10^{-5} * 0.90) * (0.8145)) + ((0.2500x10^{-5} * 0.66) * (0.8574)) + ((0.1250x10^{-5} * 0.66) * (0.9025)) + (0.1250x10^{-5} * 0.66) * (0.95)) + (0.3500x10^{-5} * 0.66)) * (0.6983) =

(0.2749x10^{-5} + 0.2749x10^{-5} + 0.1415x10^{-5} + 0.0745x10^{-5} + 0.0784x10^{-5} + 0.2310x10^{-5}) * (0.6983) = 0.7508x10^{-5} $\therefore$

Cataclysmic (((0.1875x10^{-5} * 0.90) * (0.8145)) + ((0.1875x10^{-5} * 0.90) * (0.8145)) + ((0.1250x10^{-5} * 0.66) * (0.8574)) + ((0.0625x10^{-5} * 0.66) * (0.9025)) + (0.0625x10^{-5} * 0.66) * (0.95)) + (0.1750x10^{-5} * 0.66)) * (0.6983) =

$(0.1374\text{x}10^{-5} + 0.1374\text{x}10^{-5} + 0.0707\text{x}10^{-5} + 0.0372\text{x}10^{-5} + 0.0392\text{x}10^{-5} + 0.1155\text{x}10^{-5})$ $* (0.6983) = 0.3753\text{x}10^{-5} \therefore$

There is a $3.0030\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $1.5015\text{x}10^{-5}$ probability of a partial failure, a $0.7508\text{x}10^{-5}$ probability of complete failure, and a $0.3753\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of I_1, I_2, P_1, O_1, I_6, and/or P_3 resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

Case 3:

Failure (F_{14}) of Process 7 (P_7), through O_{12} resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

F_{14}^P_7 $\{[O_{12}]\} \rightarrow M_2$

Assume:

P_e P_7	0.10
P_e $O_{12} \cup$ P7	0.95
$P_{f\ Intermittent}$ F_{14}	$1.2000\text{x}10^{-5}$
$P_{f\ Partial}$ F_{14}	$0.6000\text{x}10^{-5}$
$P_{f\ Complete}$ F_{14}	$0.3000\text{x}10^{-5}$
$P_{f\ Cataclysmic}$ F_{14}	$0.1500\text{x}10^{-5}$

Intermittent $(1.2000\text{x}10^{-5} * 0.10) * 0.95 = 0.1140\text{x}10^{-5} \therefore$

Partial $(0.6000\text{x}10^{-5} * 0.10) * 0.95 = 0.0570\text{x}10^{-5} \therefore$

Complete $(0.3000\text{x}10^{-5} * 0.10) * 0.95 = 0.0285\text{x}10^{-5} \therefore$

Cataclysmic $(0.1500\text{x}10^{-5} * 0.10) * 0.95 = 0.0142\text{x}10^{-5} \therefore$

There is a $0.1140\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0570\text{x}10^{-5}$ probability of a partial failure, a $0.0285\text{x}10^{-5}$ probability of complete failure, and a $0.0143\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of $P_{7,}$ resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

Case 4:

Failure ($F_{15.1}$) of Process 7 (P_7), and/or Failure ($F_{15.2}$) of Output 12 (O_{12}), resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

$(F_{15.1}{}^{\wedge}P_7 \ \{[O_{12}]\} \text{ or } F_{15.2}{}^{\wedge}O_{12}) \rightarrow M_4$

Assume:

P_e P_7	0.10	$P_{f\ Cataclysmic}$ $F_{15.1}$	$0.0625\text{x}10^{-5}$
P_e O_{12}	0.07	$P_{f\ Intermittent}$ $F_{15.2}$	$0.8000\text{x}10^{-5}$
P_e $P_7 \cup O_{12}$	0.95	$P_{f\ Partial}$ $F_{15.2}$	$0.4000\text{x}10^{-5}$
$P_{f\ Intermittent}$ $F_{15.1}$	$0.5000\text{x}10^{-5}$	$P_{f\ Complete}$ $F_{15.2}$	$0.2000\text{x}10^{-5}$
$P_{f\ Partial}$ $F_{15.1}$	$0.2500\text{x}10^{-5}$	$P_{f\ Cataclysmic}$ $F_{15.2}$	$0.1000\text{x}10^{-5}$
$P_{f\ Complete}$ $F_{15.1}$	$0.1250\text{x}10^{-5}$		

Intermittent $((0.5000\text{x}10^{-5} * 0.10) * (0.95)) + (0.8000\text{x}10^{-5} * 0.07) =$

$(0.0475\text{x}10^{-5} + 0.0560\text{x}10^{-5}) = 0.1035\text{x}10^{-5} \therefore$

Partial $((0.2500\text{x}10^{-5} * 0.10) * (0.95)) + (0.4000\text{x}10^{-5} * 0.07) =$

$(0.0238\text{x}10^{-5} + 0.0280\text{x}10^{-5}) = 0.0518\text{x}10^{-5} \therefore$

Complete $((0.1250\text{x}10^{-5} * 0.10) * (0.95)) + (0.2000\text{x}10^{-5} * 0.07) =$

$(0.0119\text{x}10^{-5} + 0.0140\text{x}10^{-5}) = 0.0259\text{x}10^{-5} \therefore$

Cataclysmic $((0.0625\text{x}10^{-5} * 0.10) * (0.95)) + (0.1000\text{x}10^{-5} * 0.07) =$

$(0.0059\text{x}10^{-5} + 0.0070\text{x}10^{-5}) = 0.0129\text{x}10^{-5} \therefore$

There is a $0.1035\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0518\text{x}10^{-5}$ probability of a partial failure, a $0.0259\text{x}10^{-5}$ probability of complete failure, and a $0.0129\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of P_7 and/or O_{12} resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

Case 5:

Failure ($F_{16.1}$) of Output 4 (O_4), and/or Failure ($F_{16.2}$) of Input 8 (I_8), and/or Failure ($F_{16.3}$) of Process 4 (P_4), and/or Failure ($F_{16.4}$) of Output 8 (O_8), and/or Failure ($F_{16.5}$) of Input 13 (I_{13}), through P_7 and O_{12}, resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

$(F_{16.1}{}^{\wedge}O_4 \ \{[I_8, P_4, O_8, I_{13}]\} \text{ or } F_{16.2}{}^{\wedge}I_8 \ \{[P_4, O_8, I_{13}]\} \text{ or } F_{16.3}{}^{\wedge}P_4 \ \{[O_8, I_{13}]\} \text{ or } F_{16.4}{}^{\wedge}O_8 \ \{[I_{13}]\} \text{ or } F_{16.5}{}^{\wedge}I_{13}) \ \{[P_7, O_{12}]\} \rightarrow M_4$

Assume:

$P_e\ O_4$	0.40
$P_e\ I_8$	0.40
$P_e\ P_4$	0.25
$P_e\ O_8$	0.10
$P_e\ I_{13}$	0.10
$\sum P_e\ \{P_7, O_{12}\} \cup (O_4, I_8, P_4, O_8, I_{13})$	0.9025
$\sum P_e\ \{I_8, P_4, O_8, I_{13}\} \cup O_4$	0.8145
$\sum P_e\ \{P_4, O_8, I_{13}\} \cup I_8$	0.8574
$\sum P_e\ \{O_8, I_{13}\} \cup P_4$	0.9025
$P_e\ I_{13} \cup O_8$	0.95
$P_{f\ \mathit{Intermittent}}\ F_{16.1}$	$0.5000\text{x}10^{-5}$
$P_{f\ \mathit{Partial}}\ F_{16.1}$	$0.2500\text{x}10^{-5}$
$P_{f\ \mathit{Complete}}\ F_{16.1}$	$0.1250\text{x}10^{-5}$
$P_{f\ \mathit{Cataclysmic}}\ F_{16.1}$	$0.0625\text{x}10^{-5}$
$P_{f\ \mathit{Intermittent}}\ F_{16.2}$	$0.5000\text{x}10^{-5}$
$P_{f\ \mathit{Partial}}\ F_{16.2}$	$0.2500\text{x}10^{-5}$
$P_{f\ \mathit{Complete}}\ F_{16.2}$	$0.1250\text{x}10^{-5}$
$P_{f\ \mathit{Cataclysmic}}\ F_{16.2}$	$0.0625\text{x}10^{-5}$
$P_{f\ \mathit{Intermittent}}\ F_{16.3}$	$0.8000\text{x}10^{-5}$
$P_{f\ \mathit{Partial}}\ F_{16.3}$	$0.4000\text{x}10^{-5}$
$P_{f\ \mathit{Complete}}\ F_{16.3}$	$0.2000\text{x}10^{-5}$
$P_{f\ \mathit{Cataclysmic}}\ F_{16.3}$	$0.1000\text{x}10^{-5}$
$P_{f\ \mathit{Intermittent}}\ F_{16.4}$	$0.6000\text{x}10^{-5}$
$P_{f\ \mathit{Partial}}\ F_{16.4}$	$0.3000\text{x}10^{-5}$
$P_{f\ \mathit{Complete}}\ F_{16.4}$	$0.1500\text{x}10^{-5}$
$P_{f\ \mathit{Cataclysmic}}\ F_{16.4}$	$0.0750\text{x}10^{-5}$
$P_{f\ \mathit{Intermittent}}\ F_{16.5}$	$0.6000\text{x}10^{-5}$
$P_{f\ \mathit{Partial}}\ F_{16.5}$	$0.3000\text{x}10^{-5}$
$P_{f\ \mathit{Complete}}\ F_{16.5}$	$0.1500\text{x}10^{-5}$
$P_{f\ \mathit{Cataclysmic}}\ F_{16.5}$	$0.0750\text{x}10^{-5}$

Intermittent $(((0.5000\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.5000\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.8000\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.6000\text{x}10^{-5} * 0.10) * (0.9500)) + (0.6000\text{x}10^{-5} * 0.10)) * (0.9025) =$

$(0.1629\text{x}10^{-5} + 0.1715\text{x}10^{-5} + 0.1805\text{x}10^{-5} + 0.0570\text{x}10^{-5} + 0.0600\text{x}10^{-5}) * (0.9025) = 0.5703\text{x}10^{-5}$ ∴

Partial $(((0.2500\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.2500\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.4000\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.3000\text{x}10^{-5} * 0.10) * (0.9500)) + (0.3000\text{x}10^{-5} * 0.10)) * (0.9025) =$

$(0.0815\text{x}10^{-5} + 0.0857\text{x}10^{-5} + 0.0903\text{x}10^{-5} + 0.0285\text{x}10^{-5} + 0.0300\text{x}10^{-5}) * (0.9025) = 0.2852\text{x}10^{-5}$ ∴

Complete $(((0.1250\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.1250\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.2000\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.1500\text{x}10^{-5} * 0.10) * (0.9500)) + (0.1500\text{x}10^{-5} * 0.10)) * (0.9025) =$

$(0.0407\text{x}10^{-5} + 0.0429\text{x}10^{-5} + 0.0451\text{x}10^{-5} + 0.0143\text{x}10^{-5} + 0.0150\text{x}10^{-5}) * (0.9025) = 0.1426\text{x}10^{-5}$ ∴

Cataclysmic $(((0.0625\text{x}10^{-5} * 0.40) * (0.8145)) + ((0.0625\text{x}10^{-5} * 0.40) * (0.8574)) + ((0.1000\text{x}10^{-5} * 0.25) * (0.9025)) + ((0.0750\text{x}10^{-5} * 0.10) * (0.9500)) + (0.0750\text{x}10^{-5} * 0.10)) * (0.9025) =$

$(0.0204\text{x}10^{-5} + 0.0214\text{x}10^{-5} + 0.0226\text{x}10^{-5} + 0.0071\text{x}10^{-5} + 0.0075\text{x}10^{-5}) * (0.9025) = 0.0713\text{x}10^{-5}$ ∴

There is a $0.5703x10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.2852x10^{-5}$ probability of a partial failure, a $0.1426x10^{-5}$ probability of complete failure, and a $0.0713x10^{-5}$ probability of a cataclysmic failure during the operation of O_4, I_8, P_4, O_8, and/or I_{13} resulting in an inability to prevent weapons release outside of the weapon's envelope, and Malfunction 4 (M_4)

Summary:

Failure in Case 1, Case 2, Case 3, Case 4, or Case 5, resulting in an inability to prevent weapon's release outside of the weapon's envelope, and Malfunction 4 (M_4)

$P_{M4} = \{P_{Case\ 1} \text{ or } P_{Case\ 2} \text{ or } P_{Case\ 3} \text{ or } P_{Case\ 4} \text{ or } P_{Case\ 5}\}$

Intermittent $P_{M4} = 2.8641x10^{-5} + 3.0030x10^{-5} + 0.1140x10^{-5} + 0.1035x10^{-5} + 0.5703x10^{-5} = 6.6549x10^{-5}$
Partial $P_{M4} = 1.4321x10^{-5} + 1.5015x10^{-5} + 0.0570x10^{-5} + 0.0518x10^{-5} + 0.2852x10^{-5} = 3.3276x10^{-5}$
Complete $P_{M4} = 0.7161x10^{-5} + 0.7508x10^{-5} + 0.0285x10^{-5} + 0.0259x10^{-5} + 0.1426x10^{-5} = 1.6639x10^{-5}$
Cataclysmic $P_{M4} = 0.3580x10^{-5} + 0.3753x10^{-5} + 0.0143x10^{-5} + 0.0129x10^{-5} + 0.0713x10^{-5} = 0.8318x10^{-5}$

$P_{M4\ Total} = P_{M4\ Intermittent} + P_{M4\ Partial} + P_{M4\ Complete} + P_{M4\ Cataclysmic}$

$P_{M4\ Total} = 6.6549x10^{-5} + 3.3276x10^{-5} + 1.6639x10^{-5} + 0.8318x10^{-5}$
$P_{M4\ Total} = 12.4782x10^{-5}$

There is a $12.4782x10^{-5}$ probability that the WACSS will experience a safety–related malfunction and hazardous event during system operation, resulting in an inability to prevent weapons release outside of the weapon's envelope

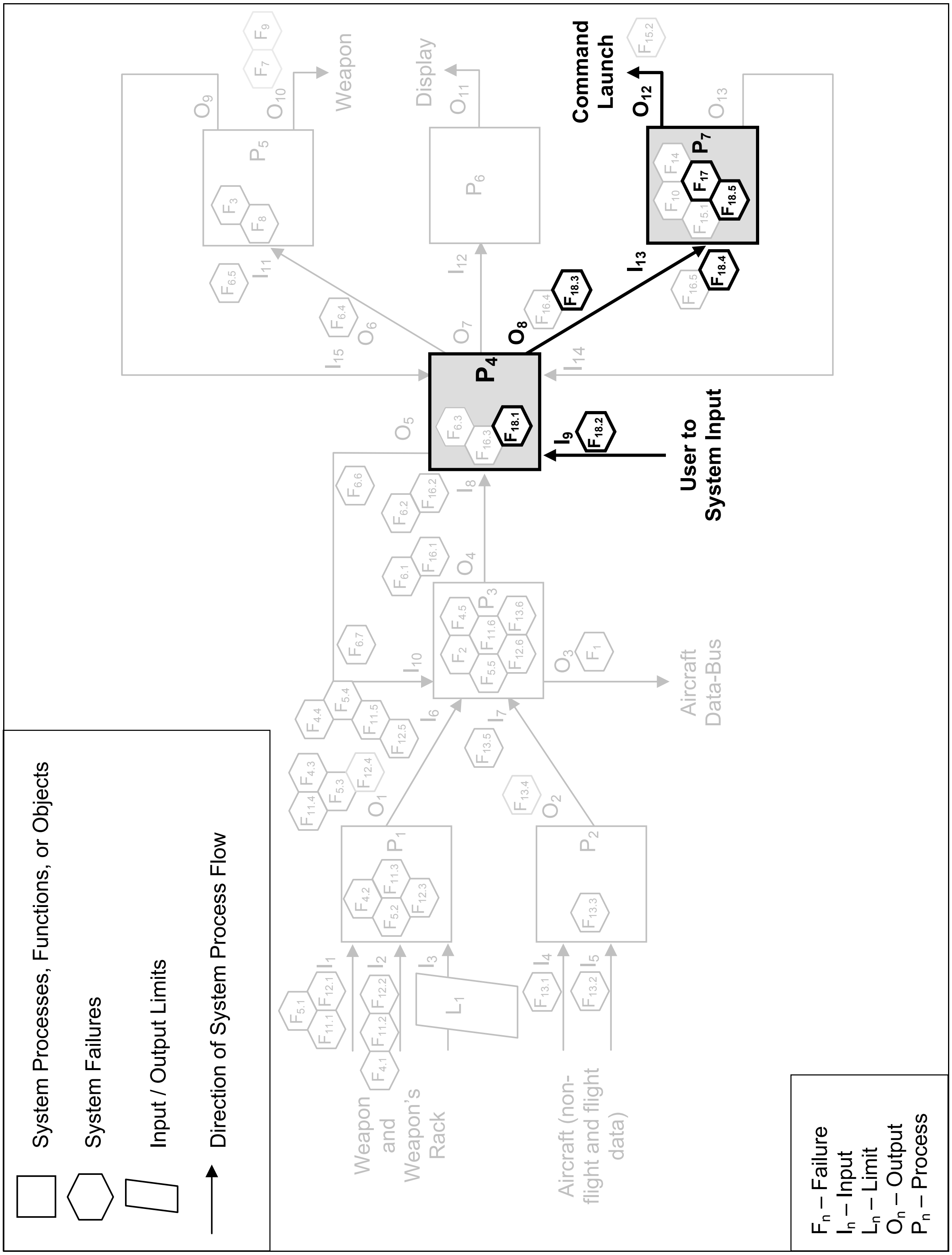

Figure 28 WACSS M_5 Malfunction Process Flow

M_5 – Drop incorrect weapon from pylon

Case 1:

Failure in weapons launch / deployment logic to select the proper weapon – P_7

Failure (F_{17}) of Process 7 (P_7), through O_{12}, resulting in the drop of an incorrect weapon from pylon, and Malfunction 5 (M_5)

F_{17}^P_7 $\{[O_{12}]\} \rightarrow M_5$

Assume:

P_e P_7	0.10
P_e $P_7 \cup O_{12}$	0.95
$P_{f\ Intermittent}$ F_{17}	$1.0000\text{x}10^{-5}$
$P_{f\ Partial}$ F_{17}	$0.5000\text{x}10^{-5}$
$P_{f\ Complete}$ F_{17}	$0.2500\text{x}10^{-5}$
$P_{f\ Cataclysmic}$ F_{17}	$0.1250\text{x}10^{-5}$

Intermittent $(1.0000\text{x}10^{-5} * 0.10) * (0.9500) = 0.0950\text{x}10^{-5} \therefore$

Partial $(0.5000\text{x}10^{-5} * 0.10) * (0.9500) = 0.0475\text{x}10^{-5} \therefore$

Complete $(0.2500\text{x}10^{-5} * 0.10) * (0.9500) = 0.0238\text{x}10^{-5} \therefore$

Cataclysmic $(0.1250\text{x}10^{-5} * 0.10) * (0.9500) = 0.0119\text{x}10^{-5} \therefore$

There is a $0.0950\text{x}10^{-5}$ probability of the WACSS experiencing an intermittent failure, a $0.0475\text{x}10^{-5}$ probability of a partial failure, a $0.0238\text{x}10^{-5}$ probability of complete failure, and a $0.0119\text{x}10^{-5}$ probability of a cataclysmic failure during the operation of P_7 resulting in a failure in the weapon launch / deployment logic to select the proper weapon and Malfunction 5 (M_5); the dropping of an incorrect weapon from a weapon's pylon

Case 2:

Failure ($F_{18.1}$) of Process 4 (P_4), and/or Failure ($F_{18.2}$) of Input 9 (I_9), and/or Failure ($F_{18.3}$) of Output 8 (O_8), and/or Failure ($F_{18.4}$) of Input 13 (I_{13}), and/or Failure ($F_{18.5}$) of Process 7 (P_7), through O_{12}, resulting in the drop of an incorrect weapon from pylon, and Malfunction 5 (M_5)

($F_{18.1}$^P_4 $\{[I_9, O_8, I_{13}, P_7]\}$ or $F_{18.2}$^I_9 $\{[O_8, I_{13}, P_7]\}$ or $F_{18.3}$^O_8 $\{[I_{13}, P_7]\}$ or $F_{18.4}$^I_{13} $\{[P_7]\}$ or $F_{18.5}$^P_7) $\{[O_{12}]\} \rightarrow M_4$

Assume:

P_e P$_4$	0.25
P_e I$_9$	0.25
P_e O$_8$	0.10
P_e I$_{13}$	0.10
P_e P$_7$	0.10
$\sum P_e$ {O$_{12}$} ∪ (P$_4$, I$_9$, O$_8$, I$_{13}$, P$_7$)	0.9500
$\sum P_e$ {I$_9$, O$_8$, I$_{13}$, P$_7$} ∪ P$_4$	0.8145
$\sum P_e$ {O$_8$, I$_{13}$, P$_7$} ∪ I$_9$	0.8574
$\sum P_e$ {I$_{13}$, P$_7$} ∪ O$_8$	0.9025
P_e I$_{13}$ ∪ P$_7$	0.95
$P_{f\ Intermittent}$ F$_{18.1}$	0.8000x10^{-5}
$P_{f\ Partial}$ F$_{18.1}$	0.4000x10^{-5}
$P_{f\ Complete}$ F$_{18.1}$	0.2000x10^{-5}
$P_{f\ Cataclysmic}$ F$_{18.1}$	0.1000x10^{-5}
$P_{f\ Intermittent}$ F$_{18.2}$	1.9000x10^{-5}
$P_{f\ Partial}$ F$_{18.2}$	0.9500x10^{-5}
$P_{f\ Complete}$ F$_{18.2}$	0.4750x10^{-5}
$P_{f\ Cataclysmic}$ F$_{18.2}$	0.2375x10^{-5}
$P_{f\ Intermittent}$ F$_{18.3}$	0.5000x10^{-5}
$P_{f\ Partial}$ F$_{18.3}$	0.2500x10^{-5}
$P_{f\ Complete}$ F$_{18.3}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}$ F$_{18.3}$	0.0625x10^{-5}
$P_{f\ Intermittent}$ F$_{18.4}$	0.5000x10^{-5}
$P_{f\ Partial}$ F$_{18.4}$	0.2500x10^{-5}
$P_{f\ Complete}$ F$_{18.4}$	0.1250x10^{-5}
$P_{f\ Cataclysmic}$ F$_{18.4}$	0.0625x10^{-5}
$P_{f\ Intermittent}$ F$_{18.5}$	1.5000x10^{-5}
$P_{f\ Partial}$ F$_{18.5}$	0.7500x10^{-5}
$P_{f\ Complete}$ F$_{18.5}$	0.3750x10^{-5}
$P_{f\ Cataclysmic}$ F$_{18.5}$	0.1875x10^{-5}

Intermittent (((0.8000x10^{-5} * 0.25) * (0.8145)) + ((1.9000x10^{-5} * 0.25) * (0.8574)) + ((0.5000x10^{-5} * 0.10) * (0.9025)) + ((0.5000x10^{-5} * 0.10) * (0.9500)) + (1.5000x10^{-5} * 0.10)) * (0.9500) =

(0.1629x10^{-5} + 0.4073x10^{-5} + 0.0451x10^{-5} + 0.0475x10^{-5} + 0.1500x10^{-5}) * (0.9500) = 0.7722x10^{-5} ∴

Partial (((0.4000x10^{-5} * 0.25) * (0.8145)) + ((0.9500x10^{-5} * 0.25) * (0.8574)) + ((0.2500x10^{-5} * 0.10) * (0.9025)) + ((0.2500x10^{-5} * 0.10) * (0.9500)) + (0.7500x10^{-5} * 0.10)) * (0.9500) =

(0.0815x10^{-5} + 0.2036x10^{-5} + 0.0226x10^{-5} + 0.0238x10^{-5} + 0.0750x10^{-5}) * (0.9500) = 0.3862x10^{-5} ∴

Complete (((0.2000x10^{-5} * 0.25) * (0.8145)) + ((0.4750x10^{-5} * 0.25) * (0.8574)) + ((0.1250x10^{-5} * 0.10) * (0.9025)) + ((0.1250x10^{-5} * 0.10) * (0.9500)) + (0.3750x10^{-5} * 0.10)) * (0.9500) =

(0.0407x10^{-5} + 0.1018x10^{-5} + 0.0113x10^{-5} + 0.0119x10^{-5} + 0.0375x10^{-5}) * (0.9500) = 0.1930x10^{-5} ∴

Cataclysmic (((0.1000x10^{-5} * 0.25) * (0.8145)) + ((0.2375x10^{-5} * 0.25) * (0.8574)) + ((0.0625x10^{-5} * 0.10) * (0.9025)) + ((0.0625x10^{-5} * 0.10) * (0.9500)) + (0.1875x10^{-5} * 0.10)) * (0.9500) =

(0.0204x10^{-5} + 0.0509x10^{-5} + 0.0056x10^{-5} + 0.0059x10^{-5} + 0.0188x10^{-5}) * (0.9500) = 0.0965x10^{-5} ∴

There is a 0.7722x10^{-5} probability of the WACSS experiencing an intermittent failure, a 0.3862x10^{-5} probability of a partial failure, a 0.1930x10^{-5} probability of complete failure, and a 0.0965x10^{-5} probability of a cataclysmic failure during the operation of P_4, I_9, O_8, I_{13}, and/or P_7 resulting in a failure in the system to comprehend which weapon was selected and Malfunction 5 (M_5); the dropping of an incorrect weapon from a weapon's pylon

Summary:

Failure in Case 1 or Case 2 resulting in the dropping of an incorrect weapon from a weapon's pylon and Malfunction 5 (M_5)

$P_{M5} = \{P_{Case\ 1}\ or\ P_{Case\ 2}\}$

Intermittent $P_{M5} = 0.0950\text{x}10^{-5} + 0.7722\text{x}10^{-5} = 0.8672\text{x}10^{-5}$
Partial $P_{M5} = 0.0475\text{x}10^{-5} + 0.3862\text{x}10^{-5} = 0.4337\text{x}10^{-5}$
Complete $P_{M5} = 0.0238\text{x}10^{-5} + 0.1930\text{x}10^{-5} = 0.2168\text{x}10^{-5}$
Cataclysmic $P_{M5} = 0.0119\text{x}10^{-5} + 0.0965\text{x}10^{-5} = 0.1084\text{x}10^{-5}$

$P_{M5\ Total} = P_{M5\ Intermittent} + P_{M5\ Partial} + P_{M5\ Complete} + P_{M5\ Cataclysmic}$

$P_{M5\ Total} = 0.8672\text{x}10^{-5} + 0.4337\text{x}10^{-5} + 0.2168\text{x}10^{-5} + 0.1084\text{x}10^{-5}$
$P_{M5\ Total} = 1.6261\text{x}10^{-5}$

There is a 1.6261x10^{-5} probability that the WACSS will experience a safety–related malfunction and hazardous event during system operation, resulting in the dropping of an incorrect weapon from a weapon's pylon

9. PROBABILITY SUMMATION

	Intermittent	Partial	Complete	Cataclysmic	Σ
M_1	2.2540x10^{-5}	1.1270x10^{-5}	0.5635x10^{-5}	0.2818x10^{-5}	4.2263x10^{-5}
M_2	5.4980x10^{-5}	2.7578x10^{-5}	1.3847x10^{-5}	0.6871x10^{-5}	10.3276x10^{-5}
M_3	3.2094x10^{-5}	1.6048x10^{-5}	0.8024x10^{-5}	0.4012x10^{-5}	6.0178x10^{-5}
M_4	6.6549x10^{-5}	3.3276x10^{-5}	1.6639x10^{-5}	0.8318x10^{-5}	12.4782x10^{-5}
M_5	0.8672x10^{-5}	0.4337x10^{-5}	0.2168x10^{-5}	0.1084x10^{-5}	1.6261x10^{-5}
Σ	18.4835x10^{-5}	9.2509x10^{-5}	4.6313x10^{-5}	2.3103x10^{-5}	34.6760x10^{-5}

Table 32 WACSS Probability Summation

The example Probability Summation demonstrated in Table 32 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 5. Action 7.

Frequency	Definition	Probability $x10^{-5}$
ALWAYS	The system will each time it is executed.	> 50.00
FREQUENT	The system will most likely fail when executed.	50.00
LIKELY	The system will likely fail when executed.	25.00
PERIODICALLY	The system will periodically fail when executed.	10.00
OCCASIONAL	The system will occasionally fail when executed.	2.50
SELDOM	The system will seldom fail when executed.	0.75
SPORADICALLY	The system will fail sporadically when they are executed.	0.20
UNLIKELY	The system is unlikely to fail when executed.	0.05
NEVER	The system will never fail when executed.	0.00

Table 33 WACSS System Failure Definition Table

The example System Failure Definition Table demonstrated in Table 33 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Steps 6.2 and 6.3.

SEVERITY		PROBABILITY								
		ALWAYS	FREQUENT	LIKELY	PERIODIC–ALLY	OCCASION–ALLY	SELDOM	SPORAD–ICALLY	UNLIKELY	NEVER
		A	B	C	D	E	F	G	H	I
CATASTROPHIC	I	Unsafe	Unsafe	Extremely	Highly	Significantly	Moderately	Minor	Low	Safe
CRITICAL	II	Unsafe	Extremely	Extremely	Highly	Significantly	Moderately	Minor	Low	Safe
MODERATE	III	Unsafe	Extremely	Highly	Significantly	Moderately	Minor	Minor	Low	Safe
NEGLIGIBLE	IV	Unsafe	Highly	Significantly	Moderately	Minor	Minor	Minor	Low	Safe

Table 34 WACSS Probability vs. Severity Table

The example Probability vs. Severity Table demonstrated in Table 34 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Steps 6.2 and 6.3

	Intermittent	Partial	Complete	Cataclysmic	Σ
M_1	E	F	F	F	D
M_2	D	E	E	F	D
M_3	D	E	E	F	D
M_4	D	D	E	E	C
M_5	E	F	G	G	E
Σ	C	D	D	E	B

Table 35 WACSS System Failure Probability Letter Designation.

The example System Failure Probability Letter Designation demonstrated in Table 35 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Steps 6.2 and 6.3

10. SAFETY ASSESSMENT INDEX SUMMATION RESULTS

M_1 Signal incompatibility / feedback to the Aircraft Data–Bus

P **Intermittent** E – Occasionally

P **Partial** F – Seldom

P **Critical** F – Seldom

P **Cataclysmic** F – Seldom

ΣP D – Periodically

ΣF F_1^$O_{3,}$ F_2^P_3

H_1 Aviation Data–Bus unable to process flight data

C_1 Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

V_2 II – Critical

S **Intermittent** Significantly Unsafe

S **Partial** Moderately Unsafe

S **Critical** Moderately Unsafe

S **Cataclysmic** Moderately Unsafe

ΣS Highly Unsafe

C_2 Inability to control aircraft – Loss of Airframe, Loss of Aircrew

V_1 I – Catastrophic

S **Intermittent** Significantly Unsafe

S **Partial** Moderately Unsafe

S **Critical** Moderately Unsafe

S **Cataclysmic** Moderately Unsafe

ΣP Highly Unsafe

C_3 Significant damage to vulnerable aviation software systems on the data–bus

V_3 III – Marginal / Moderate

$\mathbf{S}_{\textbf{Intermittent}}$ Moderately Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Minor Unsafe Issues
$\mathbf{S}_{\textbf{Critical}}$ Minor Unsafe Issues
$\mathbf{S}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
ΣP Significantly Unsafe

$\mathbf{C}_4$ Minor damage to vulnerable aviation software systems on the data–bus
$\mathbf{V}_4$ IV – Negligible
$\mathbf{S}_{\textbf{Intermittent}}$ Minor Unsafe Issues
$\mathbf{S}_{\textbf{Partial}}$ Minor Unsafe Issues
$\mathbf{S}_{\textbf{Critical}}$ Minor Unsafe Issues
$\mathbf{S}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
ΣP Moderately Unsafe

$\mathbf{M}_2$ Weapon fusing to detonate too early after weapon's release
$\mathbf{P}_{\textbf{Intermittent}}$ D – Periodically
$\mathbf{P}_{\textbf{Partial}}$ E – Occasionally
$\mathbf{P}_{\textbf{Critical}}$ E – Occasionally
$\mathbf{P}_{\textbf{Cataclysmic}}$ F – Seldom
ΣP D – Periodically
ΣF F_3^P_5, F_4^(I_2, P_1, O_1, I_6, P_3), F_5^(I_1, P_1, O_1, I_6, P_3), F_6^(O_4, I_8, P_4, O_6, I_{11}), F_7^O_{10}

$\mathbf{H}_2$ Weapon could inadvertently detonate close to delivery aircraft
$\mathbf{C}_5$ Loss of Airframe, Loss of Aircrew
$\mathbf{V}_1$ I – Catastrophic
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Moderately Unsafe
ΣS Highly Unsafe

$\mathbf{C}_1$ Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
$\mathbf{V}_2$ II – Critical
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Moderately Unsafe
ΣS Highly Unsafe

$\mathbf{H}_3$ Weapon not detonating on target
$\mathbf{C}_6$ Cost of Weapon
$\mathbf{V}_3$ III – Marginal / Moderate
$\mathbf{S}_{\textbf{Intermittent}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Moderately Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Moderately Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
ΣS Significantly Unsafe

C_1 Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

V_2 II – Critical

$S_{\text{Intermittent}}$ Highly Unsafe

S_{Partial} Significantly Unsafe

S_{Critical} Significantly Unsafe

$S_{\text{Cataclysmic}}$ Moderately Unsafe

ΣS Highly Unsafe

M_3 Inability to fuse weapon – Dead Fuse

$P_{\text{Intermittent}}$ D – Periodically

P_{Partial} E – Occasionally

P_{Critical} E – Occasionally

$P_{\text{Cataclysmic}}$ F – Seldom

ΣP D – Periodically

ΣF F_8^P_5, F_9^O_{10}, F_{10}^P_7, F_{11}^(I_1, I_2, P_1, O_1, I_6, P_3)

H_3 Weapon not detonating on target

C_6 Cost of Weapon

V_3 III – Marginal / Moderate

$S_{\text{Intermittent}}$ Significantly Unsafe

S_{Partial} Moderately Unsafe

S_{Critical} Moderately Unsafe

$S_{\text{Cataclysmic}}$ Minor Unsafe Issues

ΣS Significantly Unsafe

C_1 Inability to complete mission tasking, risk to friendly force protection, risk to own protection

V_2 II – Critical

$S_{\text{Intermittent}}$ Highly Unsafe

S_{Partial} Significantly Unsafe

S_{Critical} Significantly Unsafe

$S_{\text{Cataclysmic}}$ Moderately Unsafe

ΣS Highly Unsafe

M_4 Inability to prevent weapons release outside of the weapon's envelope

$P_{\text{Intermittent}}$ D – Periodically

P_{Partial} D – Periodically

P_{Critical} E – Occasionally

$P_{\text{Cataclysmic}}$ E – Occasionally

ΣP C – Likely

ΣF F_{12}^(I_1, I_2, P_1, O_1, I_6, P_3), F_{13}^(I_4, I_5, P_2, O_2, I_7, P_3), F_{14}^P_7, F_{15}^(P_7, O_{12}), F_{16}^(O_4, I_8, P_4, O_8, I_{13})

H_4 Weapon incapable of acquiring and striking the target

C_6 Cost of Weapon

V_3 III – Marginal / Moderate

$S_{\text{Intermittent}}$ Significantly Unsafe

S_{Partial} Significantly Unsafe

S_{Critical} Moderately Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Moderately Unsafe
$\mathbf{\Sigma S}$ Highly Unsafe

$\mathbf{H}_{\mathbf{5}}$ Danger to the airframe when deploying a weapon out of proper delivery parameters

$\mathbf{C}_{\mathbf{5}}$ Loss of Airframe, Loss of Aircrew

$\mathbf{V}_{\mathbf{1}}$ I – Catastrophic
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe
$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H}_{\mathbf{6}}$ Weapon could possibly fall on undesired target

$\mathbf{C}_{\mathbf{7}}$ Blue on White (Neutral) Collateral Damage

$\mathbf{V}_{\mathbf{2}}$ II – Critical
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe
$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H}_{\mathbf{7}}$ Weapon could possibly fall on friendly forces

$\mathbf{C}_{\mathbf{8}}$ Blue on Blue (Friendly Fire) Casualty

$\mathbf{V}_{\mathbf{1}}$ I – Catastrophic
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe
$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H}_{\mathbf{8}}$ Resulting lack of sufficient weapons to complete mission

$\mathbf{C}_{\mathbf{1}}$ Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

$\mathbf{V}_{\mathbf{2}}$ II – Critical
$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe
$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe
$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe
$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{M}_{\mathbf{5}}$ Drop incorrect weapon from pylon

$\mathbf{P}_{\textbf{Intermittent}}$ E – Occasionally
$\mathbf{P}_{\textbf{Partial}}$ F – Seldom
$\mathbf{P}_{\textbf{Critical}}$ G – Sporadically
$\mathbf{P}_{\textbf{Cataclysmic}}$ G – Sporadically
$\mathbf{\Sigma P}$ E – Occasionally
$\mathbf{\Sigma F}$ F_{17}^P_7, F_{18}^(P_4, I_9, O_8, I_{13}, P_7)

$\mathbf{H}_{\mathbf{9}}$ Loss of weapon due to incorrect targeting and delivery parameters

$\mathbf{C}_{\mathbf{6}}$ Cost of Weapon

- $\mathbf{V}_3$ III – Marginal / Moderate
- $\mathbf{S}_{\textbf{Intermittent}}$ Moderately Unsafe
- $\mathbf{S}_{\textbf{Partial}}$ Minor Unsafe Issues
- $\mathbf{S}_{\textbf{Critical}}$ Minor Unsafe Issues
- $\mathbf{S}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
- $\Sigma\mathbf{S}$ Moderately Unsafe

$\mathbf{H}_5$ Danger to the airframe when deploying a weapon out of proper delivery parameters

- $\mathbf{C}_5$ Loss of Airframe, Loss of Aircrew.
  - $\mathbf{V}_1$ I – Catastrophic
  - $\mathbf{P}_{\textbf{Intermittent}}$ Significantly Unsafe
  - $\mathbf{P}_{\textbf{Partial}}$ Moderately Unsafe
  - $\mathbf{P}_{\textbf{Critical}}$ Minor Unsafe Issues
  - $\mathbf{P}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
  - $\Sigma\mathbf{P}$ Significantly Unsafe

$\mathbf{H}_6$ Weapon could possibly fall on undesired target

- $\mathbf{C}_7$ Blue on White (Neutral) Collateral Damage
  - $\mathbf{V}_2$ II – Critical
  - $\mathbf{P}_{\textbf{Intermittent}}$ Significantly Unsafe
  - $\mathbf{P}_{\textbf{Partial}}$ Moderately Unsafe
  - $\mathbf{P}_{\textbf{Critical}}$ Minor Unsafe Issues
  - $\mathbf{P}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
  - $\Sigma\mathbf{P}$ Significantly Unsafe

$\mathbf{H}_7$ Weapon could possibly fall on friendly forces

- $\mathbf{C}_8$ Blue on Blue (Friendly Fire) Casualty
  - $\mathbf{V}_1$ I – Catastrophic
  - $\mathbf{P}_{\textbf{Intermittent}}$ Significantly Unsafe
  - $\mathbf{P}_{\textbf{Partial}}$ Moderately Unsafe
  - $\mathbf{P}_{\textbf{Critical}}$ Minor Unsafe Issues
  - $\mathbf{P}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
  - $\Sigma\mathbf{P}$ Significantly Unsafe

$\mathbf{H}_8$ Resulting lack of sufficient weapons to complete mission

- $\mathbf{C}_1$ Inability to complete mission tasking, risk to friendly force protection, risk to own protection.
  - $\mathbf{V}_2$ II – Critical
  - $\mathbf{P}_{\textbf{Intermittent}}$ Significantly Unsafe
  - $\mathbf{P}_{\textbf{Partial}}$ Moderately Unsafe
  - $\mathbf{P}_{\textbf{Critical}}$ Minor Unsafe Issues
  - $\mathbf{P}_{\textbf{Cataclysmic}}$ Minor Unsafe Issues
  - $\Sigma\mathbf{P}$ Significantly Unsafe

$\Sigma\mathbf{M}$ Failure in the operation of the WACSS

- $\mathbf{P}_{\textbf{Intermittent}}$ C – Likely
- $\mathbf{P}_{\textbf{Partial}}$ D – Periodically
- $\mathbf{P}_{\textbf{Critical}}$ D – Periodically
- $\mathbf{P}_{\textbf{Cataclysmic}}$ E – Occasionally

ΣP B – Frequent

H_1 Aviation Data–Bus unable to process flight data

C_1 Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

V_2 II – Critical

$S_{\text{Intermittent}}$ Extremely Unsafe

S_{Partial} Highly Unsafe

S_{Critical} Highly Unsafe

$S_{\text{Cataclysmic}}$ Significantly Unsafe

ΣS Extremely Unsafe

C_2 Inability to control aircraft – Loss of Airframe, Loss of Aircrew

V_1 I – Catastrophic

$S_{\text{Intermittent}}$ Extremely Unsafe

S_{Partial} Highly Unsafe

S_{Critical} Highly Unsafe

$S_{\text{Cataclysmic}}$ Significantly Unsafe

ΣS Unsafe

C_3 Significant damage to vulnerable aviation software systems on the data–bus

V_3 III – Marginal / Moderate

$S_{\text{Intermittent}}$ Highly Unsafe

S_{Partial} Significantly Unsafe

S_{Critical} Significantly Unsafe

$S_{\text{Cataclysmic}}$ Moderately Unsafe

ΣS Extremely Unsafe

C_4 Minor damage to vulnerable aviation software systems on the data–bus

V_4 IV – Negligible

$S_{\text{Intermittent}}$ Significantly Unsafe

S_{Partial} Moderately Unsafe

S_{Critical} Moderately Unsafe

$S_{\text{Cataclysmic}}$ Minor Unsafe Issues

ΣS Highly Unsafe

H_2 Weapon could inadvertently detonate close to delivery aircraft

C_5 Loss of Airframe, Loss of Aircrew

V_1 I – Catastrophic

$S_{\text{Intermittent}}$ Extremely Unsafe

S_{Partial} Highly Unsafe

S_{Critical} Highly Unsafe

$S_{\text{Cataclysmic}}$ Significantly Unsafe

ΣS Unsafe

C_1 Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

V_2 II – Critical

$S_{\text{Intermittent}}$ Extremely Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe

$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H_3}$ Weapon not detonating on target

$\mathbf{C_6}$ Cost of Weapon

$\mathbf{V_3}$ III – Marginal / Moderate

$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Significantly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Moderately Unsafe

$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{C_1}$ Inability to complete mission tasking, risk to friendly force protection, risk to own protection

$\mathbf{V_2}$ II – Critical

$\mathbf{S}_{\textbf{Intermittent}}$ Extremely Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe

$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H_4}$ Weapon incapable of acquiring and striking the target

$\mathbf{C_6}$ Cost of Weapon

$\mathbf{V_3}$ III – Marginal / Moderate

$\mathbf{S}_{\textbf{Intermittent}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Significantly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Significantly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Moderately Unsafe

$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H_5}$ Danger to the airframe when deploying a weapon out of proper delivery parameters

$\mathbf{C_5}$ Loss of Airframe, Loss of Aircrew.

$\mathbf{V_1}$ I – Catastrophic

$\mathbf{S}_{\textbf{Intermittent}}$ Extremely Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe

$\mathbf{\Sigma S}$ Unsafe

$\mathbf{H_6}$ Weapon could possibly fall on undesired target

$\mathbf{C_7}$ Blue on White (Neutral) Collateral Damage

$\mathbf{V_2}$ II – Critical

$\mathbf{S}_{\textbf{Intermittent}}$ Extremely Unsafe

$\mathbf{S}_{\textbf{Partial}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Critical}}$ Highly Unsafe

$\mathbf{S}_{\textbf{Cataclysmic}}$ Significantly Unsafe

$\mathbf{\Sigma S}$ Extremely Unsafe

$\mathbf{H_7}$ Weapon could possibly fall on friendly forces

$\mathbf{C_8}$ Blue on Blue (Friendly Fire) Casualty

$\mathbf{V_1}$ I – Catastrophic

$\mathbf{S}_{\mathbf{Intermittent}}$	Extremely Unsafe
$\mathbf{S}_{\mathbf{Partial}}$	Highly Unsafe
$\mathbf{S}_{\mathbf{Critical}}$	Highly Unsafe
$\mathbf{S}_{\mathbf{Cataclysmic}}$	Significantly Unsafe
$\mathbf{\Sigma S}$	Unsafe

$\mathbf{H_8}$ Resulting lack of sufficient weapons to complete mission

$\mathbf{C_1}$ Inability to complete mission tasking, risk to friendly force protection, risk to own protection.

$\mathbf{V_2}$ II – Critical

$\mathbf{S}_{\mathbf{Intermittent}}$	Extremely Unsafe
$\mathbf{S}_{\mathbf{Partial}}$	Highly Unsafe
$\mathbf{S}_{\mathbf{Critical}}$	Highly Unsafe
$\mathbf{S}_{\mathbf{Cataclysmic}}$	Significantly Unsafe
$\mathbf{\Sigma S}$	Extremely Unsafe

$\mathbf{H_9}$ Loss of weapon due to incorrect targeting and delivery parameters

$\mathbf{C_6}$ Cost of Weapon

$\mathbf{V_3}$ III – Marginal / Moderate

$\mathbf{S}_{\mathbf{Intermittent}}$	Highly Unsafe
$\mathbf{S}_{\mathbf{Partial}}$	Significantly Unsafe
$\mathbf{S}_{\mathbf{Critical}}$	Significantly Unsafe
$\mathbf{S}_{\mathbf{Cataclysmic}}$	Moderately Unsafe
$\mathbf{\Sigma S}$	Extremely Unsafe

System Objects	Malfunction	Hazard	Consequence	S Intermittent	S Partial	S Critical	S Cataclysmic	ΣS
F_1^O_3, F_2^P_3	M_1	H_1	C_1	II E	II F	II F	II F	II D
			C_2	I E	I F	I F	I F	I D
			C_3	III E	III F	III F	III F	III D
			C_4	IV E	IV F	IV F	IV F	IV D
F_3^P_5, F_4^(I_2, P_1, O_1, I_6, P_3), F_5^(I_1, P_1, O_1, I_6, P_3), F_6^(O_4, I_8, P_4, O_6, I_{11}), F_7^O_{10}	M_2	H_2	C_5	I D	I E	I E	I F	I D
			C_1	II D	II E	II E	II F	II D
		H_3	C_6	III D	III E	III E	III F	III D
			C_1	II D	II E	II E	II F	II D
F_8^P_5, F_9^O_{10}, F_{10}^P_7, F_{11}^(I_1, I_2, P_1, O_1, I_6, P_3)	M_3	H_3	C_6	III D	III E	III E	III F	III D
			C_1	II D	II E	II E	II F	II D
F_{12}^(I_1, I_2, P_1, O_1, I_6, P_3), F_{13}^(I_4, I_5, P_2, O_2, I_7, P_3), F_{14}^P_7, F_{15}^(P_7, O_{12}), F_{16}^(O_4, I_8, P_4, O_8, I_{13})	M_4	H_4	C_6	III D	III D	III E	III E	III C
		H_5	C_5	I D	I D	I E	I E	I C
		H_6	C_7	II D	II D	II E	II E	II C
		H_7	C_8	I D	I D	I E	I E	I C
		H_8	C_1	II D	II D	II E	II E	II C
F_{17}^P_7, F_{18}^(P_4, I_9, O_8, I_{13}, P_7)	M_5	H_9	C_6	III E	III F	III G	III G	III E
		H_5	C_5	I E	I F	I G	I G	I E
		H_6	C_7	II E	II F	II G	II G	II E
		H_7	C_8	I E	I F	I G	I G	I E
		H_8	C_1	II E	II F	II G	II G	II E

Table 36 WACSS Malfunction to Safety Assessment

The example Malfunction to Safety Assessment Table demonstrated in Table 36 serves as an illustration to the dissertation model in Chapter V.E.3.b and process Step 6. Action 3. The Malfunction to Safety Assessment and the corresponding Hazard to Consequence intersection is obtained through the relationship earlier introduced with the concept of the Safety Assessment Index as [S = Σ *P*(H) * *C*(H)] in Equation 1. Using the M_1, Intermittent Case, for Consequence C_3 as F_1^O_3 → M_1:

Where:

P_e O_3 0.40

$P_{f\ Intermittent}$ F_1 $2.5000\text{x}10^{-5}$

Intermittent $(2.5000\text{x}10^{-5} * 0.40) = 1.0000\text{x}10^{-5}$ ∴

With the resultant value entered into Table 33, to obtain to a Frequency of "OCCASIONAL." The Occasional value can be entered into the Probability axis of the Probability vs. Severity values of Table 34 with a Severity axis value of "Moderate", corresponding to the severity of the applicable causality. The resulting intersection derives a value of **III E** or "**Moderate,**" corresponds to the degree for which the system is determined unsafe. The textual definition of "Moderate" can be then referenced back to the Consequence Severity Categories defined in Table 21 of the example.

11. PROCESS PROCEDURES

Step 1. Action 1. – System Task / Safety Requirement Analysis – Identify the primary safety requirements of the system through a review of concept level requirements, including system objects, properties, tasks, and event. Identify system safety requirements as they pertain to system state and operating environment. Additional safety requirements may be identified using historical precedents and rationalization from similar systems. System requirements should be inspected for completeness and the inclusion of system safety logic controls and interlocks, where applicable. Assessments should be made to evaluate size, time, effort, defects, and system complexity.

Step 1. Action 2. – Hazard Identification – Perform a hazard identification of the software system based on concept level system requirements, system tasks, and historical precedents. Identification includes identifying the Hazards, Consequences, and Malfunctions potentially occurring from the three states of hazard occurrence.

Step 2. Action 1. – Development of Consequence Severity Categories – Develop a prioritized list of Consequence Severity Categories, ranging from the most severe to

the least severe possible consequence. Severity categories should be well defined to eliminate confusion and provide distinct boundaries between.

Step 2. Action 2. – Initial Hazard Assessment – Perform an initial hazard assessment of the system by classifying hazards according to Consequence Severity, based on an agreed table of Consequence Severity Categories.

Step 3. Action 1. – Choose a Process Depiction Model – Determine the optimal process depiction model to perform a safety assessment of the system. This process model should be capable of depicting requirement process flow, logic decisions, conflict and recovery, and the isolation of function failure to hazard execution.

Step 3. Action 2. – Identify Objects Required to Populate the Process Model – Determine the initial set of objects required to populate the process model identified in Step 3.1. using system requirements identified in Step 1.1. Once object sets are identified, populate sets with applicable high–level object items and properties. Items and properties include, but are not limited to, process inputs, outputs, and connections.

Step 3. Action 3. – Pictorially Map the System Process – In accordance with the process model identified in Step 3.1., and process objects identified in Step 3.2., map the system process, to include all high–level system processes, inputs, outputs, and limits.

Step 4. Action 1. – Identify and Match corresponding Failures to Malfunctions. – In accordance with the malfunctions identified in Step 1.2., and process objects outlined in Step 3.2., identify the potential system failures that could eventually result in identified safety–related malfunctions. If identified failures relate to malfunctions not previously identified, return, and repeat the system assessment from Step 1, Action 2. Identified failures are then matched to specific process objects.

Step 4. Action 2. – Add Identified Failures to the System Process Map – Using the process map completed in Step 3.3., and failures identified in Step 4.1., add

identified failures to their corresponding locations on the process map using agreed process graph symbology.

Step 5. Action 1. – Development of Failure Severity Categories – Develop a prioritized list of Object Failure Severity Categories with applicable definitions. Using Failure Modes, Effects, and Criticality Analysis (FMECA)[352] ***techniques, severities shall define the types of failures that a specific object could potentially experience, ranging from the benign to the catastrophic, and the potential effect of that failure on the system as a whole. As the assessment is designed to evaluate system safety, it is possible to disregard object failure types that do not relate or result in hazardous events.***

Step 5. Action 2. – Development of Execution Probability Definition Categories – Develop a prioritized list of Execution Probability Definition Categories with applicable probability levels, frequency keywords, and definitions.

Step 5. Action 3. – Assign Execution Probabilities to System Objects – Using the Process Map generated in Step 3.3., assign Execution Probabilities to all system objects that relate to system failures identified in Steps 4.1. and 4.2. Execution Probabilities should be based on system inspection, historical precedents, and examination.

Step 5. Action 4. – Development of Object Failure Probability Definition Categories – Develop a prioritized list of Failure Probability Definition Categories with applicable probability levels, frequency keywords, and definitions as they apply to specific objects within the system.

Step 5. Action 5. – Assign Failure Probabilities to System Objects – Using the Process Map generated in Step 3.3., the Failure Process Map from Step 4.2., and Failure Severity Categories defined in Step 5.1., assign Failure Probabilities to all system objects that relate to system failures identified in Steps 4.1. and 4.2. for each

[352] *NASA/SP—2000–6110, Failure Modes and Effects Analysis (FMEA), A Bibliography*, National Aeronautics and Space Administration; July 2000.

severity of failure. Failure Probabilities should be based on system inspection, historical precedents, and examination.

Step 5. Action 6. – Determine Possible System Hazard Flow – Using the Process Map generated in Step 3.3., the Failure Process Map from Step 4.2., and the Failure to Malfunction Identification of Step 4.1., determine the possible System to Hazard Process Flow. Such a Process Flow should include all system objects that could potentially result in a malfunction and eventually a failure.

Step 5. Action 7. – Determine Failure Probability for each Malfunction – Using the Object Failure Probabilities from Step 5.5. and the Hazard Flow generated in Step 5.6., determine the cause and effect failure probability of the system. System Probability should include consideration of all reliant or dependent objects to the system process.

Step 6. Action 1. – Development of System Failure Probability Definition Categories – Develop a prioritized list of Failure Probability Definition Categories with applicable probability levels, frequency keywords, and definitions as they apply to the system as a whole.

Step 6. Action 2. – Development of the Probability vs. Severity Table – Develop a two dimensional table representing System Failure Probability on the Horizontal Axis and Hazard Criticality on the Vertical Axis. Assign applicable safety values to table cells to represent the safety or un–safety of the system based on each occurrence and corresponding safety level for a given intersection scenario.

Step 6. Action 3. – Determination of the Safety Assessment Index (SAI) – Using the Probability vs. Severity Table developed in Step 6.1., and Failure Summations from Step 5, determine the SAI for malfunctions and the summation of the system by the intersection of event probability to hazard severity. SAI results should then be displayed using the method most practicable to the evaluation requirements.

Step 7. Action 1. – Determine Required Improvements – Determine the system improvements required to decrease independent and system SAI values to an acceptable level, identifying appropriate controls of Avoidance, Reduction, Spreading, and/or Transference to each element. Identify quantitative improvement goals for each object that is to be improved, countered by required resources, and cost vs. benefits of the actual improvement.

Step 7. Action 2. – Incorporate Safety Controls – Incorporate the Safety Controls identified in Step 7.1. into the Software System. Changes should be well documented in requirement specifications and code development specifications. Any refinements and improvements should take into consideration their effect on present objects as well as any related or reliant objects within the system.

Step 8. Action 1. – Determine the Subjective Elements to System Safety Development. Determine the subjective elements to system development that relate to safety and the prevention of a hazardous event. Determine applicable measures and definitions to classify and assess elements for their potential effect to the system.

Step 8. Action 2. – Evaluate System Subjective Elements. Evaluate the software system for elements identified in Step 8.1. Assign a grade or measure to system elements indicating their compliance to assigned definitions, derived from Step 2 Action 1 and Step 5, Actions 1 through 7. Summarize evaluated elements to determine the overall effect of subjective elements on software system safety.

Step 9. – Supervise the Safety Development – Using accepted methods of supervision and software management, supervise the development of the software system to ensure compliance with the principles of safety development. Ensure compliance with applicable development methods, system requirements, and safety assessments. Ensure that system developmental failures are identified and remedied as soon as possible in the current or next development cycle, or are acknowledged for

their fragility to customers. At the completion of the current developmental cycle, commence where applicable, the next successive cycle and Step 1.1 of the Safety Assessment.

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