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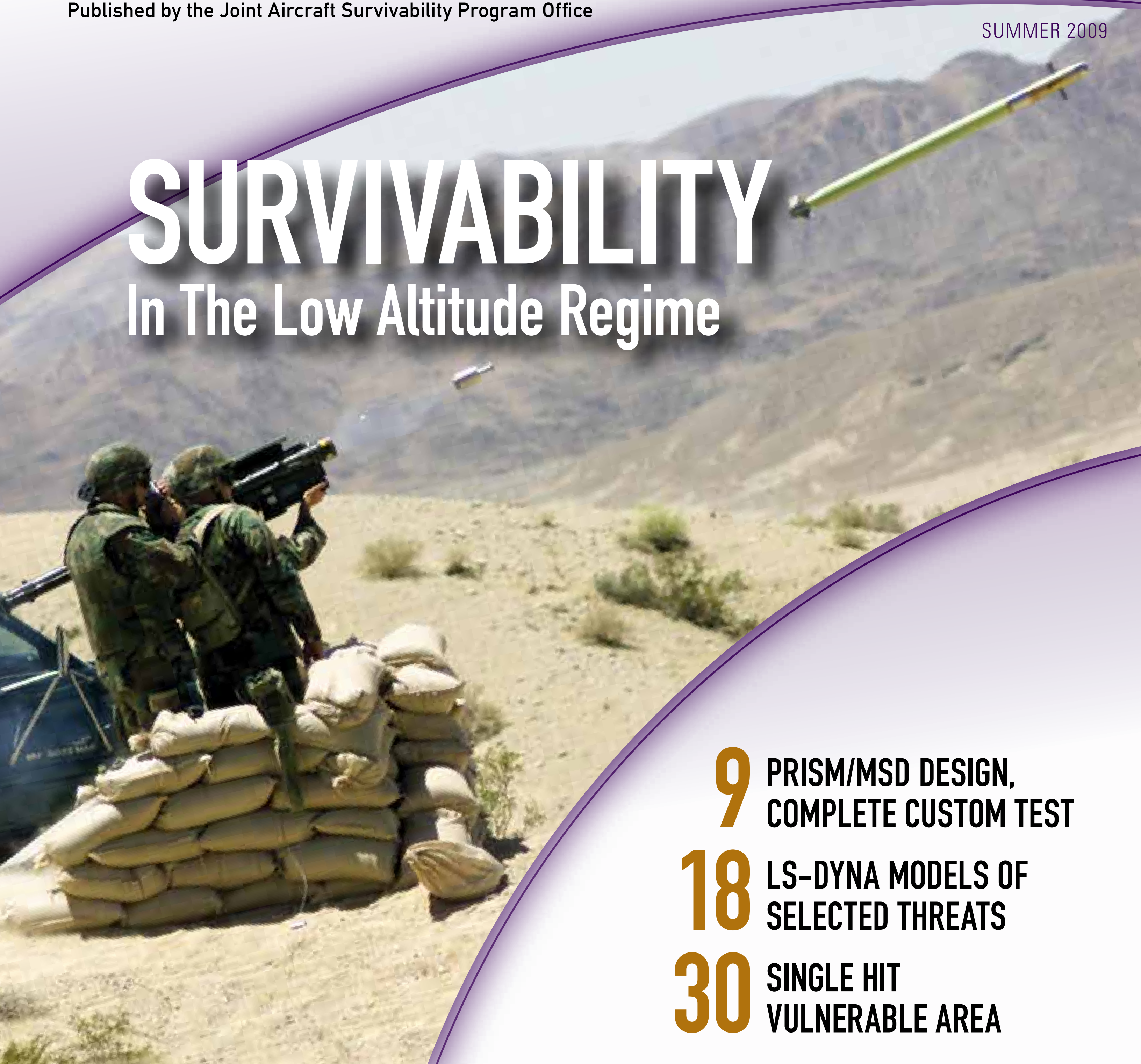
In The Low Altitude Regime



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by Jennifer Amber

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by Torger Anderson and Kenneth Mathiasmeier

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18 LS-DYNA Models of Selected Guided and Unguided Threats
by Ronald Hinrichsen and Alex Kurtz

Over the past nine years, projects have been funded to develop finite element models of selected threats for use by analysts in performing design and pre-test predictions of damage to aircraft structures. These projects have incorporated parallel efforts that integrate the first-principle, high-fidelity, nonlinear structural analysis code, LS-DYNA, and test data to advance the state of the art in vulnerability analysis techniques and in understanding aircraft-threat encounters. The work has resulted in a library of LS-DYNA models of both guided and unguided threats. This article presents a summary of methodology development and list of models currently available.

20 Relationship between Lower Explosive Limit and Ullage Combustion Reactions
by Mark Couch and Vincent Volpe

Aviation jet fuels are typically a complex blend of paraffinic, olefinic, naphthenic, and aromatic hydrocarbons controlled only by the defined boiling point ranges. The actual composition of a fuel batch is highly dependent on the source of crude oil and the manufacturer, but generally JP-8 fuel (very similar to Jet A) consists of 75 to 90% paraffins, both straight chain and cyclohexanes, the remainder consisting almost entirely of aromatic compounds, including naphthalene, benzene, xylene, and toluene. In a partially filled fuel tank, hydrocarbon molecules will escape from the liquid into the vapor space above it. In a fully enclosed fuel tank, vapor from both lighter and heavier molecules will accumulate until equilibrium is reached, provided the conditions of the tank (temperature, pressure, and volume of the liquid) remain constant.

25 Excellence in Survivability—Dr. T.N. Mikel
by Dale Atkinson

The Joint Aircraft Survivability Program (JASP) is pleased to recognize Dr. T.N. (Mike) Mikel for Excellence in Survivability. Dr. Mikel is currently the chief engineer for the US Marine Corps H-1 Upgrade Program at Bell Helicopter Textron. In this position, he is responsible for all H-1 engineering for the UH-1Y USMC Utility Helicopter and the AH-1Z USMC Attack Helicopter, as well as having program responsibilities for the Build New AH-1Z and UH-1Y. The UH-1Y is now in full rate production, having achieved initial operating capability in August 2008. The AH-1Z is in the low rate initial production phase, with full rate production and initial operating capability planned for 2011.

27 Annual NDIA Survivability Awards Presented at Aircraft Survivability 2008
by Dennis Lindell

The National Defense Industrial Association's (NDIA) Combat Survivability Division (CSD) held its annual Aircraft Survivability Symposium at the Naval Postgraduate School on 4–7 November 2008. The Aircraft Survivability 2008 theme was "Low Altitude Today, Preparing for Tomorrow." As the theme implied, the agenda was divided into sessions that explored how we can best balance our resources to meet the challenges of fighting the current Global War on Terror at low altitude, while preparing for the next major conflict.

30 The Educator's Corner—Single Hit Vulnerable Area
by Mark Couch

Welcome to the inaugural article of The Educator's Corner. Several of those involved in survivability education have volunteered to write a series of short articles for the journal. Initially, authorship of this article will rotate between CDR (Ret) Chris Adams from the Naval Postgraduate School, Maj Rich Huffman from the Air Force Institute of Technology, and Dr. Mark Couch from the Institute for Defense Analyses. Because many of our readers may have extensive expertise in specific aspects of survivability, our goal is to broaden the readers' appreciation for the diversity of the survivability discipline and maybe learn something new in the process.

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by Dennis Lindell

Bud Gilbert

Lillard E. "Bud" Gilbert passed away on 27 March 2009, while fishing in Riverside, OH. Bud spent most of his childhood on Lost Creek in Greenup County, KY. After graduating from high school, Bud attended Berea College for two years and then enlisted in the Air Force in 1951. After returning from the Air Force, he married, finished college at Morehead State University with a degree in math and physics, and taught high school math for a year. In 1960, he took a job at Wright Patt, where he began work as a physicist conducting research in impact physics. In 1965, Dale Atkinson asked him to do some gunfire tests on an F-105 wing while Dale went to SEA to determine the cause of aircraft losses. Based on the results, Dale asked Bud to set up a gunfire test facility in an old gun range left over from World War II. Bud designed and supervised the building of Ranges 2 and 3 in what is now called the Air Force Aerospace Vehicle Survivability Facility. Range 3 was a vertical firing facility to which airflow was later added to conduct realistic gunfire tests simulating aircraft in flight. Bud later volunteered to go to SEA for six months as a member of the Battle Damage Assessment and Reporting Team that was set up as a result of the recommendations from the SEA fact-finding trips. Bud became an expert in foreign warheads and conducted a number of seminars on this subject for the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), now the Joint Aircraft Survivability Program (JASP). Bud knew more about foreign warheads than anybody but the original developers, and maybe some of them. Bud always had a number of containers of warhead fragments, which greatly helped people understand these warheads when he gave the seminars. Bud was inducted into the Morehead Alumni Hall of Fame for becoming the nation's leading expert on warhead characterization. Bud retired in 1986 and continued working as a consultant in the aircraft survivability arena until he retired for good in 2000 to enjoy life with his wife, children, and grandchildren. Bud was a good man and will be greatly missed by all who knew him.

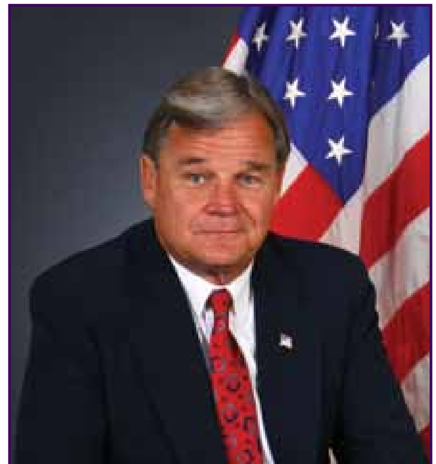
Terry Dougherty

Recently, our friend and colleague, Terry Dougherty, was diagnosed with Amyotrophic lateral sclerosis (ALS), often referred to as "Lou Gehrig's Disease." Terry is a leader in the hardware-in-the-loop simulator community and a good friend of the JASP. The work he performed for the JASP recently significantly increased our understanding of rotary wing aircraft survivability, and resulted in important equipment fielding decisions that improved the survivability of those systems. Terry was the driving force for the Threat Signal Processor-in-the-Loop facility at the Naval Air Warfare Center–Weapons Division, China Lake, but his illness required him to step down from that position. The JASP thanks Terry for his service to our country and the lasting benefit to the protection of our nation's soldiers, sailors, airmen, and marines.

Al Wearner Retires

Allan Wearner began his career in 1971 at China Lake's VX-5 Air Test and Evaluation Squadron. He worked on various weapons systems undergoing operational evaluations at China Lake and aboard aircraft carriers for carrier suitability testing. After Al's four-year stint in the Navy, he was hired by LTV Aerospace and built QT-38s and QF-86 Drones to be used as airborne targets for missile testing. He was then promoted as the LTV site manager for the Weapons Survivability Laboratory (WSL) support contract in 1977.

In 1983, he became a civil servant as a firing officer, organizing, conducting, and overseeing ballistic testing at the WSL for the JTCG/AS and the Naval Air Combat Survivability RDT&E Program. As Congress and Secretary of Defense began placing increased importance on realistic survivability testing in the 1986 time frame with the advent of the "Live Fire


Al Wearner

Test Law," Al was quick to grasp the importance of developing test methods that would realistically stress the Navy's and Marine Corps' aircraft being developed for future combat. He was instrumental in the development of test procedures and processes that enabled high confidence in test results and technical solutions for the problems found in testing.

Also during the 1980s, Al was the principal force behind the establishment and smooth operation of the Navy and Marine Corps Aircraft Battle Damage Repair (ABDR) School. Seizing the opportunity to ensure high-quality training to sailors and marines who needed to understand the nature of battle damage and develop expedient battlefield repair techniques, policies, and procedures, Al was instrumental in the co-location of the ABDR School with the WSL. Thus, the active duty students were provided training hardware that had been subjected to "combat damage" as a result of live fire testing at the WSL. The ABDR School was also able to draw on the WSL resources to develop repair methods that could be quickly applied in the field and onboard ships to regenerate damage aircraft to sustain warfighting capability.

In 1988, Al was selected as the head of the Survivability Engineering Branch and also was appointed as the Navy deputy test director for the Joint Live Fire (JLF)

Program. In this role, Al oversaw JLF test efforts conducted on the F/A-18, A-6, AV-8, F-14, H-1, H-53, and various foreign aircraft systems. Al has led the way in many cases to add as much realism to testing as possible. Through his forethought and perseverance, he was instrumental in pushing the development of many advanced test capabilities, such as firing ballistic rounds at running helicopter blades, development of the Missile Engagement Threat Simulator to fire Man-Portable Air Defense Systems (MANPADS) missiles, and the Spin Fixture to run aircraft components at actual operation speeds.

Al Wearner receiving award from the JLF-Air Joint Test Director, CAPT Ken Branham, USN. From left to right—Mr. Rick Seymour, (from DOT&E/LFT), CAPT Branham, Al Wearner and Mr. Matt Crouch, JASP Deputy Program Manager for Vulnerability Reduction

Al was also appointed as the Navy co-chair of the Vulnerability Subgroup for the JTCG/AS, now the JASP, and has provided Navy leadership to meet the goals of this joint survivability program. Al's leadership, management skills, insight, and personal commitment led to his selection to serve a key member of the Trans World Airlines 800 investigation. In this role, he was responsible for communicating and coordinating Navy engineering investigative support that provided essential conclusions to support Federal Bureau of Investigation (FBI) and National Transportation Safety Board findings. Recognizing his insight, he was invited to brief the Assistant Director of the FBI, James Kalstrom, and subsequently sold him on the development of a Portable Resource for the Investigation of Suspected MANPADS developed by the Survivability Division, which the FBI deployed internationally to support their field offices.

Al has made many contributions to the aircraft survivability design community, the JASP, and the warfighter. At the recent JASP/JLF-Air MANPADS Roadmap meeting, Al's insight and recommendations were invaluable, and he was presented with a letter of appreciation signed by the director of Life Fire Test & Evaluation. He also received an appreciation award from JASP and JLF-Air for his many contributions and life long commitment to "Saving Lives and Winning Wars."

JCAT Corner by CAPT Kenneth Branham, USN

Commander (CDR) Tim "TJ" Johnson, USN, arrived in Baghdad January 2009, serving as both the Joint Combat Assessment Team (JCAT) Officer in Charge (OIC) (FWD)/Liaison Officer and Surface-to-Air-Fire Manager (SAFIRE). He took the reins from CDR Burnette. His duties as the SAFIRE Manager, which includes collecting, organizing, and reporting SAFIRE information throughout the entire theater, are critical to combatant commanders and analysis personnel alike. CDR Johnson participated in collaborative SAFIRE working group meeting with all MND/F at the Combined Air Operations Center. The working group's results led to some substantial improvements to consistency in SAFIRE reporting throughout the Area of Responsibility and led to a major operation order update. As JCAT Liaison Officer, CDR Johnson provides Multi-National Corps-Iraq and battlefield commanders key tools to conduct aircraft battle damage assessments/investigations and forensic analysis, and provides training to combat aviation brigades. As the JCAT Operation Iraqi Freedom OIC, CDR Johnson ensures assessors are properly trained and performing assessments according to JCAT standards. CDR Johnson presented a JCAT overview and an Operation Iraqi Freedom threat trend assessment briefing at Weapons and Tactics Conference 09-01. He also has developed a working relationship with the Department of State, Field Investigative Unit, working in partnership on a Department of State incident. CDR Johnson, First Lieutenant Belliss, USAF, and the Army Shoot Down Assessment Team worked together on an extremely complex assessment.

CDR Paul Kadowaki, USN, assumed the duties of JCAT Operation Enduring Freedom OIC in Kandahar, Afghanistan, from CDR Craig Black in March 2009. He is attached to the Special Purpose Marine Air-Ground

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CDR Johnson at the Syrian Border

Survivability in the Low Altitude Regime—MANPADS Miss Distance Assessment

by Jaime Bestard and Gregory Czarnecki

The lethal, highly portable, concealable, and inexpensive Man-Portable Air Defense Systems (MANPADS) have been effective weapons in the hand of guerrillas and terrorists. MANPADS encounters with aircraft have resulted in numerous deaths and major losses. Furthermore, U.S. involvement in Afghanistan and Iraq, and the asymmetric nature of conflict in these theaters, have resulted in numerous military aircraft losses to MANPADS.

Large aircraft are particularly vulnerable to MANPADS due to their corresponding infrared (IR) signatures and exposed surface areas. In fact, over the past 26 years, 35 civilian aircraft have been attacked by these weapons, resulting in 24 shot down and more than 500 deaths. [1] Likewise, the U.S. Transportation Command (USTRANSCOM) tracks MANPADS incidents against military aircraft with most incidents occurring against large aircraft and rotorcraft, though unclassified updates are unavailable. In addition, post-attack investigations have not provided conclusive assessments, mainly due to differences in the impact points, damage, aircraft, and missiles involved. Consequently, USTRANSCOM has identified MANPADS as the most serious threat to U.S. air mobility.

Need for Miss Distance Measurements

Other than the few incidents for which the aircraft survived, damage resulting from a MANPADS attack is not adequately quantified. MANPADS can engage aircraft as high as 3.5 kilometers and as far as 5.2 kilometers at speeds in excess of Mach 2. [2] Therefore, aircraft are highly vulnerable at takeoff, landing, and during low altitude operations. MANPADS usually track an aircraft's engines due to their large IR signature. However, missiles often impact the aircraft structure, causing damage to critical systems and possible cascading effects (*e.g.*, fire initiation in the engine or wing dry bays, loss of control, and loss of thrust).

MANPADS attack on Airbus A300

Closeup of MANPADS attack on Airbus A300

Miss distance measurements present a baseline for assessing missile effectiveness. Miss distance assessments provide the modeling and simulation community with inputs necessary for determining statistically significant shot lines and endgame predictions. Adequate predictions increase the credibility of modeling and simulation results. Moreover, MANPADS miss distance measurements aid in countermeasure investment decisions by increasing the knowledge of probability of hit. Considering the benefits of measuring miss distance, the Joint Aircraft Survivability Program and the Joint Live Fire program have funded efforts to measure MANPADS miss distance during ongoing tests executed by the 46th Test Wing (46 TW).

Miss Distance Measurements

The 46 TW has been conducting MANPADS tests at Tonopah Test Range, Nevada, and at Eglin Air Force Base, Florida. These tests simulate different IR sources (*i.e.*, targets) at representative ranges and varying environmental conditions. Major program offices conduct tests to assess missile and countermeasure effectiveness. The 46 TW's Aerospace Survivability and Safety Technical Area (46 OG/780 TS/OL-AC) has been present at various tests since 2005, collecting video and other supporting data for more than 300 individual test events serving different program offices throughout the Department of Defense.

The video data collection efforts have evolved with time, with technicians and engineers gaining valuable experience involving optimal camera placement and surveying procedures. Furthermore, video data acquisition equipment has been improved with increased awareness of the miss distance assessment effort and subsequent interest by program offices to obtain this valuable measure of effectiveness.

Currently, the 46 OG/780 TS/OL-AC is able to deploy equipment and personnel with a very short notice to ranges performing MANPADS testing. Technicians collect video data from several cameras as well as supporting data that can influence each test's outcome. Supporting data collected during each test event includes launch time and range, super elevation, sun location, temperature, humidity, ozone level, visibility, cloud coverage, and wind speed and direction.

MANPADS missile test launcher and target array

Subsequently, video data is processed to obtain the missile's position as it crosses the target array plane. Processing includes a series of algorithms for data extraction and triangulation based on known stereovision concepts. Acquisition and processing of video data are constantly improving due to the imperfect conditions (*e.g.,* rugged and changing environments, surveying difficulties, and equipment limitations) and the different test ranges. Miss distance is computed as the shortest distance to any of the active targets. Afterward, updates are made to the miss distance database and correlations between miss distance and the different influencing factors (*e.g.,* weather, launch range) for each missile type.

Related Efforts

As the MANPADS miss distance assessment effort has caught the attention of program offices and joint service programs, interest has grown in applying the data acquisition and processing methods to different measurements. An example of such measurements is missile launch tipoff angle, which, according to experts in MANPADS hardware-in-the-loop simulations, has a considerable effect on the outcome of an engagement.

Requirements for ease of setup and higher fidelity data have produced a Small Business Innovation Research program request for Phase I proposals. This request seeks the development and demonstration of a portable, inexpensive, noncontact, and verifiably accurate method of measuring missile miss distance. The expected outcome is an autonomous system that can be set up by one technician and controlled remotely (even off the test range). In addition, such a system can be modularized to use a variety of sensors for different measurements.

Summary

MANPADS miss distance measurements using video data have been obtained since 2005, resulting in an increased understanding of their effectiveness and damage potential. Video data acquisition has enhanced the verifiability and accuracy of miss distance measurements. MANPADS miss distance assessment efforts have required the adaptation of processing methods and acquisition technologies to rugged and potentially unsafe environments. Successful collection of miss distance data has resulted in increased interest and the adjustment of the process for additional measurement needs during MANPADS tests.

MANPADS miss distance is a useful measure of a missile's effectiveness in support of present and future test and evaluation. Miss distance assessments will be used for verification of endgame scenarios in support of modeling and simulation. In addition, assessments will assist investment decisions for countermeasures, hardened structural designs, and other susceptibility and vulnerability reduction solutions. ■

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PRISM/MSD Design, Complete Custom Test

by Jennifer Amber

In the heat of New Mexico summer sun, at the location of a brand-new national test asset nestled amongst the sand and scrub brush in near-seclusion, members of the Patuxent River Infrared Signature Measurement (PRISM) team gathered to conduct a challenging project that many in the Test and Evaluation (T&E) community said could not be done.

The PRISM team, part of the Atlantic Test Ranges' Aircraft Signature & Avionics Measurement Branch (5.2.4.2), responded to a request to acquire infrared (IR) data every one degree around a target at multiple elevations. Despite the initial simplicity of the test concept, there were a multitude of test parameters that, when combined, required a significant level of logistical, organizational, and asset commitment. This project required the PRISM team to significantly deviate from its standard mode of operation and provide a solution that would result in several hundred thousand data points. One thing was for sure: the only way to acquire that much data with such precision was to devise a test that would be completely automated.

At the White Sands Missile Range in New Mexico, ATR's PRISM team installs one of the test targets custom designed and built for Coyote Test by AVMI Mechanical Solutions Division employee Mark Phippen.

The Target

As with most Naval Air Systems Command programs, the test requirements for this project were well defined, but the path to actualize the requirements forced each participant involved to think and derive numerous custom solutions for each component of the test. The first major task was the fabrication of the test target.

This test required five custom-built targets that represented several facets of a typical aircraft skin. The targets had to be as smooth as possible, while exhibiting flat, singly and doubly curved surfaces. PRISM selected the Mechanical Solutions Division (MSD, 5.2.8) of Air Vehicle Modification and Instrumentation to fabricate the targets.

After meeting with the PRISM team to be briefed on project requirements, MSD employee Mark Phippen began to design and create the targets. Design ingenuity, initiative, and creativity were of the utmost importance, as there were no blueprints from which to draw inspiration and guidance. In the end, Phippen designed and fabricated the targets using flush-mounted rivets, pre-curved sheet metal panels, and custom-made brackets. He also designed a method to attach and remove all fixtures to a tower using a precision slip-fit ring, which would prove to be accurate, repeatable, quick, and safe.

Often working extra hours and weekends, Phippen was able to fabricate five large and five small test fixtures. MSD employee Tommy Newton painted the equipment, and then it was shipped to the test site in New Mexico. The large fixtures were 40 inches wide, 58 inches high, and 67 inches long. Built on an aluminum frame with sheet stock steel, each target resembled a large household oil drum. Each fixture granted the user internal access through end caps, featured both flat and curved surfaces, and had 19 thermal couples mounted on the exterior surface.

The targets were built to not only be rigid and hold their shape, but to be relatively light so they could be transported to the test site and installed on the tower several times a day. Showcasing great attention to detail, the quality of the end product was well received and earned several compliments.

The Track

While Phippen was working on the design and fabrication of the test targets, the PRISM team focused its energy on other challenges. How could the PRISM cameras rotate around the fixed target and collect IR and visual data without using hard wires for power, camera control, or data acquisition? The team laid 360 degrees of model railroad track around the target, ran the test with a scale locomotive, and used wireless routers to control the cameras and other instrumentation.

The location chosen for the track was the White Sands Missile Range in New Mexico. The site—affectionately named the Coyote Site—was improved with a two-foot-wide circular concrete track bed that had a 101.5-foot radius and a 644-foot circumference. The cement track was laser-leveled and surveyed to ensure that it remained perfectly flat. Then, a railroad track was painstakingly laid on top of the concrete pad to be leveled to within 1/16 of an inch.

Mark Phippen, an AVMI Mechanical Solutions Division employee, designed and built the test fixtures used throughout the Coyote Test. He is shown here with PRISM instrumentation.

To meet the unique test requirements, a scale "G" train locomotive pulls two flatbed trailers carrying PRISM instrumentation around a 644-foot circular track.

The Train

The team used a scale "G" train locomotive to pull two custom-made flatbed trailers with all of the instrumentation. One trailer carried the cameras, and the second trailer carried the computers, routers, and an onboard generator.

PRISM team member Craig Oliver was tasked with procuring a battery-powered locomotive to pull the trailers full of instrumentation around the track. He succeeded when he found a company out of Arcadia, Oklahoma—Cannonball, Ltd.—that makes a low-cost, easy-to-build, battery-powered, 1.5-inch scale locomotive called the Super Mack. The Super Mack is powered by two electric motors deriving their energy from a 12-volt battery. Small enough to be transported in a car trunk, the Super Mack was a perfect solution for getting the PRISM instrumentation rolling.

For the design and creation of the two 72-inch flatbed trailers, PRISM once again turned to Mark Phippen and the fabrication experts in MSD. The final design of the trailers—complete with the housing used to hold all of the cameras, computers, routers, and generators—incorporated many innovative ideas and components, and was perfectly executed.

The Test

Thanks to PRISM lead technical engineer, Ritch Bullis, who oversaw most of the technical design, the foundation of the test had been built and the driving force behind it had been realized. Mounted on a calibrated pole in the center of the track, the target would rotate with respect to the sun during the test. Additionally, the cameras would move simultaneously along the new test track, collecting data at every half-degree around a 360-degree lap. There would be no operator interference during the test, no hardwire link to the PRISM trailer, and the complete, automated data acquisition would ensure the required data was acquired.

The only way to acquire approximately 200,000 data points and declare a successful test was for the PRISM team to automate the data acquisition. This meant that the PRISM team's software engineers had to deliver a rather involved piece of software to control all aspects of data acquisition. Steve Coffman, Derek Greer, Jon Norton, and Steve Shupe wrote software that calculated the sun's position every second, controlled the target positioner, defined the control parameters of the test, and allowed those parameters to be modified in real-time.

During each test set, as the train traveled around the track, the target rotated to eight different positions with respect to the sun, the cameras acquired IR data on the target, calibration data was recorded, and data was buffered. One complete data run took two laps around the track (720 degrees). Therefore, 16 laps around the track equaled one test set. With the target in its first position, the test engineers pressed a button to start the test, and the locomotive quietly pulled the equipment around the test track while the equipment gathered data—azimuth, solar position, elevation, time and space position information, IR, and thermocouple data—from over 4,000 data points. At the start of the second lap, data acquisition ceased, and the cameras buffered all of their data through a router to be saved on the onboard computers. During this second lap, the target automatically rotated to the next position. Each lap around the track took about three-and-a-half minutes.

What made this particular test special was the sheer volume of data required to be captured and processed. A typical PRISM IR test results in 100 to 200 data points. With over 200 runs around the test track, this test ended up capturing a total of over 300,000 data points—a quantity that simply has never been done before!

"Until now, we did not have the ability to test so many different modifications under so many conditions with this much precision," said Mike Falco, PRISM team lead. "This is the type of test facility that the IR community and the T&E community have needed for a long time."

Throughout six weeks of testing and data acquisition at the Coyote Site, PRISM engineers successfully gathered the extensive data required without ever having to put an actual aircraft in the air. In the process of meeting this project's specifications, the PRISM team developed a new national test site and an acquisition software package that will make this new capability even more favorable and cost effective for future test and evaluation projects. ■

A Strategy for Assessing Airborne Electronic Attack Platform Survivability

by Torger Anderson and Kenneth Mathiasmeier

New airborne electronic attack aircraft, like all other newly acquired combat systems, must be tested for survivability to assess their susceptibilities and vulnerabilities. The susceptibility evaluation presents a unique challenge because it may be difficult to assess the effectiveness of each contributing system/subsystem and integrate the results. But the combined effect of many of these systems/subsystems is to help the aircrew understand the threat situation surrounding them and make timely and correct decisions based on that information. As a result, the susceptibility can be described by two general characteristics: the aircrew decision cycle time and the threat response effectiveness. By assessing these characteristics alone, susceptibility can be quantified through a manageable test plan. This article describes these characteristics in more detail and provides some considerations for the test effort.

Table 1 Nomenclature

$t_{Acquire}$	time at which the threat system acquires the Airborne Electronic Attack (AEA) target
t_{Clear}	time at which the AEA platform clears the threat engagement zone
t_{Detect}	time at which the threat system detects the AEA target
t_{EM}	time at which the AEA platform begins evasive maneuvers
t_{Launch}	time at which the threat launches against the AEA platform
t_{SA}	time at which the AEA platform gains situational awareness of threat acquisition
t_{Track}	time at which the threat system begins tracking the AEA platform
Δt_{EA}	AEA platform decision cycle time
Δt_{Th}	threat system decision cycle time
Δt_X	time period during which the AEA platform is exposed to threat launch and fly-out

Introduction

The general definition of electronic warfare (EW) is to preserve the electromagnetic spectrum for friendly use while denying its use to the enemy. [1] EW can be broken into three elements: Electronic Support (ES), which is acquiring information on enemy radar and communications signals with the intent to neutralize their effectiveness; Electronic Attack (EA), which includes both electronic interference with the operation of radar and communications and physical attack with anti-radiation weapons and directed-energy weapons; and Electronic Protection (EP), the art of countering the measures built into radar and communications systems to overcome EA.

An airborne electronic attack (AEA) aircraft may need to perform all of these functions in a variety of mission sets that are supporting roles in a larger strike group effort. As such, the AEA aircraft provides protection for strike or other friendly assets against electronic threats. Aircraft performance and capabilities of the electronic attack system and other supporting systems in the aircraft may affect how these functions are carried out and the effectiveness of the EW effort.

In the acquisition of a new AEA aircraft, the Department of Defense must assess the effectiveness of newly acquired combat systems through realistic operational testing (OT). An assessment of the survivability of the system is also required in programs where those systems are intended for combat use and are designed to provide the users with some level of threat protection. For an AEA platform, it is important to balance the effectiveness against survivability; a more survivable platform may allow the crew to be more effective in supporting the strike group. Both effectiveness and survivability must be assessed to determine the overall capabilities of the system.

Mission Variations

A generic AEA platform mission is depicted in Figure 1. Here, the AEA platform (yellow) is supporting a strike group of two aircraft (blue) by jamming radars and communications links that are part of an integrated air defense system (IADS) in the area of a target. The AEA platform needs to be aware of threat locations and their status and may be able to get that from pre-flight information, from a wide range of off-board sources, or from its own systems onboard the aircraft. The AEA may support the strike by standing off from the threat area, proceeding in with the strikers, or something in between. The strategy would depend on several platform attributes—

- Aircraft performance in relationship to the strikers and to the threats
- Survivability: the ability to protect itself and to survive the threats (evade them or withstand hits)
- Mission effectiveness while in a defensive role

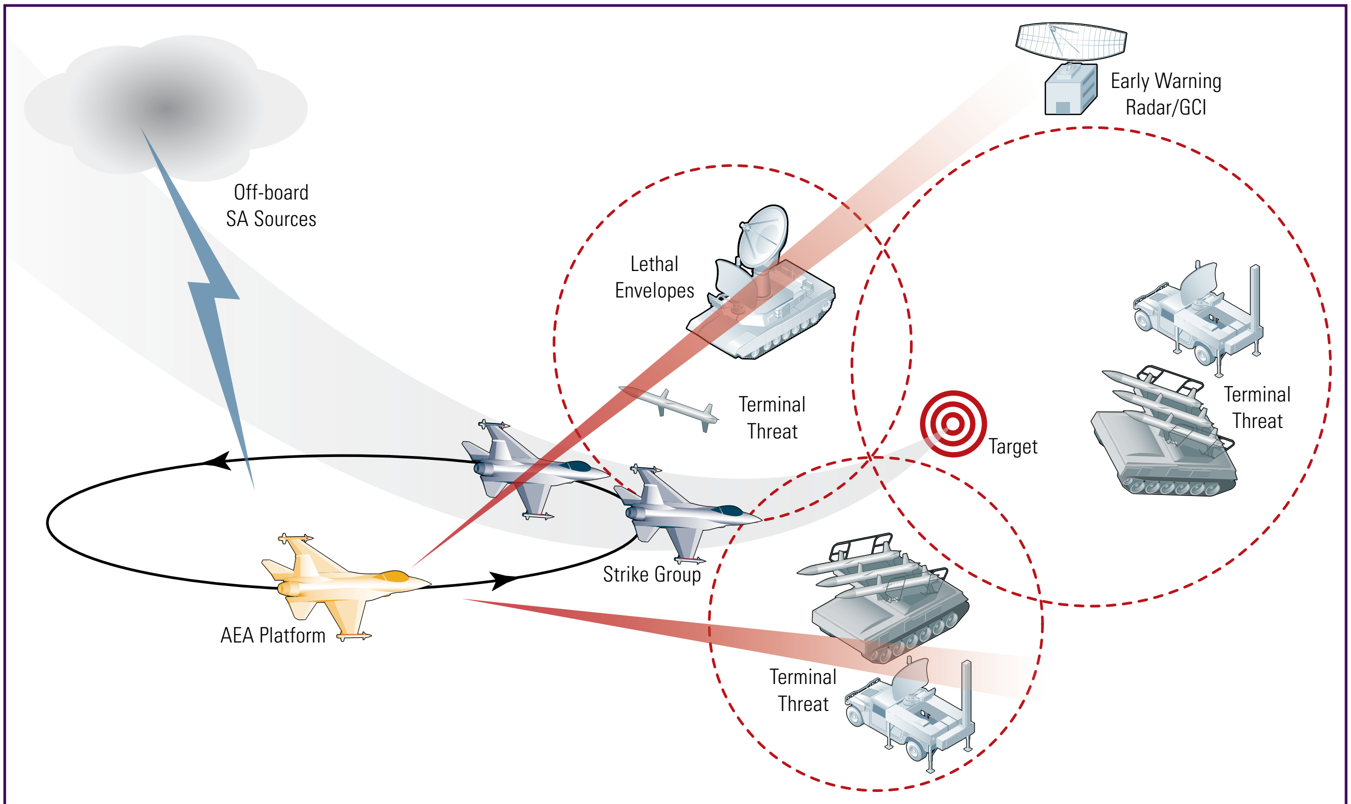

Figure 1 Example AEA Mission in Support of a Strike Group

Performance relates to speed and maneuverability of the AEA platform. If it has comparable performance to that of the strikers and has some ability to evade airborne interceptors and surface-to-air missiles (SAM), the AEA platform may proceed to the target, working in concert with the strikers' EW systems to provide jamming coverage throughout the mission profile, based on confidence that the AEA platform can support the strike group while protecting itself. In addition, the strikers might employ their own electronic countermeasures systems for self-defense against terminal threat systems. Strike group planning that includes the AEA platform would minimize exposure to known threats while ensuring the overall strike objective is accomplished. The AEA platform would perform its normal mission, jamming acquisition, early warning, and ground-controlled intercept (GCI) threat radars and IADS communications.

Survivability and mission effectiveness are complementary attributes, so both need to be evaluated together. The effectiveness of an AEA platform depends on it maintaining specific geographic orientations with respect to the strike group and the threats, and on continued use of its systems to protect those assets. If an AEA platform is forced to maneuver or use its EW systems to defend itself, its effectiveness in protecting the strikers may be degraded.

Survivability can be assessed based on two sub-elements: susceptibility (the likelihood of being hit) and vulnerability (the likelihood of being killed if hit). The latter, while extremely important for assessing the survivability of a tactical aircraft, is evaluated in the same way for an AEA platform as it is for other aircraft, so it will not be dealt with here. The susceptibility of an AEA platform may be uniquely determined by its mission and capabilities and so requires some special consideration when it is to be assessed.

Susceptibility Attributes

To understand the effectiveness/survivability relationship, consider a threat's "kill chain" that must be countered in a successful mission. A successful AEA mission requires the survivability of both AEA and striker aircraft, as well as the accomplishment of the striker's mission. The threat kill chain can be developed from the notional mission profile shown in Figure 1. Considering SAM systems alone, the enemy typically has threats surrounding one or more high-value assets such as a hydroelectric dam. For a threat system to get a kill, it must detect, encounter, and engage the strike force elements, as indicated in Figure 2. [2] Next, the threat system must launch missiles. To be effective, the SAM must have a successful endgame, *i.e.*, hit and kill the target aircraft.

The elements of susceptibility generally relate to many links in the kill chain. These elements include, but are not limited to—

- Airframe radar cross-section
- Mission scenario (*e.g.*, low level, mountain terrain)
- Platform performance (*e.g.*, speed and the ability to perform evasive maneuvers)
- Situational awareness

A low radar cross-section, or the ability to actively mask it with EW, can prevent a threat from acquiring the platform (its presence may be known, but it is not possible to determine the location with any accuracy), track it, or develop a launch solution. In the endgame, a missile may suffer from the same limitations and be unable to hit the target. It may be possible to design minimal susceptibility into the mission if threats are known beforehand and the strike force, including the AEA platform, can take advantage of terrain

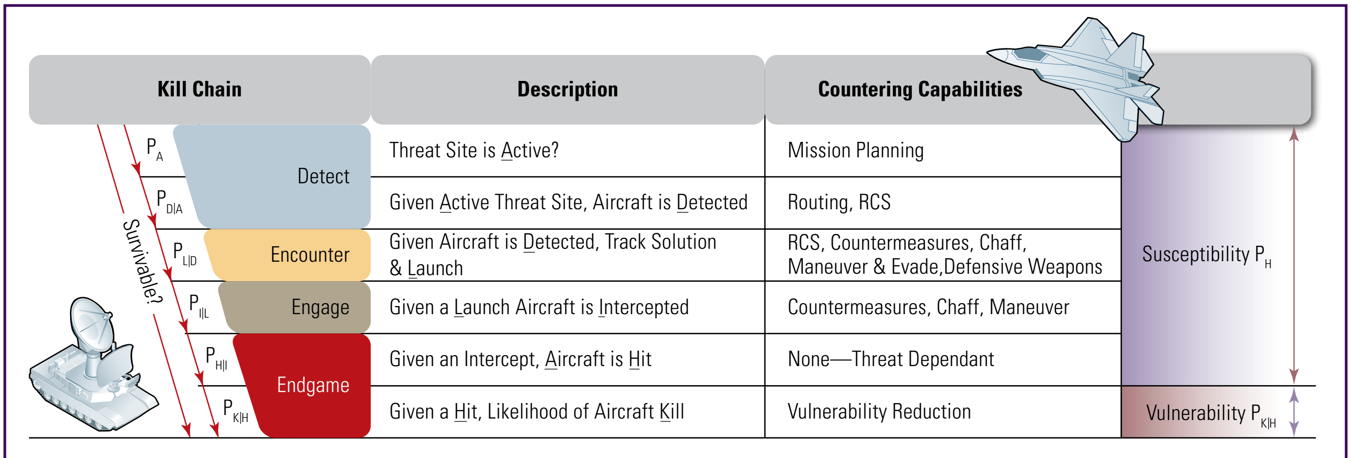

Figure 2 Kill Chain for a Surface Threat Attacking an Aircraft

masking and threat lay-downs to minimize exposure. Platform performance plays a part in several ways. Speed can reduce time available for the threat system to complete the kill chain and hit the AEA platform. Maneuverability is really only important in the latter phases of the chain, preventing the threat system or the missile itself from maintaining a track on the aircraft.

AEA situational awareness (SA) is key to surviving the first three links—the platform may be able to avoid the threats or must quickly recognize and respond to the threat appropriately. SA may come from intelligence gained during pre-flight planning, in-flight from a wide range of off-board sources, or from the AEA platform's own onboard systems. With a good pre-flight understanding of known threats and the availability of systems to provide real-time updates of a changing threat environment, the AEA crew may be able to avoid threats while effectively supporting the strike group in relatively benign environments. However, as the threat environment becomes more hostile and complex, effectiveness and survivability may end up limiting each another—the AEA platform may be forced to concentrate on self-protection, reducing its effectiveness in protecting the strike group. Again, the ability to minimize this loss of effectiveness while ensuring the greatest survivability will be based on timely, accurate, and complete SA.

SA also may play an important role in the endgame phase. The AEA platform may need to continue its mission until the threat has reached the endgame phase, but by recognizing the threat, it may be able to establish encounter conditions that reduce the effectiveness of the threat weapon or make the most effective use of countermeasures and other countering techniques.

Consequently, the whole of AEA platform survivability may depend on two very general factors: the decision cycle time necessary to recognize and respond to a threat, and the effectiveness of the possible responses. Both of these may be measurable in a test program to determine the effectiveness of the AEA platform.

We will examine these aspects, but for simplicity, limit ourselves to a discussion of radar-guided SAM threat systems alone. The concepts will apply to interactions with other kinds of SAM systems and interceptor aircraft as well.

Decision Cycle Time and Response

Decision time has been analyzed by many people, particularly with respect to business applications. However, COL John Boyd developed a description of the process in military applications, calling it an Observe, Orient, Decide,

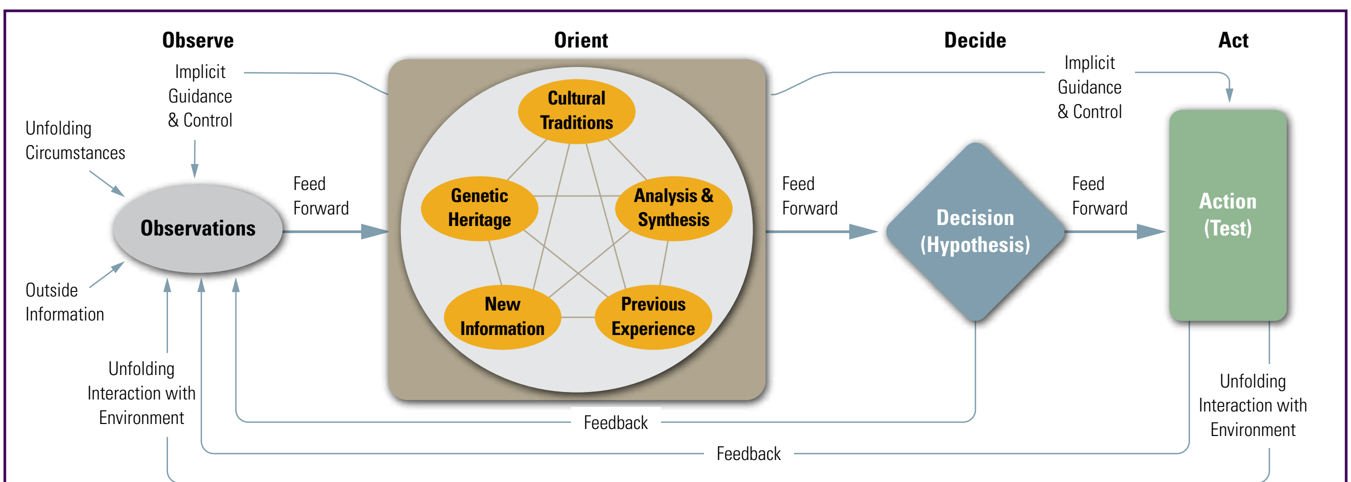

Figure 3 The OODA Loop

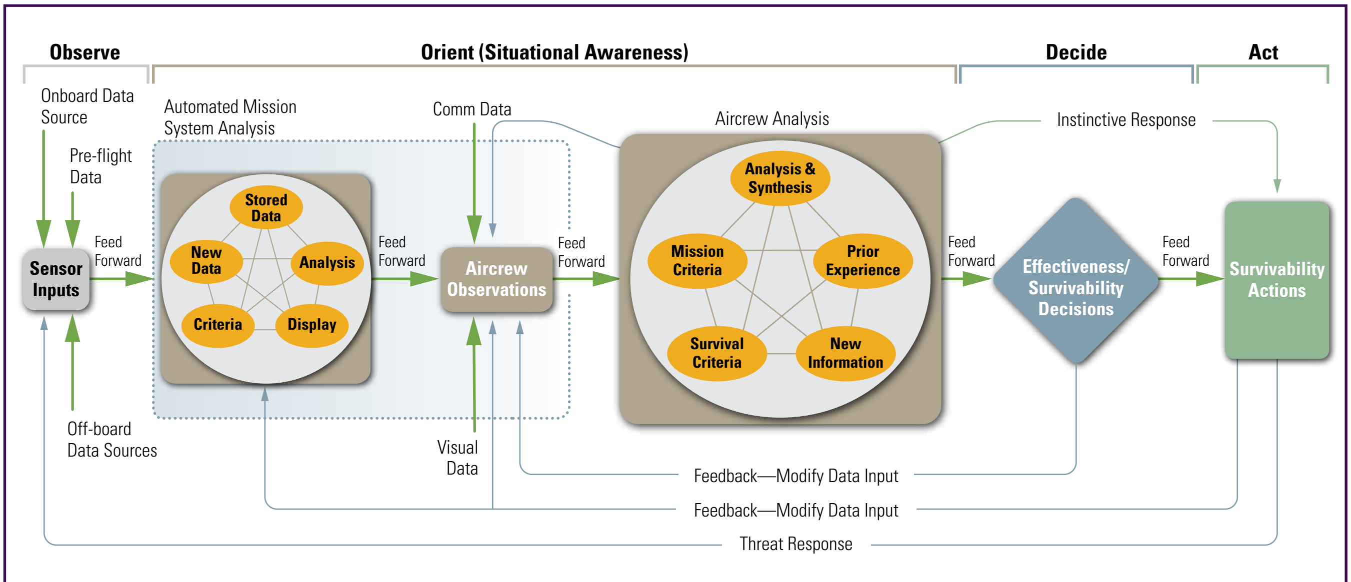

Figure 4 An AEA Application of the OODA Loop

Act (OODA) loop. [3] Col. Boyd's representation of the process is shown in Figure 3.

As the name implies, the decision process involves acquiring data relevant to the decision (observation), interpreting it in a meaningful way (orientation), making a decision based on the interpretation, and acting on that decision. This is a loop in that it is repeated over and over again and, in several ways, the results may feed back to what is being observed. This process may be performed in competition with others performing a similar process, and to succeed, the user must be able to develop the shortest decision loop that provides the most complete and accurate information for making the decision.

Situational awareness in an AEA platform certainly encompasses observation and orientation; the data on threats is acquired from a range of sources and put together in such a way that the AEA crew can understand and act on it. The competing threat systems have their own decision cycles involving target acquisition, recognition, and a decision on how and when to launch. The AEA platform may be put at an immediate disadvantage because, to be complete, their SA must encompass a larger envelope, including multiple threats and large strike groups, while the threat system may be able to focus on a single target at a time.

The AEA platform can improve its decision cycle (speed, accuracy, or completeness) by using many onboard and off-board sources of data and quickly and properly evaluating that information. The latter consideration suggests a highly automated system to quickly process the incoming information, reducing the crew workload and allowing its concentration to expand to other aspects such as survivability, and displaying the information in the most appropriate way to enable rapid and correct decisions. The system may even be capable of deciding and acting independently of the crew, further shortening the cycle. Figure 4 is a general representation for how the OODA loop applies to the AEA platform. In this case, sensor data is fed to a processing system that interprets it and presents the crew members with information to support their decision processes. They, in turn, must observe the system outputs while taking in additional data from visual observations and communications outside the aircraft, then orient themselves with respect to the inputs and make a decision. A properly designed processing system would work to reduce the time frame of the aircrew analysis while providing the most complete and accurate picture necessary for making the decisions.

While there are many aspects to every element of this process, the only real consideration of importance here is the timeliness and correctness of the survivability actions. So, to evaluate the capability of the system, only measurements of the end-to-end process are necessary: How long does it take to make a decision and act? Assessments of the individual sub-elements are not required except to identify where specific deficiencies might lie.

Beyond measuring the decision cycle time compared with that of the threat, the correctness and effectiveness of the AEA platform response needs to be assessed. This begins with an accurate determination of whether the threat is to the AEA platform (*i.e.*, it is targeted and within range of the threat) or to the strikers—the response will be different depending on who is targeted. In the self-defense case, a range of responses is possible, and the correct decisions will be based on the threat identified and the specifics of the engagement. Possible options are tabulated in Table 2.

Table 2 Survival Response Alternatives

Maneuver	• To break lock/evade threat • To depart threat envelope
Electronic Countermeasures	• Jamming • Chaffe/flare
Self-Protection	• Deploy supporting fighter aircraft (HVAACAP) • Engage with anti-radiation missiles (surface threats) • Engage with self-defense weapons (a/a missiles, guns)

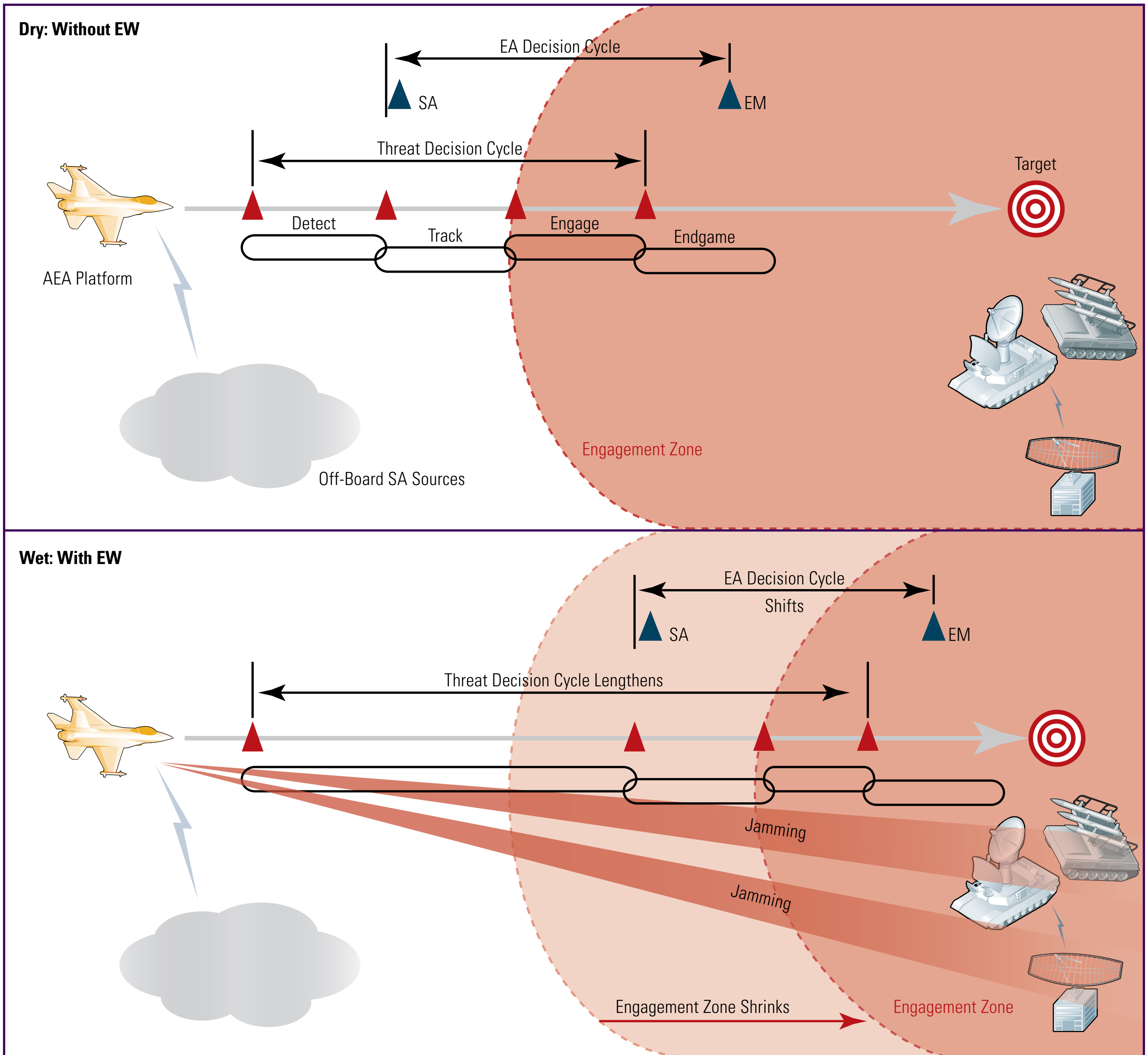

Figure 5 Effect of EW on Threat Decision Cycle

Assessing the AEA platform response may be more involved than determining the decision time. If the response simply prevents the threat system from engaging the AEA platform, the effect is to increase the threat system decision loop time. If, however, the platform is engaged and a threat weapon is launched, the effectiveness of the response must be evaluated. A fly-out model may be needed to determine time-to-impact compared to the time for the AEA platform to get out of range, or the effectiveness of maneuvers to evade the threat, because in a test environment, no threat will actually be launched. The effectiveness of countermeasures against the threat missile itself likely will have to depend on separate test results of the countermeasure systems applied to the endgame of these test engagements.

Tests of single AEA platforms against single threats should provide a good initial set of data for assessing the survivability of the platform. Adding complexity in later tests, though, will help to establish the limits of survivability and, perhaps, the mission types that are feasible given the AEA platform capabilities. Having multiple simultaneous threats and large strike groups at the same time will stress the AEA system and probably increase the decision cycle time. Additions of off-board resources such as intelligence, surveillance, and reconnaissance platforms and capabilities to quickly communicate and incorporate their threat information could significantly enhance the SA for the AEA platform, reducing the decision time and allowing decisions to be made earlier in the engagement. Realistic capabilities need to be evaluated to determine the limits of the AEA platform, the missions it is capable of performing, and the assets and tactics needed to survive the mission.

It may be simpler to assess the AEA system survivability in a relative sense with respect to a predecessor AEA platform. Decision cycle time differences between the two platforms can be determined by running them both through similar mission sets and

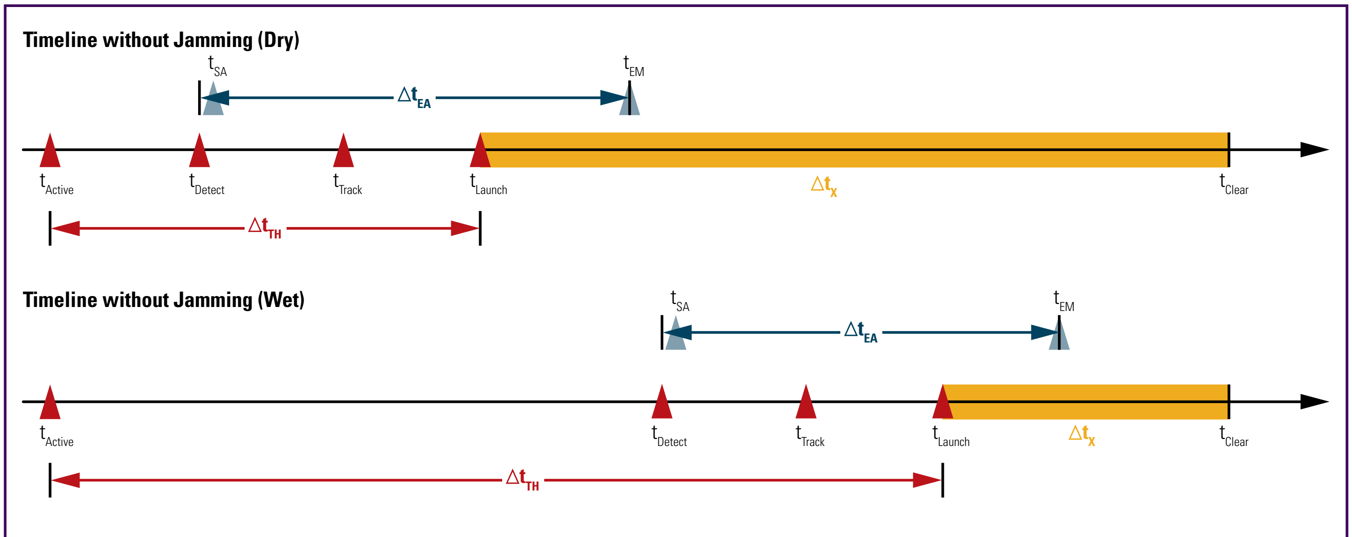

Figure 6 Threat Timelines against an Airborne Electronic Attack Platform

measuring the times. A reduction in decision cycle time indicates an improvement in survivability without having to assess the ability of the threat to engage and hit the target. If the aircraft have similar countermeasure systems (jamming and chaff), their mission effectiveness may also be similar. The only remaining factor, then, would be differences in aircraft performance that would affect the ability to evade or escape from a threat.

Susceptibility Test Measures

A test series to evaluate the survivability of an AEA platform would be focused to determine a set of measures of effectiveness (MOE)—properties that define the performance of interest—for survivability. If the AEA susceptibility is to be compared to that of the strike aircraft, the MOEs must be developed to aid in making that comparison. The AEA is most susceptible during the jamming phase of the mission because of the need to concentrate on supporting the strike group and because the jamming can interfere with onboard threat sensors. In addition, while jamming, communications with supported and supporting assets may be limited due to radio frequency interferences; consequently, situational awareness may be degraded. Therefore, the MOEs should be developed for each AEA platform to focus on this mission phase. Specific MOEs could be—

- AEA decision cycle time compared to that of the threat site
- AEA self-defense response effectiveness

Although the actual missions may involve coordination with many assets and multiple threats likely will be present, a significant understanding of the survivability capabilities and issues may be acquired from a simplified test scenario; however, it may be desirable to make a comparative analysis. If the AEA platform is intended to escort the strike force to any degree, the AEA survivability (as well as performance—comparative speed and maneuverability) should be compared with the strikers to determine the feasibility of the mission. Alternatively, the improvement in survivability of a new AEA platform with respect to its predecessor may be a desirable goal of the test series. In either case, it would be necessary to run the baseline aircraft through the same series of tests to generate comparable results.

An example scenario for these tests is shown in Figure 5. The AEA platform operates alone in this case, running into a target protected by a threat that is part of an IADS. While in reality, strikers would be present and the purpose of the AEA platform is to protect those assets, they are not necessary for evaluating the survivability in this scenario. The threat site would be a "pop-up" threat; that is, it would not radiate until an early warning radar in the IADS identified an incoming target aircraft approaching the threats engagement zone. At that point, the IADS controller would order the threat site active and it would begin acquiring the target, obtaining a firing solution and launching SAMs at the appropriate times. The kill chain, once the threat site is ordered active, is shown in the upper frame of Figure 5. In this particular example, it is initiated before the aircraft reaches the engagement zone. This is variable, however, and it may be useful to run a number of tests with variations in the activation point.

The AEA platform, using whatever means are available, should attempt to determine when the site goes active, what its type and location are, its status (the operational mode or where it is in the kill chain), and if the AEA platform is the target. If the AEA platform is the target, its response would be different than if the threat is still trying to acquire, or if it is targeting another strike group asset. Therefore, multiple tests need to be run targeting the AEA or not, and the AEA platform response must be recorded. Note that the AEA decision cycle begins once the threat begins to track the aircraft. For a survivability assessment, the decision of interest is the response to a threat, which begins with the threat targeting the aircraft. Also, the figure shows the decision cycle (ending with a response at the "EM" [evasive maneuvering] marker) ending after the threat decision cycle, which would have resulted in a missile launch. It is possible that the AEA decision cycle is shorter than that of the threat and the decision point could be before missile launch—that must be determined from the tests.

Figure 5 shows two variations on this scenario—one "dry" (no preemptive jamming) and the other "wet" (with preemptive jamming). Although the threat is a "pop-up," which, by definition means the AEA cannot preemptively jam it, it is part of an IADS, and it may be possible for the

AEA platform to jam the early warning radar or the communications link to the threat site, preventing or delaying it from activating. The first case, without preemptive jamming, forms the baseline so that the jamming effectiveness in reducing the susceptibility can be evaluated. (In fact, an initial baseline would be done without any response to evaluate the threat capabilities.) The effects of jamming on the AEA platform's ability to acquire SA data from off-board sources (*i.e.,* the effect on AEA decision cycle time) can also be assessed through comparisons of these two variations in the scenario. In all cases, the response to being targeted should include jamming of the threat site—at this point, the AEA platform needs to begin trading effectiveness (*i.e.,* support of the strike group) with its own survivability. The effectiveness of this response should be measurable as an added extension of the threat site decision cycle and kill chain.

The measures of performance (MOP) are quantifiable data that can be collected during the tests to characterize the MOEs. The timelines associated with the scenarios in Figure 5 are laid out in Figure 6, and they indicate that the time it takes to complete various activities may be good MOEs for survivability. If the AEA platform can shorten its decision cycle to operate within the cycle of the threat, it should be able to avoid the threat altogether by implementing countermeasures and maneuvers or by leaving the lethal envelope. At the same time, if effective jamming is used, the available time the threat has to make its decision is shortened, effectively making it more difficult or even impossible for the threat to complete the kill chain and launch (Figure 5). The MOPs that would assess the MOEs by measuring the cycle times (with and without jamming) for both the AEA platform and the threat might be—

- Time from the pop-up threat detecting the AEA platform as a target to AEA response (whether it be maneuver, chaff, or jamming) ($\Delta t_{EA} = t_{EM} - t_{Detect}$)
- Change in threat decision cycle time, from the pop-up threat activation until acquisition of the AEA target and launch (Change in Δt_{Th})
- Change in the AEA exposure time to the threat (time period during which the threat could launch and hit the target) (Change in Δt_X)

AEA decision cycle time controls the first MOP while AEA response effectiveness reduces the second MOP. As in Figure 5, note in Figure 6 that the time at which the AEA responds to the threat occurs after threat launch. Again, this is only notional—the actual Δt_{EA} needs to be determined. Ideally, the AEA platform could respond before the launch, preventing it from occurring. Note also that preemptive jamming may not affect the AEA decision cycle time (Δt_{EA}). This will, of course, be measured and should not be affected unless, as discussed earlier, emissions from the jamming affect AEA platform receivers, preventing the AEA from getting timely off-board SA information.

Data from a test series, as described above, would provide fundamental data describing the survivability of an AEA platform. More complex tests, involving a strike group, multiple threats, and off-board information sources would add fidelity to the results. Stressing factors, such as increased crew workload and the effects of communications degraded by the jammers, would be better assessed, but the basic test series described above would provide a very good understanding of how well such a platform could survive and what the fundamental issues might be.

Conclusion

The evaluation of the susceptibility of an airborne electronic attack platform can be accomplished through assessments of two measurable parameters: the decision cycle time for evaluating threats and the threat response effectiveness. The cycle time is a relatively easy measurement to make, but to have any meaning, must be compared to that of the threat, a reference platform, or a similar mission without jamming. The threat response effectiveness may require a combined test and modeling effort to assess, but it appears reasonable that assessments of the various response options can be achieved. ■

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LS-DYNA Models of Selected Guided and Unguided Threats

by Ronald Hinrichsen and Alex Kurtz

Over the past nine years, projects have been funded to develop finite element models of selected threats for use by analysts in performing design and pre-test predictions of damage to aircraft structures. These projects have incorporated parallel efforts that integrate the first-principle, high-fidelity, nonlinear structural analysis code, LS-DYNA, and test data to advance the state of the art in vulnerability analysis techniques and in understanding aircraft-threat encounters. The work has resulted in a library of LS-DYNA models of both guided and unguided threats. This article presents a summary of methodology development and list of models currently available.

The 780TS/OL-AC at Wright-Patterson Air Force Base in Ohio, through its contractor, RHAMM Technologies, LLC was responsible for these projects. The development of the SA-7 model was the initial effort. It leveraged RHAMM's earlier experience with hydrocodes, such as LS-DYNA, MSC/DYTRAN, CTH, and ALE3D. Initially, the plan was to use LS-DYNA's arbitrary Lagrange/Eulerian (ALE) technique to account for the explosive air and other fluids in an Eulerian domain and the warhead fragments, target, and debris in the Lagrangian. The survivability community wanted a model that could be "plug and play," and it was quickly realized that a fully coupled ALE model would not meet that requirement. Specific, specialized expertise would be necessary, and computer runs and post-processing would be costly. Therefore, the decision was made to create an SA-7 model that was all Lagrangian.

The methodology that resulted was to model the blast based on ARL's Conventional Weapons Effect (CONWEP) code, and experimental data. The warhead fragment masses and velocities were modeled based on experimental values. The threat debris and target damage and debris were modeled using nonlinear structural material models within the LS-DYNA code. Because potential users of the resulting threat model would have all Lagrangian models of their targets, the "plug and play" goal could be realized.

Once the SA-7 model (first generation Man-Portable Air Defense Systems [MANPADS]) was completed, other guided and unguided threats were addressed. Ultimately, the following threats have been modeled and are available for use—

- 1st-generation MANPADS
- 2nd-generation MANPADS
- 3rd-generation MANPADS
- 23mm HEI
- 30mm HEI
- RPG
- S5-MO rocket

Figure 1 shows a sample of the guided threats, and Figure 2 shows the unguided threats.

Each of these threats can be viewed as cylindrically shaped containers, incorporating explosives of various constituents, shapes, and sizes. Because of their similarities in these regards, common tools were developed and brought to bear in each model.

Because the SA-7 model used the CONWEP code, it produced a spherical blast profile. This was viewed as a major shortcoming, and a user-defined subroutine was written for LS-DYNA that would account for the non-spherical nature of blasts, and at the same time, handle aerodynamic drag on fragments and debris. The subroutine that was written yielded what the authors have called an "Airblast in Cluttered Environment-like," or ACE-like, blast model. ACE is the methodology used on the widely used COVART code.

The subroutine generates a spherical blast based on CONWEP equations and then scales the peak pressures at polar zones and ranges to match experimental data. The blast initiation point is based on a local coordinate system tied to the threat model. This provides directionality for the blast as well as the capability to account for a moving blast. In addition, the subroutine was written so that it can handle multiple initiation points. Any gaps in the experimental data are filled in using fine-mesh Eulerian models. These high-fidelity models are optimized to match existing data, and then the optimized model data is used to fill in the gaps. Figure 3 shows a comparison of experimental and model blast data for the 23mm HEI at 45-degree polar angle and various ranges.

Warhead fragmentation modeling is based on experimental data. A software tool was written to read experimental data files (mass, shape, material, velocity) and

Figure 1 Sample of LS-DYNA Guided Threat Models

create a finite element "fragball" or "fragcylinder." Fragments are accelerated to their initial velocities using load curves defined in the same local coordinate system used in the blast model.

Figure 4 shows a sample 23mm HEI versus a plate array at the beginning of the simulation, and Figure 5 shows the resulting fragment damage on the plate target.

Each of the threat models has been validated against experimental data. That is, the warhead fragment distribution, mass, and velocities as well as the peak pressures at various polar zones and ranges match experimental data. Thus, the user can have confidence in the threat models.

At the time this article was written, the SA-7 model has been used by various analysts to predict damage on running and non-running large aircraft engines as well as damage on large aircraft wings. It is currently being used in a project to examine engine component vulnerability and to perform pre-test predictions of MANPADS damage to a cargo aircraft wing. Additionally, the 23mm and 30mm HEI models will also be used in pre-test predictions on a cargo aircraft wing. ■

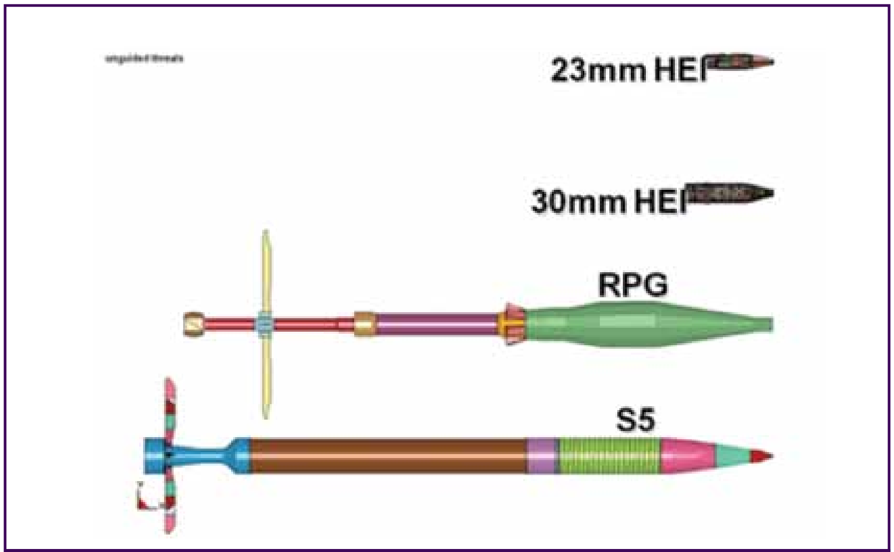


Figure 2 LS-DYNA Unguided Threat Models

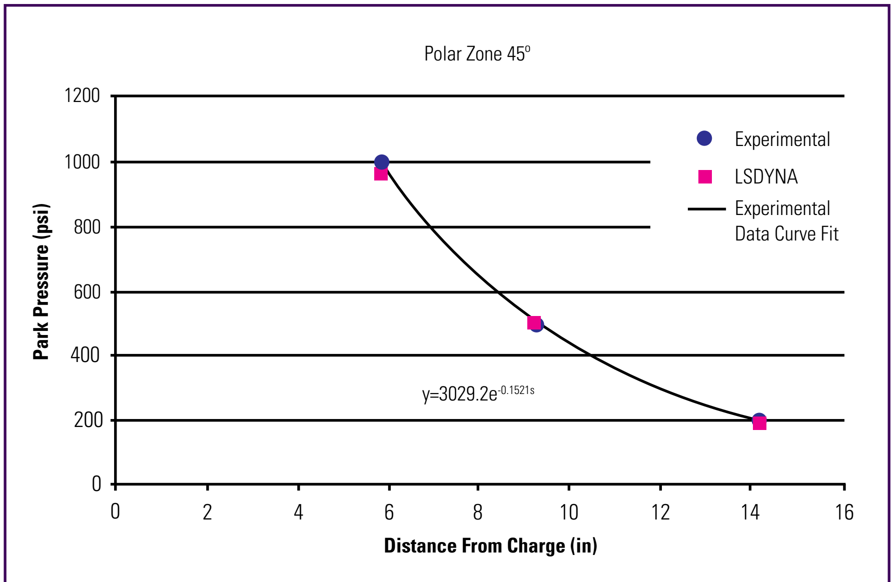


Figure 3 23mm HEI Comparison of Model and Experiment

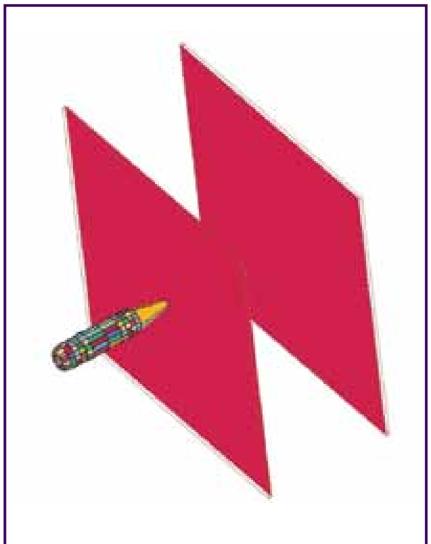


Figure 4 23mm HEI vs. Plate Array (t=0.0)

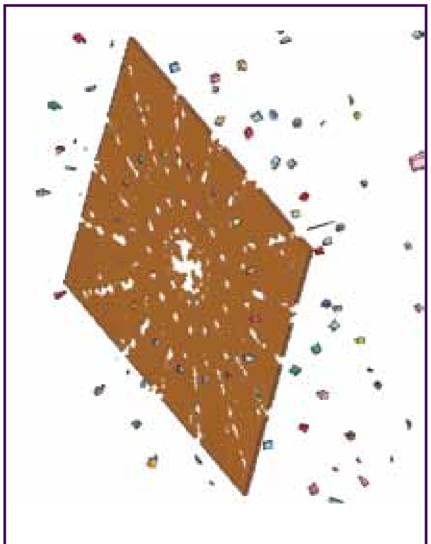


Figure 5 23mm HEI vs. Plate Array (t=0.004)

Relationship between Lower Explosive Limit and Ullage Combustion Reactions

by Mark Couch and Vincent Volpe

Aviation jet fuels are typically a complex blend of paraffinic, olefinic, naphthenic, and aromatic hydrocarbons controlled only by the defined boiling point ranges. [1] The actual composition of a fuel batch is highly dependent on the source of crude oil and the manufacturer, but generally JP-8 fuel (very similar to Jet A) consists of 75 to 90% paraffins, both straight chain and cyclohexanes, the remainder consisting almost entirely of aromatic compounds, including naphthalene, benzene, xylene, and toluene. In a partially filled fuel tank, hydrocarbon molecules will escape from the liquid into the vapor space above it. In a fully enclosed fuel tank, vapor from both lighter and heavier molecules will accumulate until equilibrium is reached, provided the conditions of the tank (temperature, pressure, and volume of the liquid) remain constant.

The ullage is defined as the vapor space above the fuel within the enclosed tank that contains a mixture of fuel vapor and air. At equilibrium and assuming no turbulence, the number of fuel molecules leaving the liquid equals the number of molecules returning into the liquid at the liquid-vapor interface. The pressure exerted in the vapor space by the fuel molecules is called the fuel vapor pressure. Therefore, if the vapor pressure at a particular temperature is known, the amount of fuel that exists in the vapor space can be calculated. For the remainder of this article, unless otherwise stated, it will be assumed that standard air will be primarily nitrogen (78%) and oxygen (21%) representing the non-inerted fuel tank. Inerted fuel tanks typically have oxygen concentrations below 12%, and oxygen-rich environments have oxygen concentrations above 23%. The presence of other gases in the air mixture, including water vapor, is assumed to have negligible effects on the combustion process.

The Combustion Process in Jet Fuels

A long-recognized hazard to aircraft fuel tanks is inflight fire and/or explosion in the ullage. The source of this hazard could come from events such as electrical arcing, *e.g.*, the TWA 800 mishap, or an incendiary round passing through the ullage in a combat aircraft. When the hazard event is related to an aircraft in combat, the term "vulnerability" is used, and the associated damage mechanism is the combustion of incendiary materials. [2] Combustion is defined as a sustained, exothermic chemical reaction of the form

$$C_NH_M + O_2 + N_2 \rightarrow H_2O + CO_2 + N_2 + \text{other products} + \text{energy released}$$

where C_NH_M refers to the mixture of hydrocarbons typically found in jet fuel. The energy released is normally referred to as the heat of combustion. The process of combustion in the ullage is best explained with the fire pyramid, or fire tetrahedron, shown in Figure 1. [3] Four elements must be present to start and sustain a fire—

- Heat or energy for ignition
- Fuel vapors
- Oxygen
- Chemical or chain reaction that produces free radicals

The ratio of fuel vapor to oxygen must be in the proper range for combustion to take place, and a flammability diagram similar to the one shown in Figure 2 for jet fuels is normally used to show the acceptable range as a function of temperature and altitude (pressure) for a specific ignition energy. The left side of each contour is referred to as the lower flammability limit or lower explosive limit (LEL), while the right side is referred to as the upper flammability limit or upper explosive limit (UEL). When the equilibrium ullage condition is between the upper and lower limits, combustion most likely will occur. If the ullage condition lies outside and to the left of the flammability curve, *i.e.,* below the LEL, the mixture is said to be too lean, and combustion is less likely to occur. If the condition lies outside and to the right, *i.e.,* above the UEL, the mixture is said to be too rich, and combustion is also less likely to occur. The flash point is defined as the lowest temperature, corrected to standard atmospheric pressure (101.3 kPa or 14.7 psi), at which the application of an ignition source causes the vapor of a liquid to ignite momentarily under specified testing conditions. The flashpoint for the fuels shown in Figure 2 is denoted by an "X" at 0 feet altitude. Because most testing is conducted at or near sea level, the flashpoint becomes a useful parameter for at least a qualitative assessment of flammability.

The flammability contours in Figure 2 are not unique dividing lines for LEL and UEL, but represent an average limit typically obtained from experimental data. The extent of the flammability contours is highly dependent on the energy of the ignition source.

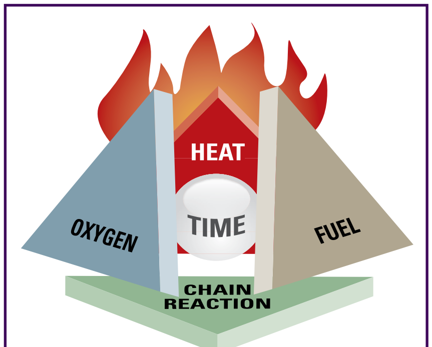


Figure 1 The Fire Pyramid

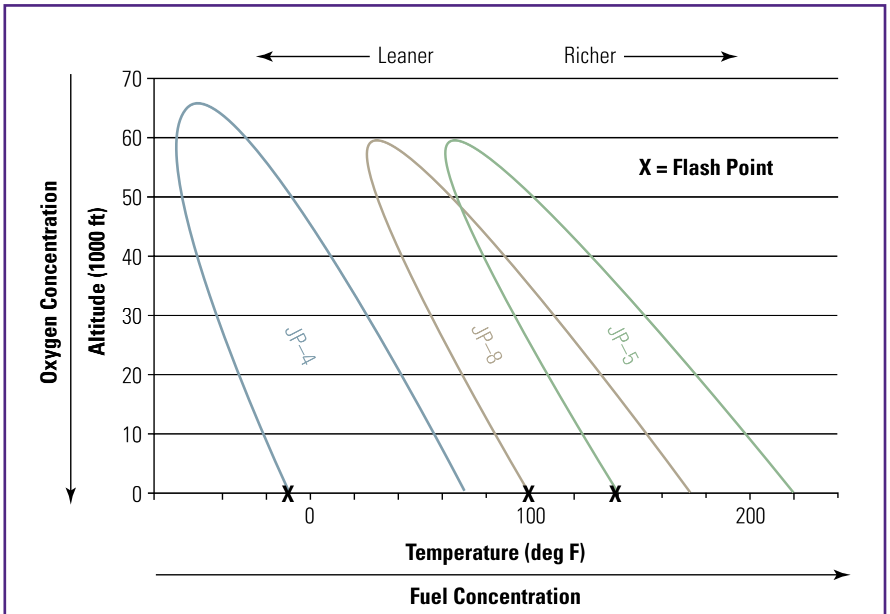
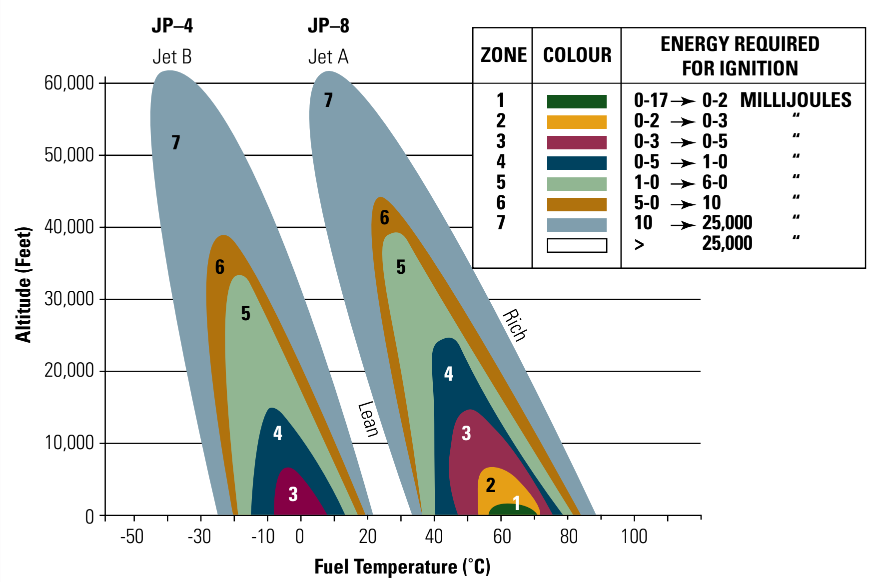


Figure 2 Flammability Diagram [3]



ZONE	COLOUR	ENERGY REQUIRED FOR IGNITION
1		0-17 → 0-2 MILLIJOULES
2		0-2 → 0-3 "
3		0-3 → 0-5 "
4		0-5 → 1-0 "
5		1-0 → 6-0 "
6		5-0 → 10 "
7		10 → 25,000 "
		> 25,000 "

Figure 3 Typical Flammability Limits for Jet Fuel [2]

Flammability contours shown in Figure 3 were developed by British Aerospace in the 1970s and were based on the prevailing literature at the time and discussions with fuel supply companies. (The contours in Figure 2 correspond to approximately 10 millijoules in Figure 3.) A recent comparison of the spark ignitability data obtained by various researchers is shown in Figure 4. [1] Although the data show the same trends as the British Aerospace contours, the accuracy and reliability of the contours cannot be quantified because of the scatter of the test data and lack of a detailed description of the test procedures and instrumentation used in making the measurements. Furthermore, the limits of the contours are for steady-state, equilibrium conditions, and it is assumed that the fuel-air ratio is uniform throughout the ullage. In fuel tanks that are not box-shaped, uniformity of the ullage may not be a valid assumption. The fuel-air ratio may be richer at the fuel-ullage interface and leaner at the top of the tank because the hydrocarbon molecules are heavier than nitrogen and oxygen, and if there is not good mixing of the different gases in the ullage, fuel vapor may not be uniformly distributed. Depending on the design of the tank, local differences in fuel-air ratios may be sufficient to keep some portion of the ullage fuel-air mixture within the flammability range of the diagram.

Flammability diagrams are typically based on spark or flame testing. For example, the incendiary material from an armor-piercing incendiary (API) projectile can provide very energetic external ignition sources and may expand the contours well beyond what is shown in Figure 3. Another concern for ullage combustion is an ignition source caused by hot material coming in contact with the fuel vapor. The hot material can be projectiles or fragments from a high explosive (HE) warhead that move through the ullage, or a hot surface that the fuel vapor flows around or with which it comes in contact. [4] This type of ignition is referred to as hot-surface ignition or autoignition, and fuels can ignite without the presence of a flame or spark. While it is generally recognized that spark ignition energies are very difficult to quantify, perhaps even less is understood about autoignition. A third concern for ullage combustion is the ignition and flame propagation of air and fuel spray mixtures. The penetration of an API round or detonation of an HE warhead in the fuel portion of the tank can create non-equilibrium conditions almost instantaneously by carrying liquid fuel droplets into the vapor-filled volume. Ignition and flame propagation require heating and vaporization of the droplets and attainment of the proper fuel/air ratio before combustion can occur. Intuition might indicate that ignition and flame propagation through a fuel spray will occur at a slower rate than a pure gaseous mixture. However, with certain initial droplet sizes, ignition can be faster, and the velocity of the flame front propagation can be greater than for vapor only. The major factors causing this difference are variations in temperature and concentrations within the ullage and the nonlinear dependence of the reaction rate on temperature and concentration. There are additional non-combat effects that can alter the ullage composition, producing flammable conditions when pressure and temperature by themselves would not necessarily predict a reaction. These effects include—

- Misting and frothing
- Fuel sloshing as a result of aircraft maneuvers
- Fuel tank vibrations

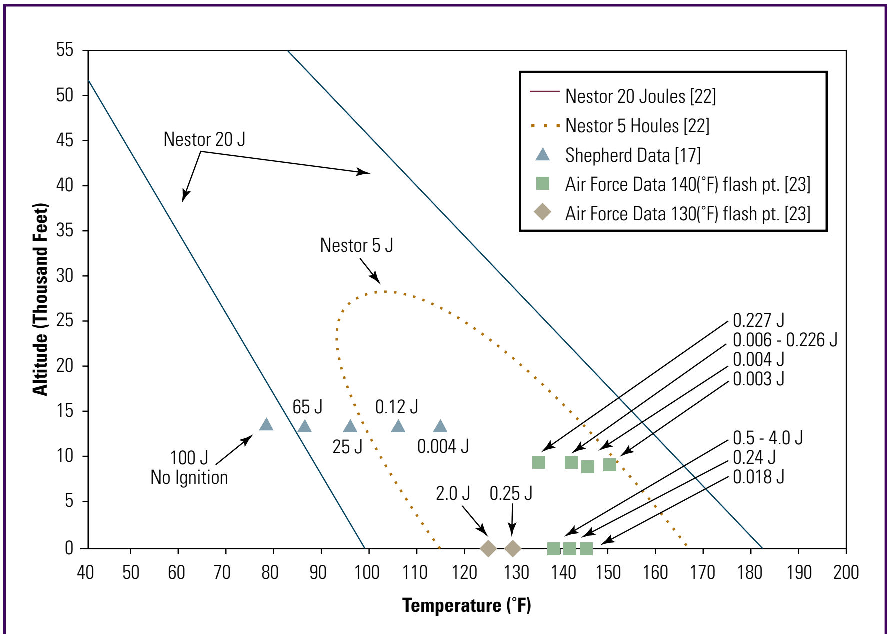


Figure 4 Comparison of Ignition Energy Data for a Jet [2]

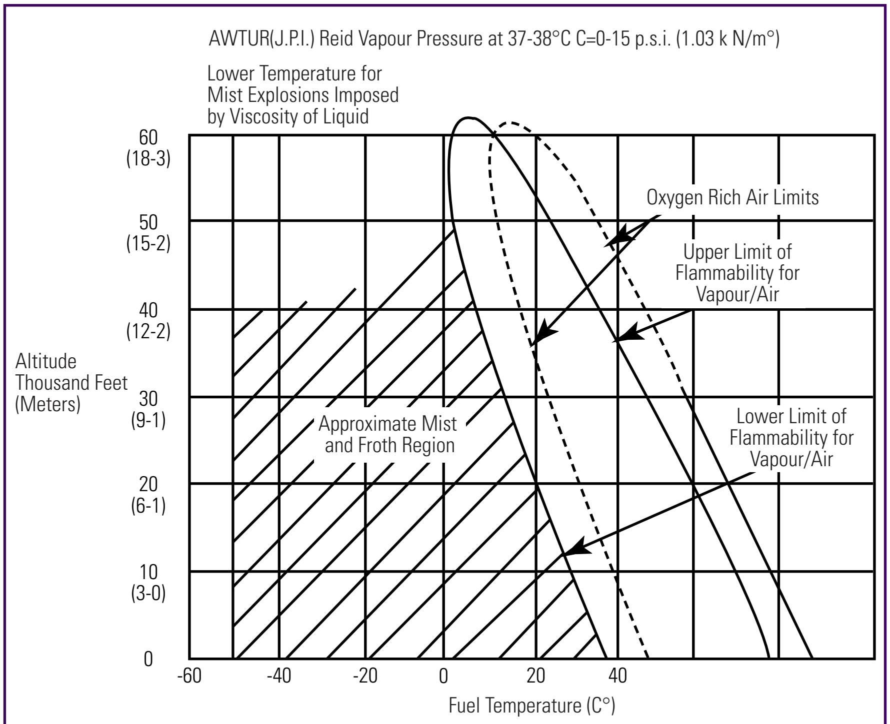


Figure 5 Non-equilibrium Flammability Limits for JP-8

- ➤ Oxygen enrichment at higher altitudes (up to 25% O_2) due to liberation of dissolved oxygen in the fuel (oxygen is more soluble than nitrogen in jet fuels)
- ➤ Fuel weathering due to the gradual release and depletion of lighter and more volatile hydrocarbons caused by temperature and pressure increases and/or ventilation-induced evaporation
- ➤ Vapor convective motion induced by temperature gradients within the tank.

Figure 5 shows estimates of non-equilibrium conditions due to misting and frothing and the effect of an oxygen-rich environment.

Measuring Lower Explosive Limits

Because the flammability contours shown in Figure 2 come from experimental data and are not unique dividing lines, establishing the 100% LEL line is somewhat tenuous at best. In the United States, manufacturers are required by the Occupation Safety and Health Administration (OSHA) to list the LEL and UEL for fire-fighting measures on their material safety data sheets. For jet fuels, typical LELs range from 0.6% to 0.8% fuel vapor by volume at room temperature. UELs range from 5.0% to 5.6% vapor by volume at room temperature. It is assumed for fire-fighting purposes that concentrations below LEL and above UEL will not support combustion. Normally, sensors used for taking LEL measurements are calibrated to 100% LEL at the 0.7% vapor by volume benchmark if they are calibrated directly for jet fuel. However, in many cases, the sensors are actually calibrated against another gas such as methane, propane, or hexane, and then corrected for jet fuel. These somewhat arbitrary calibration methods for 100% LEL may have little to do with combustion events, but rather are designed to regulate the work performed in confined spaces. [5] OSHA sets permissible exposure limits (PEL) to protect workers against the health effects of exposure to hazardous substances, which for fuel vapor has been set at 350 mg/m^3 (50 ppm) for an eight-hour time weighted average that an unprotected worker may be exposed. This PEL is typically five to 10% of the actual LEL established via the 0.7% vapor by volume method. LEL sensors are often used to measure PEL toxicity levels so that workers will know whether it is safe to enter a confined space, such as a fuel tank, in order to make repairs.

Two general classes of sensors are used to collect LEL measurements. The conventional class of sensors uses a Wheatstone Bridge to measure the heat released when a flammable gas burns on a hot catalyst bead. This type of sensor was originally designed to measure methane levels in coal mines in the 1800s. Although the technology of the sensor has evolved over time, this class of sensors lacks the sensitivity to accurately measure jet fuels, because heavier hydrocarbon vapors have difficulty diffusing towards the LEL sensor because of the increased flash point, and the display output is approximately 30% of that of methane. For example, if the sensor is calibrated on methane where 100% LEL is equivalent to 5% vapor by volume, the actual output reading for jet fuel will be 30% LEL. Even if a correction factor is applied, a 1% change of LEL for fuel vapor will represent about a 3% change on the methane-calibrated sensor. Care must be taken when using an LEL sensor that is calibrated to another gas other than jet fuel. It is easy to get a reading of 50% LEL (with jet fuel) and think that the tank is safe when in reality the corrected LEL would be over 100% for jet fuel.

A newer class of sensors used to measure LEL for jet fuel vapors is the Photo Ionization Detector (PID). PID sensors were originally designed to measure the levels of hydrocarbons for the environmental industry and typically provide more accurate and reliable readings of LEL. A PID uses an ultraviolet light source to remove an electron from the neutrally charged hydrocarbon compound, creating an electrical current that is proportional to the concentration of the compound. The amount of energy needed to remove an electron from the compound is called the ionization potential. Larger hydrocarbon molecules with more double or triple covalent bonds tend to have lower ionization potentials, but they are easier to detect in low concentrations with a PID sensor. PIDs are normally calibrated to isobutylene, with correction factors applied for other compounds, creating the same scaling problem as seen with the Wheatstone Bridge sensors.

Measurement of LEL in a fuel tank is normally accomplished using a vapor sampler with tygon tubing routed into the ullage region. Manufacturers recommend using Teflon-lined tygon tubing because ordinary tygon tubing quickly absorbs jet fuel. A small pump in the unit draws the vapor through the tubing toward the sensor. The sensor collects the data and provides a reading to the operator. Care must be made to ensure that liquid fuel does not come into contact with the tubing, or erroneous readings may occur. An alternate sensor can be used that determines the percentage of O_2 in the fuel tank. The O_2 sensor is typically used only to determine the atmospheric conditions prior to workers entering the fuel tank.

Vapor samplers are limited primarily to steady state conditions; that is, fuel sloshing and misting effects are not normally present when taking LEL measurements. Additionally, because of the method used to take LEL measurements, the LEL reading only reflects the local fuel-air ratio and not necessarily the area of interest during a test shot, such as the location of API and HEI detonations. Therefore, because there is a limited number of sampling ports, accurate representation of the entire time-dependent explosive capability of the ullage is not feasible. In order to get around the problem of not knowing which part of the ullage will fall within the explosive region, ballistic testers normally create a quasi-steady state environment prior to the shot that is favorable to ullage reactions when a reaction is desired. This may involve heating the fuel to a temperature above the flash point, and may not replicate actual flight conditions. However, LEL sensors are normally calibrated only for room temperature. If test engineers heat the fuel in order to try to get a reaction, then the measurements again might be suspect because the sensors have not been calibrated for the higher temperatures. In summary, LEL measurements taken prior to the shot only give an indication that conditions are present that are favorable or unfavorable for a reaction; they are not a guarantee that there will or will not be a reaction.

Relationship to the Explosive Reactions

Assuming that conditions exist for combustion to occur, the flame front starts at the ignition source and propagates throughout the ullage until it encounters a solid or liquid boundary, or the changing fuel-air mixture no longer supports combustion. The velocity at which the flame front travels depends on the amount and rate of energy released. A relatively large and rapid energy release causes a supersonic flame front to propagate with an associated large and rapid overpressure. This phenomenon is referred to as a detonation. On the other hand, a relatively small and slow energy release causes a subsonic flame front to propagate with a slow rise and low overpressure, and is referred to as deflagration. Aviation fuels typically deflagrate with overpressures less than 200 psi. Detonations and deflagrations may or may not lead to an aircraft fire, but both are considered combustion reactions. Because a fuel tank is an enclosed volume, it has the ability to hold pressure to some extent. However, as the combustion process begins, pressure inside the tank begins to rise, and as the pressure rises, the reaction rate tends to increase. When the combustion overpressure inside the aircraft is sufficiently high to damage or destroy portions of the aircraft structure, it is referred to as an explosion. In reducing the vulnerability of an aircraft to fire/explosion, it is normally not sufficient just to minimize the effects and possibility of catastrophic explosions. Even relatively low overpressurization (less than 20 psi) of a fuel tank may cause damage to fittings, internal fuel lines, the bladder, or the walls of the tank, allowing fuel to leak into adjacent dry bays where secondary ignition sources may start a fire.

To determine the likelihood that a fuel tank will have an explosive reaction that will result in a definable aircraft kill, the probability of kill given a hit ($P_{k/h}$) can be expressed as

$$P_{k/h}=P_{em/h}*P_{ignite/em}*P_{cd/ignite}*P_{k/cd}$$

where $P_{em/h}$ is the probability that an explosive mixture exists given a hit, $P_{ignite/em}$ is the probability of ignition given that the explosive mixture exists, $P_{cd/ignite}$ is the probability of component damage (*i.e.*, the fuel tank) given ignition, and $P_{k/cd}$ is the probability of kill given damage to the fuel tank. Attempts to quantify these probabilities may be based mostly on empirical data. Live fire testing of the ullage may provide some useful information about the third and fourth terms in the equation ($P_{cd/ignite}$ and $P_{k/cd}$) assuming that detonation of the round can be reasonably ensured by either the construction of the tank or use of striker plates. Analysis of the fuel tank design may provide insight into the second term ($P_{ignite/em}$). Functioning of API rounds typically requires penetration of a hard surface so that the metallic jacket can be stripped away, igniting the incendiary material in the tip of the projectile and allowing the hard penetrator core to push the burning material through the entry hole. Figure 6 shows possible combustion incidents in and around the fuel tank. [2] Fuel tanks made of softer, more flexible materials may not cause API rounds to function properly; however, imbedded metal fuel lines and pumps may be sufficient to cause ignition. HEI rounds have a fuzing mechanism that will cause the round to detonate at a preset time after contact and are less influenced by the design of the fuel tank. As previously discussed, quantifying the first term ($P_{em/h}$) is more difficult and can be seen by the variability in the data in Figures 4 and 5. It is safe to say that for non-inerted fuel tanks, local differences in fuel-air ratios may be sufficient to keep some portion of the ullage fuel-air mixture within the flammability range of the diagram, especially in dynamic conditions such as an API round passing through the liquid before it reaches the ullage.

Techniques for suppressing fuel tank fires and explosions are based on one or more of the following methods—

- Removal of the energy supporting the combustion process (heat removal)

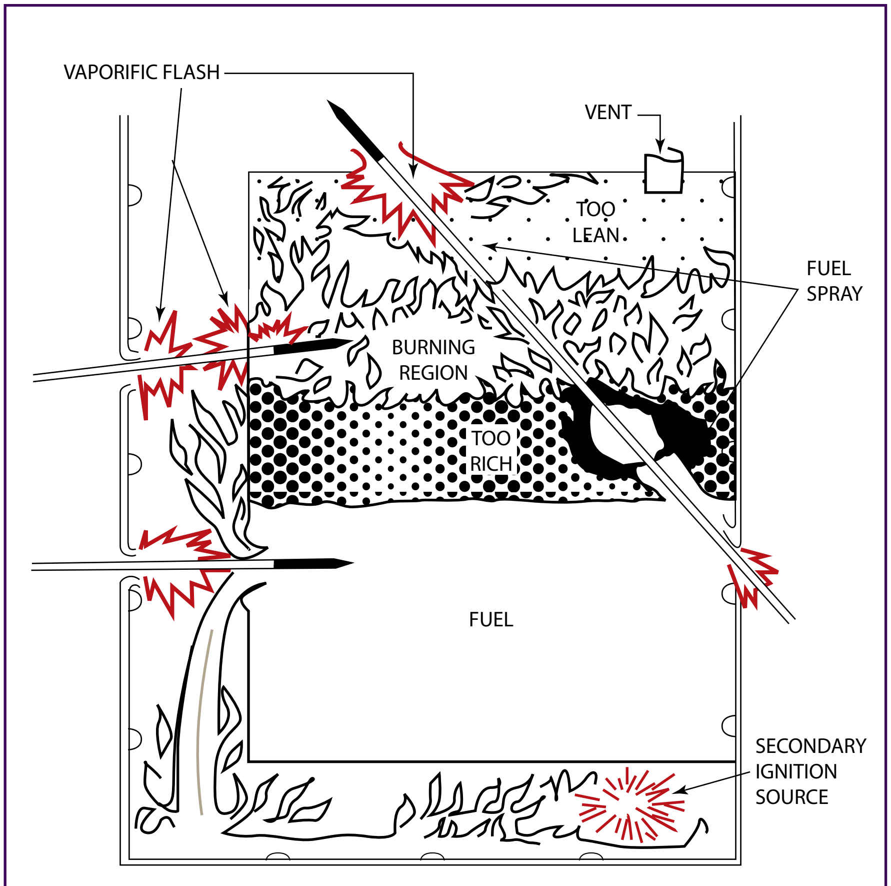


Figure 6 Possible Combustion Incidents in and Around a Fuel Tank [3]

- Interference with the combustion mixing process
- Dilution of the oxygen concentration (inerting) to approximately eight to 12% O_2
- Removal of the fuel vapors
- Breakdown of the combustion chain reaction

Examples include installation of flexible, reticulated polyurethane foam in the fuel tanks, installation of rigid, closed-cell ballistic foam in the dry bays surrounding the tanks, and introduction of an inert gas, such as nitrogen, in the ullages. Each method has its own strengths and weaknesses, but parameters such as mission profiles and desired performance characteristics, volume of the void space, and tank ullage conditions play an important role in determining which method would be appropriate.

Summary

Flammability contours are not unique dividing lines for LEL and UEL, but represent an average limit typically obtained from experimental data. Although theoretically LEL represents the lower limit of the flammability diagram for specific ignition energies under steady state conditions, in practice, actual measurements of LEL are based on an arbitrary calibration of the sensor to a gas other than jet fuel and then corrected to 0.7% fuel vapor at room temperature. LEL measurements are normally taken for safety concerns and only give an indication that conditions are present that are favorable or unfavorable for a reaction; they are not a guarantee that there will or will not be a reaction. Dynamic and non-uniform conditions within the fuel tank may cause combustion reactions when LEL readings are below 100%. The ability of the combustion process to propagate throughout the ullage is dependent on the solid and liquid boundaries in the tank and local ullage conditions. The extent of damage to the tank is dependent on tank design and the amount of energy released in the combustion process. Damage to fittings, lines, bladders, and walls is possible with relatively low overpressures, possibly allowing fuel to leak into adjacent dry bays where secondary ignition sources may start a fire. The likelihood that a fuel tank will have an explosive reaction is a stochastic parameter that is the product of terms that express the probabilities that an explosive mixture exists, ignition, component damage, and the defined kill category. Techniques for suppressing fuel tank or fuel-fed fires are based on removing or interfering with at least one portion of the fire pyramid. ■

The authors would like to thank Dr. Leonard Truett and Mr. Lawrence Eusanio from the Institute for Defense Analyses, Mr. Robert Hood from the Army Applied Technology Directorate, Mr. Fred Marsh from the Army Research Laboratory, and Dr. Peter Disimile from the Air Force 780 Test Squadron for the critique and comments provided during the preparation of this document.

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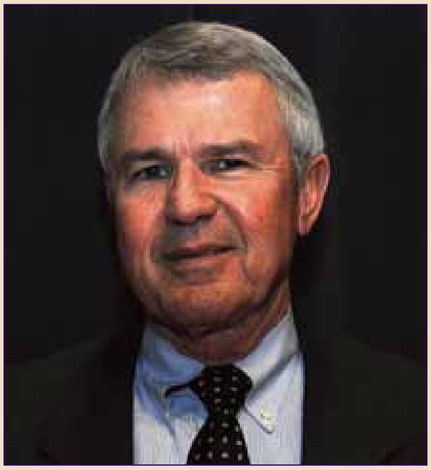
Excellence in Survivability—Dr. T.N. Mikel

by Dale Atkinson

The Joint Aircraft Survivability Program (JASP) is pleased to recognize Dr. T.N. (Mike) Mikel for Excellence in Survivability. Mike is currently the chief engineer for the U.S. Marine Corps H-1 Upgrade Program at Bell Helicopter Textron. In this position, he is responsible for all H-1 engineering for the UH-1Y USMC Utility Helicopter and the AH-1Z USMC Attack Helicopter, as well as having program responsibilities for the Build New AH-1Z and UH-1Y. The UH-1Y is now in full rate production, having achieved initial operating capability in August 2008. The AH-1Z is in the low rate initial production phase, with full rate production and initial operating capability planned for 2011.



Mike received his bachelor of science degree in industrial engineering in 1969 from Texas A&M University and was commissioned as a U.S. Army second lieutenant of infantry. He spent 12 years in the Regular Army, both as an airborne ranger infantry officer and a rotary wing aviator. He flew the range of Army aviation products of the time, including UH-1B/D/H utility helicopters, UH-1C/M gunship, AH-1G attack helicopter, and the OH-6A and OH-58A/C light observation helicopters. In addition to combat tours in Viet Nam as an infantry officer and aviator, he graduated from a range of U.S. Army schools, including the U.S. Army Command and General Staff College. Mike left the Regular Army in 1981 to pursue his current engineering career, but continued in the Army Reserve as an engineering officer. His time as an Army aviator gave him an appreciation for the need for survivability in military aircraft, an appreciation that he carried forward into his aircraft engineering role.

Through the years, Mike has continued his formal education. During his last Army assignment as associate professor of military science at Texas A&M, he earned M.S. degrees in industrial engineering–operations research (1977) and mechanical engineering (1982). He later received his PhD in industrial and manufacturing systems engineering–operations research (1996) from the University of Texas at Arlington.

At Bell Helicopter since 1982, Mike's responsibilities have addressed all aspects of the survivability and mission effectiveness of Bell's military products. He initially worked on the OH-58D Kiowa Warrior Program, cutting his survivability teeth on the ballistic vulnerability and Infrared Signature efforts of that aircraft's development. He moved on to the joint Bell-Boeing V-22 Osprey Program, working on the survivability of both U.S. Marine Corps (USMC) MV-22 and U.S. Air Force (USAF) Special Operations CV-22 versions, from preliminary design through initial low rate production. Highlights of Mike's V-22 experience included serving as the V-22 Survivability Integrated Product Team (IPT) leader and as the USAF CV-22 project engineer through Full Scale Development and Engineering Manufacturing Development (EMD) phases. On the V-22 Survivability Team from the very start of the program, he also supported the V-22 Live Fire Test Program, which was the most comprehensive and thorough live fire test program conducted through that time.

Mike has been involved throughout his tenure at Bell in all upgrade activities associated with the H-1 family of USMC helicopters. He led survivability improvement efforts to the AH-1T and AH-1W through the 1980s and was the chief of trade studies in defining the configurations of the H-1 upgrades of today. He served as the H-1 Upgrade Program Survivability IPT Leader and Live Fire Test IPT Leader during the H-1 Upgrade EMD.

Mike was Bell's engineering director for the U.S. Coast Guard Integrated Deepwater System Project, serving as the Aviation Matrix Product Team leader for the Concept Development and Functional Design phases of that effort. He was concurrently chief engineer for Bell's Unmanned Aircraft Systems, leading the development of the Bell Eagle Eye Unmanned Tiltrotor Aircraft.

In 2007, Mike returned to the H-1 Upgrade Program, initially as the AH-1Z Build New IPT leader. He retained that responsibility when he assumed the duty of Air Vehicle IPT leader in January 2008. He is now the chief engineer for H-1, with both Air Vehicle and Systems Engineering as his direct responsibility. While not directly in the survivability business today, Mike will be quick to point out that the H-1 Survivability IPT leader works for him.

Mike Joined the Combat Survivability Division of the National Defense Industrial Association in 2001. He has been an active Executive Board member since that time, serving on the Communications and Publicity Subcommittee, which he has chaired since 2006. He has served on the annual Aircraft Survivability Symposium Program Committee continuously since 2002 and was the Symposium Chair in 2003 and the "Low Altitude Today, Preparing for Tomorrow" symposium last year. He has also participated in the annual Combat Survivability Division Spring Survivability Workshops in various session leader roles.

Mike is married to the former Gayle Perryman, whom he has from time to time pressed into performing administrative assistant duties for the Aircraft Survivability symposium. They have a son, John Andrew, and a whole host of domestic animals on their small ranch northwest of Fort Worth.

It is with great pleasure that the JASP honors Dr. T.N. Mikel for his Excellence in Survivability contributions to helicopter survivability, the survivability community, and the warfighter. ■

JCAT Corner
Continued from page 5

LTJG Kiefer working with AH-1W Cobra ASE

Task Force–Afghanistan, Aviation Combat Element, planning the future JCAT footprint in Operation Enduring Freedom to support the anticipated force growth and increase in OPTEMPO while training Army, Air Force, and Marine aviation units. He works closely with the Aviation Combat Element S-2 (Intelligence), monitoring and tracking SAFIRE activity in RC-South and documents assessments with the assistance of Lieutenant Junior Grade (LTJG) Kiefer in Al Asad. This is CDR Kadowaki's second deployment to support the JCAT mission in theatre having previously mobilized to Al Asad, Iraq, in 2006.

Since November 2008, LTJG Kiefer has been manning the JCAT office at Al Asad with the Marines. In that time, he has had very few assessments in MNF-W to complete due to the great work the Marines have been doing there. However, he has been providing support to the Special Purpose Marine Air-Ground Task Force and fellow JCAT member CDR Kadowaki in Afghanistan by completing several assessments remotely from Al Asad. In the meantime, he has been working to create training drills for JCAT assessors and evaluate new JCAT gear. He has also begun working with the Marine Air Wing Intel shop to create a new threat weapons identification training brief for theater aircrew. This training combines the resources of the Marine Air Wing with JCAT to provide aircrews with the tools they need to more accurately identify enemy threat weapons when they are targeted.

Representing the US Air Force is the newest member of the JCAT Forward team, Second Lieutenant John Dlugopolsky. Working mostly with the Army aviation units, he has been stationed at Balad since his arrival in February 2009. LT Dlugopolsky has the distinction of being the first JCAT member to go through Combat Skills Training, a one-month course, prior to his deployment in theater. While CONUS, his training also included JCAT Phase I and II Assessor courses at Fort Rucker and Naval Air Warfare Center, Weapons Division, China Lake, respectively, and the Threat Weapons and Effects Seminar at Hulbert Field. ■

Annual NDIA Survivability Awards Presented at Aircraft Survivability 2008

by Dennis Lindell

The National Defense Industrial Association's (NDIA) Combat Survivability Division (CSD) held its annual Aircraft Survivability Symposium at the Naval Postgraduate School on 4–7 November 2008. The Aircraft Survivability 2008 theme was "Low Altitude Today, Preparing for Tomorrow." As the theme implied, the agenda was divided into sessions that explored how we can best balance our resources to meet the challenges of fighting the current Global War on Terror at low altitude, while preparing for the next major conflict. The keynote speakers were Brigadier General Jon "Dog" Davis, assistant deputy commandant of the Marine Corps–Aviation, and Robert "Too Tall" Kenney, executive vice president of Bell Helicopter for Government Programs. The highlight of the symposium agenda was the Combat Reports Session, featuring Marine, Army, and Air Force warfighters recently back from the battle.

The NDIA CSD Awards are presented annually at the Aircraft Survivability Symposium. These awards are intended to recognize individuals or teams demonstrating superior performance across the entire spectrum of survivability, including susceptibility reduction, vulnerability reduction, and related modeling and simulation.

The Admiral Robert H. Gormley Leadership Award, named in honor of the CSD's founder and chairman-emeritus, was presented to Captain William M. Chubb, US Navy. The NDIA Combat Survivability Award for Technical Achievement was presented to Mr. Kevin Imoto, Northrop Grumman Integrated Systems. In addition to these two annual awards, the CSD presented a special Lifetime Achievement Award to Mr. Neil G. Kacena of the Lockheed Martin Corporation. The presentations were made by Mr. Roland P. Marquis, CSD Awards Committee chairman, and Brigadier General Stephen D. Mundt, USA (Ret.), CSD chairman. Rear Admiral Robert H. Gormley joined the presentation party for the Leadership Award presentation.

Admiral Robert H. Gormley Leadership Award

The Admiral Robert H. Gormley Leadership Award is presented annually to a person who has made major contributions to enhancing combat survivability. The individual selected must have demonstrated outstanding leadership in enhancing the overall discipline of combat survivability, or played a significant role in a major aspect of survivability design, program management, research and development, modeling and simulation, test and evaluation, education, or the development of standards. The emphasis of this award is on demonstrated superior leadership of a continuing nature. Capt. Chubb received this award for exceptional leadership in the field of aircraft combat survivability. As program manager for Advance Tactical Aircraft Protection Systems (PMA-272) in the Program Executive Office for Tactical Aircraft within the Naval Air Systems Command, the breadth of requirements with which Capt. Chubb was presented is truly unique in the Department of Defense.

Taking command of PMA-272 in October 2005, Capt. Chubb personally directed the design, development, integration, testing, procurement, and transition efforts of 40 Tactical Aircraft Electronic Warfare programs and managed a Total

From left to right—Mr. Roland P. Marquis, CSD Awards Committee Chairman, Captain Paul Overstreet accepting for Captain William Chubb, 2008 Admiral Robert H. Gormley Leadership Award recipient; BG Stephen D. Mundt (USA–Ret.), Chairman, NDIA CSD, and RADM Robert H. Gormley, (USN–Ret.), Chairman–Emeritus NDIA CSD

From left to right—Mr. Roland P. Marquis, CSD Awards Committee Chairman, Mr. Kevin Imoto, Technical Achievement Award recipient; and BG Stephen D. Mundt (USA–Ret.), Chairman, NDIA CSD

From left to right—Mr. Roland P. Marquis, CSD Awards Committee Chairman, Mr. Neil G. Kacena, Technical Achievement Award recipient; and BG Stephen D. Mundt (USA–Ret.), Chairman, NDIA CSD

Obligation Authority exceeding $400 million in fiscal year 2007/2008 and $1.96 billion in domestic expenditures across the Future Years Defense Program. In addition, Capt. Chubb partnered with 21 Coalition allies in the Global War on Terrorism to provide superior electronic warfare self-protection while overseeing a Foreign Material Sales budget exceeding $125 million, including F/A-18 Electronic Warfare equipments to India, Australia, Brazil, Japan, Denmark, and Qatar.

Bringing his extensive operational, test, and acquisition experience to bear, Capt. Chubb has provided US Navy and Marine Corps aircrews with the most robust aircraft self-protection capability in the world, while displaying exceptional levels of leadership, ingenuity, and courage. The 2008 Admiral Robert H. Gormley award for leadership acknowledges the exceptional and visionary contributions of Capt. Chubb to aircraft combat survivability, the Armed Forces, and the nation. Capt. Paul Overstreet, US Navy, who is Capt. Chubb's designated successor at PMA-272, accepted the award on Capt. Chubb's behalf.

Combat Survivability Award for Technical Achievement

The NDIA Combat Survivability Award for Technical Achievement is presented annually to a person or team who has made a significant technical contribution to any aspect of survivability. It may be presented for a specific act or contribution, or for exceptional technical performance over a prolonged period. Individuals at any level of experience are eligible for this award. Mr. Kevin Imoto received this award in recognition of his exceptional technical achievement in the field of aircraft combat survivability. During the course of a long and distinguished career as a low observable technologist, he has held positions of steadily increasing responsibility at the Lockheed Martin Skunk Works, and most recently with Northrop Grumman Integrated Systems.

Mr. Imoto possesses a strong background in electromagnetics, computational methods and analysis, advanced materials, low observables testing, and the practical application of these technologies in the design and development of state-of-the-art, low observable air vehicles. He has been notably instrumental in several acknowledged programs, including the F-117, YF-22/F-22, Tier 3 Minus, and Sea Shadow. In addition, he has produced a significant body of work associated with a number of highly classified projects and programs.

His practical approach to low observable technology, along with a broad understanding of related disciplines, has allowed him to apply his expertise in optimizing designs over a vast array of requirements, constraints, and costs. In addition, Mr Imoto's remarkable work ethic and dedication to his stakeholders serves as a role model to his colleagues.

This award for technical achievement acknowledges the exceptional and visionary contributions of Mr. Imoto to aircraft combat survivability, the Armed Forces, and the nation.

Combat Survivability Award for Lifetime Achievement

Mr. Neil G. Kacena was recognized for exceptional contributions to aircraft combat survivability throughout a distinguished career in government and industry. During a lifetime of service to the Air Force and as a senior executive of Lockheed Martin Corporation, he has played a major role in the advancement of American air survivability and low

From left to right—Greg Benadom, Hardy Tyson, Kathy Russell, Ron Dexter (Poster Paper Session Chair), and Alex Kurtz

JCAT Poster Paper Team from left to right—CW4 Rick Malvarose, SMSgt Rick Hoover (holding the award), CW4 Jim McDonough, Maj Greg Thompson, and CW4 Chris Chance

observable weapon systems. A recipient of the Tactical Air Command's Instructor of the Year award, he leveraged his operational experience as a Naval Fighter Weapons School instructor and commander to provide vision and direction into the development of discriminating weapon systems technologies. Mr. Kacena demonstrated outstanding leadership, both in government and industry, by significantly influencing survivability design, program management, and delivery of low observable weapon systems to the war fighter. As director of Special Programs in the office of the Assistant Secretary of the Air Force for Acquisition, he was responsible for formulating plans, policies, advocacy, and prioritization for more than 40 Advanced Technology Programs. Mr. Kacena is a nationally recognized expert in the areas of signature management systems and survivability discriminators. Fruits of his instrumental efforts include significant contributions to the F-15, F-22, F-35, and a host of other highly classified special programs. Through the years, Mr. Kacena has served in various advisory capacities with the Department of Defense, the National Academy of Sciences, and the Air Force Science Advisory Board. His contributions within the defense industry have earned him a reputation for integrity, courage, and a fierce passion for providing the warfighter innovative solutions and capabilities.

This award for lifetime achievement acknowledges the exceptional and lasting contributions of Mr. Neil Kacena to aircraft combat survivability, the Armed Forces, and the nation.

Best Poster Paper Awards

Awards were also presented for the best poster papers displayed as part of the symposium's Exhibits and Poster Papers feature. Three awards were presented. First place went to Mr. Hardy Tyson, Ms. Kathy Russell, and Mr. Greg Bendom from Naval Air Warfare Center Weapons Division for their paper, "MK211 Projectile Threat Characterization." Second place went to Senior Master Sergeant Rick Hoover, Major Greg Thompson, and Lieutenant Colonel Chuck Larson of the Air Force Joint Combat Assessment Team along with Chief Warrant Officer 4 (CW4) Rick Malvarose, CW4 Jim McDonough, and CW4 Chris Chance of the Army Shoot Down Assessment Team, for their paper, "Joint Combat Assessment Team Data Collection and Databasing." Third place went to Mr. Alex Kurtz from the 780 TS/OL-AC and Mr. Ron Hinrichsen from RHAMM Technologies for their paper, "High Fidelity Threat Modeling."

Aircraft Survivability 2009

Preparations are now underway for Aircraft Survivability 2009: "Next Generation Requirements." Scheduled 3–6 November 2009, this important event will provide a forum to explore the robustness of current, planned, and developing systems to survive the emerging threats from complex and adaptive adversaries, across the full range of military operations through 2025. Watch for the 2009 Call for Presentations and 2009 CSD Survivability Award Nominations. ■

If you are in the Survivability Business, Monterey is the place to be in November!

The Educator's Corner—Single Hit Vulnerable Area

by Mark Couch

Welcome to the inaugural article of The Educator's Corner. Several of those involved in survivability education have volunteered to write a series of short articles for the journal. Initially, authorship of this article will rotate between CDR (Ret) Chris Adams from the Naval Postgraduate School, Maj Rich Huffman from the Air Force Institute of Technology, and Dr. Mark Couch from the Institute for Defense Analyses. Because many of our readers may have extensive expertise in specific aspects of survivability, our goal is to broaden the readers' appreciation for the diversity of the survivability discipline and maybe learn something new in the process.

Those desiring more in-depth learning may access the recently released Survivability Self Study Program developed by Distinguished Professor Emeritus Robert E. Ball. In keeping with the spirit of education, we welcome any questions, feedback, or content suggestions you might have and look forward to serving you in the future.

The single-hit vulnerable area of a component is defined as the theoretical area on the component that if hit once would cause a kill of the component. [1] The simplest method of calculating the vulnerable area assumes that an equally random hit can occur anywhere over the component's presented area (A_p) in the direction of the attack or shotline, and that the probability of component kill given a hit ($P_{k|h}$) is uniform over the component's presented area. With these assumptions, the component vulnerable area can be expressed as (note the lower case subscripts)

$$A_v = A_p P_{k|h}$$

Although an aircraft is composed of thousands of components contributing to flight or mission-essential functions, only certain ones, called critical components, contribute to its vulnerability. Critical components are defined as those components whose kill, either individually (nonredundant) or jointly (redundant), result in an aircraft kill. The ways in which the component can fail or be damaged (killed) such that the essential function(s) is (are) lost are referred to as component kill modes. The total single-hit vulnerable area of the aircraft, A_V, can be obtained by summing the contributions of the individual critical components taking into consideration redundancy, overlap, different kill modes, and cascading damage (see Chapter 5 of *The Fundamentals of Aircraft Combat Survivability Analysis and Design*). The aircraft single-hit vulnerability can be expressed as the probability that the aircraft is killed given a random hit anywhere on the aircraft and is given by (note the upper case subscripts)

$$P_{K/H} = \frac{A_V}{A_P}$$

where A_P is the presented area of the aircraft in the direction of the threat.

More complicated methods of determining the aircraft vulnerable area involve integrating the product of the individual component presented area and the probability of kill of that component given a hit at that location (kill function) over the extent of the aircraft and may include probability of fuzing for contact-fuzed high explosive warheads. Solutions to these integrals are not normally possible except in the simplest of cases; however, if the aircraft is divided into small enough grids, the integrals can be estimated by summing the vulnerable area of each grid again taking into consideration redundancy, overlap, different kill modes, and cascading damage. Analytical procedures for computing the single-hit vulnerable area of complex modern aircraft are typically performed using computer programs such as Computation of Vulnerable Area Tools (COVART), Advanced Joint Effectiveness Model (AJEM), or Modular UNIX™-based Vulnerability Estimation Suite (MUVES).

Four key points should be considered when using single-hit vulnerable area in the design process—

- Vulnerable area is a theoretical area. One cannot go out to the aircraft or show on a CAD drawing where the vulnerable area on the aircraft lies. One may point out critical components, but not a vulnerable area. This inability to point to it tangibly should not lessen its significance, but neither should it be the only parameter that drives the survivability of the aircraft.
- Vulnerable area is a function of the presented area of the aircraft in the direction of the threat. The computer programs that calculate vulnerable area take an average from many different views. The most commonly reported vulnerable area is the average of 26 views (shown in Figure 1). The problem with the 26-view average is that the equally spaced angles on two intersecting planes create equal surface area only if the aircraft is a sphere. Because real aircraft tend to have smaller presented areas along the longitudinal and lateral axes, there is an inherent bias of the results toward the top and bottom of the aircraft when using the standard 26-view average. This bias can be eliminated by using isometric views, [2] or equal steradians. Recent work by the SURVICE Engineering Company for the Joint Aircraft Survivability Program [3] shows that the isometric views provide more consistency in the calculations and recommends using 42-view isometric method for future aircraft vulnerability analyses, but the inertia of using the standard 26-view

average may be hard to overcome. However, some will argue that assuming the aircraft is equally likely to be hit from any direction is another form of biasing itself because ground-based ballistic projectiles tend to hit the aircraft in the lower hemisphere, and those areas should be weighted more in the average. Whatever method is chosen, the key is to average the calculations in the same manner so that any biases can be stated and consistently applied as comparisons are made.

- Vulnerable area is calculated for a specific threat at a given velocity from a specific aspect relative to the aircraft. In other words, vulnerable area is a function of the probability of kill given a hit for each critical component based on the velocity and obliquity of the threat at component impact. Component P_{klh} values are not based solely on live fire tests because the cost of the number of shots required would greatly exceed the funding of the live fire program. In some assessments, the P_{klh} function is determined by the product of the probability of component damage given a hit (P_{cdlh}) and the probability of component kill given the component damage (P_{klcd}). Analyses and engineering judgment are used to estimate P_{klh}, P_{cdlh}, and P_{klcd} using methodologies such as critical area removal for large components and material removal for shafts, flanges, and gears. Some of these methodologies can take into account the obliquity of the threat propagator, but small changes in the angle of obliquity can cause large changes in P_{klh} that may have huge effects on the total vulnerable area if the presented area of that component is large. Fortunately, the averaging process described previously tends to dampen large variations in total vulnerable area calculated by the computer programs, but suffice it to say that chasing the third significant digit on vulnerable area when the second is still in doubt may not be a good return on the investment. Also when the threat changes, the vulnerable area calculation from the previous threat is no longer valid. Vulnerable area must be recalculated for each threat since the P_{klh}, P_{cdlh}, and P_{klcd} values are different.
- Single-hit vulnerable area calculations are for the impact of one threat propagator on the aircraft and do not take into consideration synergistic effects of multiple systems or components failing unless all the critical components lie along the same shot-line. Recent combat data from OEF/OIF show that 40 percent of the aircraft shot with small arms or automatic weapons had multiple rounds hit the aircraft. Multiple-hit vulnerability can be calculated from the single-hit vulnerability using one of the five methods outline in Chapter 5 of *The Fundamentals of Aircraft Combat Survivability Analysis and Design*. The concern is that aircraft acquisition programs that use single-hit vulnerable area as the only survivability key performance parameter may inadvertently drive the design away from a less vulnerable aircraft to a more vulnerable one by striving to achieve a parameter instead of considering the expected threats operating in their expected environment.

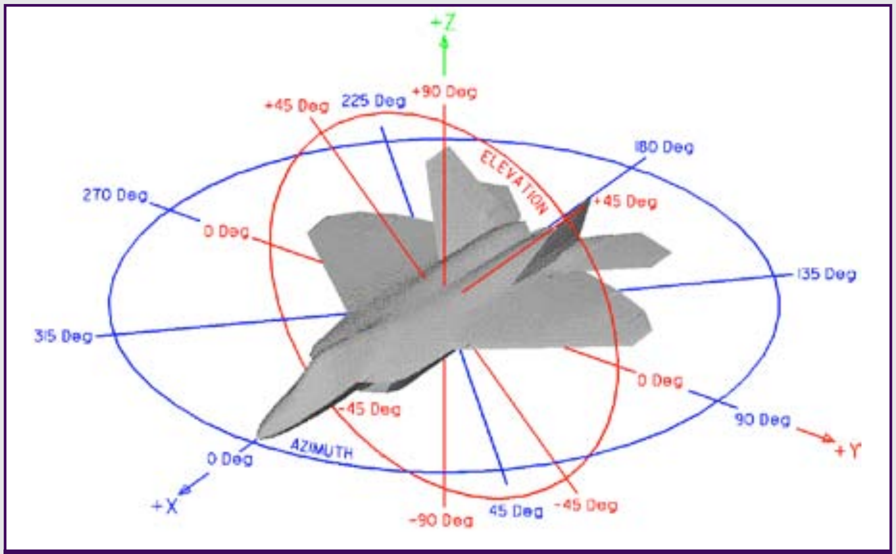


Figure 1 Diagram of the Standard 26 Views Used for Analysis (from Reference 2)

Vulnerable area calculations can be a valuable tool in the survivability engineer's toolbox. Waterfall charts can show critical components with the greatest contribution to the overall vulnerability of the aircraft, and limited resources can be used to focus redesign efforts on those areas that will give the largest reduction in vulnerability. Minimizing single-hit vulnerable area is an important technique in reducing vulnerability, but multiple hits should be considered to keep a balanced approach in protecting our warfighters. ■

References

1. Ball, Robert E., *The Fundamentals of Aircraft Combat Survivability Analysis and Design,* 2nd Edition, AIAA Education Series, AIAA, Reston, Virginia, 2003, pg 59.
2. Rosencrantz, Stephen, "Isometric Views vs. Standard 26 Views in Aircraft Vulnerability Analysis – Methodology and Comparison," ASC/ENM Technical Note, Wright-Patterson AFB, Ohio, January 2002.
3. McKay, LeAnne and Anderson, Robert, "COVART Sensitivity Studies: Input Sensitivity Studies," Report JASPO-M-07-03-012, Arlington, Virginia, 30 June 2008.

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Calendar of Events

JUL

JASP Summer PMSG
14–16 July 2009
Key West, FL

AUG

45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
2–5 August 2009
Denver, CO

AIAA Modeling and Simulation Technologies
10–12 August 2009
Chicago, IL

2009 Directed Energy Test & Evaluation Conference
10–13 August 2009
Albuquerque, NM

AUVSI's Unmanned System North America
10–13 August 2009
Washington, DC

Building Survivable Systems: A Short Course on Live Fire Testing (LFT&E)
18–20 August 2009
Belcamp, MD
http://www.survice.com/LFTE_Course.pdf

Emerging & Enabling Technology Conference
24–27 August 2009
Huntsville, AL
http://smapcenter.uah.edu/SMAP-CENTER/Conferences/etc09/Agenda.htm

SEP

The Tailhook Association: Tailhook Reunion
4–7 September 2009
Reno, NV

Introduction to Weaponeering Short Course
8–10 September 2009
Monterey CA
http://www.weaponeering.com

NGAUS General Conference
11–13 September 2009
Nashville, TN

Air & Space Conference and Technology Exposition
14–16 September 2009
Washington, DC

JASP FY09 Program Review
14–17 September 2009
Nellis AFB, NV
https://jaspo.wpafb.af.mil

9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS)
15–17 September 2009
Hilton Head, SC

OCT

19th Annual International Aircraft Fire Protection/Mishap Investigation Course
26–30 October 2009
Dayton, OH
http://www.afp1fire.com

AHS Rotorcraft Structures & Survivability
27–29 October 2009
Williamsburg, VA
http://www.ahs-hrc.org

NOV

NDIA Aircraft Survivability
4–6 November 2009
Monterey, CA
http://www.ndia.org/meetings/0940

AAAA Aircraft Survivability Equipment Symposium (ASE)
9–11 November 2009
Sheraton Music City Hotel, Nashville, TN
http://www.quad-a.org

JASP Winter JMUM
17–19 November 2009
Nellis AFB, NV
http://www.bahdayton.com/jmum

Information for inclusion in the Calendar of Events may be sent to:

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