AIRCRAFT SURVIVABILITY

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Asymmetric Threat Survivability

JAS
JOINT AIRCRAFT SURVIVABILITY PROGRAM

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JAS Program Office
200 12th Street South
Crystal Gateway #4, Suite 1103
Arlington, VA 22202
Phone: 703/607–3509
DSN: 327–3509
https://jaspo.wpafb.af.mil

Views and comments are welcome and may be addressed to the

Editor
Dennis Lindell
Phone: 703/604–1104
email:
E_GGM_GS_jasnewsletter@bah.com

Assistant Editor
Dale B. Atkinson
email:
E_GGM_GS_jasnewsletter@bah.com

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Mailing list additions, deletions, changes, and calendar items may be directed to:

SURVIAC Satellite Office
13200 Woodland Park Road
Suite 6047
Herndon, VA 20171
Fax: 703/984–0756

Promotional Director
Christina P. McNemar
Phone: 703/984–0733
mcnemar_christina@bah.com

Creative Director
K. Ahnie Jenkins

Art Director
Donald Rowe

Technical Editor
Diane Ivone

Newsletter Design
Maria Candelaria

Illustrations, Cover Design, Layout
Kacy Cummings
Dustin Hurt
Brad Whitford

News Notes

■ by Dennis Lindell

Instrumentation Roundtable

Dr. Torg Anderson of the Institute for Defense Analyses (IDA) organized and led an instrumentation round table on 20 September 2006 during the 2006 Summer Joint Program Review sponsored by the Joint Aircraft Survivability Program Office (JASPO) at Nellis Air Force Base (AFB), NV. The topic this year focused on diagnostics that might help understand fire initiation and support improvements in dry-bay fire vulnerability modeling.

Several experts on diagnostic techniques for similar processes were asked to attend and to present what they thought might be appropriate measurement techniques. These experts included the following:

- Dr. Peter Disimile, 46 OG/OGM/OL-AC, Wright-Patterson AFB, Dayton, OH, who described thermocouple and photodiode measurements conducted in recent ballistic panel tests.
- Mr. Robert Lynch, Applied Research Associates, Littleton, CO, who described a five-color radiometer thermometry technique recently used in Wright-Patterson ballistic tests.
- Dr. Jay Jeffries, Stanford University, Stanford, CA, who described a range of optical diagnostics developed for research in high-temperature gas dynamics that could be applicable to ballistic testing.
- Dr. Terry Meyer, Iowa State University, Ames, IA, who described a range of optical diagnostics developed for combustion research that could be applicable to ballistic testing. Dr. Meyer is also familiar with the capabilities related to combustion diagnostics at the Air Force Research Labs, Wright-Patterson AFB.
- Mr. Ron Dexter of SURVICE Engineering Company presented a description of the JASP's plans for a fire road map to encourage the range-test engineers to consider developing programs to resolve fire-prediction issues and, possibly, to use some of the diagnostic tools provided. In addition to providing basic data to aid in understanding fire-initiation processes, many of these diagnostics can directly support the goals of Live Fire Test and Evaluation (LFT&E). It is recommended that these instrumentation capabilities be developed through smaller JASP and Joint Live Fire (JLF) test programs.

Many test engineers attending the round table seemed positive about this meeting, stating that it provided insight into diagnostic techniques that were new to them. The organizers are encouraging discussions among presenters and representatives of the Service test ranges to determine how these methods might be developed to support their test needs.

Instrumentation topics for future instrumentation round-table sessions are requested from the aircraft survivability test and evaluation community. Topics may be sent to Torg Anderson at tanderso@ida.org. On request, Dr. Anderson will also mail a CD of the material presented on 20 September.

Joint Combat Assessment Team (JCAT)—Annual Threat Weapons and Effects Training

The 2007 annual session of the Threat Weapons and Effects Training Seminar is scheduled for 24–26 April 2007. This seminar provides practical, hands-on training in the lethality of threat air-defense systems and the damage they can inflict on friendly aircraft. Both Hurlburt Field, FL, and Eglin AFB, FL, will host seminar events. Live-fire demonstrations of selected small arms, rocket-propelled grenades, and shoulder-fired missiles will be presented. Figure 1 and Figure 2 illustrate previous demonstrations.

The seminar is sponsored by the JASP and hosted by the JCAT. Information gathered from incidents of threat exploitation, live-fire testing, and combat experience will be presented to provide a complete picture on threat lethality. Hands-on experience will be provided with threat munitions and missiles, test articles, damaged-aircraft hardware, live-fire demonstrations, and by videos from test and combat. Experienced instructors will offer current, relevant information on threat-system upgrades, proliferation, and lethality. Additional information is available on the JCAT website, https://threat-hit.wpafb.af.mil, or by telephoning Maj Chuck Larson, U.S. Air Force Reserve (USAFR) at 850/678–8333 or emailing him at charles.larson3@wpafb.af.mil.

Figure 1. Stinger Launcher Training

Figure 2. Stinger Live Fire Demonstration

National Defense Industrial Association (NDIA) Symposium Session on Survivability and Force Protection Key Performance Parameters (KPP)

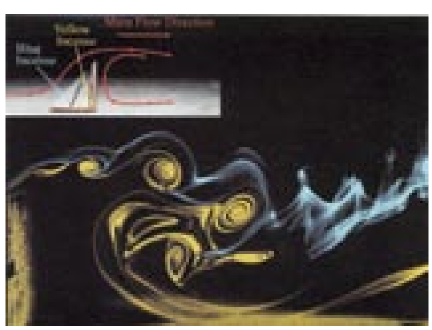
Recent legislation requires that acquisition programs, as part of their system requirements, include Key Performance Parameters (KPP) for countering asymmetric threats and for force protection. On 7 November 2006, the NDIA Combat Survivability Division (CSD) hosted a session at its workshop in Monterey, CA, which combined several efforts to define KPP for asymmetric threats and force protection and explored ways in which to bring this issue to closure. The session included several briefings on these various efforts, including the following:

- An introduction to the session and a summary of the 23 May NDIA Asymmetric Threat Workshop by Mr. Kevin Crosthwaite, Director of the Survivability/Vulnerability Information Analysis Center (SURVIAC).
- A briefing by Dr. Lowell Tonnessen of the IDA entitled *Formulating and Evaluating Key Performance Parameters for Force Protection of Aircraft Occupants from Asymmetric Threats*. This briefing described the results of a recent IDA study by Dr. Tonnessen and Dr. Joel Williamsen.
- *Survivability and Force Protection KPP in the JROC Process* by LtCol Frank J. Svet, USMC, from the Joint Staff/Joint Theater Air and Missile Defense Organization (JTAMDO). LtCol Svet described the Joint Capability Integration and Development System (JCIDS) process and how it applies to this issue, provided some legislative background behind the asymmetric threat KPP requirement, and discussed efforts by the Joint Staff to describe asymmetric threats and KPP.
- A briefing by Mr. David Hall, SURVICE Engineering Company, describing a JASPO effort to expand on the NDIA Workshop results to further define what is meant by *Asymmetric Threat*, to develop draft KPP, and to assess modeling and simulation and test and evaluation resources to measure those KPP

Following the briefings, Kevin Crosthwaite and Dave Hall facilitated a discussion session with the audience to develop recommendations for addressees for the NDIA Workshop final report and letter, comments on asymmetric threat definitions, and inputs to the JASPO study.

Dr. Disimile and Colleagues Win Award

Dr. Pete Disimile and two of his colleagues recently won an "Excellent Visualized Image for 2006" award from The Visualization Society of Japan (VSJ) for a photograph published in the Journal of Visualization in January 2006. This photograph was selected from *all* those published in VSJ journals for 2006. Pete is from the Aerospace Survivability and Safety Flight, 46th Test Wing, Wright Patterson AFB, and is a valued member of the Joint Aircraft Survivability Program. His colleagues are Mr. Luke Swanson from the University of Cincinnati Ohio and Mr. John Davis from the Engineering and Scientific Innovations Company of Blue Ash, OH. The photograph, shown below, is based on work funded under the Next Generation Fire Protection Program. The goal of the project was to examine the transport of fire suppressants in the cluttered environments found in aircraft engine nacelles and was taken during the facility check-out phase of the project. Congratulations to you and your colleagues, Pete.



Award Winning Image

Threat Effects DVD Available from SURVIAC

Threat Effects in Aircraft Combat Survivability is a documentary video project funded by the Joint Aircraft Survivability Program Office (JASPO). This project substantially updates the material presented in the original Threat Effects video released in 1986 and uniquely presents the primary threat weapons to aircraft and the ballistic response or "effect" of an aircraft when hit by a threat. It contains combat and gun-camera footage and both lethality and survivability test-analysis video, all of which are combined and edited to demonstrate the cause-and-effect relationship among threats and their effects on an aircraft on the battlefield. The benefits gained from using technologies in Vulnerability Reduction (VR) will further increase a viewers' interest in, knowledge of, and appreciation for the survivability discipline. The response to the *Threat Effects in Aircraft Combat Survivability* DVD documentary developed by Robert E. Ball, Jr., has been overwhelming, swamping the JASPO with requests. As a result, JASPO has arranged for DVD distribution through the Survivability/Vulnerability Information Analysis Center (SURVIAC). Please send all future requests to SURVIAC by completing the request form on the SURVIAC website, http://www.bahdayton.com/surviac/inquiry.aspx or by contacting A. J. Brown, SURVIAC, by phone at 937/255-3828, ext 284, or by email at Alvin.brown@wpafb.af.mil. ■

Asymmetric Threat Survivability Workshop

■ by Dave Hall and Kevin Crostwaithe

There is a growing concern in the U.S. over the evolution of "asymmetric threats" to our military forces. The concern is so great that recently Congress passed a law requiring that acquisition programs include Key Performance Parameters (KPPs) for countering asymmetric threats as part of their system requirements. However, there is no agreement on what constitutes an asymmetric threat, particularly to air systems, nor is there guidance to programs on how to incorporate asymmetric threat KPPs into their requirements.

In response to those issues, the National Defense Industrial Association (NDIA) Combat Survivability Division (CSD) conducted a workshop on Asymmetric Threat Survivability at the Institute for Defense Analyses (IDA) in Alexandria, VA. The workshop, held on 23 May 2006, was sponsored by the Deputy Director, Operational Test and Evaluation/Live Fire Test and Evaluation (DDOT&E/LFT&E), and focused on identifying the steps necessary to better understand, evaluate, and defeat asymmetric threats to air vehicles.

The workshop was planned and organized on three premises:

- As peer or near-peer opponents become less likely, terrorists and non-state threats will predominate.
- Asymmetric threats and assaults will be the preferred method of attacking U.S. forces.
- The rising cost of weapons systems and sensitivity to casualties is causing decision makers at the U.S. Department of Defense (DoD) to reconsider survivability requirements and methods.

Workshop Approach

The workshop opened with several background briefings in the morning followed by discussion sessions in the afternoon. Kevin Crosthwaite of the Survivability/Vulnerability Information Analysis Center (SURVIAC) presented a paper that described examples of asymmetric threats throughout history, focusing on asymmetric threats to aircraft. He introduced a draft definition of the term "asymmetric threat" and a potential list of threats to be discussed in the afternoon.

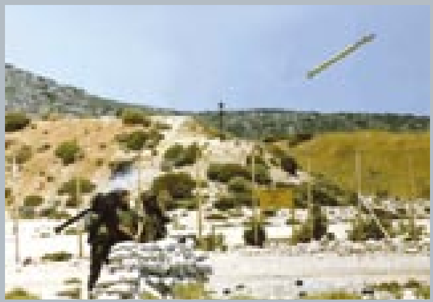


Figure 1. MANPADS launch

Next, Randy Davis of the Defense Threat Reduction Agency (DTRA) discussed differences and similarities between High-Power Microwave (HPM) and nuclear Electromagnetic Pulse (EMP) threats to aircraft. He discussed a hierarchy of steps that can be taken to protect systems; applicable DoD policy, instructions, and standards and hardening guidelines; and several computer codes and test methods used in system design and evaluation. There were questions about the adequacy of current Military Standards (MIL STDs) for hardening and whether these should be revisited.

Dr. Lowell Tonnessen of the Institute for Defense Analyses (IDA) then presented the background on the Congressional law that requires acquisition programs to plan for countering asymmetric threats. He stressed that the primary motivation is to protect people and reduce casualties. He also stressed that the terminology is not officially defined. He underscored that, while this was not an extension to the T&E law, the resulting KPPs will require T&E.

Dr. Joel Williamsen, also of IDA, followed Dr. Tonnessen with a proposed approach for establishing KPPs for force protection and survivability against asymmetric threats. He proposed a definition of asymmetric threats, discussed crew casualty considerations, and distinguished force protection from aircraft survivability.

Following Dr. Williamsen, Hugh Griffis, Aeronautical Systems Center/Engineering (ASC/EN), presented a range of ideas on potential scenarios and vignettes under which asymmetric threats might engage aircraft. A discussion ensued about the levels of detail required in a vignette to enable consistent evaluation at the same time as avoiding a too detailed point design and ensuring necessary robustness. He emphasized that we need a diversity of scenarios and need to do parametric analysis within them.

And David Hall, of SURVICE Engineering Company, wrapped up the morning's briefings by discussing how threats, scenarios, and metrics interrelate in an integrated survivability assessment. Survivability still comes down to breaking the "kill chain" for asymmetric and traditional threats. He described potential asymmetric threat KPPs that could drive future survivability design.

During the afternoon session, discussions focused on defining an asymmetric threat, listing and prioritizing asymmetric threats, discussing possible scenarios, enumerating ways in which to counter asymmetric threats, and establishing potential metrics for evaluating system force protection and survivability measures against asymmetric threats. Several scenarios were proposed to illustrate different types of asymmetric threats and their potential effects. Because this was a one-day workshop, developing KPP guidance was postponed to a future date.

To better define the term "asymmetric threat," workshop attendees developed Figure 2, which illustrates three axes that reflect the asymmetry of an attack:

- Cost Asymmetry
  (easy-to-use, inexpensive)
- Employment Asymmetry
  (irregular tactics)
- Effect Asymmetry
  (gains greater than effort expended)

In this chart, the "asymmetry" of the threat grows toward the upper-right corner. The chart includes a number of examples showing how "traditional" or "regular" threats to aircraft could be considered asymmetric by changing their employment tactics. For example, Man-Portable Air Defense System (MANPADS) attacks using traditional forces meet the "cost" criterion, but they would be considered more asymmetric if employed in non-traditional ways (such as from the back of a pickup truck in an urban area or against commercial aircraft). Threats can be expected to migrate in and out of consideration as asymmetric threats depending on cost, employment and/or effect. Proliferation can move costly threats into the realm of asymmetric threats, because an end user doesn't have to invest in developing the weapon.

Workshop attendees derived a proposed definition of "asymmetric threat" to aircraft systems based on inputs from the morning's briefings and from discussing the three elements shown in Figure 2. Combining these considerations and the workshop discussions yielded the following proposed definition and expansion to aircraft:

Asymmetric threats are threats used to attack a technologically superior force, usually through improvised or inexpensive means and/or irregular tactics, to achieve political, economic, or military (tactical and strategic) gains.

For aircraft, these attacks have most recently been directed against slow- or low-flying platforms and usually involve readily available, unsophisticated weapons—small arms, Rocket-Propelled Grenades (RPGs), unguided rockets, and MANPADSs—employed by dispersed forces using irregular tactics. Typical features of asymmetric threats include focusing on producing casualties and using surprise or out-of-the-box tactics by irregular forces to exploit a perceived weakness in systems or operations. Other more sophisticated threats, such as lasers or HPM systems, could also be used as an asymmetric threat. Aircraft

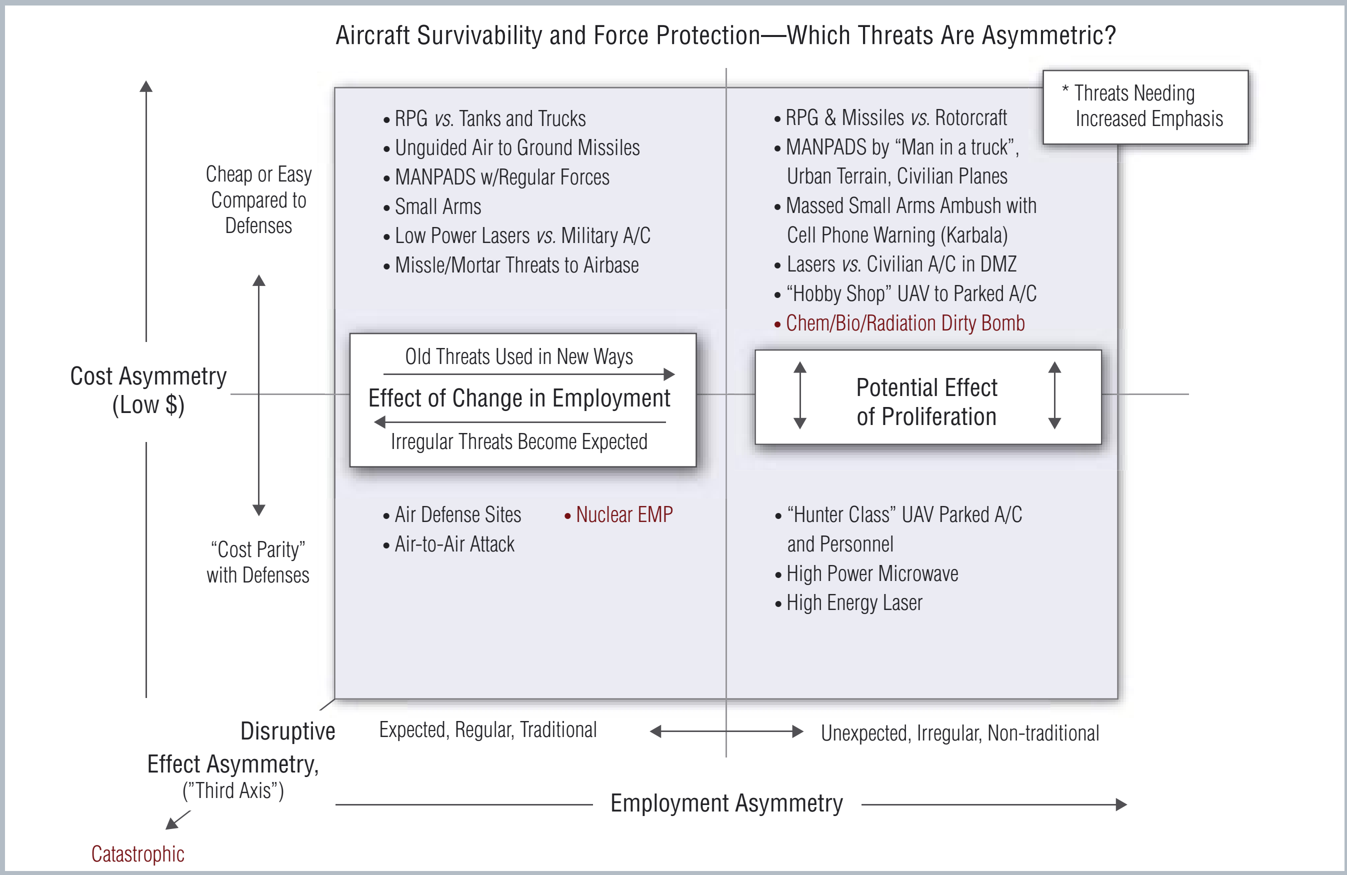


Figure 2. Aspects of asymmetry

could also be attacked when parked or wherever aircraft might be deemed most vulnerable.

This definition is being incorporated into an IDA paper entitled, *Establishing and Evaluating Key Performance Parameters for Force Protection of Aircraft Crews and Passengers from Asymmetric Threats*.

There was considerable discussion of potential scenarios for asymmetric threats, in categories described by Hugh Griffis' paper from the morning session: air-to-air, ground-to-air, air-to-space, ground-to-ground, *etc.* There was also some discussion of potential metrics for use in defining KPPs to asymmetric threats. These discussions did not yield specific results but rather a variety of possibilities for scenarios and KPPs. There was general agreement that further work will be required to better define scenarios and recommend KPPs for these types of threat.

Workshop Recommendations

Based on inputs from workshop participants, the National Defense Industrial Association (NDIA) Aircraft Combat Survivability Division is recommending in its workshop report that DoD perform the following:

- Establish a formal definition of asymmetric threats to develop Congressionally mandated force protection and survivability KPPs. The definition developed during the workshop is offered as a starting point.
- Publish clarifying guidance to aid in establishing force protection and survivability KPPs for combat aircraft.
  - Force protection KPPs should consider crew casualty evaluation metrics, taking into account both immediate casualties from combat events and from those caused by aircraft egress and/or crash landings that result from combat events.
- Survivability KPPs should consider evaluation metrics for both susceptibility (probability of aircraft hit) and vulnerability (probability of aircraft kill given a hit).
- Support the development of models and tools to evaluate asymmetric threats and crew casualty evaluation metrics.
- Encourage the development, coordination, and prioritization of asymmetric threat scenarios and vignettes for use in System Threat Assessment Reports (STAR) and the guidance documents of the Department of the Army's program to organize total army to meet contingencies (Capstone).
- Promote the formation of aircraft-oriented asymmetric threat Red Teams, similar to those of the Space Countermeasures Hands On Program (CHOP). Individual system programs should form Red Teams to postulate and evaluate potential asymmetric threats.

Figure 3. The asymmetric threat challenge

Summary

Asymmetric threats are a real and growing challenge to our forces, but there remains considerable confusion about what constitutes an asymmetric threat, and how we should evaluate the ability of our aircraft to survive those threats. This workshop was successful in improving our common understanding of asymmetric threats to aircraft systems. A definition of asymmetric threats has been proposed, and a number of recommendations made to DoD. Careful review and consideration of these recommendations would be a first step on the path toward improved force protection. ■

About the Authors

Mr. David Hall is the Chief Analyst for SURVICE Engineering Company, under contract to the NAWCWD Survivability Division for analysis support services. SURVICE provides the Navy with analyses of air weapon systems, test, and analysis support services; and simulation and software support including model W&A. Before his retirement from the government in January 2002, he was Chief Analyst of the NAWCWD Survivability Division, head of the Survivability Methodology Subgroup for JASPO, and interim JASA Director. From 1992–1996, he was also the Joint Project Manager of the SMART project, which developed and demonstrated Joint M&S VV&A and configuration-management processes for DoD. Mr. Hall has Bachelor of Science and Master degrees in mathematics from California State University at Long Beach, CA.

Mr. Kevin Crosthwaite is Director of the Survivability/Vulnerability Information Analysis Center (SURVIAC). He has worked on several technical analysis and test programs involving a wide variety of weapons systems. Mr. Crosthwaite has a masters in nuclear physics from Ohio State and is a licensed professional engineer. He serves on the NDIA Combat Survivability Division Executive Board and on the AIAA Survivability Technical Committee. He may be reached at 937/255-4840, DSN 785- 480, or via email at crosthwaite_kevin@bah.com

NPS Distinguished Professor Emeritus Robert E. Ball Wins Prestigious AIAA Best Book Award

■ by Barbara Honegger, M.S.

Naval Postgraduate School (NPS) Distinguished Professor Emeritus of Mechanical and Astronautical Engineering Robert E. Ball, "The Father of Aircraft Combat Survivability Education," has won the prestigious American Institute of Aeronautics and Astronautics (AIAA) Summerfield Book Award for his pioneering textbook, *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition*, the only book to address all aspects of aircraft survivability.

Aircraft combat survivability addresses active and passive man-made threats to the successful operation of military and civil aircraft and missiles and how to design air vehicles to minimize the effectiveness of such threats.

Distinguished Professor Emeritus Robert Ball displays the second edition of his book, *The Fundamentals of Aircraft Combat Survivability and Design*, which has won the prestigious American Institute of Aeronautics and Astronautics (AIAA) 2006 Summerfield Book Award.

Ball received the award at a ceremony attended by over 1,000 members at the 45th annual Aerospace Sciences meeting in Reno, NV, 9 January. The honor is presented to the author of the book judged the best recently published by the professional association.

"I'm truly honored by this award," Ball said in an interview after the ceremony. "It's a good feeling, because it shows that the book, which grew out of the lectures and course notes for my aircraft combat survivability course at NPS—the first course on the subject taught anywhere in the world—has value."

The creator and long-time editor of AIAA's education series and former senior dean of the Air Force Institute of Technology, Dr. John S. Przemieniecki, underscored the importance of Ball's book.

"Looking back at all the major AIAA book publications, I am convinced that Dr. Ball's book made the most significant contributions to the state of the art in the aircraft industry, and specifically to improvements in survivability and reduction in vulnerability of the new generation of U.S. Air Force aircraft now entering the inventory for the new millennium," Przemieniecki said in support of the nomination.

The second edition of the book, which was released in 2003, is significantly different from the first edition published in 1985.

"The second edition is more than just an expansion of the original," Ball explained. "Though large amounts of new material have been added throughout—the new edition is more than twice as long as the original—it's been rewritten to make it truly a student's textbook. The essentials are contained in chapter one, and more detailed information follows in the sub-areas."

The second edition also has an additional appendix on the application of probability theory to survivability assessments, as well as student learning objectives at the beginning of each major section and problems at the end. Some examples of new content are the survivability features of a number of current U.S. military aircraft, including stealth and electronic countermeasures, and combat data from Operation Desert Storm only recently released to the public.

Looking back, Ball recalled how the book grew out of his notes and lectures for the pioneering NPS course.

"For survivability to become a design discipline, an educational program first had to be developed," Ball noted, "and there was no better place to develop such a program than the Naval Postgraduate School, where officer students learn how to become aircraft engineers and designers. So I developed the first aircraft combat survivability course ever offered at an educational institution, at

NPS in 1977. Its primary goal was to teach these officers how to design survivable aircraft so they could establish realistic survivability requirements when they became Department of Defense program managers."

Many of Ball's former NPS students are doing just that, including RADM Timothy Heely, program executive officer for Strike Weapons and Unmanned Aviation.

"Of all the courses leading to my Master of Science degree from the Naval Postgraduate School (1985, Aeronautical Engineering), the one with the most applicability to me as both a single-seat jet pilot in A-7s and FA-18s and as the Chief Engineer for Naval Aviation was Dr. Ball's course on aircraft survivability," said Heely in his letter to the selection committee.

"The education I received from him at NPS has been applied directly to the design of the FA-18 Super Hornet, and the results of that design are superb.

"I am now ensuring that the same principles are being applied to Navy and Marine Corps unmanned aviation, of which I am the program executive officer," Heely added. "This critical design aspect, survivability, is absolutely essential in today's combat and its importance will only grow as we move forward. There is no doubt in my mind that, were it not for Dr. Robert Ball's pioneering efforts and sustained leadership, we would be far, far behind where we are today."

Many of Ball's former students are now in leadership positions in the DoD and the aircraft industry.

"Many in DoD with the mission to increase the survivability of our military aircraft have been students of Bob's here at NPS and in his many years of teaching short courses in the U.S. and throughout the world," said NPS Professor Emeritus of Mechanical and Astronautical Engineering Conrad Newberry, who submitted Ball's letter of nomination to the selection committee.

"Universities are the last institutions in any civilization to change," Newberry stressed, "and though aircraft are essentially useless unless they're survivable, and survivability needs to be addressed in the design of every plane, civilian universities don't recognize aircraft survivability as a unique and separate discipline. So there are few, if any, doctoral researchers in this vital field. Notably, it was Robert Ball and the NPS who were the first to transcend such specialized concerns. Bob's course, and his textbook which came out of it, are the only articulation of survivability as an engineering discipline in and of itself, which is what makes it so important. Simply put, *Aircraft Combat Survivability Analysis and Design* is the bible of the field."

"Professor Ball is the world's leading authority on aircraft combat survivability," agreed Dr. John P. Fielding, professor of aircraft design and head, Department of Aerospace Engineering, Cranfield University, England. "Without his book, it would be impossible to produce realistic preliminary designs for combat aircraft. The first edition was outstanding, but the second is brilliant. It is extremely accessible, comprehensive and scholarly."

"Not only is Bob's the only book on all aspects of this critical subject available in the public domain anywhere in the world," said NPS Professor of Mechanical and Astronautical Engineering Morris Driels, "it serves as the basic reference work for new students and experienced practitioners alike and is a single-source reference for all who work in the area. Anyone involved in any aspect of aircraft design should have a copy."

"When I was appointed the first director of live-fire testing when Congress passed the live-fire test requirement for all major DoD weapons and platforms in 1987, Dr. Ball was already leading the charge to not only encourage aircraft survivabilty in our weapons platforms, but also doing something about it," said James F. O'Bryon, who guest lectured in Ball's courses at NPS. "His book is a world-recognized reference on the subject of aircraft combat survivability and the only book of its kind anywhere. I have copies of both the first and second editions and use them frequently for reference. I teach live-fire testing across the country and always recommend his book as required reading."

When Ball retired from NPS in 1998, military instructor CDR Mark Couch, one of his former students, took over teaching his course. Five years later the NPS aeronautics program moved to the Air Force Institute of Technology, Couch was transferred to Japan and there was no one left at NPS to teach survivability. Fortunately, CDR Chris Adams, another of Ball's former students, returned to NPS in 2005 as Associate Dean of the Graduate School of Engineering and Applied Sciences.

Naval Postgraduate School Distinguished Professor Emeritus Robert Ball (right) receives the AIAA Summerfield Book Award for his pioneering textbook *The Fundamentals of Aircraft Combat and Survivability Analysis and Design, Second Edition*, from AIAA President Roger Simpson at the 45th AIAA Aerospace Sciences Meeting awards luncheon, 9 January in Reno, NV.

"In addition to his duties as associate dean, I'm delighted to say that Chris has revived the teaching of survivability at the NPS, moving beyond aircraft survivability to teaching a course on the survivability of all types of military platforms for the Mechanical and Astronautical Engineering Department," Ball noted.

Adams is teaching his platform survivability course ME 4751, an evolution of Ball's course focused on aircraft, this Winter quarter.

Also this quarter, NPS will further build upon Ball's pioneering foundation by standing up a new NPS Center for Survivability and Lethality.

"Twenty faculty members have already agreed to participate in the research of the new center, under MAE," said Adams, who assisted with expanding the vulnerability reduction section of the first edition of Ball's book. "A lot of air combat groups and people in industry want to take the platform survivability course via distance learning through the center."

Since the first survivability course in 1977, Ball has taught approximately 4,000 military officers, DoD civilians, and U.S. aircraft industry personnel the fundamentals of the discipline and delivered short courses throughout the U.S. and to NATO in Europe, Canada, Greece, and Great Britain.

To spread the word about survivability, Ball's course was selected in 1994 to be the first distributed learning (DL) course of the Department of Aeronautics and Astronautics' new Master of Science degree program for the Naval Air Systems Command (NAVAIR). It was also the first NPS DL course to use two-way video and audio technology to present content simultaneously to students at NPS in Monterey and NAVAIR in Washington, DC. The most recent offering of Ball's course was sent to six off-campus sites.

Ball's textbooks, which have sold approximately 13,000 copies, including 4,000 purchased by the Department of Defense, were sponsored by the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), now the Joint Aircraft Survivability Program Office (JASPO). The Original JTCG/AS was established by the Joint Logisitics Commanders shortly after the end of the Vietnam War as a result of the large number of U.S. aircraft downed by enemy fire in that conflict. One of its primary goals was to establish aircraft combat survivability as a design discipline to ensure that survivability is built into all U.S. military aircraft.

Ball received his bachelor's and master's degrees in civil engineering from Northwestern University, and his Ph.D. in structural mechanics, also from Northwestern, in 1962. After half a decade in industry directing research in structural and solid mechanics, he joined the Naval Postgraduate School faculty as an assistant professor in 1967. Ball was promoted to associate professor in 1970, full professor in 1978 and distinguished professor in 1994. He retired from teaching, becoming an NPS distinguished professor emeritus, in 1998.

The AIAA Summerfield Book award caps Ball's many honors. He received the AIAA's Survivability Award in 1996 and the DoD Deputy Director, Operational Test and Evaluation/Live-Fire Testing Arthur Stein Memorial Cup for Excellence in 2000 in recognition of his lifetime achievement in support of live-fire testing. The following year, Ball received the National Defense Industrial Association's (NDIA) Combat Survivability Lifetime Achievement Award.

An AIAA Fellow, Ball established and served as the first chairman of the society's Survivability Technical Committee from 1989 to 1992. In 1991, he was appointed chairman of the National Research Council's Committee on Weapons Effects on Airborne Systems, serving until the final report was written in November 1992. In 1997, Ball served as an expert witness on the National Transportation Safety Board's public hearing on the TWA Flight 800 mishap.

The mission of the American Association of Aeronautics and Astronautics is to advance the state of aerospace science, engineering and technological leadership. The international professional association serves over 35,000 members in 65 regional sections and 79 countries.

To learn more about aircraft combat survivability, visit Professor Ball's Aircraft Combat Survivability Education website at http://www.aircraft-survivability.com/. For more information about the new NPS Center for Survivability and Lethality, contact CDR Chris Adams at caadams@nps.edu, 831/656-2682. For detailed information about all NPS programs, go to http://www.nps.edu. ■

About the Author

Barbara Honegger, M.S. is Senior Military Affairs Journalist at the Naval Postgraduate School, the nation's premier defense and security research university. Prior to coming to NPS in 1995, Ms. Honegger held a number of positions in the federal government, including White House Policy Analyst and Special Assistant to the Assistant to the President in the first Reagan Administration; the President's liaison to the Defense Advisory Committee on Women in the (Military) Services (DACOWITS); and Director of the Attorney General's Task Force on Legal Equity in the U.S. Department of Justice. She is co-author of *The Military Draft* (Hoover Institution Press, Stanford University), and author of *October Surprise*, on the genesis of Irangate. Ms. Honegger is a Naval War College graduate in National Security Decision Making, and holds a bachelor's degree in Honors Writing from Stanford University and a master's degree in Psychology from John F. Kennedy University, in California. Over the past decade, she has written and published hundreds of articles on the Naval Postgraduate School's cutting edge research and educational programs. For current and archived articles, see http://www.nps.edu.

Key Performance Parameters (KPPs) for Force Protection of Aircraft Occupants

by Dr. Lowell Tonnessen, Dr. Joel Williamsen, Larry Eusanio, and Dr. Vincent Volpe

The Statutory Requirement for Force Protection

This article arose out of questions as to how to implement the force protection requirements of Section 141 of the National Defense Authorization Act (NDAA) of Fiscal Year 2005, which requires (in part) that Key Performance Parameters (KPPs) for force protection and survivability be included as part of documenting system requirements for any manned system that "is expected to be deployed in an asymmetric threat environment."

Although the term "asymmetric threat" has no official definition within the U.S. Department of Defense (DoD), the working definition below [1–3] seems appropriate for application to manned aircraft systems:

Asymmetric Threats
Threats that permit an enemy to attack a superior force, usually by easy-to-use, inexpensive means and irregular tactics, in order to achieve political, economic, or military (tactical and strategic) gains.

The most commonly employed anti-aircraft threats that meet these criteria in recent conflicts have been massed small arms, Rocket-Propelled Grenades (RPGs), and Man-Portable Air Defense Systems (MANPADSs) employed in irregular ways against low-altitude aircraft, often during approach and landing.

Quite often, the intent of asymmetric attacks is to inflict casualties as well as loss of expensive assets. This is reflected in the law's dual emphasis on survivability and force protection.

What's the difference between force protection and survivability? General Peter Pace gave a succinct summary of their meanings in his memo [4] implementing the law:

Force Protection Attributes
Are those that contribute to protection of personnel.

Survivability Attributes
Are those that contribute to the survivability of manned systems.

One can infer that the overriding intent of requiring force protection KPPs is to address issues that otherwise wouldn't be addressed by survivability—those centered on protecting U.S. personnel. For aircraft systems, this would include all aircraft occupants, both crew and passengers.

A Good Example?

Aircraft programs are beginning to develop KPPs for force protection. The following example is from the Future Cargo Aircraft program:

The FCA must have pilot/copilot protection from small arms fire up to 7.62 mm at a range of 400 m (threshold) and 7.62 mm APM2 at 100 ft with armor protection for loadmasters (objective).

It doesn't address all threats, but that's acceptable for a KPP, which represents only a subset of requirements—in essence, those that aren't tradable.

The draft KPP addresses force protection through protective features for the crew. It clearly addresses personnel casualties and is relatively easy to verify through test and evaluation. Its primary drawback is that it assumes a design solution—the provision of armor. Armor is heavy and its protection is directional.

Is it a good KPP? It depends on the analysis that supported the formulation. The following section presents a process to help formulate force protection KPPs for aircraft.

Scoping the Problem

First, we recall that Section 141 requires KPPs for both survivability and force protection. These should complement each other. Although there is an overlap, the primary emphasis of a survivability KPP is survival of the aircraft, whereas the primary emphasis of a force protection KPP is survival of personnel.

In the schematic presented in Figure 1, we're assuming that susceptibility reduction (preventing a hit) is addressed, where appropriate, through the survivability KPP, even though it will affect personnel survivability. For this reason, we'll narrow our force protection focus here to survivability of occupants after a hit. This would include issues normally considered beyond the scope of aircraft survivability: features that might protect against personnel casualties even after a system is considered "killed."

In the area of intersection, survivability and force protection have different emphases. Survivability emphasizes preventing system kill, given a hit, whereas force protection emphasizes preventing personnel casualties, given a hit. These different emphases should be reflected in different analytic measures used to express the survivability and force protection KPPs.

We recognize that force protection can be more broadly defined. For example, one could argue that an aircraft provides force protection if it is used to protect other manned systems or ground troops. We chose to limit our scope, however, to considerations that would apply to all manned aircraft.

In 2005, the Institute for Defense Analyses (IDA) in Alexandria, VA, conducted a preliminary review of the causes of personnel casualties in recent combat incidents involving helicopters. [5] Not surprisingly, the review found that most casualties were caused by a crash that ends a mission, not from personnel being hit directly by threat munitions.

It seems to us that crashworthiness and ejection systems might be considered force protection features, in addition to features that protect both aircraft and occupants. If so, then our consideration of force protection KPPs should allow us to consider a broad spectrum of force protection features, rather than narrowly looking at design solutions such as armor.

Distinct Design Trades

Although force protection and survivability overlap in scope, they address distinct design trades. Design features that are optimal for reducing aircraft attrition are not necessarily optimal for reducing casualties. For example, crashworthiness features or ejection seats might be the best solution to reduce casualties, but they don't address aircraft attrition at all.

As another example, the IDA looked at the causes of H-60 accidents for Army and Navy aircraft over a five-year period and found loss of power and loss of flight control to be important for different reasons. [6] Loss of power resulted in more Class A accidents than loss of flight control, but loss of control caused more casualties because crashes were worse. If we want the optimal solution for reducing aircraft losses, we would place greater importance on power loss; but if we want the optimal solution for reducing casualties, we would place greater importance on flight controls.

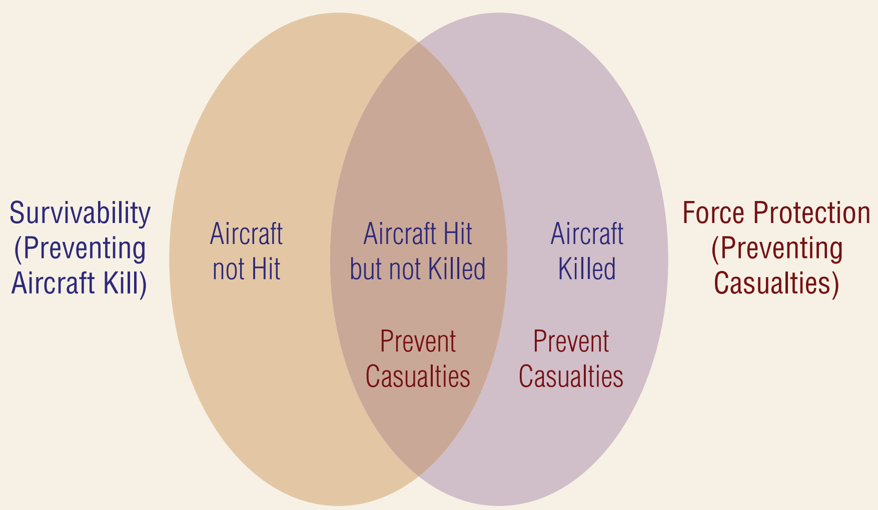


Figure 1. Comparative Emphases of Survivability and Force Protection

A Suggested Process

With these considerations in mind, we propose a four-step process for formulating and evaluating force protection KPPs for aircraft.

1. Establish threat-encounter conditions of interest by considering either combat data or scenarios that realistically reflect how aircraft have been or might be attacked by asymmetric threats.

2. Base the KPP on some quantitative measure of crew casualties. This might be the probability of one or more casualties or the expected number of casualties following an asymmetric attack. In many cases, the required level might be "better than the existing system."

3. Adapt available models and test methods to quantify casualties for existing and new aircraft. In most cases, the quantification of *immediate casualties* will require minimal adaptation. *Casualties during ejection or egress*, however, are not normally assessed during survivability test and evaluation nor are *casualties during a crash landing*. Initial adaptations are likely to be established with a broad brush, using estimates based on combat and mishap reports.

4. Reduce probability of aircrew or passenger loss through design iterations. Basing force protection KPPs on an estimate of occupant casualties offers a number of advantages over other approaches discussed earlier:

   – It offers a direct metric for addressing the central issue that gave rise to the KPP law—a concern over casualties.

- It does not limit a developer to a single design approach (armor) but allows the developer a variety of design options for reducing casualties, including armor, ullage protection, fuel bladders, fire detectors, fire suppressors, system redundancy, system separation, ejection systems, crashworthy design features, and crew egress after landing.

- It is a way to consider aircraft vulnerability reduction, crashworthiness, and crew egress features together under one metric, thereby allowing development of a "global" solution to reduce casualties that is directly supportable through cost/benefit analyses. Crashworthy features, for example, would at last have a way of "buying" their way onto a helicopter—historically, a difficult "sell" to program management but (as we have shown) vital to occupant survivability.

An Example: EA-6B Force Protection

An IDA paper [2] applied this process to an example of EA-6B force protection enhancement. Although the example has some basis in a real evaluation, simplifying assumptions were made both to keep the example unclassified and because certain types of data are lacking. The results are intended for illustration only.

The example considers three kinds of personnel casualties: *immediate casualties, casualties following ejection,* and *casualties during a forced or crash landing*. The analysis compares a baseline aircraft with a new system containing one or more potential product improvements. Various threat scenarios are considered in the Table 1. Recall that the KPP does not address *all* threat scenarios, only those considered important enough that the resulting requirement is not tradable.

The threat selection takes into account both assessed risk and consequence of a successful attack. An actual study would result in considerations that would be classified. These scenarios are given only as examples. In Table 1, the scenario of interest is a MANPADS attack on takeoff or landing.

Force Protection Measures

As mentioned earlier, the measure selected for force protection should, in most cases, be a *quantifiable measure of personnel casualties*. In this example, we've selected *P(C/A)*, which is defined as the probability of one or more crew casualties following an attack. For this metric, one casualty counts the same as four casualties. (An alternate would be the expected number of casualties given an attack.)

A casualty in this case is defined as a crew fatality. This can be caused by an immediate injury to a crew member, an inability to safely eject, or a fatality during landing and/or ditching. In a pilot's case, any physical condition that affects his ability to fly results in an ejection of the remaining crew, which can lead to additional casualties.

The Capabilities Development Document (CDD) would describe the threat scenario and all aspects of the vignette that would be required to determine the *P(C/A)*, including aircraft altitude, attitude, velocity at the time of attack, and procedures to be taken following an attack.

Estimates of Personnel Casualties

We next estimate the expected probability of one or more casualties for the baseline EA-6B. Three kinds of casualties are considered: immediate casualties, casualties resulting from ejection, and casualties during a crash landing.

1. Estimates of *immediate casualties* require minimal adaptation of existing vulnerability assessment methodologies, as is the case for estimates that a failure would require ejection.

2. A broad-brush estimate that an *ejection* would result in a casualty is based on historical records of ejection safety. The estimate does not take into account precise ejection conditions. This is an area in which methodologies might be refined if force protection is to be given the same attention as survivability.

3. The *crash casualty* analysis is performed because some hits might cause hidden damage to systems that would only be apparent during landing. In the IDA study, these values are "made up" for purposes of illustration. Crash casualties would be a much larger concern for helicopters, in which landing (not ejection) must occur to save occupants. Analysis of crash casualties would require revision of existing analytic models—Computation of Vulnerable Areas and Repair Times (COVART)—with

Potential Threat Scenario	Considerations	Rating
Small Arms Attack Upon Takeoff or Landing	Airport security prevents sufficient firepower to be brought to bear	Medium
MANPADS Attack Upon Takeoff or Landing	Single attacker may use urban terrain to approach aircraft, strike at aircraft with low to moderate risk	High
Chemical/Biological Attack Upon Takeoff/Landing, or When Parked	Consequence Moderate, Probability Moderate	Medium
EM Attack During Mission Phase	Consequence Moderate, Probability Low	Low
Nuclear Attack During Mission Phase	Consequence High, Probability Low	Low

Table 1. Considerations in the Choice of EA-6B Threat Scenario

additional input data. This would be the most difficult part of the evaluation given current analytical capabilities.

Evaluating Against the KPP

The next step would be to estimate the potential to reduce crew casualties to meet threshold and objective levels. Similar methodologies would be used for the baseline assessment.

In the example analysis, a first-cut estimate indicated a 25% reduction in casualties could be achieved through installation of an On-Board Inert Gas Generating System (OBIGGS) or through some combination of four other options. These would have to be explored against cost, weight, and performance characteristics to determine which systems should be pursued.

Although this example has been greatly simplified, it illustrates an approach to defining and evaluating KPPs for force protection of aircraft. It also illustrates which elements of the problem can be addressed with very little modification to vulnerability reduction analytical methodologies and which parts of the problem will require more substantial modifications to analytical capabilities.

Conclusion

- The intent of the law, and the focus of a force protection KPP, should be on occupants, not one specific technology (such as armor).
- The proposed casualty-focused process involves the use of many existing aircraft survivability models at key points in the evaluation procedure. The process, however, will need expansion of models to consider the following:
  - Effect of threat-induced damage on ejection, return to base, egress, escape
  - Effect on landing maneuvers and systems
  - Prediction of crash conditions and estimates of crash damage
  - Probability of occupant casualties given damage of critical components
  - Encounter conditions for new threats
- The approach meets Joint Requirements Oversight Committee (JROC) guidance that KPPs should be measurable and testable. ■

Acknowledgment

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About the Authors

Dr. Lowell Tonnessen is Assistant Director of the Operational Evaluation Division at the IDA. Dr. Joel Williamsen, Dr. Vincent Volpe, and Mr. Larry Eusanio are Research Staff Members at the IDA and specialists in the Live Fire Test and Evaluation of aircraft systems.

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"Asymmetric Threats and Integrated Survivability Assessment"

Survivability KPPs might be derived from these and from the other metrics that are directly related to survivability of the platform (such as threat system probability of kill envelopes for missile systems, which assesses the probability of killing the air vehicle at a variety of locations within the threat envelope, with and without countermeasures, for various maneuvers, speeds, and altitudes). We are suggesting that these metrics can form the basis of asymmetric threat KPPs development in those many cases in which they match the characteristics of asymmetric threat systems. For asymmetric threats that are totally unrelated to conventional threats, other metrics will be required.

In summary, the anticipated threat drives air vehicle design for survivability, but the unanticipated threat can drive actual system survivability. Therefore, the system design process must consider a wide variety of scenarios and conditions to derive a robust survivability design. The vignette approach described by the ISA process can ensure that the missions and scenarios used in design and testing will "cover the waterfront" for anticipated (and, to some extent, unanticipated) threat situations. The ISA survivability metrics can form the basis for developing KPPs in the asymmetric threat environment. However, it all depends on what "asymmetric threat" actually means for aircraft. We hope that the NDIA Workshop has begun the process of developing some answers to that question. ■

Vulnerability Reduction (VR) Features for Commercial Derivative Combat Aircraft

■ by Torger Anderson, Joel Williamsen, and Leonard Truett

Large commercial aircraft have often been selected as platforms to accomplish high-value, combat-related missions without incurring the costs of a dedicated design. They provide state-of-the-art performance in which mission profiles are similar to that of the commercial application—usually long-range or long-endurance flights at high altitude and steady cruise conditions with limited maneuverability requirements or special takeoff and landing performance. High-value missions in which commercial designs are used include the following:

- Airborne tanker (KC-10, KC-X)
- Airborne Command and Control (E-3 Sentry, E-10A)
- Intelligence, Surveillance, and Reconnaissance (ISR) (E-8C Joint Stars, Aerial Common Sensor)

These platforms are defined as High-Value Airborne Assets (HVAAs), whose roles are so important that the loss of even one could seriously impact U.S. warfighting capabilities or provide an enemy with significant propaganda value. [1] The costs of developing the commercial platforms they are based on have already been borne by the manufacturer. Although considerable effort may be necessary to modify the design for Service application, the intent is to gain as much benefit as possible from the commercial development.

In most cases, combat survivability was not a consideration in the commercial designs. While safety is an important requirement for commercial applications, it is only a starting point for survivability requirements. A wide spectrum of techniques is available for protecting commercial derivatives from combat threats, and the selected approach varies depending on the application and the Service involved. (See Figure 1.) In general, though, extensive hardening of an existing design to resist battle damage—Vulnerability Reduction (VR)—can be extremely costly and impractical and is largely avoided. The philosophy has been that Susceptibility Reduction (SR) alone—preventing threats from hitting a target—is adequate to protect these platforms. This is primarily done through Concept of Operations (CONOPS) that keep aircraft out of reach of known threats and protect them with supporting fighter aircraft. In some cases, radar and infrared (IR) countermeasures have been added to prevent threats that reach the aircraft from hitting it. These approaches have been successful to date.

However, that could change as developing threats challenge the survivability approach based on CONOPS. Potential adversaries recognize that a few HVAA platforms are critical to U.S. combat operations. The Russians and Chinese have weapons-development programs focused on attacking those assets. Table 1 lists some example threats cited in the open literature. [1, 2] Weapons specifically designed with the range, speed, and targeting capabilities to threaten HVAAs are being promoted for this purpose and, once developed, are likely to proliferate to current or potential U.S. adversaries. At the very least, these threats reduce the effectiveness of our CONOPS-based survivability approaches. HVAAs will be put at increased risk or forced to operate at greater distances from the battlefield, reducing their operational effectiveness.

To complement a CONOPS-based approach to protecting HVAAs against these emerging threats by depending solely on countermeasures is risky. The success of countermeasures is uncertain, and threats are continually upgraded to overcome countermeasure strategies. As Figure 1 indicates, some level of VR may be necessary to achieve an acceptable level of survivability on HVAA platforms in the future. Furthermore, VR features, when combined with countermeasures, can offer synergies that greatly improve survivability beyond the sum of the individual contributors. This is

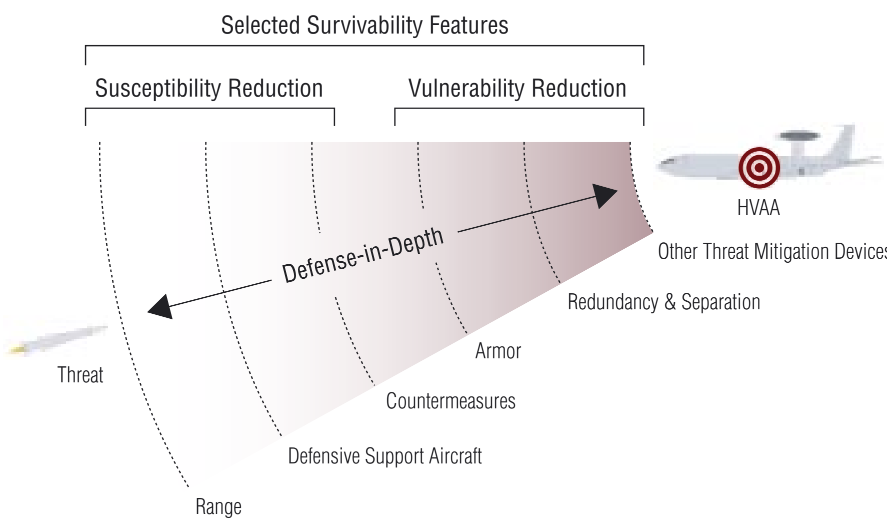

Figure 1. Defense-in-Depth

System	Type	Nation	Range (mi.)	Modes	Status
FT-2000 / FT-2000 A	SAM	China	62	Passive Home on Jam /RF	Deployed (?) For Export
S-400 Triumf	SAM	Russia	249	I. Semi-active RF I. Active RF	Deployed 2001 For Export
SD-10	AAM	China	43	I. Command Guidance, Inertial, Active Terminal II. Inertial, Active Search III. Fire & Forget, Active Seeker IV. Home on Jam / RF	In Development
R-77M -PD	AAM	Russia	99	Inertial, Mid-Course Correction, Terminal Active RF	Development complete (?)

Table 1. Sample HVAA threats

especially true when the SR and VR techniques are carefully integrated into the design process. Furthermore, integrated SR and VR strategies do not necessarily require extensive changes to a commercial platform. Electronic and IR countermeasures can be, to a large degree, "strap-on" systems, while significant reduction in vulnerabilities can be achieved by incorporating fuel-system protection that does not alter the basic aircraft design.

SR, including electronic countermeasures, has been more readily accepted as a survivability approach for commercial-derivative HVAAs. However, relatively simple modifications to a platform design for VR, especially when integrated with countermeasures, can yield some significant improvements in survivability. As a result, the focus should be on VR features that are practical for commercial-derivative HVAAs.

Vulnerability in Commercial Derivative Aircraft

Vulnerabilities and VR can be understood only by examining how potential threats can affect aircraft systems. Major damage mechanisms can be summarized as follows:

- Direct ballistic damage to structural members may be a risk to modern commercial aircraft designs. Their high-aspect ratio wings provide aerodynamic efficiency but also increase risks that ballistic damage could reduce load-carrying capacity or lead to flutter or limited control authority. However, it is recognized that modern commercial designs do have structural redundancies and design margins to satisfy safety and service-life requirements. In any case, significant design changes for HVAAs are impractical.

- Ballistic impacts to full fuel tanks can result in hydrodynamic ram damage —the hydraulic transfer of impact loads to the walls of the tank—that can not only rupture the tank but also destroy the integral structure. Military aircraft are usually designed to withstand these loads to some degree, but commercial and combat aircraft alike share this concern. For existing commercial aircraft, there is currently no practical way to modify the design to enhance hydrodynamic ram tolerance.

- Ballistic penetration into the ullage—the air space above the fuel in the tank—can cause a fuel/air explosion leading to significant structural damage if the fuel/air ratio is within the flammability limits. Past considerations of cost, weight, and maintenance made ullage protection impractical for commercial design. However, the FAA has recently demonstrated a ullage-protection system for commercial aircraft [2], while designs for combat aircraft have evolved into acceptably small, light, and reliable systems.

- Ballistically induced fires in quiescent dry bays that are located adjacent to fuel tanks are a serious threat because (1) commercial designs have large amounts of fuel distributed over large areas of the aircraft, and (2) ballistic threats provide both ignition sources and means of mixing the fuel and air. Since commercial designs don't address this issue, there are significant opportunities for improving derivative designs.

- Engines are similar on commercial and commercial derivatives, and they have common vulnerabilities. Although the vulnerabilities of high-bypass turbofans, typical of modern commercial aircraft, have not been carefully assessed, some aspects of commercial designs may actually reduce vulnerability: (1) they all have multi-engine redundancies, and (2) their podded-engine configurations reduce the risk of cascade-damage effects between engines and other aircraft systems.

- There may be limited opportunities to improve control-system vulnerabilities in commercial derivatives. Experience gained from accidents and incidents in commercial service [3] has produced robust designs that incorporate redundancy and separation of system components.

- Ballistic injury to crew members can be of concern on HVAA designs, primarily because they carry large crews. It would be difficult to reduce this vulnerability with methods other than armoring, which adds significant weight penalties.

Addressing ballistically induced, fire-related issues might offer the greatest improvement in vulnerability: they seem to be major contributors in this list, and practical methods exist to reduce risks of ullage explosion and dry-bay fires in commercial derivative aircraft.

The Multi-Mission Maritime Aircraft (MMA) Example

The U.S. Navy's P-8A Multi-Mission Maritime Aircraft (MMA) program has investigated the effectiveness of VR as it relates to fuel systems and determined that, when integrated with threat countermeasures, it can have a large influence on the survivability of a commercial derivative aircraft. The MMA effort provides an excellent example of how commercial derivative aircraft can be practically and effectively modified to be survivable. This program uses the Boeing 737-800 design, with -900 wings for extended range, as the basis for a long-range, armed, maritime patrol aircraft. Modifications are to be included in the design to accommodate mission-related systems and weapons and to provide a level of survivability in intended missions. The MMA does not perform missions typical of an HVAA nor does it depend almost exclusively on the CONOPS-based SR strategy. However, the commercial platform it is derived from has vulnerabilities similar to those of typical HVAA platforms, and it benefits from VR methods that could be directly applied to newly developed HVAAs.

Figure 2 contains side and top plan views of the MMA aircraft, with a qualitative designation of fuel-tank locations derived from MMA program descriptions. The tank volume contributes significantly to overall vulnerability since it is a large fraction of the overall aircraft cross-sectional area, especially from a top (or bottom) view. An early computational assessment by Boeing indicates that fuel-related vulnerabilities for a specified threat are more than half the total vulnerabilities of the aircraft. These are much greater than any other single vulnerability issue.

The MMA VR efforts began with attempts to mitigate fuel-tank vulnerabilities in the legacy P-3 patrol aircraft (MMA's predecessor). The approaches considered were (1) fuel-tank ullage inerting to prevent fire and explosion inside the fuel tanks and (2) dry-bay fire protection in spaces adjacent to the tanks. The technologies to provide these capabilities were not defined; levels of effectiveness in ullage and dry-bay protection were assumed. However, current technologies are available that can achieve those goals.

The P-3 analysis included a dry-bay fire suppression system that was assumed to be 95% effective in extinguishing a ballistically induced fire from a specified threat, and ullage protection was assumed to be 100% effective for the tanks in which it was installed. The results, shown in Figure 3, reveal the dramatic effects of combining these VR techniques with electronic countermeasures for a missile threat against the P-3. The combination of fuel-tank inerting and dry-bay fire protection greatly reduces the vulnerability of this platform and, when combined with a countermeasures system that ensures a specified miss distance, can reduce the risk from a nearly 100% probability of kill (Pk) to a 95% likelihood of survivability in this encounter.

While the absolute reduction in Pk may be debated, two design considerations can be taken from the trends shown in Figure 3. To reduce fuel-tank vulnerabilities significantly, both ullage explosion and dry-bay fires must be effectively addressed. Each reduces this set of vulnerabilities by about half, and together almost eliminate it as a concern if the miss distance is adequate.

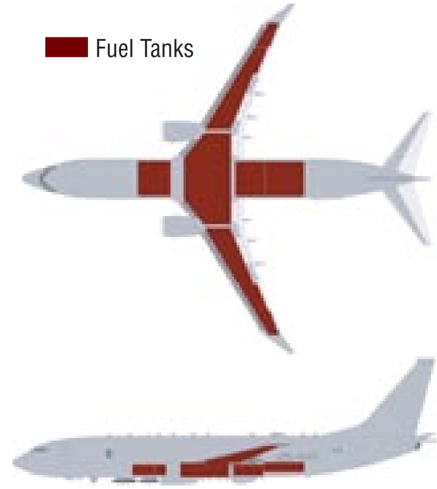

Figure 2. MMA fuel-tank distribution

A second observation from this plot reveals a clear point in the miss distance at which fuel-tank VR becomes effective. (Note green circle.) Electronic countermeasures would be required to drive the miss distance up and ensure the survivability of the aircraft. This further emphasizes the need for careful integration of SR and VR features in the design.

Fuel-tank VR effectiveness became better understood as the MMA design effort progressed. Figure 4 is a "burn-down" chart showing the calculated VR associated with various aircraft fuel tanks and dry bays. It shows that the single greatest benefit comes from inerting the wing fuel tanks.

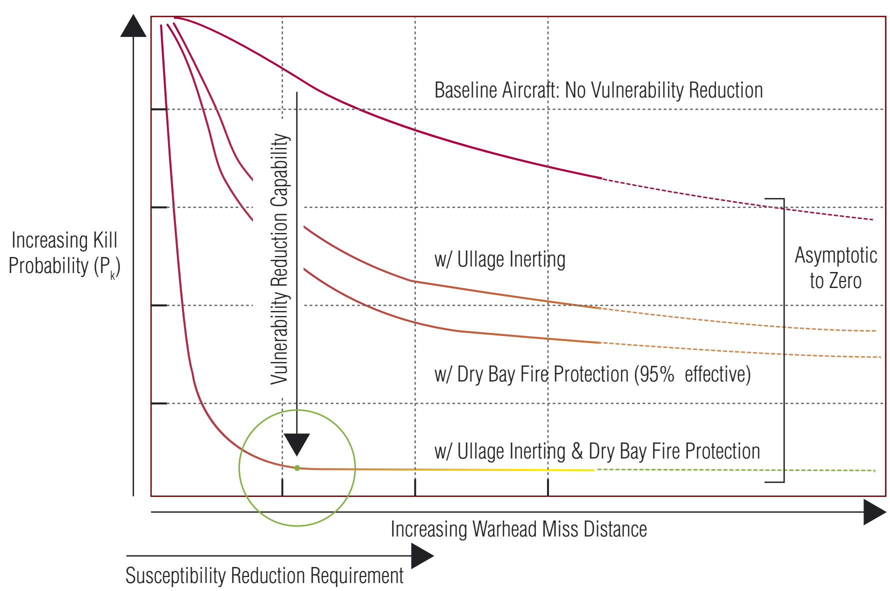

Figure 3. Effects of miss distance and VR on survivability

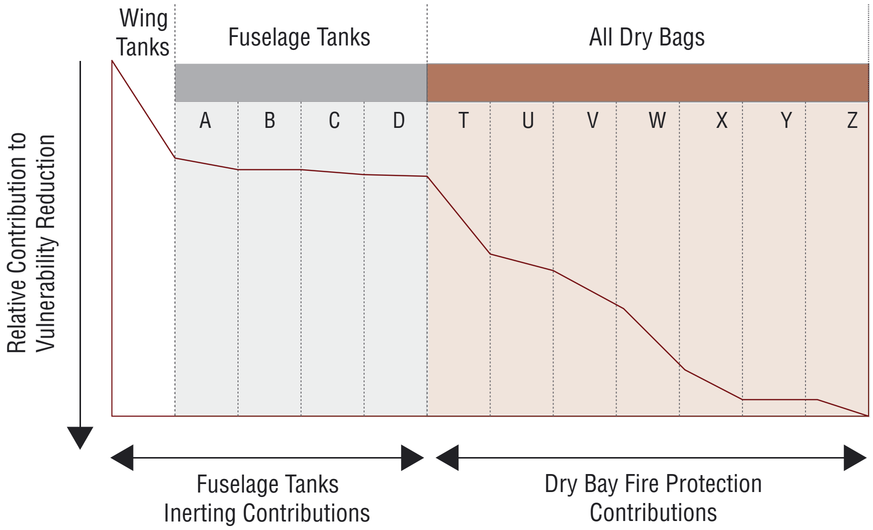

Figure 4. Vulnerability improvements from fuel-tank inerting and dry-bay fire protection

This is not surprising, given the large area of the tanks indicated in Figure 2. Figure 4 also shows that dry-bay fire protection reduces overall vulnerability more than does fuel-tank inerting, but a large number of dry bays must be addressed. However, it also indicates that protecting some dry bays (*e.g.*, the dry bay designated Y) offers little benefit, and it may not pay to address them.

It should be emphasized that, while dry-bay protection offers less of a weight penalty than ullage protection, the comparisons are not entirely made for purpose of making trades—dry-bay protection and fuel-tank inerting are both necessary to significantly reduce the vulnerability of the platform. The MMA program has evaluated a number of technologies to address fuel-tank fire suppression and dry-bay protection to achieve the most effective capabilities while minimizing cost, weight, and reliability penalties. An Onboard Inert Gas Generating System (OBIGGS) and active dry-bay fire suppression are currently being designed into the aircraft.

Conclusion

Survivability in combat environments depends on a well-integrated design of countermeasures and VR features. Practical and reliable technologies to attack major vulnerabilities in commercial derivative HVAA platforms—fuel-related vulnerabilities—are available and being incorporated into aircraft designed for combat use. Their integration into commercial derivative aircraft can be done with minimal effect to basic design and provide significant survivability benefits to HVAAs. ■

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About the Authors

Dr. Torger Anderson, a member of the Operational Evaluation Division at the IDA, supports aircraft LFT&E for several programs, including those of the F–35, the MMA, and the E-10A. He has 25 years of experience at United Technologies Research Center and Pratt & Whitney, primarily working in aircraft engine combustor development and design and combustion diagnostics development. He is an active member of the AIAA Weapon Systems Effectiveness Technical Committee. He may be reached by email at tanderso@ida.org

Dr. Joel Williamsen is task leader for fixed-wing aircraft Live Fire Test & Evaluation (LFT&E) within the Operational Evaluation Division of the Institute for Defense Analyses (IDA), Alexandria, VA. Dr. Williamsen supports fixed-wing aircraft LFT&E for acquisition programs and Joint Live Fire (JLF) assessments for existing fixed-wing aircraft and rotorcraft in support of the Director, Operational Test and Evaluation (OT&E) of DoD. Dr. Williamsen has received the Army's Research and Development Achievement Award for armor/anti-armor design and the Exceptional Achievement Medal from the National Aeronautics and Space Administration (NASA) for "advancement in the state-of-the-art of orbiting spacecraft hypervelocity impact and survivability analyses." He is an Associate Fellow of the American Institute of Aeronautics and Astronautics, Inc. (AIAA) and a former chairman and active member of the AIAA Survivability Technical Committee.

Dr. Lenny Truett, a member of the Operational Evaluation Division of the IDA, supports aircraft LFT&E for several programs, including those of the C-5, C-17, C-130J, C-130 AMP, and Airborne Laser. Before joining the IDA, he was a project engineer with the 46th Testing Wing at Wright-Patterson Air Force Base, OH, where he specialized in fire and explosion suppression. He may be reached by email at ltruett@ida.org

Steve Polyak

Excellence in Survivability

■ by Rick Grote and Eric Edwards

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Stephen F. Polyak for Excellence in Survivability. No stranger to most in the community, Steve has been involved in aircraft vulnerability for more than 25 years. He has been a leader in testing and analyzing all U.S. Army helicopters in today's fleet, and he currently serves as the Program Coordinator for the Systems Engineering and Experimentation Branch and the System Leader for Kiowa Warrior and Armed Reconnaissance Helicopter (ARH) programs at the Army Research Laboratory's (ARL) Survivability/Lethality Analysis Directorate in Aberdeen Proving Ground (APG), MD.

Steve's passion for aircraft began long before his career did. The oldest son of a U.S. Marine Corps officer, Steve grew up in a home that emphasized task discipline and attention to detail, two traits well suited for his eventual occupation: analyzing precision-engineered aircraft. This military upbringing also meant, however, that Steve never stayed in one place too long. His boyhood addresses included Camp Lejeune, NC; Philadelphia, PA; Quantico, VA; Pearl City, HI; and Coronado, CA. But despite this continuous state of change, there was one thing that didn't change—the presence of aircraft.

As far back as Steve can remember, he was "surrounded by airplanes." And they fascinated him so much that he rarely let one fly over without looking up. Thus, his pastime as a youth involved either building models of his favorite WWII warbirds or researching their histories. Also, during his family's tour near North Island Naval Air Station in Coronado, it was not unusual to find young Steve and a like-minded friend wandering through the aircraft hangars, exploring the workings of WWII-vintage planes such as the R4D Skytrain (a Navy version of the C-47), the C-45 Expeditor, and other aircraft parked there. Steve recalls that the secret to not being evicted (and to achieving the ultimate prize, a seat in the cockpit) was to show interest and ask questions. And it usually worked, until the day a stern test pilot caught him advancing on an early OV-10 Bronco. Steve also recalls from this time seeing combat-damaged A-1 Skyraiders and other naval aircraft returning from Vietnam. Early experiences such as these formed quite an impression on a boy who kept his head in the clouds.

Following his father's retirement from the Marine Corps, Steve and his family settled in Pennsylvania. He graduated from Reading Senior High School in 1972 and then attended Pennsylvania State University, earning an A.S. in mechanical engineering technology in 1975 and a BS in aerospace engineering in 1979. While pursuing his BS, Steve also enlisted in the Marine Corps through the Platoon Leader Class officer candidate program for undergraduates. His goal was to become a pilot. But when an injury during summer training at Quantico forced him to leave the program, he had to plot a new course in aviation.

And that course initially came via a college friend, who encouraged Steve to accept an engineering internship at the Naval Air Rework Facility (NARF) in Norfolk, VA, in 1979. The NARF performed inspection, repair, and overhaul of TF-30 turbofan engines used in F-14 and A-7 aircraft. Steve served as technical liaison between the engine manufacturer (Pratt & Whitney) and the land and sea units that used the engines. Although he didn't know it then, this experience would play a major role in helping Steve secure his next position, one that would launch his career in aviation survivability.

After only a year in Norfolk, Steve decided to travel north to join the Aerial Targets Branch of the Army Ballistic Research Laboratory (BRL) (now part of ARL) at APG, MD. There were several reasons for the move. It was an opportunity to better apply his theoretical ability; it was an opportunity to work with helicopters and foreign aircraft; and, most importantly, it was an opportunity to be three hours closer to Reading, PA, and Nicolene—Steve's high-school sweetheart and soon-to-be wife.

Based on his previous engine experience, Steve was hired by BRL to investigate the use of thermodynamic cycle analysis to model the effects of ballistic damage on turbine engines. However, the aircraft phase of the Joint Live Fire (JLF) test program was also being formulated at this time, and Steve began to work with several senior analysts and mentors who introduced him to the world of live fire testing and allowed him to "cut his teeth in vulnerability." Of particular importance was the late Walt Thompson, whom Steve credits for contributing to the success of not only his career but also to the survivability discipline as a whole.

From 1980 to 1989, Steve served in numerous capacities, including vulnerability and aerodynamic analyst, Project Engineer, Deputy Test Director, and Test Director. Most notably, he was selected to serve on two engine Source Selection and Evaluation Boards (SSEBs), first for the Army Modern Technology Development Engine and then for the Army T800. He also served as the Project Engineer for the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS, now the JASP) Advanced Engine Materials Ballistic Penetration Study and was involved in the first post-Vietnam assessments of actual combat-damaged helicopters (UH-60 Black Hawks from Grenada and, later, AH-64 Apaches from Panama).

In addition, on the Black Hawk JLF test program—which stands as the first Army JLF helicopter program and a benchmark for other JLF and Life Fire Test and Evaluation (LFT&E) programs—Steve served as both Test Director and Project Engineer. He was also the JLF Deputy Test Director for Army aircraft, and he contributed to developing rotorcraft weapon systems by leading the component qualification tests on systems such as advanced rotor systems, hydraulic actuators, engine materials, and lightweight armor development/qualification programs. Finally, his participation during this time in developing data sets for assessing helicopter engine-out autorotation helped lay the groundwork for vulnerability analysis methods that are still in use at ARL today.

Throughout the 1990s, having been promoted to Aviation Engineering Team Leader, Steve continued to lead efforts to better understand damage effects to helicopter rotor blades. He coordinated with Sikorsky Aircraft Corporation and the University of Maryland to analytically determine methods and perform wind-tunnel tests to measure effects. He also continued as the Army's JLF Test Director, pushing the Army's requirements for developing ballistically tolerant designs and leading analytical and test evaluations of risk reduction and LFT&E programs for the RAH-66 Comanche, AH-64 Apache, and CH-47 Chinook helicopters.

Today, Steve continues his long-standing work of enhancing the survivability of both old and new aircraft. As mentioned, he is the System Leader for Kiowa Warrior and ARH programs, and he has recently served as the lead evaluator for vulnerability and Live Fire on the ARH SSEB. And following in the footsteps of those who helped him so much early in his career, Steve has also increasingly assumed the role of mentor, especially for new hires in the System Engineering and Experimentation Branch (SEEB). In addition, he has served as a mentor in various programs for visiting West Point cadets, as well as in the Army Science and Engineering Apprenticeship Program (SEAP) and the Foreign Scientist Exchange Program.

And Steve's mentorship hasn't stopped at the office. He's been active in the Boy Scouts of America for nearly 20 years, seeing each of his three sons excel in the organization. Christian (24) and Alex (22) are both Eagle Scouts, and Viktor (12), now a Star Scout, is well on his way. In addition, although Steve is careful to say that he wants his sons to follow in his aviation footsteps only if they want to, it seems that they may do just that. Christian is a 2004 graduate of the Coast Guard Academy and a Lieutenant, Junior Grade, flying HH-65 Dolphin helicopters in Washington state. Alex has also recently decided to join the Coast Guard.

Finally, as if Steve doesn't get enough of airplanes during work hours, he has a long-standing hobby of collecting military aviation relics—specifically, identification/data plates from the airframes of WWII-era planes. These plates were favorite wartime souvenirs of veterans, and Steve says the hobby allows him not only to "hold something that is a part of history" but also to interact with people around the world. For instance, he was able to find and correspond with the German pilot of a Messerschmitt 109 (from which one of Steve's plates was taken) who was shot down over North Africa. Also included in Steve's collection are several plates from aircraft downed during the Battle of Britain.

Looking back on his career, Steve says he doesn't really feel "excellent." He says he has just kept "plugging away." Nonetheless, there are a few areas of which he is especially proud: his leading of the first Army helicopter LFT (on the Apache Longbow), his 15 years as Deputy Test Director managing JLF Army Air programs, his aircraft design support and qualification testing, and his service on three SSEBs, where he felt he has had the most direct impact on the survivability of new aircraft. But despite his personal achievements, Steve says the highlight of his career has definitely been to work with many of the tri-Service and industry pioneers of survivability.

As for young analysts just entering the business, Steve has several words of advice: (1) Make sure you find out what's been learned in the past before stepping too far into the future. (2) Get involved in the survivability community [JASPO, JLF, the American Institute of Aeronautics and Astronautics, Inc. (AIAA), etc.] as early as possible. (3) Make sure you document and share your accomplishments with others. And for anyone interested in rotorcraft survivability, Steve says he always has time to talk—that is, if he's not looking up. ■

About the Authors

Rick Grote is currently Chief of the System Engineering and Experimentation Branch of ARL's Survivability/Lethality Analysis Directorate at APG, MD. He has more than 22 years in the field of survivability, especially live fire testing. Most notably, he was a participant in planning and conducting the very first live fire test (on the Bradley Fighting Vehicle), and he has specialized expertise in building engineering model inputs for vulnerability/lethality analysis. Mr. Grote holds B.S. and M.S. degrees in Mechanical Engineering from the West Virginia Institute of Technology and the University of Delaware, respectively.

Eric Edwards is a technical writer/editor for the SURVICE Engineering Company, in Belcamp, MD. He has supported ARL and other Defense organizations for 17 years, editing numerous technical reports, articles, and books, including *Ballisticians in War and Peace , Volume III; Lessons Learned From Live Fire Testing; and Fundamentals of Ground Combat System Ballistic Vulnerability.* Mr. Edwards holds a B.A. in print journalism from Bob Jones University and an M.S. in professional writing from Towson University.

Asymmetric Threats and Integrated Survivability Assessment

■ by David Hall

Air vehicle systems must protect themselves from anticipated (and unanticipated) threats by breaking the threat kill chain somewhere, preferably in multiple places. How best to do this and how to evaluate an air system's ability to do it depend on the types of threats the system will face. Asymmetric threats may pose some unique challenges for assessment—some survivability techniques may apply to all threats, and some technologies may not translate well to asymmetric threats. It depends on what we mean by "asymmetric threats."

The new Congressional and Joint Service Direction mandates that systems must include force protection and survivability Key Performance Parameters (KPPs) in asymmetric threat environments: what those programs must do is to determine what "asymmetric threats" threaten their systems; where and how they will encounter these threats; what KPPs are appropriate; and how they will measure the results for those KPPs, using a combination of Modeling and Simulation (M&S) and Test and Evaluation (T&E) resources.

An accepted definition for asymmetric threats does not exist. [The National Defense Industrial Association (NDIA) Workshop has provided a suggestion, based on a definition proposed by the Institute for Defense Analyses (IDA)]. The Microsoft Network (MSN) Encarta Dictionary defines "asymmetric" as "**not equal**: lacking equality, balance, or harmony." Generally speaking, asymmetric threats are thought of as being easy-to-use, inexpensive threats deployed in some unconventional manner. Examples might be using Man-Portable Air Defense Systems (MANPADSs) systems off the back of pickup trucks to threaten aircraft on takeoff or landing or while conducting predictable maneuvers to avoid terrain or man-made obstacles (such as power lines). Asymmetric threats might also include suicide missions using small manned aircraft (or unmanned aircraft) armed with homemade bombs. On the other side of the coin, asymmetric threats can also be thought of as unconventional weapons—directed-energy weapons, chemical or biological agents, or even nuclear devices (dirty bombs)—that may have widespread effects.

Whichever type of asymmetric threat is encountered by an air vehicle system, there are conventional methods of "breaking the threat kill chain" that may or may not be appropriate to that threat. (See Figure 1.) From threat suppression to threat or hit tolerance, there are techniques available that apply to some asymmetric threats but not to others. For example, onboard infrared (IR) countermeasures would apply as equally to MANPADS launched from the back of a pickup truck as they would to MANPADS launched from conventional military vehicles; however, an aircrew's situational awareness and ability to respond to MANPADS may differ in those two scenarios. By the same token, most ballistic Vulnerability Reduction (VR) features would be effective against either conventional or unconventional ballistic threats [radar-directed gun systems and Improvised Explosive Devices (IEDs), for example]. However, susceptibility to RPGs, IEDs, or information warfare is unlikely to be materially affected by current countermeasures systems.

Over the past several years, the Joint Aircraft Survivability Program (JASP) has funded development of an Integrated Survivability Assessment (ISA) process. The goal of this process is to perform Survivability assessment [and Operational Test & Evaluation (OT&E) and Live Fire Test and Evaluation (LFT&E)] in the context of missions and scenarios for the system under test by using appropriate mission/threat *vignettes*—single-mission, multiple aircraft, and multiple threat situations that describe expected interactions with threat systems. The matrix of anticipated *vignettes* provides a framework for assessing system

Some Techniques Apply to Asymmetric Threats, Some Don't	
Threat Suppression	Tactics, Standoff Weapons, anti- radiation missiles, off-board EA/EC, self-defense weapons
Detection Avoidance	Off-board EA, night/all weather capability, threat warning, situational awareness, signatures, chaff
Engagement Avoidance	On-board EA, Signatures, chaff, speed and altitude, good target acquisition (standoff)
Threat or Hit Avoidance	On-board EC, chaff and flares, speed and altitude, maneuverability, agility (last ditch maneuver)
Threat or Hit Tolerance	Fire/explosion protection, self-repairing flight controls, redundant and separated hydraulics, HRAM protection, nonflammable hydraulic fluid, rugged structure, armor

Figure 1. Breaking the Threat Kill Chain

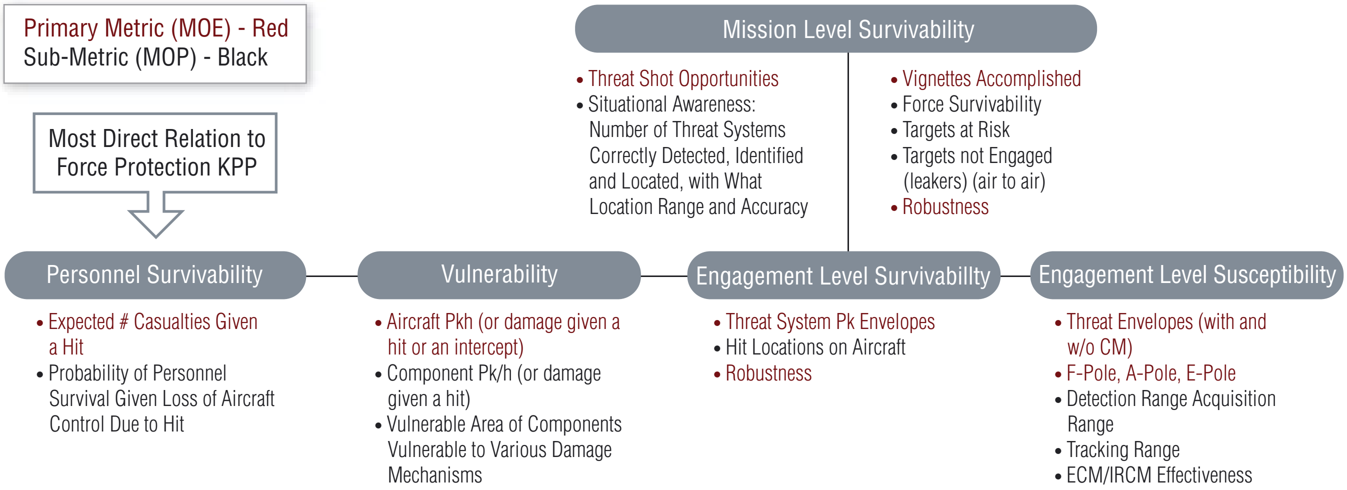

Figure 2. ISA Metrics

survivability throughout the acquisition of a system; such a matrix also provides a roadmap for using M&S in support of Test and Evaluation Master Plan (TEMP) development.

Figure 3 illustrates the ISA process, in which the threat assessment and the characteristics of the system under development combine to drive the development of the vignette matrix. These vignettes are then used to support analysis of the systems' survivability and to develop test conditions for Developmental Test and Evaluation (DT&E), OT&E, and LFT&E. The process as laid out in the figure is for applying the ISA process to testing—when used earlier in the system acquisition process, ISA can support requirements development, system design, and specification compliance. It can also be used later to support mission rehearsal and mission planning.

Measuring the survivability of a system in those vignettes depends on selecting the appropriate set of metrics: the question is, what metrics should we use to assess survivability to asymmetric threats, and how can we translate those metrics into KPPs? Are asymmetric threat metrics any different than those developed for conventional threats? The ISA process developed by JASP identified metrics for assessing survivability, and we believe that these metrics can form the basis for KPPs. The metrics were developed for conventional threats, but they should, in many cases, be expandable to the asymmetric threat environment, depending on how we define "asymmetric threat." Figure 2 shows a set of metrics developed for the ISA process, broken out into various subheadings of survivability assessment.

The metrics most directly relevant to developing force protection KPPs are under the "personnel survivability" heading, including expected number of casualties given a hit and probability of personnel survival given loss of control. Other force protection metrics that may be appropriate include expected number of casualties on a mission or probability of losing at least one person on a mission.

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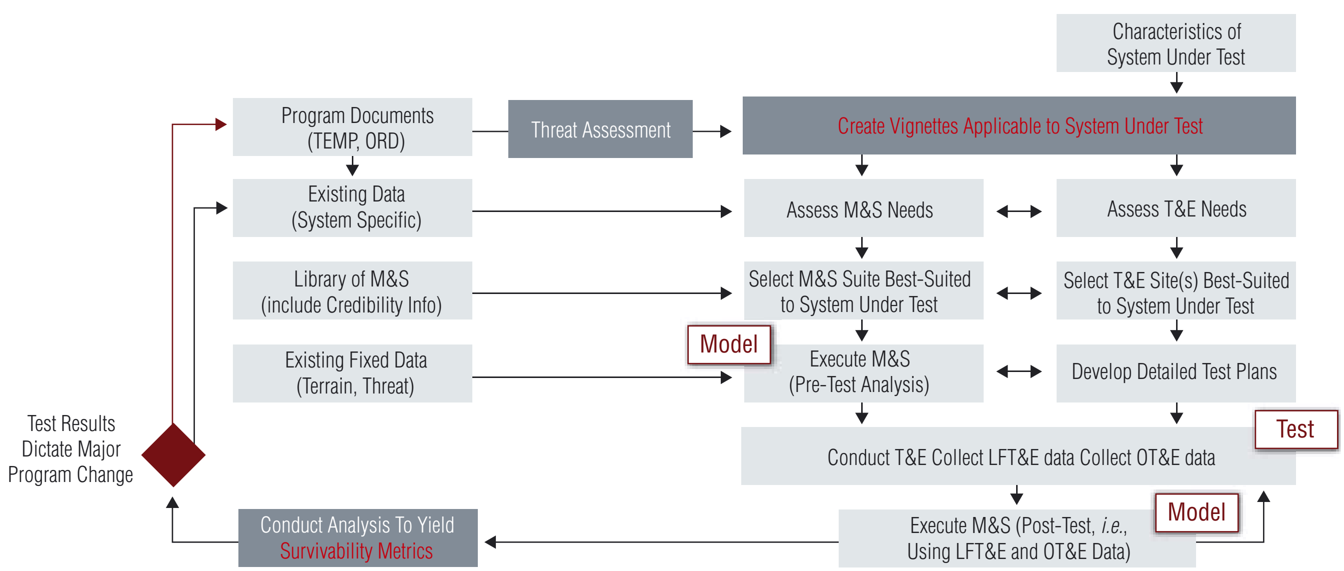


Figure 3. ISA Process

Asymmetric Threats Within the System Acquisition Process

■ by Hugh Griffis and Stacey Almeter

Public Law, Section 141 of the Defense Authorization Act for Fiscal Year 2005 mandates that U.S. Department of Defense (DoD) acquisition programs assess warfighter survivability and system suitability against asymmetric threats. [1] Force Protection and Survivability Key Performance Parameters (KPPs) are mandated for weapon systems expected to be deployed in an asymmetric threat environment.

While the intent of the Congressional language is reasonably clear, the term "asymmetric threat" is ill defined. Therefore, the National Defense Industrial Association (NDIA) Combat Survivability Division (CSD) conducted an Asymmetric Threat workshop. The workshop successfully developed the following workable asymmetric threat definition:

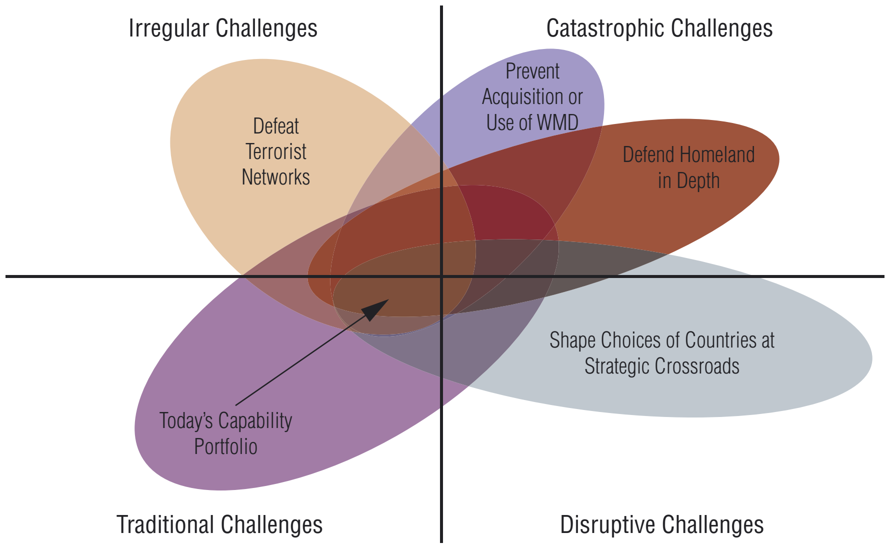


Figure 1. Challenges

"Asymmetric threats are threats used to attack a technologically superior force, usually through improvised or inexpensive means and/or irregular tactics, in order to achieve political, economic, or military (tactical and strategic) gains."

The definition provides good insight relative to irregular, catastrophic, and disruptive challenges, shown in Figure 1. These are challenges as identified by the National Defense Strategy (NDS) and addressed by the 2006 Quadrennial Defense Review (QDR) Report.

Capabilities-Based Planning (CPB) has become a central theme of the defense acquisition process. CPB is designed to provide weapon systems with capabilities suitable for a wide range of modern-day challenges and circumstances. The Joint Capabilities Integration and Development System (JCIDS) process provides the framework to identify, assess, and prioritize joint military capability needs. The JCIDS process addresses all functional areas that are required to accomplish a mission and underpins the adequacy of materiel and non-materiel solutions to identified capability gaps. The JCIDS process is composed of a four-step methodology. (See Table 1.)

The results of this process form the basis for further evaluation during an Analysis of Alternatives (AoA). The analysis process steps used within the JCIDS process and AoA are very similar.

Historically, traditional challenges have been evaluated within these types of assessments. Traditional assessments of challenges are founded on analytical baselines developed from several authoritative intelligence data resources, including the information found in Table 2.

As the NDS has shifted to address more non-traditional challenges, so have the intelligence and analytical communities. Because of their improvised or inexpensive nature,

Functional Area Analysis (FAA)	Identifies the operational tasks, conditions, and standards to achieve military objectives.
Functional Needs Analysis (FNA)	Produces a list of capability gaps and shortcomings that require a solution.
Functional Solutions Analysis (FSA)	Examines the ability of the identified materiel and non-materiel approaches to provide desired capability.
Post Independent Analysis (PIA)	Provides an independent review of the FSA to ensure that it was thorough and reasonable to deliver the capability identified in the FAA and FNA.

Table 1. JCIDS four-step methodology

asymmetric threats will lack the typical infrastructure trail that accompanies the development of major weapon systems. Also, because of the diverse nature of asymmetric threats, the permutations and combinations of potential challenges and scenarios can be overwhelming. Figure 2 shows a sample of potential asymmetric threats. The intelligence and analytical communities have the difficult task of defining the "expected" asymmetric threat.

Early identification of potential challenges is critical to support the development of the Warfighters' Capability Development Document (CDD). Well-defined challenges are needed to prioritize the required warfighting capabilities. Frequently, warfighters' CDDs are general and non-numerical. Significant analytical assessment is needed to convert the CDD into a consistent, technically achievable, and affordable performance-based specification.

Deriving a performance-based specification is an iterative process that is underpinned by analytical assessments and system maturation. These activities are time consuming and require technical expertise from multiple disciplines, complex computer models, and vast quantities of technical data. These assessments evaluate weapon-systems performance within the context of a diverse set of technical disciplines, such as cost; vehicle flight performance; avionics; software; and operational effectiveness, including susceptibility and vulnerability reduction, reliability, supportability, and many others.

Ultimately, requirements in the form of performance specifications prescribe an item's required performance, operating requirements, operational environment, interfaces, and interoperability. Performance specifications are *not* established to prescribe how a performance requirement is to be achieved such as requiring the use of specific materials or parts or detailed requirements for the design or construction. Performance-based specifications are verifiable by inspections, demonstrations, analyses, and tests or by a combination of these actions. KPPs are special, critical, performance-based specifications and should meet the following criteria:

- Contribute to significant improvement in warfighting capabilities, operational effectiveness and/or operational suitability
- Be achievable and affordable
- Be verifiable

In summary, Congress has directed DoD acquisition programs to assess and require Force Protection and Survivability requirements against asymmetric threats. Irregular, catastrophic, and disruptive challenges encompass all asymmetric threats. The NDIA's definition of asymmetric threat is a useful working definition. The intelligence and analytical communities are engaged in defining the "expected" asymmetric threat. Whether the challenge is traditional or asymmetric, the acquisition Capabilities-Based Planning and Performance Based Specifications rely on early and robust threat definitions. ■

(1) JCOFA	Joint Country Force Assesment	A non-scenario-specific projection of a country's units, equipment, and personnel
(2) DPS	Defense Planning Scenarios	A set up of scenarios that depict the strategic challenge space for analysis
(3) MSFD	Multi-Service Force Deployment	For a given scenario, contains US and Non-US Concept of Operations (CONOPS) plus D-Day/H-Hour order of battle data
(4) AB	Analytic Baseline	A package comprising a scenario, CONOPS, and integrated data used as a foundation for strategic analysis
(5) DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities	Data

Table 2. Intelligence data sources

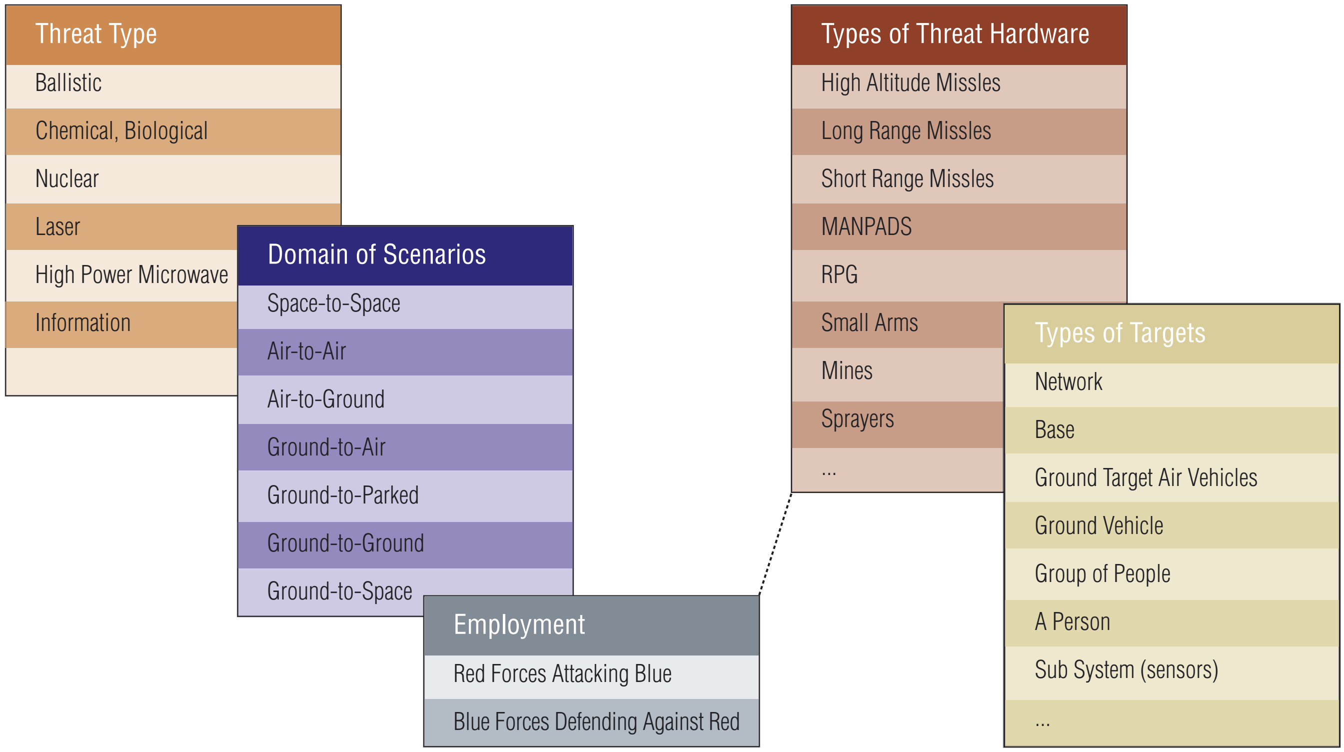


Figure 2. Potential asymmetric threats

Reference

1. Public law, Section 141 of Defense Authorization Act for Fiscal Year 2005:

(a) Requirement for Systems Development—The Secretary of Defense shall require that the Department of Defense regulations, directives, and guidance governing the acquisition of covered systems be revised to require that:

(1a) An assessment of warfighter survivability and of system suitability against asymmetric threats shall be performed as part of the development of system requirements for any such system; and

(2a) Requirements for key performance parameters for force protection and survivability shall be included as part of the documentation of system requirements for any such system.

(b) Covered Systems—In this section, the term "covered system" means any of the following systems that is expected to be deployed in an asymmetric threat environment:

(1b) Any manned system;

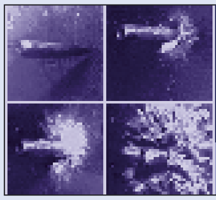
(2b) Any equipment intended to enhance personnel survivability.

(c) Inapplicability of Development Requirement to Systems Already Through Development—The revisions pursuant subsection (a) to Department of Defense regulations, directives, and guidance shall not apply to a system that entered low-rate initial production before the date of the enactment of this Act.

About the Authors

Hugh Griffis is a nationally recognized authority in the areas of chem/bio hardening, weapon system vulnerability, endgame analysis, and Live Fire Test and Evaluation (LFT&E). Mr. Griffis is an expert in the design of survivable aircraft, including considering the effects of chemical hardening and decontamination, high-power microwave hardening, and nuclear weapon effects. His current position is Division Chief of the Design, Analysis, and Simulation Division at the Aeronautical System Center's Directorate of Engineering (ASC/EN). He can be reached at Hugh.Griffis@wpafb.af.mil.

Stacey Almeter is the technical expert for mission and campaign analysis in the Aeronautical System Center, Engineering Directorate, Operational Analysis Branch (ASC/ENMM). She has supported numerous acquisitions programs, most notably the Joint Strike Fighter (JSF), the Joint Unmanned Combat Air System (J-UCAS), the Next Generational Long Range Strike (NG-LRS) system, and Airborne Networking initiatives. She can be reached at Stacey.Almeter@wpafb.af.mil.



Lightweight Armor for Military Aircraft

■ by Jack Plessinger

The U.S. Navy (USN) and the U.S. Marine Corps (USMC) are seeking to protect many rotary and fixed-wing aircraft in their inventory against the damaging effects of small arms fire. One solution to this problem is to add armor; however, the weight penalty suffered by installing such systems can be excessive and would result in a loss of payload and range. Significant reduction of armor weight would allow incorporating ballistic protection on more aircraft. The Naval Air Systems Command (NAVAIR) has funded three Phase II contracts through the Small Business Innovative Research (SBIR) Office with companies that show the potential to develop a lightweight armor system that can be installed on aircraft without incurring a substantial weight penalty.

Brief History

Today's best lightweight armor systems are composite structures consisting of a hard (typically ceramic) front layer backed by a soft, fiber-resin layer. Though the use of ceramics has been around for centuries, it wasn't until the late 1960s that it was used in body armor. With the development of Kevlar in the 1970s and 1980s, it became possible to incorporate a lightweight armor system into a vest that could be worn with relative comfort in the line of duty. Advances in even lighter-weight technology make it possible to increase the amount of armor that the troops can wear, which in turn increases their chances of surviving a hit from small arms fire. Military aircraft manufacturers have also taken advantage of current technology by incorporating ceramic armor systems into crew seats, floors, and exterior panels. Improvements to armor over the past 30 years have been accomplished almost entirely by manipulating the core materials, while the design has remained essentially unchanged: a hard ceramic strikeface backed by a soft, fiber-resin layer.

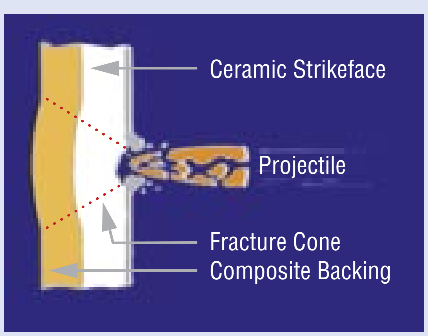


Figure 1. Typical composite armor

Material	Thickness (Inches)	Weight (lbs)
Steel	0.6	25
Aluminum	1.5	21
Ceramics	~1.0	~7

Table 1. Armor required to stop a 7.62 mm APM2 projectile at muzzle velocity

Current Technology

The design of current ceramic armor systems to protect against Armor Piercing (AP) rounds is based on the ability of the ceramic strikeface to fracture the projectile, coupled with the fragment-catching capability of the composite backing. During the fracturing phase, the projectile breaks up on the surface of the ceramic plate and initiates a *fracture cone wave* through the armor system, beginning at the point of impact. During the catching phase, the shattered ceramic and projectile pieces lose enough energy to be stopped by the composite backing material. This concept is illustrated in Figure 1.

The key to developing an effective lightweight armor system, other than choosing the right materials, is in calculating how to absorb the kinetic energy and spread it over the largest possible area.

To help get a better understanding of the weight savings offered by a two-piece composite armor over that of a metal plate, consider the numbers in Table 1.

NAVAIR SBIR Solicitation

In 2004, the NAVAIR Aircraft Survivability Division submitted an SBIR solicitation for lightweight aircraft armor (Topic No. N05-023). The solicitation was seeking technology that could significantly reduce the weight of ballistic armor so it could be used to protect an increased area on Navy and Marine aircraft. The original goals of the solicitation were aimed at the following protection levels and weights:

- **Protection Level 1:** 7.62 x 39 mm Ball Round; Velocities up to 2500 feet per second (fps); 0° Obliquity Angle; Goal of <3.5 lbs per sq ft
- **Protection Level 2:** 7.62 x 51 mm (NATO) Armor Piercing (AP); Velocities up to 2500 fps; 0° Obliquity Angle; Goal of <4.5 lbs per sq ft
- **Protection Level 3:** 12.7 x 99 mm M2 AP; Velocities up to 2000 fps; 0° Obliquity Angle; Goal of <9 lbs per sq ft

NAVAIR received 66 proposals. Seven were selected to go into a Phase I contract, and three of the seven have been awarded Phase II contracts. The three companies

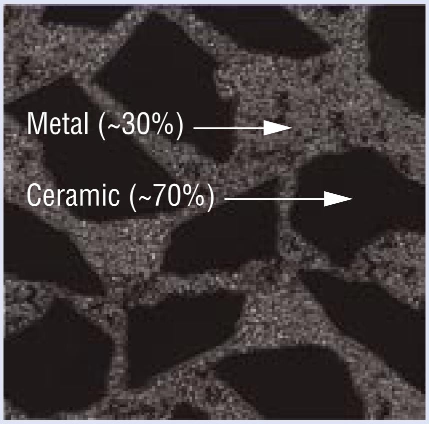


Figure 2. Excera's ONNEX material

Figure 3. Excera's ability to form complex shapes

Material	Density
Hotblox	1.95
Silicon Carbide	3.1
Boron Carbide	2.5
Alumina	3.96
Zirconia	5.68

Table 2. Density of commonly used ceramics in armor vs. Hotblox

that were chosen to proceed into Phase II contracts are Excera Materials Group, Inc. of Columbus, OH; American Technical Coatings, Inc. of Cleveland, OH; and Systems & Materials Research Consultancy of Spicewood, TX.

Excera Materials Group, Inc.

Excera's armor solutions are based on its patented, proprietary ONNEX technology, a family of reaction-formed metal ceramic composite materials tailored to meet the demands of a wide variety of applications. (See Figure 2.) The armor variant of ONNEX technology, the BlueStar™ system, is a multi-phase material that comprises boron carbide, alumina, and a number of other hard boride and carbide phases. Produced by a unique chemical reaction process, the ONNEX/BlueStar system materials exhibit a number of advantages over the ceramic materials traditionally used in armor applications (*e.g.*, hot-pressed boron carbide, silicon carbide, and alumina):

- High-performance, lightweight armor can be generated from this concept. High toughness (from the metal), high hardness (from the included B4C and other hard phases), and low density allow for a lightweight armor that, with development, should yield higher performance and/or lower areal density than is found in many competitive systems.
- Because of a small volume of metal content in the composite, the system can be designed to be more robust against fracture compared with those systems based on conventional armor ceramics. While the fracture toughness of this particular material has not yet been measured, similar materials produced by Excera have values of measured fracture toughness at nearly 10 MPa•m0.5, which is similar to that of cast iron and much greater than that of a typical ceramic. This also gives the Excera armor materials much better multi-hit capability than those of traditional monolithic armor ceramics.
- Complex shapes can be easily created from this composite. Many conventional and proprietary ceramic-shaping methods can be used to fabricate a pre-form that is later transformed to a hard composite. (See Figure 3.) Additionally, large shapes can be produced that eliminate inter-tile seams (essentially an engineered "crack") typical of current armor systems.
- The material is more readily manufacturable than that of existing ceramic armor materials. The primary reasons for this are (1) the use of lower-cost and more readily available raw materials as compared with competing technologies; (2) processing temperatures are substantially lower than those of competing ceramic materials (ONNEX is processed at 1,200°C as compared with B4C, which is processed at 2,200°C); and (3) hot pressing is not used (as it is in high-performance competing systems), so both processing cost and capital cost is lower.

American Technical Coatings, Inc.

American Technical Coatings, Inc. has developed a unique armor concept based on its patented material technology, Hotblox. Hotblox is a lightweight ceramic material (1.95 g/cc) with unique molding characteristics that enable novel armor design approaches. These new design concepts could lead to a leap in armor technology and reduce armor weight by over 30%. Table 2 relates the density of Hotblox to other ceramics commonly used in composite armor.

Hotblox can be molded in typical thermoplastic processes at temperatures below 400°F. Because of the low molding temperature and the ease of manufacture, many unique architectures can be readily formed. These include embedding ballistic materials, such as Kevlar and other high-strength fabrics, into the backing plate or the use of a volume interface (as compared with a planar interface) between the strikeface and backing plate. Since Hotblox can be manufactured and molded in an efficient process, these design concepts can be produced very economically.

Ultimately, the goal is to produce structural armor in the form of vehicle body parts or panels, which results in further weight reduction as the original steel body parts are eliminated.

Initial ballistic testing in a Phase I SBIR project has revealed strong performance potential for the design concept. Phase II will begin in early 2007.

Systems & Materials Research Consultancy

Systems & Materials Research Consultancy (SMRC) has developed a lightweight, transparent armor that offers significant advantages over current aircraft transparent armor. The SMRC team is currently developing a transparent armor product line, CycloShield™, in partnership with Texas State University. CycloShield is based on a CBDO copolymer that is expected to achieve ≈40% better notched Izod impact strength than that of today's ballistic grade polycarbonate. In addition, nanocomposites of CBDO copolymer are expected to be hard-face ply materials. CycloShield offers the following improvements over existing transparent armor:

- CycloShield offers increased aircraft transparency ballistic protection at a reduced areal density and thickness.
- It can be easily formed to fit aircraft canopies.
- It is scratch and chemical resistant, and, if a scratch occurs, the transparency can simply be repaired with heat.
- It provides good multi-hit capability.
- It provides low ultra-violet yellowing.

CycloShield is currently under consideration for use in NAVAIR's Advanced Survivable Canopy research and development effort for USN and USMC helicopters.

Future Work

To further develop detailed designs and manufacturing techniques for the armor, NAVAIR will work with the three companies that have progressed into Phase II. Each company will construct samples, and in-depth testing will be performed on the samples to determine their ballistic capability. Results will be judged on weight, performance, cost to manufacture, and ease of aircraft integration. On meeting Navy requirements and receiving Program Office approval, a Phase III contract will be awarded and the armor will be transitioned to testing on an in-service aircraft in need of lightweight ballistic protection.

This technology has the potential to be used across all Services on virtually any platform. The armor could be tailored for ground-vehicle applications or body armor to reduce overall system weight or to increase coverage without increased weight penalty. ■

About the Author

Jack Plessinger, an Aircraft Survivability Engineer (4.9.6) at NAVAIR, Patuxent River, MD, since June 2004, is the V-22 survivability Integrated Product Team (IPT) lead and the Navy representative to the Vulnerability Reduction Subgroup Armor Committee under the Joint Aircraft Survivability Program (JASP). Before filling this position, he was a 2.75" Rocket Engineer and a Special Program Engineer at the Naval Sea Systems Command (NAVSEA), Indian Head Division, MD. He received a BS degree in Mechanical Engineering from The Ohio State University in 2001 after serving as an Aircraft Armament Systems Specialist in the Air Force from 1992–1995. He loaded ordnance on the B-1B while stationed at Ellsworth AFB, SD. He may be reached by telephone at 301/342-0201 or by email at jack.w.plessinger@navy.mil.

Annual NDIA Survivability Awards

■ by T. N. (Mike) Mikel

The National Defense Industrial Association's (NDIA) Combat Survivability Awards, presented annually at NDIA's Combat Survivability Division (CSD) Aircraft Survivability Symposium, recognize individuals or teams who demonstrate superior performance across the entire spectrum of survivability, including Susceptibility Reduction (SR), Vulnerability Reduction (VR), and related Modeling and Simulation (M&S). The NDIA Combat Survivability Award for Leadership was presented to Dr. Robert DelBoca, and the NDIA Combat Survivability Award for Technical Achievement was presented to Dr. Charles Liang. In addition to these two annual awards, a special award presentation, the NDIA Combat Survivability Lifetime Achievement Award, was made to Mrs. Natalie Crawford. Following the NDIA CSD Awards, NDIA President, Lt Gen Lawrence Farrell, Jr., presented Mr. John Vice with the NDIA Gold Medal for dedicated, extended service on the CSD Executive Board. All four awards were presented at the Aircraft Survivability 2006 "Enhancing the Survivability of Civil & Military Aircraft," held 6–9 November, 2006, at the Naval Postgraduate School (NPS), Monterey, CA.

Combat Survivability Award for Leadership

The NDIA Combat Survivability Award for Leadership 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 (R&D), M&S, Test and Evaluation (T&E), education, or the development of standards. The emphasis of this award is on demonstrated superior leadership of a continuing nature. The 2006 CSD Leadership Award was presented to Dr. Robert DelBoca for exceptional leadership in aircraft combat survivability. Before assuming his current position as General Manager of Northrop Grumman Corporation's Defensive Systems Division, Dr. DelBoca was Vice President of its Infrared Countermeasures (IRCM) and Laser Systems.

Dr. DelBoca was instrumental in pioneering the development of the laser-based Directional Infrared Countermeasures (DIRCM) system and its rapid deployment on U.S. and Coalition aircraft in support of Operation Enduring Freedom and Operation Iraqi Freedom. In response to an urgent operational requirement issued by U.S. Special Operations Command, Dr. DelBoca organized a staff and program that resulted in the first combat deployment of a laser DIRCM system by designing, installing, flight testing, and delivering the initial capability in only 62 days. He also responded to a U.S. Air Force (USAF) requirement to accelerate the integration and installation of the Large Aircraft Infrared Countermeasures (LAIRCM) system for Air Mobility Command's C-17 aircraft by eliminating a full year from the schedule, thereby allowing the nation's newest mobility aircraft to be deployed into areas defended by Man-Portable Air Defense Systems (MANPADS). Dr. DelBoca's insight is recognized as the driving force behind the first and only production-laser DIRCM system in operation today. His efforts have been instrumental in preventing the combat loss of U.S. and Coalition aircraft and for saving countless warfighters' lives.

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. The 2006 CSD Technical Achievement Award was presented to Dr. Charles Liang for exceptional technical achievement in the field of aircraft combat survivability. For more than 35 years, first with General Dynamics Corporation, then Lockheed Martin Aeronautics Company, from which he recently retired as chief scientist for signature integration, Dr. Liang pioneered the development of stealth technologies and their integration into survivable weapons systems.

Dr. Liang has made significant contributions to developing low-observables technologies applied to cruise missiles and tactical aircraft. These include the Tomahawk and Advanced Cruise Missile, the reduced signature F-16 multi-role fighter, the A-12 naval medium attack aircraft, the B-2 Stealth Bomber, and the F-35 Joint Strike Fighter. Dr. Liang has made important contributions to backscattering analyses and measurements of complex aerospace vehicles, multiple diffraction phenomena, deep cavity returns, tapered resistive cards, absorptive corrugated coatings, and periodic artificial dielectrics. A fellow of the Institute of Electrical and Electronic Engineers (IEEE), Dr. Liang has published extensively in the technical literature. In 1991, he won the Lockheed Corporation Robert E. Gross Award, which recognizes excellence in science and engineering.

Combat Survivability Award for Lifetime Achievement

Mrs. Natalie Crawford was recognized for exceptional contributions to aircraft combat survivability throughout a distinguished career in government and industry with the presentation of the NDIA Combat Survivability Award for Lifetime Achievement. During a lifetime of service to the USAF as a senior executive of the RAND Corporation, she has played a major role in advancing American air and space capabilities. Her strong analytical and managerial skills have helped transform American military power and the way in which the U.S. undertakes advanced aerospace system development. Through her years of work with the U.S. Department of Defense, the National Academy of Sciences, the National Academy of Engineering, and the USAF Scientific Advisory Board, she has served as a senior advisor and mentor to generations of USAF leaders, and her judgment on programs and activities is recognized throughout the aerospace community as representing the "gold standard" of aerospace analysis. Her legacy of work reads as an abbreviated history of aerospace development and national security during the most critical years of the Cold War and in the formative years of the ongoing global war on terror. She is well known throughout the defense community for her integrity, independence, courage, and fierce commitment to "telling it like it is," regardless of prevailing opinions. The NDIA Combat Survivability Award for Lifetime Achievement acknowledges the exceptional and lasting contributions of Mrs. Natalie Crawford to aircraft combat survivability, the U.S. Armed Forces, and the nation.

NDIA Gold Medal for Outstanding Service

The NDIA Gold Medal in recognition of outstanding service was presented to Mr. John Vice for his extended, dedicated service as a founding member of the NDIA's CSD. Mr. Vice was a member of CSD's Executive Board for 16 years, serving as the Chairman of the CSD's Communication and Publicity Committee from 1995–2005. He twice chaired the annual symposia, "Transport Aircraft Survivability" in 1993 and "Vulnerability Reduction Technology" in 1997. Mr. Vice could always be counted on for ideas to improve CSD operations and symposia content. He enjoyed the respect of division members and frequently represented the CSD Chairman at NDIA headquarters where he planned meetings and appeared before the association's Board of Directors' Division Review Council. He was a key contributor to programs and initiatives that enhanced the survivability of U.S. combat aircraft. He was a founder and the Director of DoD's Survivability/Vulnerability Information and Analysis Center (SURVIAC) during its formative period. His expertise and contributions were recognized in 1996 when he received the first NDIA Combat Survivability Leadership Award. Mr. Vice retired from active membership on the CSD Executive Board at the end of 2005, taking with him the sincere gratitude and great respect of the many association members and DoD personnel who benefited from his contributions.

Best Poster Paper Awards

Three awards were presented for the best poster papers displayed as part of the symposium's Exhibits and Poster Papers feature. First place was awarded to Mr. Dan Fisher, Lockheed Martin Aeronautics Company, Marietta, GA, for his paper, *Hybrid Aircraft Survivability*. Second place was awarded to Mr. Chad Sparks, Bell Helicopter Textron, Inc., for his paper, *Operationally Representative Vulnerability Analysis of the AH-1W*. Third place was awarded to Mr. Andy Kurpik, USAF Aeronautical Systems Center (ASC/ENMM), for his paper entitled *CAT Combat Assessment Tool*.

About the Author

Dr. T. N. (Mike) Mikel is the Chief Engineer for Unmanned Aircraft Systems at Bell Helicopter Textron, Inc. where he has more than 25 years of experience in the rotary-wing aircraft design and survivability disciplines. He is a former U.S. Army Aviator and Infantry Officer. He holds a B.S. and two M.S. degrees from Texas A&M University and a Ph.D. from the University of Texas at Arlington. Dr. Mikel has been a member of the NDIA CSD Executive Board since 2000 and currently serves as the Communications and Publicity Committee Chair. ■

From left to right: Lt Gen Lawrence Farrell, Jr. (USAF, Ret), NDIA President and CEO; Dr. Robert DelBoca, Leadership Award recipient; and Maj Gen John Hawley (USAF, Ret), Chairman, NDIA CSD

From left to right: Lt Gen Lawrence Farrell, Jr., NDIA President and CEO; Dr. Charles Liang, Technical Achievement Award recipient; and Maj Gen John Hawley

Left to right: Lt Gen Lawrence Farrell, Jr. (USAF, Ret.), NDIA President and CEO; Mrs. Natalie Crawford, Lifetime Achievement Award recipient; and Maj Gen John Hawley (USAF, Ret), Chairman, NDIA CSD

From left to right: Lt Gen Lawrence Farrell, Jr. (USAF, Ret.), NDIA President and CEO; Mr. John Vice, NDIA Gold Metal recipient; and Maj Gen John Hawley (USAF, Ret.), Chairman, NDIA CSD

From left to right: Mr. Ron Dexter, NDIA CSD Poster Paper Session Chair; Mr. Chad Sparks, Bell Helicopter; Mr. Dan Fisher, Lockheed Martin Aeronautics; and Mr. Kelly Kennedy, USAF Aeronautical Systems Center (accepting for Mr. Andy Kurpik), Poster Paper Award Recipients

Calendar of Events

April

2–5, Monterey, CA
JASP Aircraft Combat Survivability Short Course
jeng_paul@bah.com

10–12, San Diego, CA
Advanced Technology Electronic Defense Systems (ATEDS)
http://www.ateds.com

23–26, Charlotte, NC
Annual Armament Systems: Gun and Missile Systems Conference and Expo

23–26, San Antonio, TX
Fiesta Crow 07 Network Warfare (NW) and Non-Traditional EW-Combat in the Digital Age
program@fiestacrow.com

24–26, Hurlburt Field, FL
JCAT Threat Weapons Effects Seminar
larsonca@cox.net

May

1–3, Virginia Beach, VA
AHS 63rd Annual Forum & Technology Display "Riding the Wave of New Vertical Flight Technology"
kwilliams@ndia.org

9–12, Atlanta, GA
2007 AAAA National Convention 50th Anniversary
https://www.quad-a.org

15–18, Atlanta, GA
Infrared Countermeasures
http://iac.dtic.mil/sensiac

21–24, Orlando, FL
MSS Tri-Service Radar Symposium (TSR)
http://iac.dtic.mil/sensiac

June

12–14, McLean, VA
MSS National Symposium on Sensors and Data Fusion
http://iac.dtic.mil/sensiac

12–15, Las Vegas, NV
Military Laser Principles and Applications
http://iac.dtic.mil/sensiac

19–21, Colorado Springs, CO
JASP Model Users Meeting (JMUM)
jeng_paul@bah.com

25–28, Charleston, SC
NDIA National Live Fire Test and Evaluation (LFT&E) Conference
hhoran@ndia.org

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

SURVIAC, Washington Satellite Office
Attn: Christina McNemar
13200 Woodland Park Road, Suite 6047
Herndon, VA 20171

Phone: 703/984–0733
Fax: 703/984–0756

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