18
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On the cover:
Sikorsky CH-53K *(© Sikorsky Aircraft Corporation 2018. All rights reserved).*

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Self-sealing fuel bladders used on military aircraft (both rotorcraft and fixed-wing aircraft) serve as vulnerability reduction technologies to mitigate fuel leaks and fire caused by a ballistic hit to a fuel tank. Over the past decade, interest within the Department of Defense (DoD), the survivability communities, and the aircraft fuel containment communities has risen regarding deficient self-sealing fuel tank performance in fielded and soon-to-be-fielded U.S. aircraft. On several occasions, live fire test and evaluation (LFT&E) efforts performed on newly developed and older fielded U.S. aircraft fuel tanks (bladders), qualified to military specification (MIL-SPEC) MIL-T-27422 (aka MIL-DTL-27422) and MIL-T-5578 (aka MIL-DTL-5578), have demonstrated self-sealing performance below their expected qualified and intended level.

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by Mark Couch and Robert E. Ball

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Christopher Adams for his Excellence in Survivability. Chris currently serves as a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the Naval Postgraduate School (NPS) in Monterey, CA. Prior to holding this position, Chris served in the Navy for 21 years as a Naval Flight Officer, flying the F-14 Tomcat and EA-6B Prowler in numerous combat sorties over Iraq and Afghanistan. Additionally, he served on several major staffs during his Navy career, and his final assignment was serving as Associate Dean of NPS's Graduate School of Engineering and Applied Sciences.

16 JASPO FUNDING OF SMALL PROJECTS IN BRAWLER: BRINGING MICROFINANCE TO GOVERNMENT CONTRACTING

by Dale Johnson

For years, model managers for Brawler, the Enhanced Surface-to-Air Missile Simulation (ESAMS), the Computation of Vulnerable Area Tool (COVART), and several other models have made proposals to the Joint Aircraft Survivability Program Office (JASPO) committees for major, multiyear enhancements to these models. Unfortunately, despite these enhancements, the underlying models themselves have sometimes deteriorated because of inadequate funding for ongoing model maintenance or inconsistent configuration management.

20 THE DEVELOPMENT OF AIRCRAFT COMBAT SURVIVABILITY AS A DESIGN DISCIPLINE OVER THE PAST HALF CENTURY

by Robert E. Ball, Mark Couch, and Christopher Adams

The term "aircraft combat survivability" (ACS) is defined in The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition as "the capability of an aircraft to avoid or withstand a man-made hostile environment" [1]. This definition forms the basis for the ACS design discipline.

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NEWS NOTES

By Dale Atkinson

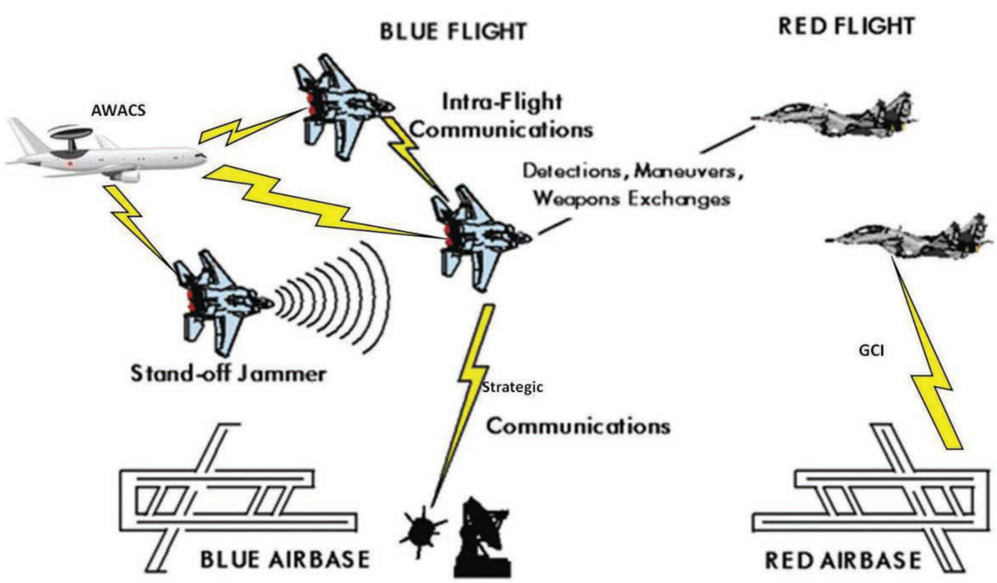
BRAWLER V8.4 RELEASED

The Defense Systems Information Analysis Center (DSIAC) has announced the release of Brawler V8.4. Brawler is the standard for high-fidelity air-to-air engagement modeling within the Air Force, Navy, airframe manufacturing, and avionics communities. This Government-owned simulation tool provides a detailed representation of air-to-air combat engagements involving multiple flights of aircraft in both the visual and beyond-visual-range arenas. Because of the importance of cooperative tactics and the critical role of human factors (such as surprise, confusion, situation awareness, and the ability to innovate tactical responses in unexpected situations), special emphasis has been placed on simulating these command-and-control aspects of the engagement process.

New features of Brawler V8.4 include the following:

- IR Modeling Enhancements
- Signal-to-Noise Ratio (SNR) Threshold Inputs for Infrared Search and Track (IRST)
- Probability of Detect Standard Deviation Linked to SNR
- User-Defined Infrared (IR) Background Types
- Higher-Fidelity Projected Area and Reflected Energy Representations
- Earth Curvature for Line-of-Sight Calculations
- New Modes for IR Detection Table Plot (plmain)
- Band-Dependent IRST Noise Equivalence Irradiance (NEI)
- Missile Additive Drag Alternative Methodology
- New Mission-Radius Plot (plmain)
- New Keywords to Suppress IOUT and/or HIST Outputs
- Modern Fortran Uplifts
- Remainder of Avionics Devices: Radar, OTD, ESM, DLD, IFF
- SAN and SFD
- Pods, Smart Jammers, Noise Jammers
- Missile Status
- Gun, Surface-to-Surface Missiles
- Updated and New National Air and Space Intelligence Center (NASIC) Datasets and Models
- 48 Resolved/Closed Software Change Requests

For more information or to request the package, visit DSIAC's Brawler model page at *https://www.dsiac.org/resources/models_and_tools/brawler.* ASJ



JCAT CORNER

By CW5 Scott Brusuelas, CAPT Matt Butkis, and LTC Ron Pendleton

Figure 1. C-12 Live Fire Demonstration at APG.

The Joint Combat Assessment Team (JCAT) remains busy with current combat damage assessments, the aircraft combat damage reporting initiative, refresher training, and qualification training. In December, JCAT conducted a joint refresher training event at Aberdeen Proving Ground, MD. The team conducted the live fire demonstration on an Army C-12 aircraft (shown in Figure 1), enabling the team to see first hand the effects of munitions and hydrodynamic ram on aircraft components. The aircraft will be incorporated as a training aid in the Aircraft Combat Damage Forensics Laboratory at Fort Rucker, AL. The C-12 is the first fixed-wing training aid to be used during JCAT Phase 1 training.

In addition, JCAT held its annual Phase 1 training event from 29 January through 2 February at Fort Rucker. In all, 24 (9 Army, 6 Navy, and 9 Air Force) personnel received an introduction to aircraft combat damage collection and assessment techniques (see Figure 2). The products that this class produced were some of the best collection and assessment presentations that have been completed during this phase of training. Congratulations to all the students for a job well done.

Figure 2. JCAT Phase 1 Training Class.

Finally, the Aviation Survivability Development and Tactics Team (ASDAT) bids farewell to CW4 Mark Chamberlin and CW3 Chris Crawford. Mark served as the CH-47 subject-matter expert (SME) for more than 4 yrs, while Chris served as a UH-60 SME during his 2-yr assignment with the team. The entire JCAT would like to thank Mark and Chris for their hard work and dedication and wish them luck as they move on to new assignments. In addition, ASDAT is looking forward to the arrival of CW4 Tyson Martin in July. Tyson has recently completed the JCAT Phase 1 and Phase 2 training and will be a welcomed addition to the team.

ANTI-RPG WARHEAD: AN AIRCRAFT PROTECTION SOLUTION

by Vincent Schuetz

Photo by SSgt Ezekiel Kitandwe, U.S Marine Corps

Rocket-propelled grenades (RPGs) pose a significant and growing threat to military aircraft. RPGs are heavily proliferated in all military theatres and are increasingly used to target U.S. and allied aircraft. To counter this prolific threat, multiple solutions are being researched by the Joint Aircraft Survivability Program Office (JASPO). The research project described herein investigates several warhead damage mechanisms against RPGs that also meet stringent active protection system (APS) requirements for effectiveness and collateral damage mitigation.

TO KILL AN RPG

The greatest weakness of an RPG is also arguably one of its greatest strengths. An RPG is an unguided weapon, meaning it contains no seeker or other electronics designed to guide the weapon toward a target. This weakness has typically required operators to position themselves close enough to ensure a direct hit on a moving targeted aircraft.

A weapon of this nature also brings forth many challenges to defend against it. An RPG, such as the one shown in Figure 1, does not have any guidance electronics capable of being jammed/tricked/or spoofed; wherever the RPG has been aimed, it is going to hit. Thus, a kinetic approach is one of the defense mechanisms being considered to counter RPG engagements against aircraft. One such method is to use an APS to detect, track, and deploy a defensive missile (aka a kill vehicle [KV]) and destroy the incoming RPG before it can make contact with the aircraft.

The focus of this project is to determine what types of KV payloads are capable of destroying an RPG once the KV has successfully guided to its intercept. Our design objective was constricted to fit the KV within the standard Mobile Jettison Unit (MJU) flare size for the ALE-47 flare dispenser (shown in Figure 2). In the event that the objective could not meet lethality requirements, however, the ALE-47 tubes could be modified to fit a larger warhead.

Another critical performance requirement was to minimize collateral damage, whether it be to troops on the ground, a wingman, or the launching aircraft itself. Strict timelines of intercepting close-range RPGs, near-by friendly troops during landing or take-off, and wingman aircraft could cause some

Figure 2. ALE-47 Flare Dispenser.

engagements to occur extremely close to friendly aircraft or troops. Thus, lethal fragments from either the KV or RPG itself must be minimized.

NOTABLE WORK

Destruction of RPGs has been studied in the past by many Government laboratories and contractors. Most related to the work for this project is the research that was conducted by Lovelace et al. [1] at the U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) and Suarez et al. [2] at the U.S. Army Armament Research, Development and Engineering Center (ARDEC). In addition, based on the similarities in their goals, the U.S. Naval Air Warfare Center – Weapons Division (NAWCWD) teamed up with ARDEC to further the research in this area.

The new warhead designs were based on work performed by Suarez and this team in 2014, where they statically tested both pure blast warheads and controlled fragmentation warheads against RPGs at specific standoff distances. The team concluded that pure blast warheads were not reliable at breaking up or "dudding" an RPG at tested distances. Their controlled fragmentation warheads, however, were highly effective, many times sympathetically detonating the explosive within the RPG. Nonetheless, the controlled fragmentation warheads would not meet the low collateral damage criteria for this project and could also produce jetting of the shaped charge liner, which could be lethal to nearby friendly aircraft or troops.

NAWCWD's approach to reduce collateral damage uses an optimized liner designed to produce high-velocity fragments in the near field of the engagement but to slow down rapidly shortly after the engagement. The material, shape, and size of the fragments have been specifically chosen to provide effectiveness within the miss distance of the APS projectile and then slow down rapidly from air-induced drag.

Additionally, Lovelace et al. were able to demonstrate improved performance against RPGs over pure blast explosives by adding additional impulse to the engagement. However, there was some concern if this approach would be viable, when combined with the smaller amount of explosive, and ultimately be able to damage the RPG.

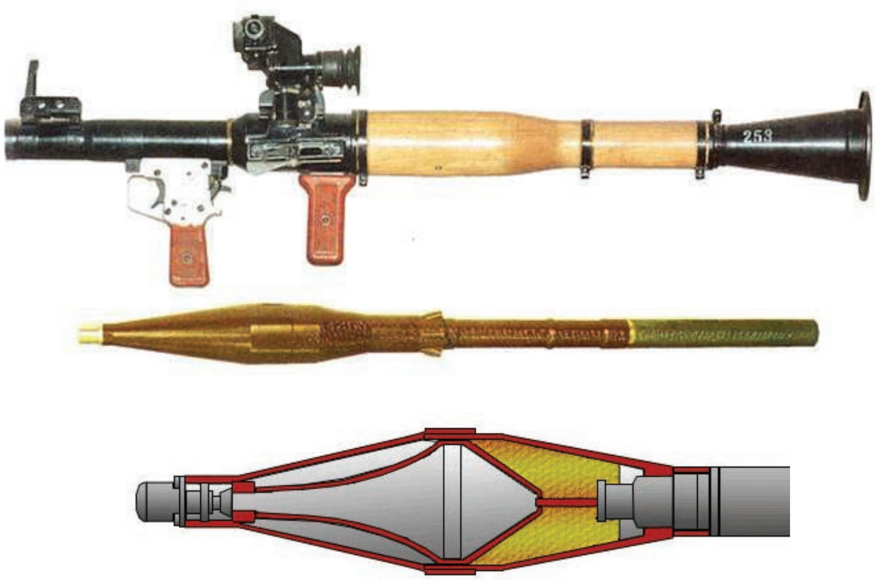


Figure 1. Depiction of a Notional RPG With Launcher (Top) and Cross Section of a Notional RPG Variant Warhead (Bottom).

As such, a related approach was further investigated. Mike Jenkins from the U.S. Air Force Research Laboratory (AFRL) has performed multiple experiments on the efficiency of driving liners by explosive [3]. Using his research, a warhead configuration was optimized for the destruction of RPGs. Figure 3 provides an example of estimating liner ejection velocity and pattern as a function of distance from explosive detonation.

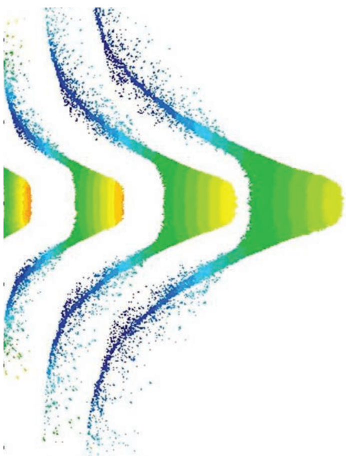


Figure 3. AFRL Hydrocode Modeling.

NAWCWD formulated two different types of experimental explosives: one impulse-loaded explosive and one highly brisant explosive. The impulse-loaded explosive is designed to produce a longer lasting pushing force on the warhead liner, where the brisant explosive is designed to produce a sharp high-amplitude force on the liner. These warhead designs were then both fabricated in two different diameters for a total of four warhead designs (shown in Table 1).

To test the effectiveness of the experimental warheads, two RPGs were placed at the same distance from the center of the warhead prior to detonation (as shown in Figure 4). One RPG was placed on its side to represent perpendicular intercept geometry, while the other RPG was placed nose down, representing parallel intercept geometry. To test the low collateral nature of the warheads, plywood boards and foam panels were also set up at selected distances.

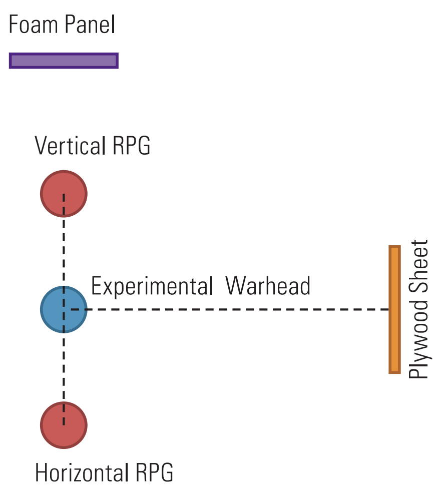


Figure 4. Experimental Warhead Arena Depiction.

RESULTS

All four experimental warheads exhibited effectiveness against the perpendicular RPG in a similar manner; the RPG warhead section was pitted and ripped apart, much of the explosive remained inside the RPG, and the shaped charge jet (SCJ) liner was jettisoned from the body. In addition, the RPG section facing the warhead

Figure 5. RPG Warhead Section With Evidence of High-Velocity Liner Impact.

showed evidence of being blasted with high-velocity liner material (as shown in Figure 5). The nose cone on the front of the RPG was also blown off of the body, removing the impact sensor. The potential damage by the RPG debris from a successful KV interception is being studied simultaneously in a separate JASP-funded project.

The parallel RPG was affected most by Warhead B (see Figure 6). As shown, the RPG was severed at the base of the nose cone, and the SCJ liner was jettisoned along with some of the explosive material.

Interestingly, Warhead D was the same warhead design as Warhead B, albeit scaled to a larger diameter, yet it produced less damage against the parallel RPG. It was later assessed that the increase in the amount of explosive in Warhead D shocked the

Figure 6. RPG Warhead Section Severed From Nose Cone (Top), and SCJ Liner Folded and Jettisoned From RPG (Bottom).

Table 1. NAWCWD Warhead Designs

Name	Explosive	Diameter
Warhead A	Impulse	Small
Warhead B	Brisant	Small
Warhead C	Impulse	Large
Warhead D	Brisant	Large

liner in the warhead hard enough to spall it into smaller fragments before they made contact with the RPG. This phenomenon has been studied by Ripley et al. [4]. The smaller fragments had much less mass and were unable to impart as much kinetic energy onto the RPG as Warhead B.

Warhead B showed the most effectiveness against both parallel and perpendicular engagement geometries, but the collateral damage metric still needed to be evaluated. The foam and plywood panels were examined after each test and revealed no perforations through the material from any of the tests. The foam material was much closer than the defined nonlethal distance and still remained undamaged. High-speed video evidence showed rapidly decelerating fragments ricocheting off the foam barrier, unable to impact with enough energy to penetrate into the foam (as shown in Figure 7). The only blemishes on the foam were blast marks created from panels set up in the arena to protect instrumentation (aka "testism," or artifacts resulting from the test setup itself), indents from where the parallel RPG would make contact after being heaved, and bits of plastic foam from the test stand. All of the warhead designs were extremely low collateral, with one of the designs showing improvements in effectiveness over the others.

Figure 7. Foam Panel Exhibited No Lethal Indications Within the Minimum Engagement Distance.

FUTURE PLANS

For the future, we will focus on increasing the effectiveness against RPGs using another unique lethality mechanism: self-consuming fragments. These fragments start reacting upon impact with the detonation wave and start ejecting mass until they become nonlethal. The idea behind these fragments is that they will be potentially more lethal within the expected miss distance of the engagement but will consume themselves shortly after and become nonlethal. ASJ

ABOUT THE AUTHOR

Mr. Vincent Schuetz is currently a warhead design engineer at the Naval Air Warfare Center Weapons Division – China Lake. For the past 5 years, he has developed warheads for both aircraft defeat and protection. Mr. Schuetz is also an annual instructor in warhead effects for the Joint Combat Assessment Team (JCAT). He holds a B.S. in mechanical engineering from Gonzaga University.

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[4] Ripley, R. C., L. Donahue, and F. Zhang. "Fragmentation of Metal Particles During Heterogeneous Explosion." *Journal of Shock Waves*, vol. 25, no. 1, January 2015.

SELF-SEALING PERFORMANCE: A 45-YEAR STATUS REPORT

By Marty Krammer

Sikorsky CH-53K *(© Sikorsky Aircraft Corporation 2018. All rights reserved).*

Self-sealing fuel bladders used on military aircraft (both rotorcraft and fixed-wing aircraft) serve as vulnerability reduction technologies to mitigate fuel leaks and fire caused by a ballistic hit to a fuel tank. Over the past decade, interest within the Department of Defense (DoD), the survivability communities, and the aircraft fuel containment communities has risen regarding deficient self-sealing fuel tank performance in fielded and soon-to-be-fielded U.S. aircraft. On several occasions, live fire test and evaluation (LFT&E) efforts performed on newly developed and older fielded U.S. aircraft fuel tanks (bladders), qualified to military specification (MIL-SPEC) MIL-T-27422 (aka MIL-DTL-27422) and MIL-T-5578 (aka MIL-DTL-5578), have demonstrated self-sealing performance below their expected qualified and intended level.

The lack of self-sealing capability of a fuel tank can negatively impact military aircraft acquisition, affecting multiple factors, including aircraft vulnerability, key performance parameters (KPPs), cost, schedule, and weight. Accordingly, the causes as to why self-sealing performances witnessed in LFT&E are not in alignment with MIL-SPEC qualification continue to be questioned and studied within the DoD communities. In addition, the lack of understanding of the problem is causing a hesitation in making changes or improvements to the governing self-sealing MIL-SPEC standards.

Therefore, a Navy-led effort, sponsored by the Joint Aircraft Survivability Program Office (JASPO), was undertaken in 2014 by members of DoD's Fuel Bladder Roundtable (FBR) working group to study and gain a greater understanding in the self-sealing performance of U.S. aircraft fuel tanks over the past 45 years. Goals were as follows:

- Understand the history of U.S. aircraft fuel tank self-sealing performances.
- Identify issues and potential causes for mismatches in performance between qualification, live fire test, and combat events.
- Acquire information for mitigating future acquisition program KPP risks and impacts associated with self-sealing fuel bladders and associated vulnerability.
- Provide recommendations for improving MIL-SPEC self-sealing standards to better align with the intended ballistic threat level capability of the aircraft.

As illustrated in Figure 1, the study brought together results from past component-level, MIL-SPEC qualification gunfire tests aircraft fuel tank LFT&E, and more recent combat incident damage reporting. The study evaluated performance of internal, external, and auxiliary self-sealing fuel tanks. These results were combined and analyzed to identify trends in self-sealing performances.

Questions raised and addressed under the effort included the following:

- What does "being qualified" and having a "self-sealing capability" actually mean? Are they the same?

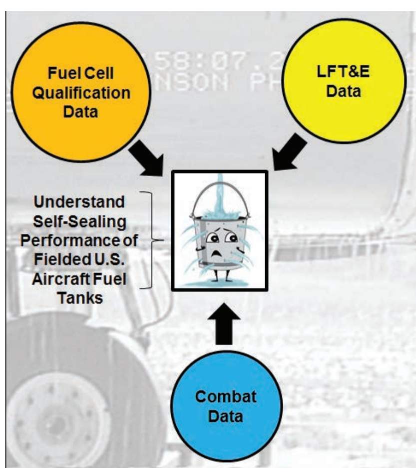

Figure 1. Comparative Understanding of Self-Sealing Performance.

- Does the current level of self-sealing capability meet the performance expectations of today, and of the future?
- Are the current military-standard gunfire qualification test methods adequate for addressing platform-level survivability self-sealing performance needs?

The study aimed to document recommended improvements to these military standard qualification tests to better address platform-level survivability requirements.

APPROACH

Navy and Army members of the DoD FBR working group performed literature searches that produced data dating back as far as 1971 and as recent as 2015. In total, 23 MIL-SPEC qualification gunfire test reports, 12 LFT&E reports, and 107 combat incident reports involving self-sealing fuel tank hits provided insight into the self-sealing performance of U.S. fielded aircraft systems over the past 45 years. The data obtained applied to self-sealing fuel tanks associated with U.S. military fixed-wing aircraft and small, medium, and large rotorcraft platforms. The literature searches produced data for 26 MIL-SPEC qualified fuel cell constructions on aircraft and their subsequent suppliers.

Navy members conducted a comprehensive side-by-side comparison of all data (qualification, LFT&E, combat incidents), reviewing in detail the following:

- Aircraft fuel bladder specifications.
- Aircraft vulnerability requirements.
- Fuel bladder materials and constructions.
- Aircraft fuel tank materials and constructions.
- Data from various fuel bladder constructions and aircraft platforms:
  - Qualification Phase I cube tank gunfire tests (50–100 °F and -40 °F temperatures).
  - Qualification Phase II aircraft fuel tank gunfire tests.
  - LFT&E (Title 10 U.S.C. § 2366).
  - Combat: Afghanistan (Operation Enduring Freedom) and Iraq (Operation Iraqi Freedom).
- MIL-SPEC cell qualification deviations.
- MIL-SPEC cell qualification waiver by similarity.
- Self-sealing performance against various projectiles (threats).
- Self-sealing performance for types of tank penetrations (entrance vs. exit).
- Self-sealing performance for various projectile (threat) orientations.
- Fuel tank test conditions (warmer vs. cold temperatures, internal pressures).
- Test conditions and execution (methods, equipment, setups, tank articles).
- Fuel cell bladder damage (new and in-service fielded cells).
- Other impacts on aircraft acquisition due to substandard self-sealing performance.

HIGHLIGHTS/FINDINGS

As shown in Figure 2, the study showed that, over the past 45 years, three fuel cell manufacturers have supplied self-sealing fuel cells to the U.S. military aviation community. Although names have changed through those years as a result of mergers and acquisitions, facilities, people, manufacturing methods, and capabilities have remained fairly constant. Furthermore, the majority of internal self-sealing fuel cells installed on or in U.S. aircraft during this time were supplied by two fuel cell suppliers or manufacturers: MEGGITT Rockmart (formerly Engineered Fabrics Corp.) and American Fuel Cell and Coatings Fabrics Company (AMFUEL).

The study revealed that the technologies, materials, and methods used in manufacturing and ballistic testing have not significantly advanced or changed over the past 60 years. Fuel cell manufacturing remains a highly labor-intensive effort, requiring significant operator skill for producing consistent and ballistically tolerant fuel cells.

Per today's standards, the study indicated that, on average, U.S. aircraft self-sealing fuel tanks, which had been considered fully MIL-SPEC-qualified, did not fully achieve the self-sealing performance specified within the MIL-SPEC prior to going into full-rate production. Additionally, findings indicate that changes are needed within the MIL-SPEC standards to meet the self-sealing fuel tank capability needs against threats of today and tomorrow.

The outcome of the study produced a comprehensive report titled "Understanding the Self-Sealing Performances of U.S. Aircraft Fuel Tanks." The (limited-distribution) report can be obtained through the Defense Technical Information Center (DTIC) archives.

Conclusion and recommendation topics addressed in the report include the following:

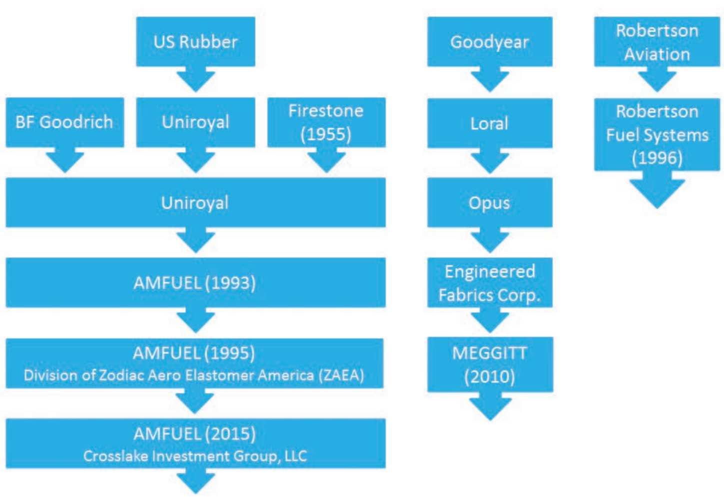

Figure 2. U.S. Fuel Cell Manufacturers/Suppliers.

- U.S. aircraft fuel tank self-sealing capabilities, deficiencies, and gaps.
- MIL-SPEC Phase I self-sealing performances for normal and low (-40 °F) temperatures.
- MIL-SPEC Phase I/II test approach and execution issues.
- MIL-SPEC Phase I/II projectile shot selections/distributions issues.
- MIL-SPEC Phase I/II fuel leakage assessments and reporting issues.
- MIL-SPEC Phase I qualification by similarity issues affecting multiple aircraft programs.
- MIL-SPEC recommended changes and improvements.
- On-Board Inert Gas Generator System (OBIGGS) effects on self-sealing performance.
- Better and worse performing fuel tanks/cell constructions.
- Vulnerability impact pertaining to fuel tank $P_{c/d}$ methodology.
- Age of fuel cell and self-sealing performance.

The report provides a single-source reference to the DoD and the Services for aircraft self-sealing fuel bladder performances and capabilities. In 2018, the DoD FBR working group plans to address the MIL-SPEC issues and recommendations identified in the study. The findings acquired will support future improvements and changes in the MIL-DTL-27422 Phase I/II gunfire test and evaluation aspects of the standard. ASJ

ABOUT THE AUTHOR

Mr. Marty Krammer is an aircraft vulnerability engineer at the Naval Air Warfare Center Weapons Division in China Lake, CA, currently leading LFT&E activities on the CH-53K and CMV-22 programs. With more than 27 years of experience, he has supported numerous aircraft vulnerability reduction and live fire test programs, including AV-8B, F-15, F-14, F/A-18, JSF, AH-1, UH-1, H-60, V-22, and CH-53, and has provided subsequent recommendations to reduce the vulnerability of these aircraft. Specializing in aircraft fire, fuel tank self-sealing, and explosion protection, Mr. Krammer also serves as the Navy co-chairman of JASPO's Vulnerability Reduction and Analysis Subgroup, as well as the Navy Deputy Test Director for the Joint Live Fire Aircraft program, investigating vulnerability issues associated with fielded Navy aircraft. He holds a bachelor's and master's degree in mechanical engineering from California State University, Chico and California State University, Northridge, respectively.

EXCELLENCE IN SURVIVABILITY
CHRIS ADAMS

by Mark Couch and Robert E. Ball

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Christopher Adams for his Excellence in Survivability. Chris currently serves as a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the Naval Postgraduate School (NPS) in Monterey, CA. Prior to holding this position, Chris served in the Navy for 21 years as a Naval Flight Officer, flying the F-14 Tomcat and EA-6B Prowler in numerous combat sorties over Iraq and Afghanistan. Additionally, he served on several major staffs during his Navy career, and his final assignment was serving as Associate Dean of NPS's Graduate School of Engineering and Applied Sciences.

Chris first got plugged into the survivability community in the mid-1990s as an aeronautical engineering student at NPS when he took Dr. Robert Ball's course in Aircraft Combat Survivability (ACS) and became one of his thesis students. This beginning effort would go on to influence the rest of his Navy career, as he found many ways to implement the concepts of survivability in his daily work.

Perhaps his largest impact on the ACS community was upon his return to NPS in 2005, 2 years after the NPS Aeronautical Engineering program (along with all of its aviator students) was moved to the Air Force Institute of Technology, when he discovered that the ACS course was no longer being taught at NPS. He was so concerned that the remaining aviator students at NPS were not learning about ACS that he approached the Chair of the Mechanical and Aerospace Engineering Department and volunteered to teach the ACS course, in addition to performing his normal responsibilities as Associate Dean.

Chris not only took on the extra load of teaching ACS, but he made a major modification to it. Because there were not as many aviator students left at NPS to take his ACS course, he developed a broader combat survivability course that would appeal to NPS students from all major military platforms: aircraft, surface ships and submarines, spacecraft, and eventually ground vehicles. This new course became MAE4751, "Combat Survivability, Reliability, and Systems Safety Engineering."

Chris knew this change would require many changes to the ACS course he took in the 1990s, and he also knew that the NPS students whom he would be teaching would probably know a lot more about ships and submarines, spacecraft, and ground vehicles than he did. This was a risky venture, but Chris had the ability to successfully pull it off. His new NPS multiplatform combat survivability course (ME 4751) has been taught twice a year since 2005. The course allows the students to apply the knowledge that they have gained and developed over the course of their graduate education into critical thinkers on issues of significant importance to the U.S. Government. And platform survivability and weapon lethality continue to be fundamental issues facing the U.S. military now and in the future.

In 2008, Chris became founding director of the Center for Survivability & Lethality, an interdisciplinary research center focused on the Warfighter. He promotes intracurricular initiatives in combat systems, mechanical, aerospace, and systems engineering to provide a complete solution to Navy/Department of Defense (DoD) technical needs, including engaging in the scientific and engineering activities associated with research, development, test, evaluation, fielding, and sustainment of military system design (including safety and survivability). Part of this research also includes infrastructure survivability and applying the ACS concepts to locations such as Las Vegas to protect against terrorist attacks.

In addition, as part of his development of surface ship survivability, beginning in 2009 Chris attended the Naval Sea Systems Command (NAVSEA) Carderock ship design course at the Massachusetts Institute of Technology (MIT) to help introduce the ACS principles to the ship people. His participation with MIT/NAVSEA in their Ship Survivability Short Course led them to expand their coverage of survivability and adapt the use of the concepts of susceptibility and vulnerability as originally taught by Dr. Ball.

Starting in late 2011, Chris, working with Dr. Ball and Drs. Lowell Tonnessen, Jim Walbert, and Mark Couch, began the development of a combat survivability educational program for Army and Marine ground vehicles, titled "The Fundamentals of Ground Vehicle Survivability and Force Protection (GVS&FP)," under the sponsorship of the Live Fire Test and Evaluation Office. Together, these men developed the fundamentals for GVS&FP based upon the fundamentals of ACS, and Chris led the organization and presentation of several GVS&FP short courses. The course has taught students how to take user and system requirements and integrate them into a better product, while reducing life-cycle costs with the enhanced survivability of ground vehicles and the protection of occupants.

Since 2007, Chris has also been one of the lead instructors for the annual JASP-sponsored ACS short course. This course provides DoD, industry engineers, and managers with the opportunity to learn the fundamentals of survivability engineering and their application to actual aircraft. The course covers topics such as threats and threat effects, susceptibility and susceptibility reduction, vulnerability and vulnerability reduction, modeling and simulation, and live fire testing. It also includes practical presentations describing specific aspects of the survivability design for the latest fighters, large transports, and helicopters.

Congratulations, Chris, for your Excellence in Survivability and for your distinguished contributions to today's and tomorrow's aircraft survivability community. (For more information on Chris's contribution to ACS education, see the "Aircraft Combat Survivability Education and Educators: A Personal Perspective Over 40 Years" in the spring 2018 issue of *Aircraft Survivability*.)

ABOUT THE AUTHORS

Dr. Mark Couch is currently the Warfare Area Lead for Live Fire Test and Evaluation in the Operational Evaluation Division at the Institute for Defense Analyses (IDA). Prior to joining IDA in 2007, he enjoyed a 23-year Navy career flying the MH-53E helicopter. He has a Ph.D. in aeronautical and astronautical engineering from NPS and has taught numerous courses in aircraft combat survivability.

Dr. Robert E. Ball is an NPS Distinguished Professor Emeritus who has spent more than 33 years teaching ACS, structures, and structural dynamics at NPS. He has been the principal developer and presenter of the fundamentals of ACS over the past four decades and is the author of The Fundamentals of Aircraft Combat Survivability Analysis and Design (first and second editions). In addition, his more than 55 years of experience have included serving as president of two companies (Structural Analytics, Inc., and Aerospace Educational Services, Inc.) and as a consultant to Anamet Labs, the SURVICE Engineering Company, and IDA. Dr. Ball holds a B.S., M.S., and Ph.D. in structural engineering from Northwestern University.

JASPO FUNDING OF SMALL PROJECTS IN BRAWLER: BRINGING MICROFINANCE TO GOVERNMENT CONTRACTING

by Dale Johnson

Photo by MSgt Kevin J. Gruenwald *(U.S. Air Force)*

For years, model managers for Brawler, the Enhanced Surface-to-Air Missile Simulation (ESAMS), the Computation of Vulnerable Area Tool (COVART), and several other models have made proposals to the Joint Aircraft Survivability Program Office (JASPO) committees for major, multiyear enhancements to these models. Unfortunately, despite these enhancements, the underlying models themselves have sometimes deteriorated because of inadequate funding for ongoing model maintenance or inconsistent configuration management.

In addition, while JASPO and other agencies have often been willing to fund many larger modification/enhancement efforts, smaller changes requiring only a few programmer-days or -months of effort have sometimes stacked up, without a good way to get them accomplished. After all, who really wants to let task orders of, say, $5,000 (a labor-week) or $20,000 (a labor-month) at a time, given the relatively large number of hours and amount of effort just to get that contract vehicle in place? And Government model experts generally cannot take a few months away from their other primary tasks to work on the backlog of projects in the model-improvement "job jar." So, where does one go to solve these problems?

This is where JASPO has stepped in to throw out a lifeline—at least to Brawler, COVART, and ESAMS—by means of a dedicated annual funding stream that can be applied to configuration management, day-to-day software maintenance, and responding to some of the longstanding smaller problems previously described. Starting in FY16, JASPO started providing $150,000 each year to Brawler (and slightly more for COVART and ESAMS), which has allowed a regularized annual version release of the software, incorporating all of the changes from JASPO-sponsored projects, projects sponsored by other agencies, all of the user-developed software improvements that get added to the code through the JASPO-sponsored software change request (SCR) process throughout the year, and configuration control of the final release version of the code.

The more intriguing portion of this process, however, has been the impact that the balance of this annual funding has had, as it can be used to address some of the longstanding smaller projects, as well as the promise it shows in sparking a growth and in-flow of other funding steams, which can be equated to the *microfinance* revolution.

A MICROFINANCING SOLUTION

Microfinancing is the ongoing effort in third-world economies to turn those economies around. Much like venture capitalists in Silicon Valley who spread around millions of dollars looking for the next Google or eBay, philanthropists who were tired of seeing foreign aid squandered (or, more often, the fattening of the Swiss bank accounts of the leaders of those mismanaged countries) went out among the people in those nations and *made small direct loans where they would matter most.* Third-world entrepreneurs did not need $100,000 to open a restaurant or a store. They often needed only $200 for a sewing machine or $500 for a street-merchant's handcart. These amounts would be too little for a bank to worry about, and yet they are perfect for the philanthropist who wants to see a return on his/her investment.

And a similar situation has occurred in Brawler model management. Previously, Brawler's annual Configuration Control Board (CCB) meetings, held in conjunction with the now annual JASPO-sponsored Joint Model User's Meeting (JMUM), had become a bit of a formality. All SCRs were accepted, and because most were accompanied by the suggested code modifications that the users had worked out through their initiative, it took only a few hours for the Configuration Manager to determine that the new code worked and did not introduce any unwanted effects elsewhere in the code. And thus the code was accepted into the code base.

In the case of actual bugs that did not come with a solution from the user, they generally only involved a few hours to "fix." Then these too were accepted into the code base for the next release. In addition, because many of these SCRs had already been closed by the time of the the annual CCB meeting, the meeting became a rubber stamp for the SCRs that had already been worked and for the more recent submissions that were next up in the job jar.

This was not the case, however, for the rarer of the SCRs, those requesting small changes or enhancements to Brawler. They were accepted by the CCB when validated as a useful enhancement to the code, but it was understood that they would not go into the job jar, as neither A9 nor any other Brawler user was budgeted to take on other people's code modifications. As a result, those SCRs languished, and, as might be expected, that is why that type of SCR was so rare.

But this situation began to change in 2016 when JASPO's funding was introduced into this process. Beginning with the 2016 JMUM/CCB, all of those old requests that had been sitting and gathering dust were discussed. Additionally, a prioritized list of those small projects was developed, based on the expected benefit, how many users would use the new capability, and the anticipated level of effort to code-out these enhancements. And work was initiated over the next year to accomplish as many items on the "punch list" as funding would allow.

At the 2017 JMUM/CCB, in addition to A9 discussing the major changes to the code that had been made throughout the year, as well as several other Brawler users discussing the changes they had made and how they employed the code (the usual fare of the break-out session), additional time was also scheduled to discuss our success in tackling the punch list and to field nominations for new items on the list. The 2016 list had started with 7 entries, and 6 were addressed prior to the 2017 JMUM; but we left the 2017 meeting with 16 entries to be addressed. In addition, because we had had success with the 2016 list, several Brawler users who could not attend JMUM in person requested that we hold a virtual follow-up to the CCB, which resulted in a 17th entry and a reordering of project priorities (see Table 1). Without a doubt, success has energized the process.

And success may also be leveraging new funding streams. For example, one of the Government Brawler users went to one of its customers, an aircraft System Program Office (SPO), and asked that customer to pay for the annual Brawler User Fee ($5,000) for them, as well as to include an additional $15,000 to get a code enhancement accomplished to help with the analysis that the customer required. *(Note that the Air Force Fiscal, Ethics and Administrative Law Division cautions that any new funding streams must comply with fiscal law. Not all new funding streams will be appropriate across the board. Fiscal rules may dictate the approval would be unsuitable for other users.)*

By demonstrating the agility to make these small enhancements in a timely fashion, we have taken users out of the old paradigm of "I really hate that

Table 1. 2016 and 2017 Brawler Punch Lists

Year	Punch List Entry
2016	1. Integrate NAVAIR provided DLD/COM Jammer.
	2. Create IR Cue Ball (with plume=0) for use like RCS Cue Ball.
	3. Create a vulnerable area data test for gun models.
	4. TSPI mover to be investigated for Brawler implementation.
	5. Allow for a Table Based WEZ (Type 6) in Brawler.
	6. Develop a Single Shot EGMAIN (Became #6 in 2017 List).
	7. Add the ability to output comma-separated value (CSV) files for common missile output variables.
2017	1. Additive RCS for Stores – Much like doors opening and closing.
	2. Bitmask Revision –Help with setting Bitmasks - Have the user enter T/F for specific named variables, and do the conversion for them. Then convert internally to store/use as a bitmask.
	3. More CSV Output Options – Now that we have opened up this capability, we should create new CSV Logs, such as a Sensor Log (users to determine which logs and level of detail when we are ready to start).
	4. plmain IRSIG Mods – NAVAIR has a plmain IRSIG mode that allows user to specify speed/altitude, then throttle setting is calculated, rather than having to specify throttle. EZJA says they have a modification for plotting the input IRSIG data, rather than these derived signatures, which is useful for verifying that you have correctly entered your data. If each of these organizations provides this code, we can get both enhancements integrated.
	5. Integrate Commander-in-the-Loop (CITL) Graphics – Investigate the possibility of porting some of the enhanced graphical output capabilities Earl Lazarus wrote to accompany CITL enhancements to Brawler, and making them a part of "mainline" Brawler (as a graphical option to grmain).
	6. EGMAIN IR Weapon Fix – Because EGMAIN creates repeated weapon firings, when done for weapons that must uncage their seekers and acquire before launch a delay needs to be built in. A9F to provide the code.
	7. SIMDIS Standard Interface – Allow preset preferences to be read into SIMDIS to speed up use.
	8. Allow the Output of Pilot Mental Model Perceptions to SIMDIS.
	9. Create a Calling Tree – To trace the linkages between Brawler routines.
	10. HDF5 Module for Handling Large Data Files – NAVAIR Pax agreed to prototype this capability in at least one place within Brawler.
	11. Target-Specific Missile Envelopes – Lockheed has already sent the code for V8.2. It will require uplift (since misdat is uplifted for V8.3 and there are other missile changes as well).
	12. Using R for Plotting Data – This project would develop a series of "R" programs to plot existing weapon flyout, aircraft trajectory, and sensor performance files.
	13. Dynamic Array Sizing Rather Than Templates File – Allow for dynamic sizing of templated arrays. The array size required to hold templated data sets would be calculated dynamically during the read-in process.
	14. Turn Rules Into Modules – Modularize Rules into distinct blocks and allow each flight to call and employ its own unique rules.
	15. Instructions on perl script for gnuplot.
	16. Modularize the Kalman Filter – Brawler's Extended Kalman Filter performs fairly well for a general-purpose algorithm. However, it may be desirable to experiment with other alternative formulations. This project would encapsulate the existing Kalman filter into a module to enable "dropping in" a new filter.
	17. Add JAAM-Like Interface to GRMAIN – Possibly rehost entire blocks of JAAM code to allow for analysis using slide bars and entity data such as is now possible in JAAM.

the code acts that way; why didn't they design the code to do such and such" and into the new paradigm of "I could be much more efficient if the software would just do this one additional step," and then they go out and proactively seek the funding to get it done.

CONCLUSION

Brawler is continuing to see its major evolutionary changes occur through large infusions of cash to make major modifications to the model. Developers are currently in the process of designing a major overhaul to the code, which will bring it in line with other modeling and simulation (M&S) tools within the Air Force and Department of Defense and which will (hopefully) greatly simplify the process for new users to adopt the code. But this infusion of model maintenance funding, targeted at smaller projects—in essence, microfinancing for the modeling software world—has breathed new life and energy into the Brawler user base and may be an example for other M&S tools to follow in the future. ASJ

ABOUT THE AUTHOR

Mr. Dale Johnson is a member of the Air Force Office of Studies Analyses and Assessments (HQ USAF/A9FM) and has been the Brawler Model Manager since 2004. In addition to his 20 years of active duty service in the U.S. Air Force, he has served as a Government civilian since 2009. Mr. Johnson holds a B.S. and M.S. in aerospace engineering from the University of Michigan.

(Note that A9 owns and manages Brawler, while JASPO provides supplemental funding and the Defense Systems Information Analysis Center handles model distribution, SCR management, and user group administration.)

SAVE THE DATE, 12–14 JUNE 2018

JASPO and DSIAC are pleased to announce that the 23rd JASP Model Users Meeting (JMUM) will take place at the Air Force Institute of Technology in Dayton, OH, 12–14 June 2018. We are looking forward to a full 3-day classified agenda with a plenary session, breakout meetings, and new technical content. The purpose of the JMUM is to provide model users, managers, stakeholders, and others with the latest developments and updates on JASP-sponsored models and other models used throughout the aircraft survivability (susceptibility and vulnerability) technical community. Attendees will be briefed on the latest software developments, upgrades, and threat model updates.

We are actively soliciting session topics and presentations to enhance your meeting experience. If you know of a topic you would like to see on the agenda or if you are interested in presenting, please contact DSIAC's Alfred Yee at 937-255-4608 or at *alfred.yee@dsiac.org*. Registration information, security clearance instructions, and the preliminary agenda are available at *www.dsiac.org.*

JAS
JOINT AIRCRAFT SURVIVABILITY PROGRAM

THE DEVELOPMENT OF AIRCRAFT COMBAT SURVIVABILITY AS A DESIGN DISCIPLINE OVER THE PAST HALF CENTURY

by Robert E. Ball, Mark Couch, and Christopher Adams

(U.S. Navy)

A BRIEF INTRODUCTION TO THE BASICS OF ACS

The term "aircraft combat survivability" (ACS) is defined in *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition* as "the capability of an aircraft to avoid or withstand a man-made hostile environment" [1]. This definition forms the basis for the ACS design discipline.

"To avoid" means to avoid being detected, tracked, engaged, and physically "hit" by one or more of the damage (causing) mechanism(s) carried or generated by a threat weapon or warhead, such as a gun-fired ballistic armor-piercing projectile with incendiaries (AP-I) and the blast and fragments generated by the detonation of a high-explosive (HE-frag) warhead. The inability of an aircraft to avoid the hostile environment is referred to as the aircraft's *susceptibility*. Aircraft susceptibility can be measured by the probability that the aircraft is hit by one or more damage mechanisms, P_H. Avoiding the hostile environment (i.e., reducing the aircraft's susceptibility) can be achieved using the six susceptibility reduction concepts:

- Threat Warning.
- Noise Jamming & Deceiving.
- Signature Reduction.
- Expendables.
- Threat Suppression.
- Weapons & Tactics, Flight Performance, and Crew Training & Proficiency.

"To withstand" means the aircraft continues to function at some useful or acceptable level after any unavoidable hits by the enemy's damage mechanisms. The inability of an aircraft to withstand the hostile environment is referred to as the aircraft's *vulnerability*. Aircraft vulnerability can be measured by the probability that the aircraft is killed given a hit, $P_{K|H}$. Withstanding the hostile environment (i.e., reducing the aircraft's vulnerability) can be achieved using the six vulnerability reduction concepts:

- Component Redundancy With Separation.
- Component Location.
- Passive Damage Suppression.
- Active Damage Suppression.
- Component Shielding.
- Component Elimination or Replacement.

An aircraft that is unable to both avoid and withstand one or more damage mechanism hits is said to be killed, and the product $P_H \bullet P_{K/H} = P_K$ is a measure of its killability. The probability an aircraft survives the man-made hostile environment is P_S, the complement of P_K. Thus, $P_S = 1\text{-}P_K$.

There are two primary categories of an aircraft's inability to withstand hits (i.e., its inability to continue to function at a usable or acceptable level): an aircraft *attrition kill* and an aircraft *mission kill*. An aircraft suffers an attrition kill if it loses one or more flight-essential functions (lift, thrust, control, and structural integrity) due to combat damage (i.e., we say the aircraft was totally unable, or failed, to withstand the hit[s]). An aircraft suffers a mission kill if it loses one or more mission-essential functions due to combat damage (i.e., we say the aircraft was partially able to withstand the hits[s]). Mission kills include mission abort, forced landing, etc.

Any particular characteristic of the aircraft, specific piece of equipment, design technique, armament, or tactic that reduces either the susceptibility or the vulnerability of the aircraft has the potential for increasing an aircraft's survivability and is referred to as a survivability enhancement feature. Table 1 lists some of the many, varied design features and operational tactics and techniques that can contribute to an aircraft's combat survivability. Each of these features is an example of 1 of the 12 susceptibility and vulnerability reduction concepts listed previously.

The two goals of the ACS discipline are (1) the early identification and successful incorporation of those specific survivability enhancement features that will increase the combat cost effectiveness of the aircraft as a weapon system; and (2) in those situations where the damage will eventually lead to an aircraft attrition kill, the ability of the survivability enhancement features to allow a graceful degradation of the system capabilities, giving the crew a chance to depart the aircraft over friendly territory.

Table 1. Some Survivability Enhancement Features [1]

Speed and altitude	Maneuverability/agility	Lethal standoff weapons
Fire/explosion protection	Terrain following	Fighter escort
Self-repairing flight controls	No fuel adjacent to air inlets	Chaff and flares
Redundant & separated hydraulics	Self-defense missiles and guns	Rugged structure
Night-time capability	Crew situational awareness	Good target acquisition capability
More than 1 engine-separated	Hydrodynamic ram protection	Onboard electronic attack equipment
Low signatures	Mission planning system	Anti-radiation weapons
Tactics	Crew training & proficiency	Standoff electronic attack equipment
Threat warning system	Nonflammable hydraulic fluid	Armor

Of particular interest here is the development of ACS as a design discipline for aircraft that has taken place over the past 50 years. In general, design disciplines for the individual aircraft systems or capabilities, such as structures, fuel, propulsion, flight controls, aerodynamics, power train, and rotor blades—and now combat survivability—have a terminology, a methodology for assessing or quantifying the important capability metrics (e.g. measures of performance [MOPs]), a design technology for achieving the desired capabilities (e.g., key performance parameters [KPPs]), a set of user requirements that can be validated by testing, a place in the acquisition process, and an infrastructure that includes educational opportunities in the discipline.

The ACS design discipline must also be broad in concept and coverage, and it must be an integral part of systems engineering (SE) for military aircraft because it can have a major impact on all of the other aircraft design disciplines (e.g., rugged structures; explosion-proof and leak-proof fuel tanks and lines; stealthy propulsion; redundant and separated self-repairing flight controls; highly maneuverable, agile, and stealthy aerodynamic shapes; and rugged rotor blades, drive shafts, and run-dry gear boxes), as well as on the operational tactics of military aircraft.

THE MOTIVATION FOR ESTABLISHING ACS AS A DESIGN DISCIPLINE

Military aircraft have been shot at; hit; and downed, lost, or killed ever since they were first used in combat in the early 1900s. As a consequence of the loss of hundreds of thousands of military aircraft in combat (nearly 50,000 U.S./UK fighters and bombers were lost in combat in Europe in World War II)—not to mention the accompanying death, injury, or incarceration of their crews—many actions, both operational and design, have been taken over the past 100+ years to enhance the combat survivability of military aircraft to the increasingly effective man-made threats, starting with the early ground and airborne guns and progressing to the modern ground and airborne guns and guided missiles.

From the beginning of the 20th century up to, and particularly including, the Southeast Asia (SEA) conflict (1964–1973), most military aircraft were not *required* to have much in the way of survivability in their original design. Furthermore, any design and operational actions taken to enhance an aircraft's survivability were mostly a reaction to an empirically discovered aircraft killability in combat.

The quickest remedy was often to try new tactics, including mission and force package changes, that reduced the susceptibility of the participating offensive aircraft. These changes included flying higher to avoid the enemy's air defense weapons; employing metal chaff to create detection and tracking problems for radar-directed weapons; employing on-board threat warning and noise-jamming and deceiving electronic equipment (known as aircraft survivability equipment [ASE]); and adding fighter escorts, electronic countermeasures (ECM) aircraft, flak suppression aircraft, and search and rescue aircraft to the mission package.

Unfortunately, these actions often resulted in fewer offensive aircraft available to accomplish a given mission (such as bombing a bridge), as well as possibly reduced effectiveness of the weapons used (such as bombing the bridge from high altitude using dumb bombs). Furthermore, these operational actions were not always successful in preventing aircraft losses. (Perhaps the most successful action taken to enhance aircraft survivability in the SEA conflict was the later introduction of smart [precision-guided] weapons, which could be launched from a distance and guided to the target.)

The other survivability enhancement option was to reduce the vulnerability of the recently discovered killable aircraft [2]. This option usually took longer to achieve and could result in a less-than-optimum enhancement of survivability, as well as degradations in other important operational capabilities of military aircraft (e.g., reduction in aircraft payload, range, speed, and maneuverability due to added weight) and an increase in the aircraft's initial and operational costs and downtime.

This problem of not designing for ACS from the beginning of any aircraft program peaked before the SEA conflict when the goal was to develop fast, high-flying fixed-wing aircraft with long-range air-to-air and air-to-surface weapons (possibly nuclear) and helicopters that would be mostly operating (it was assumed) in safe skies. Simply put, most of the aircraft used in SEA were never designed to survive in the man-made hostile environment in which they were eventually assigned to operate.

This lack of available ACS-designed aircraft in SEA resulted—according to the most recent combat loss data—in the loss of approximately 4,100 U.S. aircraft (2,052 fixed-wing and 2,066 rotary-wing) due to hostile combat action from all three U.S. military departments over 10 years. (An additional 4,300 aircraft [1,117 fixed-wing and 3,193 rotary-wing] were lost to nonhostile action [i.e. mishaps]—many of which occurred while intentionally flying to avoid enemy detection in a hostile environment, such as low-level flights and night-time flights without night vision devices [3].) This long-term neglect, inadequate consideration, and/or simple omission of the importance of ACS in the design and operation of military aircraft had to be changed.

MAJOR ACTIONS IN THE ACS DESIGN DISCIPLINE DEVELOPMENT

Perhaps the first public recommendation that U.S. military aircraft must be designed—from the beginning—for combat survivability was a 1969 paper by Dale Atkinson, Paul Blatt, Levelle Mahood, and Don Voyls titled "Design of Fighter Aircraft for Combat Survivability" [4]. In 1967, a forensic team from Wright-Patterson AFB, led by Dale, went to SEA to find out why the Air Force was losing so many of its fighter aircraft to the relatively primitive air defenses used by North Vietnam. The team discovered that the aircraft being used in SEA were both susceptible (because of the missions flown and the tactics being used) and vulnerable (because the aircraft were not designed to withstand hits by gun-fired ballistic projectiles and the HE warhead blast and fragments they encountered while on these missions).

The results of the team's study were summarized as follows (in the paper's abstract) [4]:

> ***Aircraft survivability must be considered during preliminary design and during every succeeding phase of airplane subsystem and airframe construction.*** *To enhance survivability a minimization of vulnerability of critical systems and components must be designed and engineered into the aircraft system. Some areas wherein design application can reduce vulnerability of aircraft are crew protection as well as structural and fuel system components. Experience in Southeast Asia indicates that many aircraft losses occur due to vulnerability of flight control systems to ground fire. This paper reviews in detail design parameters for hydraulic logic isolation elements, emergency flight control techniques, less flammable fluids, and integrated actuator packages which, together with redundancy and dispersion techniques, will increase the survivability potential of flight control systems. In conclusion,* ***a systematic design procedure must be developed for all critical systems in the aircraft to assure that survivability is given prime consideration during the complete design cycle.*** *[Bold added for emphasis.]*

Some context for the team's call for development of a systematic design procedure for aircraft survivability is appropriate here. Around 1970, the discipline now known as ACS (or simply survivability) was then known as nonnuclear survivability/vulnerability (or simply S/V) [5]. The definition of survivability at that time was "the capability of an aircraft to avoid and/or withstand a man-made hostile environment without sustaining an impairment of its ability to accomplish its designated mission."

Likewise, susceptibility was defined as "the combined characteristics of all the factors that determine the probability of hit of an aircraft component, subsystem, or system by a given threat mechanism." Threat mechanisms were defined as "mechanisms, embodied in or employed as a threat, which are designed to damage (i.e., to degrade the functioning of or to destroy) a target component or the target itself." Vulnerability was defined as "the characteristics of a system that cause it to suffer a finite level of degradation in performing its mission as a result of having been subjected to a certain level of threat mechanisms in a man-made hostile environment."

Apparently, there was no definition at the time for susceptibility reduction, but the definition of vulnerability reduction was "any technique that enhances the aircraft design in a manner that reduces the aircraft's susceptibility to damage when subjected to threat mechanisms."

In the early 1970s, the aircraft nonnuclear survivability/vulnerability discipline had a terminology that was acknowledged to be inconsistent among the Services; the capability metrics and associated assessment methodology were in their infancy as the digital computer came on the scene; both the design technology for enhancing survivability and the user demands (both informal and formal) for incorporating survivability enhancement features on existing aircraft were beginning to grow as the SEA losses grew; and testing in combat was pretty much the norm. Also, the survivability/vulnerability infrastructure at the time was relatively small, and there was no opportunity for an education in how to design more survivable aircraft.

To rectify this unacceptable situation, numerous major actions initiated by the Department of Defense (DoD) and the Services over the following five decades have moved ACS from a commonly held attitude of "Yes, ACS is an important aircraft capability; but payload, range, cost, etc., are more important" to "ACS is an extremely important aircraft capability—perhaps one of the most important—and it must be considered from the beginning to the end of any aircraft acquisition program."

The following subsections provide a brief description (in rough chronological order) of some of the most important actions that have contributed to the establishment of ACS as a design discipline, as called for by the Atkinson team in 1969. Note that this list of actions is far from complete, and the authors thank the many individuals (both named and unnamed) throughout the DoD, aircraft industry, and acquisition communities who have contributed to the growth of ACS during the last five decades.

1971 – Establishment of the JTCG/AS and JASP

One of the most important actions taken by the DoD near the end of the SEA conflict to improve combat survivability—and thus prevent unacceptable losses in future conflicts—was the establishment of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) by the Joint Aeronautical Commanders Group in 1971. The proposal to establish the JTCG/AS came from the Survivability Task Force created earlier in 1969 by Dr. Joe Sperazza, Chairman of the existing Joint Technical Coordinating Group on Munitions Effectiveness (JTCG/ME).

One of the major (Atkinson-proposed) goals of the newly formed JTCG/AS was to establish survivability as a formal design discipline. The rationale for this goal was based upon the belief that when survivability becomes an established design discipline for military aircraft, designing for survivability will be a major consideration in the design and SE processes, starting from the initial concept of the aircraft to the final design (and not as an afterthought when the bad news starts to show up after the shooting begins).

Two of the early actions taken by the JTCG/AS consisted of (1) three biennial survivability symposia held at the Naval Postgraduate School (NPS) starting in 1974, followed by cosponsored symposia with the American Defense Preparedness Association (ADPA), which later became the National Defense Industrial Association (NDIA); and (2) the start of the JTCG/AS quarterly newsletter in 1977. The newsletter mailing list grew from approximately 400 in the early days to approximately 10,000. (Note that this newsletter was eventually replaced by the current *Aircraft Survivability* journal, and the JTCG/AS became the current Joint Aircraft Survivability Program [JASP] in 2003.)

Early 1970s – The Birth of Stealth Aircraft

Another crucial action taken at this time as a result of the heavy losses in SEA (and the prospect of flying over a hostile Soviet Union some day in the future) was the decision that susceptibility reduction, in the form of significantly reduced aircraft signatures, required a serious, long-term commitment, extending throughout the lifetime of an aircraft. Because an aircraft's signatures are strongly dependent upon many factors that are set early in the aircraft's design (e.g., external shape, surface materials, tolerances, size and placement of engines, etc.), nearly all of the important capabilities of a military aircraft are impacted when signature reduction is the design driver. Consequently, a new and prominent design discipline in ACS, as proposed by the JTCG/AS, was needed to properly account for all aspects of this new driving capability, which was called *stealth*.

The early U.S. stealth, or low observables, program was developed by the Defense Advanced Research Projects Agency and demonstrated via the Have Blue program. This program produced the world's first practical combat stealth aircraft, leveraging new design concepts, new radar cross section prediction tools, new materials, and eventually new tactics. It also led directly to the Air Force's procurement of the state-of-the-art F-117 stealth fighter [6].

The decision to rely on full-blown, all-in stealth as the primary survivability design feature for certain types of high-risk aircraft (and a major feature for other, less exposed aircraft) carried with it the risk that our enemies, if they knew that we were engaged in the development of stealth aircraft, would attempt to learn about the specific stealth technology we were using and would (1) develop sensors and weapons that could defeat our stealth advantage, and/or (2) embark on their own stealth aircraft development programs using our advanced technology. The solution to this problem consisted of the imposition of a level of security from the beginning of the program that was unprecedented in military aircraft acquisition programs.

(U.S. Air Force)

Unfortunately, the movement of everything related to the development of stealth aircraft into a "black" world significantly complicated the development of ACS as a design discipline, particularly the signature reduction aspect of susceptibility reduction. Whereas spreading the word about how to do ACS was essential to developing ACS as a design discipline, spreading any word about stealth aircraft was strictly forbidden. The world of vulnerability reduction was also classified, but at a much lower level, so it did not pose the same problem.

1972–1973 – Designing New Post-SEA Aircraft for Reduced Vulnerability

An unprecedented action taken by the Army near the end of the SEA conflict to reduce helicopter vulnerability was the ground-breaking requirement that the latest Army helicopters in development, the UH-60A Black Hawk and the AH-64A Apache, be designed to *withstand* a single hit by a particular ballistic projectile anywhere on the helicopter by flying for 30 minutes after the hit. This requirement eliminated the single-hit "cheap kills" by small-caliber projectiles that were seen in SEA. (Note that the single-hit requirement, in effect, built in a capability to withstand multi-hits.) The Air Force's A-10A Thunderbolt II and the Navy's F/A-18A Hornet, which were also initiated near the end of the SEA conflict, were also designed with vulnerability reduction as a major consideration, particularly the now-famous A-10 Warthog. The Navy's F/A-18A also included some design features intended to reduce susceptibility.

1976–1982 – Post-SEA Military Policies for ACS

There was a flurry of official documents issued after the SEA conflict involving first nonnuclear S/V and later survivability. Although the fundamental objective of the three Services during this time was to require a thorough and systematic survivability program be incorporated in current and future U.S. airborne weapons systems, each Service had its own policies, procedures, and organizations. The Army had Army Materiel Development and Readiness Command Regulation 70-3, "Survivability," in 1976 [7]; and the Navy had Naval Material (NAVMAT) Instruction 3900.16, "Combat Survivability of Naval Weapon Systems," in 1979 [8]. This instruction was the result of the 1974 policy memorandum by ADM I. C. Kidd, Chief of Naval Material, who said [9]:

> *Survivability should be treated as follows during the weapon system acquisition process. (1) Threat analysis should be conducted and firm survivability objectives established during the conceptual phase of the acquisition process. (2) It is essential that both survivability requirements and measurement and validation criteria be specified upon entry into full scale development; these requirements must be included in the contract. (3) The request for authorization to proceed into production must specify the survivability requirements to be imposed and the means for measuring their attainment. (4) Weapon systems should be tested against expected threat weapons wherever practical. I expect each of you to ensure that survivability is fully considered in development proposals and that they are properly reflected in contracts.*

In addition, Air Force Regulation 80-38, "Management of the Air Force Systems Survivability Program" (1982), stated that survivability must be considered in developing the requirements for, and the trade-offs leading to, the basic design of an Air Force system [10]. To achieve acceptable survivability with the minimum impact on the performance of each system, survivability must be "balanced" with the other performance parameters of the system.

1977 – Development of the First ACS Academic Course at NPS

In general, all aircraft design disciplines (such as structures, fuel systems, flight controls, et al.) have academic engineering courses available in that discipline. Prior to 1977, however, there was no similar academic course available anywhere that taught all aspects of ACS as an engineering design discipline. No one had ever learned in school how to design a military aircraft to make it more survivable in combat. Consequently, to assist in the establishment of ACS as a design discipline that was similar to the other aircraft design disciplines, the development of a brand new academic course in the fundamentals of ACS was essential.

In the mid-1970s, Dr. Robert E. Ball, an Associate Professor originally hired by NPS in 1967 to teach aircraft structures, was being funded by the JTCG/AS to develop a computer program to predict the structural response of a B-1 aircraft wing fuel tank to the impact of a ballistic projectile. Because Bob was working closely with the JTCG/AS, he knew of the stated goal of establishing ACS as a design discipline, and he believed NPS was the perfect place to provide specialized educational training to support that goal.

Bob's students in 1977 were military aviators, including a number who had flown in combat. Many of his students after graduation would go to work in (and possibly lead) numerous engineering offices involved in the development of Navy aircraft. Thus, a graduate-level education in ACS would turn out to be highly beneficial to both them and the Navy. It didn't take much persuasion to convince Dale Atkinson (then at the Naval Air Systems Command [NAVAIR]) and the JTCG/AS leadership to fund Bob to develop such a program at NPS. The first ACS course was offered in the fall of 1977 to 26 students, and it continues today, with two offerings annually. A similar course was established at the Air Force Institute of Technology (AFIT) for Air Force and Navy resident students in 2014. (For more information on ACS education and the educators, see the article in the spring 2018 issue of *Aircraft Survivability* [11].)

1978 – Development of the First ACS Short Course

In the spring of 1978, shortly after the first NPS ACS academic course, the JTCG/AS sponsored the first ACS short course. It was held in a packed auditorium at the NAVAIR Headquarters in Washington, DC. Dale and Bob had strongly believed that if ACS was ever going to become a formal design discipline, many others involved with (or influencing) the design of military aircraft should have the opportunity for an education in the ACS fundamentals. So Dale asked John Morrow (from the Naval Weapons Center, China Lake) and Bob to work with him to develop an ACS short course based upon Bob's NPS course. The first short course was well received, and a second one was held at NPS a few months later, followed by at least one per year for most of the next 40 years at NPS and other important ACS locations.

1981 – Publication of DoD MIL-STD-2069 and Other MIL-STDs and MIL-HDBKs

As a result of a major focus by the JTCG/AS on developing ACS as a design discipline, several DoD military standards and handbooks were developed by the group over the first decade. For example, the JTCG/AS sponsored the development of DoD MIL-STD-2089 ("Survivability Terms and Definitions") in 1981, which tackled the challenging problem of getting a uniform agreement on a consistent terminology for all organizations involved [12]. (Note the change of title from the earlier survivability/vulnerability to survivability. The old S/V was being replaced by survivability during this time frame.)

Another major 1981 DoD document, MIL-STD-2069 ("Requirements for Aircraft Nonnuclear Survivability Program"), also contributed to ACS design discipline development by requiring a standardized systems approach to designing for ACS [13]. This DoD document, which replaced the earlier individual Service requirements documents, provided the requirements and guidelines for establishing and conducting aircraft survivability programs while maintaining the flexibility required by acquisition program managers in the development of a survivability program compatible with the needs of the procuring Service and the scope of the acquisition program. It also required the weapon system contractor to have a survivability program, a survivability organization, a program plan, program reviews, and specific program tasks—including a mission-threat analysis; Failure Mode, Effects, and Criticality Analysis (FMECA); aircraft susceptibility, vulnerability, and survivability assessments; survivability enhancement trade-off studies; and combat damage repair assessment.

The popular four-volume DoD MIL-HDBK-336 ("Survivability, Aircraft, Nonnuclear") and two-volume

"Countermeasures Handbook for Aircraft Survivability" were also developed by the JTCG/AS during this time [14, 15].

1984 and 1987 – The JLF Program and Live Fire Test Law

The Joint Live Fire (JLF) Program was chartered in 1984 by the Office of the Under Secretary of Defense, Director Defense Test, and Evaluation, due to concerns regarding (1) the vulnerability of current U.S. military aircraft and ground vehicles to foreign weapons and (2) the lethality of current U.S. weapons against foreign targets. JLF's initial aircraft program consisted of firing live threat-representative rounds at frontline U.S. aircraft, including the F-15, F-16, F/A-18, A-6E/F, AV-8B, UH-60, and AH-64. The JTCG/AS was responsible for oversight of the vulnerability testing.

To address the perceived inadequacy of the (then) current platform vulnerability and weapon lethality testing, the Live Fire Test Law was passed by the U.S. Congress in FY87. It consisted of an amendment to Title 10, U.S. Code, which added Section 2366 ("Major Systems and Munitions Programs: Survivability and Lethality Testing; Operational Testing"). The law requires that the Secretary of Defense conduct realistic survivability and lethality testing on covered weapons systems before they proceed beyond low-rate initial production (LRIP). Covered systems include new, major acquisitions, or any product improvement that significantly affects vulnerability or lethality.

According to the law, realistic survivability testing means testing for the vulnerability of the system in combat by firing munitions likely to be encountered in combat (or munitions with a capability similar to such munitions) at the system configured for combat, with the primary emphasis on testing vulnerability with respect to potential user casualties and taking into equal consideration the susceptibility to attack and combat performance of the system. (The DoD term for such testing is "full-up, system-level testing.") The law states that this testing shall be carried out sufficiently early in the development phase of the system to allow any demonstrated design deficiency to be corrected in the design before proceeding beyond LRIP.

Although modified slightly since its passage, the Live Fire Test Law has proven to be both enduring and flexible, permitting test realism to be balanced against cost and practicality. Most importantly, the law has had a significant positive impact on the development of ACS as a design discipline because it has ensured that program managers are giving a sizable amount of motivation, attention, and resources to design a survivable aircraft because they know it will be tested.

1985 – Publication of the First ACS Textbook

As the NPS ACS course notes grew in size and improved in content, the decision was made to publish a formalized textbook on the subject. This text, titled *The Fundamentals of Aircraft Combat Survivability Analysis and Design*, published by the American Institute of Aeronautics and Astronautics (AIAA) in 1985, was the first book to cover all aspects of ACS as a design discipline. From the Preface [16]:

> *The U.S. Eighth Air Force, operating over Germany in daylight and without fighter escort, suffered a 24% attrition rate in October 1943 in raids against the ball bearing factories in Schweinfurt. This heavy loss of aircraft led to the termination of the Air Force's daytime unescorted, deep penetrations into Germany.*
>
> *During the Korean War, U.S. Air Force B-29s suffered a 20% loss rate during a series of daylight missions, causing the Bomber Command to cancel the daylight raids and operate only at night.*
>
> *The heavy losses of Israeli A-4 aircraft on the first day of the Yom Kippur War in 1973 resulted in cancellation of the close air support missions over the Golan Heights. When the ground situation absolutely required resumption of the close air missions, the tactics were changed so that the A-4s operated at the outer fringes of the battle zone and were not faced with the intense Syrian air defenses.*
>
> *All of the above examples, both strategic and tactical, illustrate the overwhelming requirement for the consideration of survivability in the design and utilization of military aircraft. As a result of this requirement, a technology for enhancing survivability and a methodology for assessing survivability has evolved over the past 70 years. However, because the importance of survivability is sometimes either forgotten or neglected in the design and development of military aircraft during periods of peace, aircraft designers, program managers, and operators must be reminded that survivability considerations must be neither overlooked nor ignored. They need to be informed about the current technology for increasing survivability and about the methodology for assessing the payoffs and the penalties associated with survivability enhancement features. This text is devoted to that end.*

Approximately 10,000 copies of the 400-page book were sold in 5 printings between 1985 and 2003.

1985 and 2014 – Establishment of SURVIAC and DSIAC

A major part of the ACS infrastructure created by Dale Atkinson while he was the JTCG/AS Chairman was the establishment of the Survivability/Vulnerability Information Analysis Center (SURVIAC) in 1985. SURVIAC, which was operated by Booz Allen Hamilton, was designed to be a dedicated center of excellence, providing a centralized information and analytical resource for all aspects of nonnuclear survivability, lethality, and munitions effectiveness. After serving nearly 30 years in this role, SURVIAC and its responsibilities were integrated into the Defense Systems Information Analysis Center (DSIAC) in 2014. Operated by the SURVICE Engineering Company under the sponsorship of the Defense Technical Information Center, DSIAC consolidates the activities of multiple DoD Information Analysis Centers, focusing on S/V, advanced materials, autonomous systems, directed energy, energetics, military sensing, non-lethal weapons, reliability/maintainability, and weapon systems.

1988 and 1989 – Establishment of the NDIA CSD and AIAA STC

The establishment of the National Defense Industrial Association's (NDIA) Combat Survivability Division (CSD) by RADM Robert Gormley in 1988, as well as the establishment of the AIAA's Survivability Technical Committee (STC) by Professor Ball in 1989, added to the ACS infrastructure by providing an open-communication link between the industrial companies that design and build military aircraft. The NDIA CSD holds an annual Aircraft Survivability Symposium at NPS, and the AIAA STC holds annual meetings at one of the principle AIAA meetings.

1991 – DoD Directive 5000.2

The February 1991 version of DoD Directive 5000.2 included survivability as a "critical system characteristic"—that is, a characteristic of the system that has a critical role in the successful operation of the proposed system as it functions in its operational environment. The directive went on to say [17]:

> *(a) The survivability of all systems that must perform critical functions in a man-made hostile environment shall be an essential consideration during the acquisition life cycle of all programs, to include developmental and nondevelopmental programs.*
> *(b) Survivability from all threats found in the various levels of conflict shall be considered. This includes conventional; electronic; initial nuclear weapon effects; nuclear, biological and chemical contamination (NBCC); advanced threats, such as high-power microwave, kinetic energy weapons, and directed energy weapons; and terrorism or sabotage.*

(Note: This DoD guidance on survivability is now contained in DoD Instruction 5000.02 and the *Defense Acquisition Guidebook*.)

1996 – Survivability Included as One of the Four Program Pillars of the F-35

By 1996, ACS had advanced in importance from the old attitude of "nice to have, but..." to the very top level of aircraft attributes. One notable example of this advancement was the inclusion of survivability in the four stated program pillars for the state-of-the-art Joint Strike Fighter (JSF)/F-35 program—namely, affordable, lethal, survivable, and supportable. With inclusion such as this in major high-visibility programs, it was clear that survivability had secured a permanent position as a formal design discipline in military aircraft development and acquisition.

2003 – Publication of the Second Edition of the Ball ACS Textbook

After 15 years of adding new ACS content; improving existing content; and adding learning objectives, many more notes and references, and a long list of questions, it became time to publish a new, much more extensive edition of the ACS fundamentals textbook. Among other things, the revised text strongly encouraged the continued development of ACS as a formal, unified design discipline across the community. From the text's Prologue [1]:

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

FY05 – The Statutory Requirement for Force Protection and Survivability KPPs

Section 141 of the National Defense Authorization Act of Fiscal Year 2005 (also known as Public Law 108-375) requires in part that KPPs for force protection and (vehicle or system) survivability be included as part of the documenting system requirements for any manned system that "is expected to be deployed in an asymmetric threat environment." Although the term "asymmetric threat" was not formally defined, it is a threat that permits an enemy to attack a superior force, usually by easy-to-use, inexpensive means and irregular tactics, to achieve political, economic, or military (tactical and strategic) gains. The most commonly employed threats against aircraft in recent conflicts that meet these criteria are small arms, machine guns, rocket-propelled grenades, and man-portable air defense systems.

In the Joint Requirements Oversight Council memorandum on implementation of this law, Gen. Peter Pace summarized the meanings of force protection and survivability attributes. Force protection attributes are those that contribute to the protection of personnel, while survivability attributes are those that contribute to the survivability of the manned systems. In other words, force protection is concerned about designing the aircraft to protect all of the occupants in the aircraft, not just the critical operating crew, whereas survivability is concerned about the survival of the aircraft itself. This law implies that in addition to the traditional approach used in the second edition of the Ball ACS texbook," in which the focus is on the survivability of the aircraft, we should also be concerned about the separate, but related, capability of protecting the on-board force.

2018 – The Current Role of ACS in the SE and T&E of Military Aircraft

Chapter 3 of the Defense Acquisition University's on-line *Defense Acquisition Guidebook* defines "systems engineering" as follows [18]:

> *SE solves systems acquisition problems using a multi-disciplined approach. The Systems Engineer should possess the skills, instincts and critical thinking ability to identify and focus efforts on the activities needed to enhance the overall system effectiveness, suitability,* ***survivability*** *and sustainability. [Bold added for emphasis.]*

In other words, ACS is one of the four primary capabilities of a military system, and therefore the system engineer should know understand, and apply the fundamentals of ACS.

Similarly, DoD Instruction 5000.02 states [19]:

> *The fundamental purpose of test and evaluation (T&E) is to enable the DoD to acquire systems that work. To that end, T&E provides engineers and decision-makers with knowledge to assist in managing risks, to measure technical progress, and to characterize operational effectiveness, suitability, and* ***survivability****. [Bold added for emphasis.] [Note that T&E does test and evaluate sustainability.]*

LEARNING ABOUT THE ACS DESIGN DISCIPLINE TODAY

Today, there are several opportunities available to DoD and military aviation personnel for an education in the ACS design discipline. As mentioned, NPS has been teaching ACS since 1977, and AFIT has been teaching a similar course to Air Force and Navy resident students since 2004. Additionally, off-campus educational opportunities include the annual JASP-sponsored ACS short course taught at various locations. The short course is intended for DoD and contractor personnel who work in aircraft survivability fields; however, the course also benefits personnel working the program management and acquisition of DoD aircraft. The most recent new educational opportunity in combat survivability is the AIAA STC 8-hour classified short course "Aerospace Survivability," which was offered for the first time during the AIAA Defense Forum at Johns Hopkins University in May 2018.

SUMMARY AND CONCLUSIONS

As ACS approaches a half century of development as a formal design discipline, it is clear that it has been firmly established and now holds a prominent place in the acquisition and SE processes. As with other aircraft design disciplines, ACS has a relatively standardized terminology, a methodology for quantifying the important capability metrics, a design technology for achieving the desired survivability capabilities, a set of user requirements that can/must be validated by testing, and a strong infrastructure that includes educational opportunities in the discipline. Additionally, ACS is one of the four major SE activities, consisting of overall system effectiveness, suitability, survivability, and sustainability.

As for the next half century, the ACS discipline must continue to evolve to address the ever-emerging new and different threats. In addition, to keep the discipline relevant, timely, and essential, new educational materials and instruction will need to be developed to cover topics such as advanced anti-air weapons (including improved guns and guided missiles), as well as new weapons with different damage mechanisms (such as lasers and cyber attacks) and the new topics of cyber survivability, aircraft recoverability, and force protection.

In conclusion, Figures 1 and 2 provide a visual timeline and summary of the actions taken to establish ACS as an aircraft design discipline and their adoption into some of the major U.S. air systems. ASJ

ABOUT THE AUTHORS

Dr. Robert E. Ball is an NPS Distinguished Professor Emeritus who has spent more than 33 years teaching ACS, structures, and structural dynamics at NPS. He has been the principal developer and presenter of the fundamentals of ACS over the past four decades and is the author of *The Fundamentals of Aircraft Combat Survivability Analysis and Design* (first and second editions). In addition, his more than 55 years of experience have included serving as president of two companies (Structural Analytics, Inc., and Aerospace Educational Services, Inc.) and as a consultant to Anamet Labs, the SURVICE Engineering Company, and the Institute for Defense Analyses (IDA). Dr. Ball holds a B.S., M.S., and Ph.D. in structural engineering from Northwestern University.

Dr. Mark Couch is currently the Warfare Area Lead for Live Fire Test and Evaluation in the Operational Evaluation Division at IDA. Prior to joining IDA in 2007, he enjoyed a 23-year Navy career flying the MH-53E helicopter. He has a Ph.D. in aeronautical and astronautical engineering from NPS and has taught numerous courses in aircraft combat survivability.

Mr. Christopher Adams is the Director of the Center for Survivability and Lethality at NPS, where he currently teaches combat survivability. He is also the former Associate Dean of the Graduate School of Engineering and Applied Sciences, and he has more than 20 years of operational flight experience in F-14s and EA-6Bs, serving multiple tours in Iraq and Afghanistan. Mr. Adams holds a B.S. in aerospace engineering from Boston University and an M.S. in aerospace engineering from NPS.

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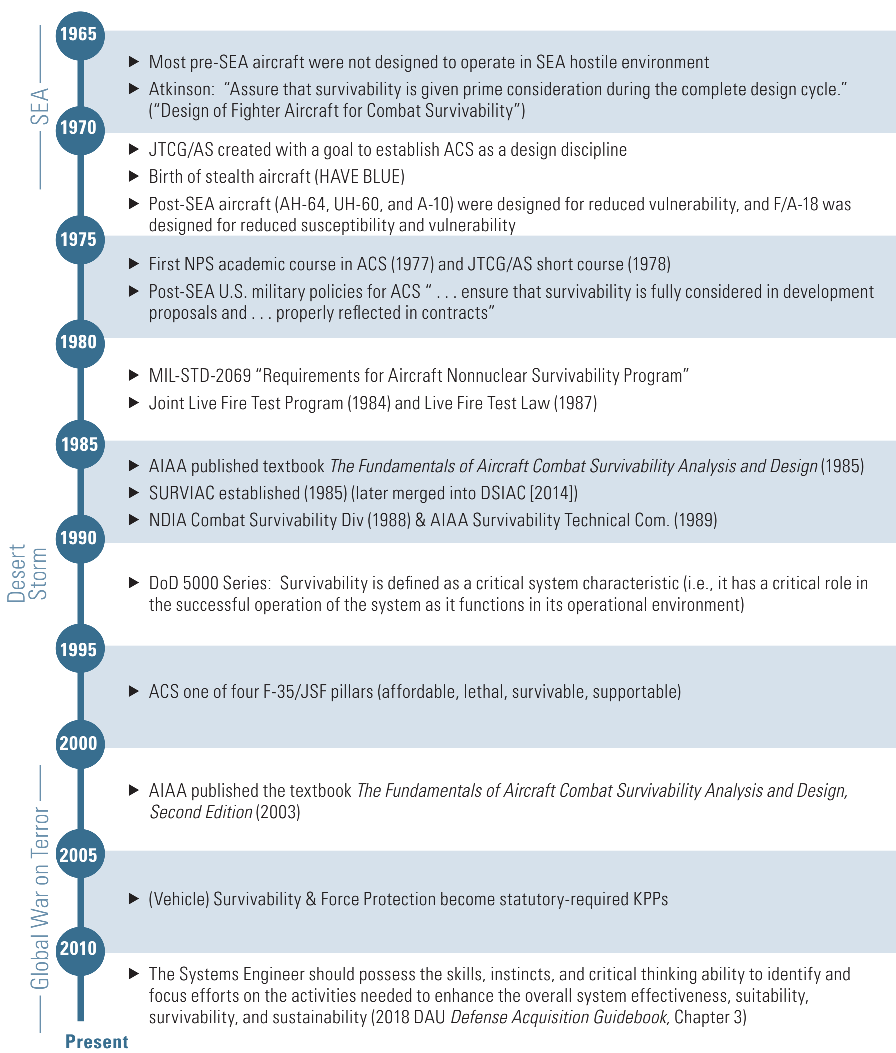

Figure 1. Major Actions Taken to Develop ACS as a Design Discipline.

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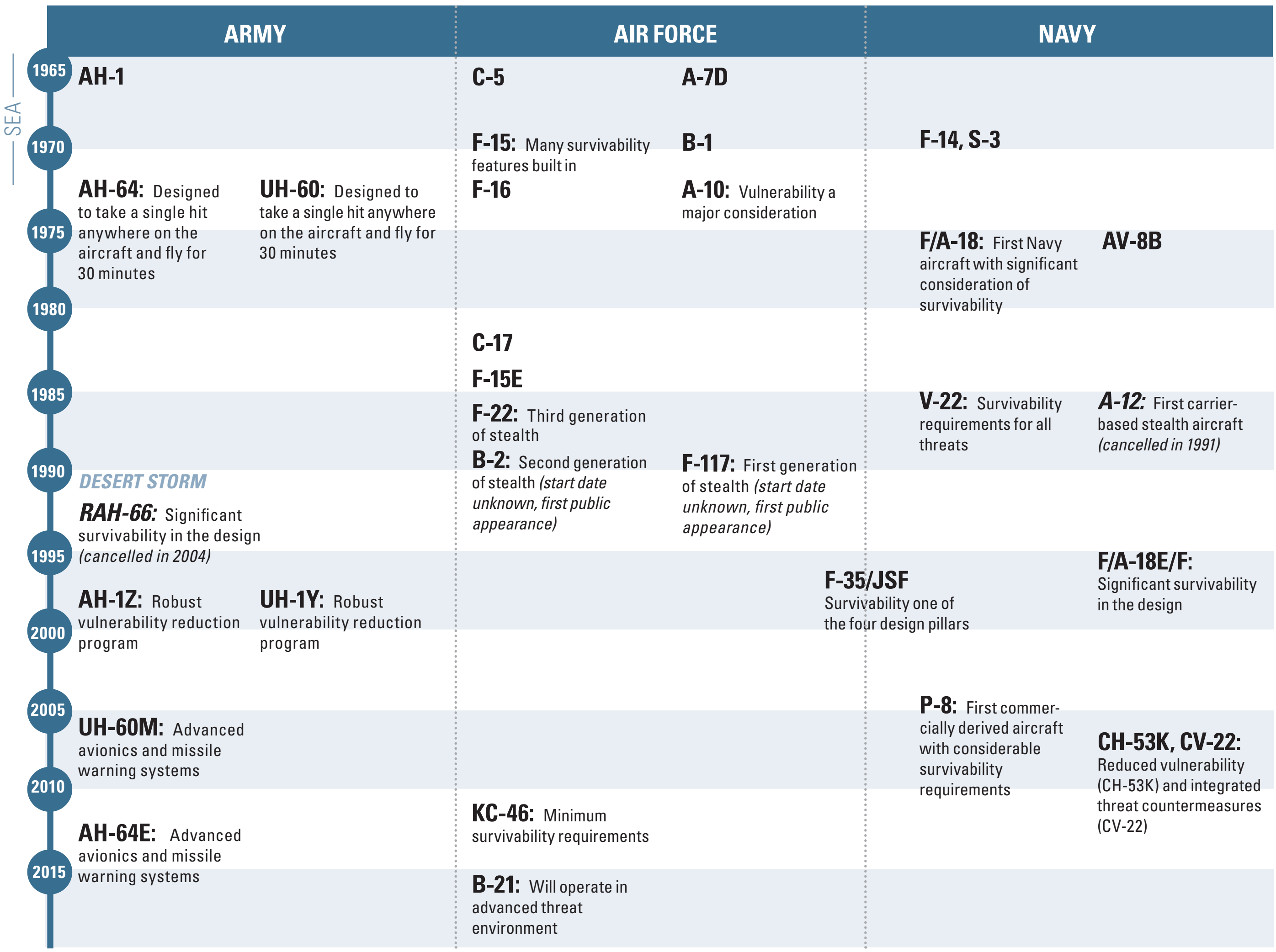

Figure 2. The Adoption of Survivability Into Modern Aircraft Development (Adapted From Figure 1.18 of Reference [1]).

NOTE: The systems listed in Figure 2 have been discussed in previous Aircraft Survivability *journal issues, as follows:*

- C-5 *(summer 2004)*
- AH-64 *(summer 2004)*
- UH-60 *(summer 2004)*
- V-22 *(summer 2000, summer 2010)*
- F-22 *(summer 1998, summer 2002, summer 2004)*
- F/A-18E/F *(summer 1998, summer 2000, summer 2004)*
- F-35/JSF *(fall 2003, fall 2007, spring 2010)*
- AH-1Z *(summer 2004, fall 2007, summer 2010)*
- UH-1Y *(summer 2004, fall 2007, summer 2010)*
- P-8 *(spring 2008)*
- UH-60M *(summer 2010)*
- CH-53K *(summer 2010, spring 2012, spring 2018)*
- AH-64D *(spring 2011)*
- KC-46 *(spring 2015)*

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http://www.ndia.org/events/2018/8/21/army-science

Hypersonics Technology & Systems Conference
27–30 August in Hawthorne, CA
https://www.usasymposium.com/Hypersonics/2018/default.php

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NOVEMBER

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