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   The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Michael Schuck for his Excellence in Survivability. Currently the Manager of the SURVICE Engineering Company’s Dayton Area Operation, Michael has provided critical computational, analytical, and test support on more than two dozen fixed-wing, rotary-wing, and unmanned aircraft programs since he joined the survivability community in 2004. In addition, he has made great strides in enhancing capabilities and methods for vulnerability testing and analysis, and he has distinguished himself as a leader and promoter of the survivability discipline through numerous survivability-focused organizations.
16 DEVELOPING THE FUNDAMENTALS OF AIRCRAFT CYBER COMBAT SURVIVABILITY: PART 1
by William O. Bryant and Robert E. Ball

Shortly after the advent of the aircraft as a successful flying machine, humans started using military aircraft in the man-made hostile environment known as “combat.” Not surprisingly, given their high visibility, effectiveness, and ultimate importance to military operations, these aircraft quickly became primary targets while operating over hostile enemy territory. In fact, over their first 50 years of combat use, aircraft were attacked by both surface-based and airborne guns and, later, during the 1964–1973 Southeast Asia (SEA) conflict, by new surface-based and airborne guided missiles, which were deployed to down or kill both fixed-wing and rotary-wing platforms. In total, since the beginning of the 20th century, several hundreds of thousands of aircraft—including almost 50,000 U.S. and British fighters and bombers lost during World War II alone—have been killed in world-wide combat by a wide range of guns and guided missiles.

24 WSL COMMEMORATES 50 YEARS OF SURVIVABILITY LFT&E
by Marty Kammer

The year 2020 marks the 50th year that the Weapons Survivability Laboratory (WSL) at the Naval Air Warfare Center Weapons Division (NAWCWD) in China Lake, CA, has been performing tests and generating data for the survivability community. The results of this half century of work have been incorporated into countless designs to make succeeding generations of air platforms tougher, safer, and more dependable. And many fixed-wing and rotary-wing aircraft flying in the skies today have directly benefited from WSL’s important efforts.

33 2019 NDIA AIRCRAFT SURVIVABILITY SYMPOSIUM AWARDS
by Robert A. Gerhard

Each year, the National Defense Industrial Association (NDIA) Combat Survivability Division (CSD) recognizes superior contributions to combat survivability by presenting awards for leadership, technical accomplishment, lifetime achievement, and excellence in a young professional. This year’s awards, which were part of the annual NDIA Aircraft Survivability Symposium on 5–7 November 2018, were once again presented at the Naval Postgraduate School’s historic Herrmann Hall in Monterey, CA.
LEG NAMED COMBAT SURVIVABILITY DIVISION DIRECTOR AND JASP NAVY PRINCIPAL MEMBER

Mr. David Legg has been named the new Combat Survivability Division Director of the Naval Air Warfare Center Aircraft Division (NAWC-AD), as well as the new Navy Principal Member of the Joint Aircraft Survivability Program (JASP). He assumes these positions from Mr. Bill Dooley, who retired last year.

With more than 36 years of both Government and industry experience in the aircraft survivability discipline, Mr. Legg previously served as NAWC-AD’s Fixed-Wing Aircraft Branch Head, as well as the Survivability Team Lead for many U.S. Navy aircraft, including the P-8A Maritime Patrol and Surveillance Aircraft. In addition, he was chosen to be a Naval Air Systems Command (NAVAIR) Associate Fellow in 2011 and was the recipient of the Gormley Combat Survivability Award for Leadership from the National Defense Industrial Association in 2015. Mr. Legg holds bachelor’s degrees in mathematics and mechanical engineering from Saint Vincent College and the University of Pittsburgh, respectively.

HARRELL NAMED JASPO MILITARY DEPUTY PM

LT Tyler “Sloth” Harrell has become the newest addition to the Joint Aircraft Survivability Program Office (JASPO) and is now serving as Military Deputy Program Manager (PM). A pilot by trade, LT Harrell graduated from Western Michigan University in 2011 with a B.S. in aviation flight science, along with his commercial multi- and single-engine pilot’s licenses. In 2013, he received his Navy commission from Officer Candidate School and then started flight training as a Student Naval Aviator in Pensacola, FL. In 2015, LT Harrell received his “Wings of Gold” from Helicopter Training Squadron 18 and was sent to San Diego, CA, to learn how to fly the Mighty MH-60S Knight Hawk with the “Merlins” of Helicopter Sea Combat Squadron 3.

LT Harrell then reported to Helicopter Sea Combat 14, where he immediately deployed aboard the USS John C. Stennis in support of the 2016 WESTPAC/RIMPAC Cruise. Over the next 3 years, he trained to become a fully qualified aircraft commander and led the squadron on its first “Around the World” deployment in 2018.

Now at JASPO, LT Harrell will be leveraging all of his operational and field experiences to support and enhance future aircraft survivability capabilities.

NICK CARAVASOS PASSES AWAY

For those in the community who may not have heard, long-time aircraft survivability expert Mr. Nicholas Caravasos passed away last year at the age of 80. A native of Zoupna, Greece, Mr. Caravasos immigrated to the United States at an early age and became the first in his family to finish college, earning a B.S. in mechanical engineering from the University of West Virginia and a master’s in management and organizational dynamics from the University of Pennsylvania.

Mr. Caravasos worked for The Boeing Company for almost 40 years and became a well-known specialist in composites and survivability. After his retirement from Boeing, he continued his work as a consultant for the Institute for Defense Analyses. He authored many technical publications and presentations and received numerous awards and honors during his career; and in 1998, he was recognized by the American Institute of Aeronautics and Astronautics as a “pioneer and [then] 30-year veteran of design and implementation of survivability improvements to fixed- and rotary-wing aircraft.”

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The Joint Combat Assessment Team (JCAT)—which consists of Army, Navy, and Air Force elements—continues to focus on the collection of aircraft combat damage data in support of operational commanders and the aircraft survivability research and development community. JCAT stands ready for worldwide deployment to investigate and report on aircraft combat damage incidents whenever and wherever they occur. The data collected from these incidents are used to assess the threat environment and support the development of susceptibility and vulnerability reduction technologies.

JCAT hosted the second annual Susceptibility Reduction Working Group (SRWG) in Huntsville, AL, from 3 to 6 September 2019. The group brought together members from organizations such as the Director of Operational Test and Evaluation; the Army Aeromedical Research Laboratory; the Joint Aircraft Survivability Program Office; the Program Executive Office — Aviation; the 160th Special Operations Aviation Regiment; the Armament Research, Development, and Engineering Center; the Naval Air Warfare Center Weapons Division’s Combat Survivability Division; the Army Aviation Survivability Branch; the Army Combat Capabilities Development Command Aviation and Missile Center; the Institute for Defense Analyses; Pratt & Whitney; and Booz Allen Hamilton. The main topic was modeling and simulation with regard to rotary-wing aircraft and radio frequency surface-to-air missiles.

In addition, JCAT trained 27 Joint personnel as part of the JCAT class of 2019. The personnel completed the JCAT training curriculum and were designated as fully qualified JCAT assessors. Four of the Air Force JCAT members will be deploying to various overseas locations this year and are dual-hatted with battle damage repair and JCAT duties.

In 2020, the Air Force JCAT will be sending six Aircraft Battle Damage Repair Engineers and two C-130 maintainers through the JCAT training program. All will be welcomed additions to the Air Force JCAT team.

Navy JCAT recently created two new assessor positions. These positions will serve as subject-matter experts (SMEs) on survivability systems/countermeasures and threat weapons, respectively. The concept provides JCAT team members with additional training in these areas of expertise to provide timely information to deployed JCAT assessors before needing to go to more specialized support. These SMEs will help other assessors collect more accurate data on survivability system effectiveness and threat weapons effects.

Navy JCAT has also returned to having a team of assessors on standby to deploy and assess a combat-related incident if called upon. Each team consists of two Navy JCAT assessors, with another two as backup, who will be ready to respond within a couple of days to wherever needed around the world to examine battle-damaged aircraft as needed.

Army JCAT would like to hail CW4 Mark Chamberlin back to the team. Mark originally joined the Aviation Survivability Development and Tactics (ASDAT) Team in 2014 as a CH-47D/F SME. In March of 2018, however, he left the team to serve a 1-year tour in Korea. Army JCAT now welcomes Mark back, as he once again brings a wealth of experience and knowledge to the team.

Additionally, Army JCAT hails Mr. Bart Schmidt and CW3 Andrew McCowen. Bart officially retired from active duty at the end of May 2019 after a 26-year career and was then hired on as the ASDAT Survivability Training Specialist. Andrew is coming to the team after completing a 1-year tour in Kuwait. He brings a wealth of experience with multiple combat tours as both an infantryman and aviator. His previous duty stations include Fort Campbell and Fort Riley. ASDAT is looking forward to integrating Andrew into the team as an UH-60A/L/M SME.

Finally, in May the entire JCAT farewelled Mr. Greg Fuchs as he retired after 25 years as an aircraft survivability SME. Greg made numerous contributions to the Army and Joint aircraft survivability communities through the analysis of enemy tactics, techniques, and procedures and threats to aviation; the assessment of aircraft survivability equipment capabilities and limitations; and the assessment of combat damage to improve the survivability of aircraft and its aircrews. He has left an indelible mark on the aircraft survivability community and will be sorely missed. JCAT wishes Greg and his wife, Kathy, the best in their next adventure.
JMUM: ACHIEVING BETTER M&S THROUGH CLOSE COLLABORATION

by James Davis and Eric Edwards

The Joint Aircraft Survivability Program Model Users Meeting (JMUM) is celebrating its 22nd year of promoting aircraft survivability collaboration and support. This year’s JMUM, hosted by the Defense Systems Information Analysis Center (DSIAC) in partnership with the Joint Aircraft Survivability Program Office (JASPO) and select model managers, was held 10–12 March 2020 at the Georgia Tech Research Institute in Atlanta, GA.
Initiated in 1998, the annual JMUM helps inform models that are supporting billion-dollar design, acquisition, and operational decisions to be improved, to be better applied and used, and to produce better data for decision-makers. In addition, the meeting provides an opportunity for model users to come together and to interact directly with model managers, developers, and other users to influence the direction of aircraft survivability modeling and simulation (M&S).

Approximately 100 industry and Government personnel from across the country participate in the JMUM each year, with attendees ranging from senior managers to new model users. The format of the JMUM is a combination of formal presentations, model overview briefings, model demonstrations, and working forums.

The first day of the JMUM includes a plenary session of threat briefings, model overviews, model success stories, and future development plans. The second day includes concurrent group breakout sessions for the air-to-air engagement, surface-to-air engagement, and vulnerability/lethality model groups (generally covering the models listed in Table 1).

TABLE 1. M&S Tools Covered at the JMUM

<table>
<thead>
<tr>
<th>Model Group</th>
<th>Model</th>
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<tbody>
<tr>
<td><strong>Air-to-Air Engagement Group</strong></td>
<td>• BRAWLER* – Air-to-Air Combat Model</td>
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<tr>
<td></td>
<td>• J-ACE – Joint Anti-Air Combat Effectiveness</td>
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<tr>
<td></td>
<td>• JAAM – Joint Anti-Air Model</td>
</tr>
<tr>
<td></td>
<td>• AFSIM – Advanced Framework for Simulation Integration and Modeling</td>
</tr>
<tr>
<td><strong>Surface-to-Air Group</strong></td>
<td>• ALARM* – Advanced Low Altitude Radar Model</td>
</tr>
<tr>
<td></td>
<td>• BLUEMAX* – Flight Path Generator</td>
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<tr>
<td></td>
<td>• DREAMa – Directed RF Energy Assessment Model</td>
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<tr>
<td></td>
<td>• ESAMS* – Enhanced Surface-to-Air Missile Simulation</td>
</tr>
<tr>
<td></td>
<td>• RADGUNS* – Radar-Directed Gun System Simulation</td>
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<td></td>
<td>• ADAM – Air Defense Artillery Model</td>
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<tr>
<td></td>
<td>• Amber – Ground-Based Radar Model Implemented in Matlab/Simulink</td>
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<tr>
<td></td>
<td>• MOSAIC – Modeling System for Advanced Investigation of Countermeasures</td>
</tr>
<tr>
<td></td>
<td>• RPEGM – Rocket-Piloted Grenade Engagement Model</td>
</tr>
<tr>
<td></td>
<td>• AFSIM – Advanced Framework for Simulation Integration and Modeling</td>
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<tr>
<td><strong>Vulnerability/ Lethality Group</strong></td>
<td>• COVART* – Computation of Vulnerable Area Tool</td>
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<td></td>
<td>• FASTGEN* – Fast Shotline Generator</td>
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<tr>
<td></td>
<td>• FATEPEN* – Fast Air-Target Encounter Penetration Endgame Framework</td>
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<tr>
<td></td>
<td>• NGFM* – Next Generation Fire Model</td>
</tr>
<tr>
<td></td>
<td>• AJEM – Advanced Joint Effectiveness Model</td>
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<tr>
<td></td>
<td>• ProjPen – Projectile Penetration Model</td>
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</table>

* Part of the JASP model suite

In these sessions, managers present details on the model support/model user support efforts undertaken in the past year, such as software change requests submitted by the user community. In addition, model developers review and discuss their recent development efforts, as well as planned efforts for the upcoming year. Model users then present example use cases, any updates that they have made to the models to fit their specific needs, and any identified deficiencies they would like to have addressed. Overflow briefings and Configuration Control Board (CCB) meetings typically close out the JMUM’s third and final day.

One key behind the JMUM’s long-standing success is that leaders recognize that model users are the backbone of survivability M&S and that their participation in working forums and CCB discussions provides invaluable information not readily available otherwise. JMUMs have also proven themselves to be a highly valuable venue to access intelligence agency SMEs and threat briefings, especially for industry partners who often find this level of access to threat information to be difficult.

While JMUMs are primarily focused on JASP-supported models, the meetings also strive to include participation from across the M&S
One key behind the JMUM’s longstanding success is that leaders recognize that model users are the backbone of survivability M&S.

community, especially in areas where JASP models are leveraged or used by other related tools or frameworks. This year’s JMUM presentations include the Joint Technical Coordinating Group for Munitions Effectiveness discussing developments in its Joint Munitions Effectiveness Manuals, the Joint Anti-Air Model (JAAM), and other tools that support the operators through test, training, and mission planning; as well as the Air Force Research Laboratory discussing the

Advanced Framework for Simulation Integration and Modeling (AFSIM), a framework that JASP is working on to integrate select models with, and expose JASP models to, a much larger M&S community across the Services.

JMUM planners are continuously seeking input from users of JASP and other survivability-related models, especially regarding topics that they would like to see presented at next year’s JMUM. To find out more information or to submit abstracts, input, and/or suggestions, please contact Mr. Alfred Yee at alfred.yee@dsiac.org.

Note

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

ABOUT THE AUTHOR

Mr. James Davis currently serves as a Deputy Program Manager and the Modeling and Simulation (M&S) lead at JASPO. He has been involved in aircraft combat survivability for more than 17 years, working areas such as live fire test and evaluation, susceptibility reduction and countermeasure effectiveness evaluation, aircraft survivability technology development and fielding, and aircraft combat effectiveness and survivability M&S. Mr. Davis holds a B.S. in mechanical engineering from the University of Dayton and an M.S. in engineering design from Wright State University.
EGRESS CASUALTY ANALYSIS

by Shakila Taylor

Figures 1. CH-53E

Historically, aircraft combat survivability design metrics and evaluations have focused heavily on the conditions of the aircraft and not on casualties caused by aircraft damage or loss while in combat. Although aircrew injuries and fatalities due to in-flight escape, crash events, and post-crash egress have been documented, crew and passenger survivability evaluations have not typically been incorporated into aircraft survivability assessments. In 2007, however, the Deputy Director of Operational Test & Evaluation/Live Fire Testing stated a need for tools that will predict the probability of casualties given various crash and landing conditions/effects and failed egress. This identified need and gap in the survivability design process thus prompted the implementation of the Crew and Passenger Survivability (CAPS) project.
CH-53 INTEGRATED CAPS ANALYSIS OVERVIEW

In 2015, the Joint Aircraft Survivability Program Office (JASPO) funded the CH-53 Integrated CAPS Analysis project (M-15-07) to establish baseline CAPS metrics and determine the impact of data uncertainties on casualty metrics, as detailed in the Integrated Crew and Passenger (CAPS) Methodology Report [1]. The CH-53E (shown in Figure 1) was selected as the target aircraft for the CAPS evaluation. The CAPS analysis involves evaluating the probability of casualties due to direct contact and indirect effects caused by various threats in flight, as well as the ability of a passenger to successfully egress a damaged aircraft once landed, before becoming a casualty. The egress casualty mechanisms are casualties that occur during the egress portion of the incident, including blocked egress and post-crash fire effects (thermal, toxicology, etc.).

EGRESS METHODOLOGY

The egress methodology was developed to generate casualty metrics due to a cabin fire in an in-flight scenario. For these purposes, a “casualty” is defined as an aircraft occupant who becomes incapacitated as a result of a threat interaction with the aircraft and/or with the occupant, whether directly or indirectly. Likewise, the term “incapacitated” is defined as an occupant being unable to successfully egress on his/her own. The following two casualty metrics were considered:

- **Probability of a casualty given a cabin fire before landing** ($P_{\text{cas}}$) - This metric considers the time period between the start of a cabin fire through the time of landing. It is the probability that an occupant will be incapacitated due to the hazards, or indirect effects, from a cabin fire before the aircraft is able to land.

- **Probability of casualty given a cabin fire prior to safe egress** ($P_{\text{cas|egress}}$) - This metric considers the time period between the start of the cabin fire through the time required to egress. It is the probability that an occupant will be incapacitated due to the hazards from a cabin fire before being able to complete egress.

The Advanced Joint Effectiveness Model (AJEM) was used in these evaluations because it is the only modeling and simulation tool currently available that can handle the complex fault trees to support this analysis. That said, AJEM does have some modeling limitations. Thus, the aircraft model was divided into four zones (shown in Figure 2), which allowed for a method to approximate the expected number of casualties due to inability to egress for each zone and for the entire aircraft.

TIME ANALYSIS FOR CABIN FIRE AND CASUALTIES

A time analysis was performed, considering the landing time, incapacitation times, and egress times associated with a cabin fire. By finding the difference between the landing and incapacitation times plus time to egress, one can determine how survivable a certain engagement can be and can identify a window of time for egress, if one exists. The following relations were used to compute $P_{\text{cas|egress}}$ for each occupant:

- If the time required to land exceeds the time it takes to incapacitate an occupant due to fire, then the occupant is a casualty due to fire or indirect effects.

![Figure 2. Aircraft Zones for CAPS Analysis.](jasp-online.org)
By finding the difference between the landing and incapacitation times plus time to egress, one can determine how survivable a certain engagement can be and can identify a window of time for egress, if one exists.

INCAPACITATION TIMES

The incapacitation times were derived from the data contained in the “Crew Compartment Fire Survivability Report,” funded by Joint Live Fire Air [2]. The report’s focus was to provide an assessment of time-to-incapacitation due to various hazards associated with onboard fuel fires. Based on the report, there were four hazards that contributed to incapacitation ($T_{inc}$):

- Time required for second-degree burns ($T_{2° Burn}$)
- Time required for inhalation of temperatures greater than 400 °C ($T_{400°C}$)
- Time required for loss of visibility due to smoke ($T_{vis}$)
- Time required for toxic gas levels ($T_{tox}$)

The actual values of $T_{inc}$ for each fire zone/occupant zone combination are the minimum values of $T_{2° Burn}$, $T_{400°C}$, $T_{vis}$, and $T_{tox}$. If $T_{inc}$ was less than $T_{land}$, then $P_{cal/ind} = 1.0$ for all occupants in that fire zone and occupant zone pair.

EGRESS TIMES

The times available to egress ($T_{egress}$) for each zone were calculated by

![Figure 3. Time to Land vs. Altitude.](image-url)
subtracting $T_{\text{land}}$ from $T_{\text{off}}$. To find $P_{\text{cas}}$, the number of occupants that would become casualties due to incapacitation after landing, egress data were extracted from a 2016 rotary-wing egress study and documented in the Integrated Crew and Passenger (ICAPS) Methodology Report [1]. This study assessed $T_{\text{egress}}$ for various equipped soldiers from a CH-47 helicopter, in realistic cabin conditions, following simulated emergency landing conditions. The data generated from the tests recorded individual egress times for each soldier.

### PROBABILITY OF CASUALTIES

By having individual egress times, it was then possible to determine the probability of casualty due to incapacitation prior to egress $P_{\text{cas}}$. Probability of casualties for each zone were determined by comparing the individual egress time to the available time-to-egress values. If an occupant in the zone had an egress time longer than the time available, they were considered a casualty. To obtain the value of $P_{\text{cas}}$ for each zone, the number of occupants considered a casualty in a zone was divided by the number of occupants in the zone.

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**ABOUT THE AUTHOR**

Ms. Shakila Taylor is a combat survivability analyst at the Naval Air Warfare Center Weapons Division in China Lake, CA. She has experience operating and maintaining threat systems and has supported various aircraft programs and studies, including CAPS, CH-53K, V-22, and (currently) CMV-22. Ms. Taylor has a B.S. in mechanical engineering from Tuskegee University.

**References**


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**CONCLUSION**

Since the initial request for casualty prediction tools in 2007, gaps in the survivability design process have continued to be addressed with new crew and passenger survivability methodologies and roadmaps. These methodologies are making it possible to determine how survivable an aircraft is for the passengers and to include passenger survivability as part of the aircraft design process. In addition, establishing ICAPS metrics for Navy aircraft is allowing future Naval aircraft programs to incorporate passenger survivability, in addition to aircraft survivability, into specification requirements, thus potentially reducing the number of casualties in future conflicts.
EXCELLENCE IN SURVIVABILITY

MICHAEL SCHUCK

by Ron Dexter

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. Michael Schuck for his Excellence in Survivability. Currently the Manager of the SURVICE Engineering Company’s Dayton Area Operation, Michael has provided critical computational, analytical, and test support on more than two dozen fixed-wing, rotary-wing, and unmanned air system programs since he joined the survivability community in 2004. In addition, he has made great strides in enhancing capabilities and methods for vulnerability testing and analysis, and he has distinguished himself as a leader and promoter of the survivability discipline through numerous survivability-focused organizations.

An Ohio native and mechanical engineering graduate of the University of Cincinnati, Michael began his survivability career as an entry-level engineer at SURVICE shortly after graduation. From his initial work conducting modeling and simulation (M&S) vulnerability assessments to his growth into a project lead, team lead, and regional operation manager, Michael has consistently demonstrated strong technical and leadership qualities, a keen understanding of the greater problems at hand, and the ability to challenge not only himself but also those around him to excel in their efforts.

Michael was indoctrinated in the world of vulnerability assessment through his early support of such projects as the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) Non-nuclear Consumables Annual Analyses (NCAA), the General Electric F136 engine vulnerability analysis, and the MH-60S Live Fire Test and Evaluation (LFT&E) program for the Naval Air Warfare Center Weapons Division (NAWCWD). While working on the NCAA task, he also quickly learned the Advanced Joint Effectiveness Model (AJEM), where he efficiently generated the detailed input data sets and developed thorough debugging approaches to identify geometry and code errors. Most importantly, these early projects made it clear that Michael had a bright future in the survivability and lethality discipline.

Michael’s first exposure to jet engine vulnerability came on the F136 program, where he became skilled at modeling highly detailed target descriptions and developing approaches for linking geometry to the Damage Modes and Effects Analysis (DMEA). As his experience grew on this program, he also developed FASTGEN target descriptions and conducted COVART analyses. And he was part of the SURVICE team that developed COVART pre-processor tools to quickly set up execution runs to evaluate a multitude of threats and conditions.

Michael continued to build on his vulnerability knowledge base through his work on numerous other projects, including the Sikorsky Heavy Lift Replacement (HLR) program (which led to the CH-53K), the Sikorsky CH148 program (a Canadian version of the H-92 platform), and the T-6 Texan for Hawker-Beechcraft program. Additionally, his first project lead opportunity came on the HLR crew protection study, where he evaluated cockpit and cabin crew protection levels for multiple armor configurations and provided recommendations to minimize
armor weight while maintaining comparable armor protection levels.

One of Michael’s most notable assets has always been his drive to develop enhanced methodologies and approaches to more efficiently answer questions at hand. For example, on the T-6 Texan program, he led the vulnerability analysis and led development of new approaches for conducting a hybrid qualitative/quantitative assessment. This approach provided an efficient method to conduct functional analyses of the aircraft to identify vulnerability strengths and areas for enhancement. It also led to the conduct of an armor integration and design optimization study that resulted in a weight- and protection-optimized solution for the platform. Michael would also later use this enhanced methodology to support A-29 Super Tucano and AW139 vulnerability assessments.

In 2012, Michael turned his focus more to test and evaluation. During the KC-46 LFT&E program, he was a member of the Test Integrated Product Team that developed several testing methodology enhancements, including the detailed characterization of dry bay fire variables in an LFT&E environment and the employment of design of experiments (DOE) for test matrix development, pre-test predictions, and post-processing test data. These new applications resulted in a more accurate, consistent, and efficient method for integrating test data into the M&S environment and supported a model-test-model approach for evaluating vulnerabilities while enhancing M&S.

In 2015, Michael was named to be the lead of SURVICE’s Emerging Technologies Team, whose primary focus is to expand the company’s capabilities into future technologies. In this role, he supported SURVICE’s expansion into new technology areas, including evaluating aircraft subsystems to high-energy laser (HEL) engagements, characterizing material damage and subsystem effects at varying irradiance levels; as well as conducting nuclear survivability programs, characterizing the platforms’ inherent hardness to nuclear threats as well as base escape capabilities to nuclear engagements.

In addition, in 2016 Michael was tasked with helping to transition the newly established Defense Systems Information Analysis Center from the legacy Information Analysis Center at Wright-Patterson Air Force Base. Part of his responsibility includes working with JASP, the Joint Combat Assessment Team, and the National Ground Intelligence Center to upgrade the database of the Combat Damage Incident Reporting System (CDIRS) to ensure it meets the security requirements for classified environment operation. This ongoing effort is critical to ensuring that the CDIRS database does not become obsolete and continues to provide survivability analysts and operators with crucial combat damage data.

Michael became Manager of SURVICE’s Dayton Area Operation in 2018. In this role, he not only is responsible for all of the day-to-day operations of a regional office, but he continues to be involved in numerous survivability programs as well, identifying and quantifying platform vulnerabilities and providing design recommendations for programs such as the Combat Rescue Helicopter (CRH), the UH-1N Replacement, and the Next Generation Fire Model (NGFM).

Not surprisingly, as a result of his efforts and contributions, Michael has been recognized in numerous letters and accolades from both Government and industry customers, including military leaders such as Gen. Arnold Bunch Jr. and Lt. Gen. John Thompson. He has also published numerous survivability reports and presented many survivability briefings at local and national events.

Finally, “going above and beyond” to promote the survivability discipline has been a hallmark of Michael’s efforts in the community. Most notably, since 2007 he has been an active member and leader of the American Institute of Aeronautics and Astronautics (AIAA) Survivability Technical Committee (SURTC). Serving as the SURTC Chair from 2018 to 2020, Michael was responsible for all committee activities, including conferences, publications, awards, membership, and educational activities in the field.

IN SEARCH OF EXCELLENCE

The Joint Aircraft Survivability Program (JASP) is always looking for deserving candidates to recognize for their Excellence in Survivability. If you know of a colleague or someone else in the community who has made, or is making, important technical or leadership contributions in the field and you would like to submit their name for consideration, please contact Mr. Dale Atkinson at daleatk@gmail.com.
outreach. He also previously served as the committee's Secretary, Vice Chair, and the Awards Committee Chair, where he coordinated the selection and presentation of the coveted AIAA Survivability Award.

Outside of work, Michael enjoys coaching youth basketball and baseball, as well as spending time with his wife, son, and daughter as they explore new places and meet new people in their recreational vehicle. The family also volunteers for the JoyRide organization, a unique car club to support kids with special needs.

Congratulations, Michael, for your Excellence in Survivability; and thank you for your past, present, and future contributions to the aircraft survivability community.

ABOUT THE AUTHOR

Mr. Ron Dexter is the Vice President of the Air Force and Navy Sectors at the SURVICE Engineering Company. He has more than 30 years of experience in aircraft and munitions survivability and lethality, including nearly a decade at Sikorsky Aircraft.

WANT MORE AIRCRAFT SURVIVABILITY?

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DEVELOPING THE FUNDAMENTALS OF AIRCRAFT CYBER COMBAT SURVIVABILITY: PART 1

by William D. Bryant and Robert E. Ball

PART 1 – WHAT IS A CYBER ANTIAIRCRAFT WEAPON, AND HOW CAN IT KILL AN AIRCRAFT?

• Learning Objective 1 – Describe the Major Elements of a Cyber Antiaircraft Weapon
• Learning Objective 2 – Describe How a Cyber Antiaircraft Weapon Can Kill an Aircraft

Photo by Airman 1st Class Alexander Guerrero, U.S. Air Force
BRIEF INTRODUCTION TO THE ACS DESIGN DISCIPLINE

Shortly after the advent of the aircraft as a successful flying machine, humans started using military aircraft in the man-made hostile environment known as “combat.” Not surprisingly, given their high visibility, effectiveness, and ultimate importance to military operations, these aircraft quickly became primary targets while operating over hostile enemy territory. In fact, over their first 50 years of combat use, aircraft were attacked by both surface-based and airborne guns and, later, during the 1964–1973 Southeast Asia (SEA) conflict, by new surface-based and airborne guided missiles, which were deployed to down or kill both fixed-wing and rotary-wing platforms. In total, since the beginning of the 20th century, several hundreds of thousands of aircraft—including almost 50,000 U.S. and British fighters and bombers lost during World War II alone—have been killed in world-wide combat by a wide range of guns and guided missiles.

(For more information on the use and losses of aircraft in 20th-century conflicts, see David Legg’s series of historical articles in Aircraft Survivability [1–3].)

These guns and guided missile antiaircraft weapons, with their warheads, are known today as kinetic energy weapons (KEWs), in recognition of their reliance on the kinetic energy associated with their warhead’s damage-causing mechanisms—or simply damage mechanisms—for their lethality. The primary KEW warhead damage mechanisms include ballistic penetrators fired from guns (armor-piercing [AP]), ballistic penetrators with incendiaries (armor-piercing incendiary [API]), and the air blast and high-velocity warhead case fragments created by the detonation of the high-explosive (HE) core.

In 1971, as a result of an unacceptable number of U.S. aircraft losses during the SEA conflict (which eventually totaled more than 4,000), the U.S. Department of Defense (DoD) established the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). One of the major goals of the JTCG/AS was the development of a new survivability design discipline for combat aircraft threatened by gun and guided missile weapons. Fifty years later, this discipline—known as Aircraft Combat Survivability (ACS)—is well-established within the DoD acquisition process; survivability requirements are routinely imposed on all new U.S. combat (and some noncombat) aircraft; and congressionally mandated, rigorous live-fire testing is conducted on full-scale systems configured for combat. As a result, these aircraft are the most survivable aircraft operating in hostile environments containing KEWs [4].

The only textbook describing “how to do” ACS, titled The Fundamentals of Aircraft Combat Survivability Analysis and Design, was first published by the American Institute of Aeronautics and Astronautics (AIAA) in 1985 [5]. The second edition of the text was published in 2003 [6]. The 900-page second edition covers all aspects of the ACS design discipline for both fixed-wing and rotary-wing aircraft threatened by KEWs. The primary goal of ACS, as stated in the first edition, is “the early identification and successful incorporation of those specific survivability enhancement features that increase the effectiveness of an aircraft as a weapon system.” These textbooks articulate the foundations of ACS and have continued to be widely used across the aircraft survivability design discipline.

THE CURRENT PROSPECT OF CYBER AS A POTENTIAL ANTIAIRCRAFT WEAPON

The vast majority of cyber attacks throughout the world have been conducted on traditional information technology (IT) systems, such as desktop computers and servers that communicate using the transmission control
The reality is that modern U.S. military aircraft today have transitioned from mostly physical systems, with little reliance on computers, to extensive “cyber physical” systems, which rely heavily on computers to control flight- and mission-critical physical functions. In many cases, the malfunctions will only prevent the aircraft from accomplishing its mission, known as a *mission kill* or *soft kill*. The physically undamaged but functionally affected aircraft can cease the prosecution of its mission and fly back to base; and any permanent malfunction effects caused by the cyber weapon can be patched or mitigated, just as the physical damage caused by a KEW’s physical damage mechanisms can be repaired. Furthermore, the vulnerability in the aircraft’s operations that allowed the malfunctions to occur can be searched for and removed.

For example, an executed cyber malfunction could degrade an aircraft’s mission computer by deleting the section of code that releases ordnance when the pilot commands. The aircraft could not accomplish its mission (e.g., bombing a target), but it could still return safely to base where the vulnerability that caused the mission kill could be eliminated.

Unfortunately, cyber weapons may also be able to achieve an *attrition kill*, *permanent kill*, or *hard kill* similar to those that can be caused by the KEW damage mechanisms, by causing malfunctions that can significantly affect the functioning of flight-critical components within systems such as flight controls or fuel systems.

For example, a single-engine aircraft in flight with a single sump tank and fuel pump can be permanently downed by a gun-fired ballistic penetrator hit on the fuel pump, which causes the pump to stop pumping, followed by a subsequent kill of the engine due to fuel starvation and the eventual crash of the aircraft from the loss of essential engine thrust within minutes after the hit. Likewise, the same sequence of events could
occur if the threat was a cyber weapon, with the malfunction mechanism being the malicious command to the fuel pump to stop pumping fuel while the aircraft is in flight.

(Not that although the cyber weapon, in general, causes component malfunctions without any physical damage to the components, there are certain component malfunctions that can be commanded that will result in physical damage to the component [e.g., Stuxnet].)

**DEVELOPING THE FUNDAMENTALS OF ACCS BASED UPON THE FUNDAMENTALS OF THE ACS DESIGN DISCIPLINE FOR KEWs**

Although the anticipated cause of an aircraft kill by a cyber weapon is not due to physical damage to the aircraft but to malfunctions within the aircraft's critical operations, many of the fundamentals of the ACS design discipline for damage-causing KEWs are applicable when considering the survivability of aircraft faced with this new, nonkinetic threat weapon. An understanding of the ACS fundamentals and how they relate to the cyber weapon's effectiveness as a weapon can thus enable aircraft survivability analysts and designers to more quickly and effectively field aircraft that are survivable when attacked by a cyber weapon.

Accordingly, this article is the first of a series of articles written for the Aircraft Survivability journal that develop the extension of the ACS guns and missile fundamentals to the new discipline we call the Aircraft Cyber Combat Survivability (ACCS) design discipline. In addition, the goal of ACCS will be the same as the goal of ACS—“the early identification and successful incorporation of those specific survivability enhancement features that will increase the combat cost effectiveness of an aircraft as a weapon system.”

It is also crucial to understand that the cyber weapons we are considering are only those that directly impact the aircraft in flight, similar to an antiaircraft KEW’s damage mechanisms hitting an aircraft in flight, regardless of when the set of malicious instructions was implanted in the aircraft’s internal cyber system. Admittedly, this limitation in scope provides a much smaller subset of a much wider world of expected cyber attacks against many types of systems [8]. However, even a small number of cyber weapon attrition or mission kills of U.S. aircraft could be extremely costly in the loss of life and aircraft over time.

**COMPARISON OF KEWs AND CYBER WEAPONS AND HOW THEY KILL AIRCRAFT**

The fundamentals associated with any antiaircraft weapon include the following three primary weapon elements:

- A **warhead** that consists of, contains, or generates the entities that can cause either physical damage to (the damage mechanisms) or malfunctions of (the malfunction mechanism) an aircraft’s critical components (those components whose kill or loss or degradation of capability results in the loss of a flight- or mission-essential function).

- An aircraft **detection and tracking subsystem** that is capable of detecting or determining the presence of a potential target aircraft and of determining the physical or cyberspace location of the aircraft that can be sent to the third element of the weapon.

- The **warhead transporter subsystem** that transports the warhead from the warhead’s current location (the shooter’s location) to the target aircraft’s location and subsequently delivers the weapon, with its damage or malfunction mechanisms, to or into the targeted aircraft. (Note that in the second edition of the AIAA ACS textbook [6], the term used to denote either a ballistic projectile or a guided missile was threat propagator.)

Our comparison of cyber weapons with KEWs thus starts with the weapons themselves, their three primary elements, and their effects on aircraft (see Table 1).
### Table 1. Comparison of KEW and Cyber Anti-aircraft Weapons

<table>
<thead>
<tr>
<th>Kinetic Energy Weapons (KEWs)</th>
<th>Cyber Weapons (CWs)</th>
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<tr>
<td><strong>The Weapon’s Warhead</strong></td>
<td></td>
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<tr>
<td>KEWs include guns, with their gun-fired ballistic projectiles, and guided missiles, with their tube or rail launchers. Every KEW has a warhead, which consists of, contains, or generates the physical entity(s) that can cause damage to an aircraft’s components when the warhead impacts, or hits, the aircraft. For smaller guns, the warhead is the ballistic projectile itself, which may consist of an AP penetrator or contain incendiary particles intended to start an internal fire (API). For both larger guns and guided missiles, the warhead contains an HE core with a surrounding metal case. The core detonates upon impact on, or in proximity to, the aircraft, generating a blast wave and high-velocity warhead case metal fragments. The penetrators, incendiary particles, blast wave, and warhead case fragments are the warhead’s damage mechanisms.</td>
<td>A CW warhead is of a set of malicious computer instructions or commands designed to gain access to the aircraft’s internal cyber system and subsequently command one or more aircraft flight- or mission-critical components to malfunction. The set of instructions is analogous to the KEW warhead, and the specific component malfunction(s) contained therein is known as the warhead’s malfunction mechanism (analogous to the KEW damage mechanisms).</td>
</tr>
<tr>
<td><strong>The Weapon’s Capability to Detect and Track the Target</strong></td>
<td></td>
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<tr>
<td>Most KEWs employ a type of aircraft detection and tracking system that uses electromagnetic radiation, such as radar, infrared, or visual, to initially detect the presence of an aircraft in a defended area, identify it as an enemy aircraft, and subsequently track its location in physical space (and its velocity vector if possible) as a function of time. This information is then sent to the third weapon element for an eventual gun firing or missile launching.</td>
<td>The second element of a CW, the aircraft detection and tracking subsystem, is referred to herein as the cyber radar element of the CW. The cyber radar gathers information from a variety of sources and uses this information to (1) detect the presence of a potential target aircraft in cyberspace, and (2) determine the cyberspace location of the aircraft at a chosen time, which can then be sent to the third element of the CW.</td>
</tr>
<tr>
<td><strong>The Weapon’s Capability to Transport and Deliver the Warhead to or Into the Target</strong></td>
<td></td>
</tr>
<tr>
<td>The KEW gun-fired ballistic projectile is both the warhead and the warhead transporter. When fired from a properly aimed gun, the projectile/warhead follows (is transported along) a ballistic path toward the aircraft, possibly hitting (delivering the warhead to) it. The KEW rocket-powered guided missile is the HE warhead transporter. It is launched from a tube or rail and flies a guided path using a type of missile guidance, such as command guidance or passive infrared homing, possibly hitting the aircraft or coming sufficiently close such that a proximity-fuzed HE warhead detonates and fragments and blast from the warhead possibly hit (are delivered to) the aircraft.</td>
<td>In the third element of the CW, the cyber warhead (the set of malicious computer instructions) is commonly packaged within another cyber component, referred to herein as the cyber missile. The cyber missile consists of a different set of computer instructions whose role is to transport the cyber warhead, either wirelessly or over a physical (hard) connection, from the shooter’s location to the target aircraft. Typically, this component will also play a role in implanting the cyber warhead into the aircraft’s internal cyber system.</td>
</tr>
</tbody>
</table>

**CONTRASTS BETWEEN KEWs AND CYBER WEAPONS**

Not surprisingly, there are also some important differences between the operations and physics of the KEWs and those of the cyber weapon that can have critical implications when using the fundamentals of ACS to develop the fundamentals of ACCS.

One important difference is that the kinetic effects of the KEWs are easily observable, follow the laws of physics, and can be repeated in a lab. Admittedly, the dynamics of ballistic projectiles and fragmenting warheads hitting an aircraft can be complicated; however, analysts today largely understand the underlying physics, which has allowed them to create accurate models and predictions. A certain type of warhead exploding at a certain distance from an aluminum plate will produce a measurable blast wave.
and various-sized fragments with predictable kinetic energy.

Cyber weapons, on the other hand, fundamentally consist of a set of malicious instructions that attackers insert into an immensely complex set of instructions in a computer that likely has millions of lines of code and numerous connections to other computing elements. The interactions and results, even inside a carefully controlled lab, are thus often much more unpredictable and unconstrained.

For example, consider how often the dreaded “BSOD” (Blue Screen of Death) appears on Windows computers that are carefully engineered, extensively tested, and not under attack. The cyber warhead triggering (detonating) within an aircraft or weapon system may do absolutely nothing because the friendly cyber system is ever so slightly different than the attacker thought. Alternatively, it might do catastrophic damage beyond what the attacker intended or even knock out an airliner hundreds of miles away that was not targeted.

Another important difference between KEWs and cyber weapons is that there are more than 100 years of kinetic air combat history that analysts can rely on to validate models and theories. While modelling ACS in future threat environments can have a large amount of uncertainty, any model that cannot provide reasonably accurate results when applied to historical campaigns is typically considered deeply suspect. For cyber attacks on aircraft, however, there is no historical campaign to compare models against because they have not happened yet. But that doesn’t mean cyber weapons can thus be ignored.

Most analysts agree that cyber weapons, on the other hand, can typically target only a particular aircraft containing a particular piece of hardware and running a particular version of software. Sometimes changes in hardware and software versions may be completely transparent to users (who are often unaware the systems are different), but these changes can radically alter whether or not cyber weapons function.

That said, if cyber weapons do function, they can have essentially unlimited range, extending to virtually any place cyberspace reaches. And while cyber weapons are extremely narrow in target focus, a cyber weapon’s effect can be extremely wide. Depending on the method of transport and delivery, it might be able to target every aircraft of a particular variant at the same time no matter where each is physically located. This gives cyber weapons essentially unlimited “magazine depth.”

Also, despite a cyber weapon’s potentially unlimited range, aircraft can still “terrain mask” and be hidden from the weapon. An aircraft that is powered down and not connected to anything may be unreachable to a cyber weapon.

The cyber warfare analyst today is in much the same position as an air warfare analyst was just before World War I.
until that aircraft “unmasks” by connecting to some communication medium accessible to an attacker. Unfortunately for defenders, typical operations require numerous communication pathways onto and off of modern combat systems, so staying masked can normally only be done for a short time.

A fourth significant difference between kinetic and cyber weapons is that while there are numerous ways for operators to know they are under attack from kinetic weapons, it is often extremely difficult for operators to know they are under attack from cyber weapons. Typical combat aircraft are heavily instrumented with defensive systems that are intended to defeat the KEWs, that detect hostile radars, that sense incoming missiles, and that dispense last-ditch countermeasures. And even during the early days of Vietnam, when aircraft did not have this equipment, the explosion of the warhead close to the aircraft generally left no doubt that the aircraft was under attack.

But current systems do not have any cyber equivalent of radar warning or missile approach sensors. Operators may even not know they are under attack after the cyber warhead “detonates.” The effects may be deliberately hidden (i.e., enemy aircraft are no longer detected, or the bomb “just misses”) or may be taken as random system failures. At the current time, essentially every cyber threat is mobile and can attack from anywhere, is stealthy because it cannot be seen, and is unknown because its signature and characteristics are unfamiliar.

A final important difference between KEWs and cyber weapons is that when the latter lose their stealth, they are typically easy to render harmless. When a combat aircrew knows that a SA-10 surface-to-air missile system is in the

At the current time, essentially every cyber threat is mobile and can attack from anywhere, is stealthy because it cannot be seen, and is unknown because its signature and characteristics are unfamiliar.

target area, they can take precautions and adjust their tactics; but the SA-10 can remain an extremely lethal and ongoing threat. However, when a cyber weapon is discovered, it is normally easy for defenders to block, find, and remove it or, alternatively, reset the system (if there is a clean backup available to reload from), thus rendering the cyber weapon ineffective [9].

For example, when eight known nation-state cyberspace attacks were examined several years ago, only Stuxnet lasted more than a few weeks (and that was only because the defender did not know it was under attack) [10]. In short, cyber weapons can be lethal and sharp, but they tend to shutter on the first swing. Thus, attackers may sometimes be hesitant to use them and risk having them unavailable for future use.

CONCLUSION OF PART 1

Cyber weapons present a real and growing threat to our current and future combat aircraft. Accordingly, the effort presented herein (as well as in following issues of Aircraft Survivability) to develop a set of fundamentals for an ACCS design discipline is increasingly vital in helping the aircraft survivability community develop the needed tools and methodologies to design and operate future generations of cyber-survivable aircraft.

Despite the differences between kinetic and cyber-based weapons, it has been shown that the previously developed ACS fundamentals provides a useful foundation and framework for engineers to understand how to design aircraft to survive in hostile threat environments, whether the weapons targeting the aircraft are kinetic, cyber, or both. In addition, the terminology defined herein shows how neatly ACCS fits within the larger ACS construct.

The taxonomy that will be presented in subsequent articles will likewise illustrate how the terms are interconnected and nested within the larger mission assurance context. With these tools, threat weapon characteristics and their effects on the survivability of an aircraft will be further explored and developed. These weapon characteristics and their effects include the warhead damage and malfunction mechanisms, target detection and location methods, and warhead transport and delivery methods, which will ultimately lead us to the survivability enhancement features, the goal of ACS and ACCS.

Part 2 of this series will discuss a cyber attack on an aircraft and the associated cyber kill chain, the definition of aircraft susceptibility and vulnerability to the cyber weapon, and the definition of ACCS. Succeeding articles will then be devoted to how to measure and test an aircraft’s cyber survivability, how to enhance an aircraft’s cyber survivability, and how to determine which survivability enhancement features and mitigation strategies should be included in an aircraft’s design and operations.
ABOUT THE AUTHORS

Dr. William D. “Data” Bryant is a cyberspace defense and risk leader with a diverse background in operations, planning, and strategy. His experiences includes more than 25 years of service in the Air Force, where he was a fighter pilot, planner, and strategist. Dr. Bryant helped create Task Force Cyber Secure and also served as the Air Force Deputy Chief Information Security Officer while developing and successfully implementing numerous proposals and policies to improve the cyber defense of weapon systems. He holds multiple degrees in aeronautical engineering, space systems, military strategy, and organizational management. He has also authored numerous works on various aspects of defending cyber physical systems and cyberspace superiority, including *International Conflict and Cyberspace Superiority: Theory and Practice* [10].

Dr. Robert E. Ball is a Distinguished Professor Emeritus at the Naval Postgraduate School (NPS), where he has spent more than 33 years teaching ACS, structures, and structural dynamics. He has been the principal developer and presenter of the fundamentals of ACS over the past four decades and is the author of *The Fundamentals of Aircraft Combat Survivability Analysis and Design* (first and second editions) [5, 6]. In addition, his more than 57 years of experience have included serving as president of two companies (Structural Analytics, Inc., and Aerospace Educational Services, Inc.) and as a consultant to Anamet Labs, the SURVICE Engineering Company, and the Institute for Defense Analyses (IDA). Dr. Ball holds a B.S., M.S., and Ph.D. in structural engineering from Northwestern University.

### References


WSL COMMENORATES 50 YEARS OF SURVIVABILITY LFT&E
The year 2020 marks the 50th year that the Weapons Survivability Laboratory (WSL) at the Naval Air Warfare Center Weapons Division (NAWCWD) in China Lake, CA, has been performing tests and generating data for the survivability community. The results of this half century of work have been incorporated into countless designs to make succeeding generations of aircraft tougher, safer, and more dependable. And many fixed-wing and rotary-wing aircraft flying in the skies today have directly benefited from WSL’s important efforts.

THE HISTORY OF WSL

In 1969, the Naval Air Systems Command (NAVAIR) initiated the Aircraft Survivability Program (ASP) to address survivability issues that had continued to plague combat aircraft from their first use in World War I and II and throughout the Korean and Vietnam conflicts. The primary motivation at the time was to address the unexpectedly high rate of U.S. aircraft losses (more than 5,000) to small arms threats in Southeast Asia, as well as the high number of incidents (more than 30,000) resulting in combat damage. The program’s focus was to conduct research, studies, full-scale experiments, and analysis on aircraft fuel systems, subsystems, and components to determine vulnerability of aircraft and provide solutions for survivability issues.

That same year, NAVAIR selected the Naval Weapons Center (NWC) in China Lake as the lead laboratory to conduct research and development work aimed at understanding vulnerability and survivability of Navy combat aircraft (e.g., the A-4 Skyhawk, F-4 Phantom, F-14 Tomcat, and A-7 Corsair).

In 1970, NWC established the Aircraft Vulnerability/Survivability Gun Range (shown in Figure 1) to address Navy aircraft survivability initiatives. Likewise, the Navy’s first vulnerability live fire test site was completed and testing marked the beginning of the Navy’s history of evaluating the lethality of foreign threats against U.S. aircraft.

The A-4 Skyhawk testing marked the beginning of the Navy’s history of evaluating the lethality of foreign threats against U.S. aircraft.

went into operation in 1970, first testing the Navy’s A-4 Skyhawk. This testing marked the beginning of the Navy’s history of evaluating the lethality of foreign threats against U.S. aircraft and identifying potential vulnerabilities associated from hits to the aircraft’s fuel system (tanks) and surrounding structure (shown in Figure 2).

Now with a facility dedicated to evaluating aircraft systems, it didn’t take long for NWC engineers involved in A-4 testing to determine that there were limitations with testing capabilities, primarily due to a lack of airflow.

Figure 1. JTCG/AS Members Visiting NWC Aircraft Survivability Range (1970) (Left to Right: Jerry Reed, Chuck Waiden, Dale Atkinson, Tom McCants, Henry Morrow, Jim Biocac, Millard Mitchell, Walt Thompson, Arthur Churchill, and George Lins lead).
The need for a more realistic test environment thus led to the development of the facility’s first High Velocity Airflow System (HIVAS) in 1975 (see Figure 3). HIVAS provided, and continues to provide, the realism needed for aircraft vulnerability live fire testing by simulating in-flight airflow conditions over aircraft surfaces or engine inlets during testing.

In 1976, under the newly created Survivability and Lethality Division, the Aircraft Survivability Range became its own branch, along with the Analysis Branches, Vulnerability, Susceptibility, and Lethality. Now combining live fire testing and analysis within NWC established a model-test-model approach to identify and test vulnerabilities and make recommendations to improve the survivability of U.S. aircraft and weapon systems. The Aircraft Survivability Range would go on to change its name in 1980 to that of the Weapons Survivability Laboratory to reflect the change that was taking place within the facility in providing a laboratory environment rather than a modest range operation.

THE MANDATE FOR REALISTIC TESTING

Survivability is now an essential and formal part of the U.S. Department of Defense (DoD) acquisition process. In 1991, the DoD 5000 series of directives and instructions for the acquisition of weapons systems defined survivability as a critical system characteristic—that is, a characteristic of the system that has a critical role in the effectiveness of the systems. Accordingly, the Live Fire Law passed in 1987 (Title 10, U.S. Code Section 2366) requires that the Secretary of Defense conduct realistic survivability, lethality, and initial operational testing and evaluation on covered weapons systems before they proceed beyond low-rate initial production. Realistic survivability testing—that is, full-up system-level testing—means testing for the vulnerability of the system in combat by firing at the system those munitions likely to be encountered in combat.

WSL FACILITIES AND CAPABILITIES

The WSL mission has remained consistent through the decades, ensuring the DoD is provided mission-effective survivable air platforms both now and in the future. WSL is the Navy’s field activity for weapons systems nonnuclear survivability, weapons lethality, and Live Fire Test and Evaluation (LFT&E), supporting all of the major Services. WSL excels at live-fire testing of military aircraft against a broad spectrum of threats, including munitions from small arms to antiaircraft artillery (AAA) rounds, rocket-propelled grenades (RPGs), warheads, fragments, and newer emerging threats.
HIVAS continues to provide the realism needed for aircraft vulnerability live fire testing by simulating in-flight airflow conditions over aircraft surfaces or engine inlets during testing.

As shown in Figure 4, WSL is located within the boundary of NAWCWD China Lake, in a remote and secure 11-square-mile area. The laboratory is divided into two major physical areas: the test sites and the preparation and administration area. Testing is performed at five primary sites (shown in Figure 5) that can accommodate military aircraft ranging in size from small, unmanned air vehicles to jumbo-sized transports.

Test Sites 1–4 each contain a test area or pad, control room building, data acquisition, fire-fighting capabilities (aqueous film-forming foam [AFFF] and CO₂), and fluid waste collection capabilities to support testing operations. Sites 2 and 4 became operational in 1970, and Sites 3 and 1 added in 2003 and 2010, respectively. All of the sites have similar facilities and capabilities but vary in pad size, airflow, and explosive-limit capabilities. Sites 2 and 3 each include dedicated airflow systems (HIVAS and Super HIVAS), while Sites 1 and 3 include an under-the-pad tunnel for firing threats at test articles from below.

Test Site 5 became operational in 2010 to support the development, test, and evaluation of the Hostile Fire Indicator (HFI) system on board helicopters. Evaluating HFI systems within an operating helicopter presents a significant challenge due to obvious safety concerns of firing threat projectiles near a manned helicopter. With that in mind, the HFI facility (Site 5) was developed to enable testing of HFI systems while installed within a remotely operated helicopter. This site provides for firings of threat weapons from 5.45-mm small arms to 40-mm anti-aircraft gun systems, including ball, armor-piercing (AP), armor-piercing incendiary (API), and high-explosive incendiary (HEI) projectiles. In addition, RPGs and other unguided rockets with inert warheads are currently approved for test firings. And more recently, the

![Figure 4. WSL Range/Test Sites.](image-url)
Figure 5. WSL Test Sites 1–5.

Site 1’s terrain and capabilities have shown the site to be well-suited for testing smaller, unmanned air vehicle threats.

Because of the cost and safety hazards associated with actual in-flight survivability testing, in-flight airflow conditions are simulated using WSL’s four-engine HIVAS (Site 2), nine-engine Super HIVAS (Site 3), and single-engine Portable HIVAS (shown in Figure 6). Both HIVAS and Super HIVAS systems redirect and combine bypass airflow from multiple turbofan.
The WSL mission has remained consistent through the decades, ensuring the DoD is provided mission-effective survivable air platforms both now and in the future.

engine to produce up to 600 knots of airflow. In addition, these HIVAS systems provide the capability to support additional types of testing and analyses, such as aerodynamic studies, ordnance testing of flares and rocket motors, stores ejection and separations, aircraft canopy and seat ejections, windblast, and parachute deployment testing. These capabilities, on a fixed, ground-based test complex with full instrumentation, ultimately reduce research, development, test, and evaluation (RDT&E) costs and allow testing that otherwise would be difficult, if not impossible, to perform.

Survivability tests at WSL range from full-scale U.S. and foreign aircraft and subsystems to smaller-scale developmental hardware, simulators, replicas, components, and materials. U.S. aircraft evaluated at the facility since 1970 include the A-4 Skyhawk, A-6 Intruder, A-7 Corsair, AV-8 Harrier, F-86 Sabre, F-89 Scorpion, F-4 Phantom II, F-111 Aardvark, F-14 Tomcat, F-16 Fighting Falcon, F-15 Eagle, F/A-18 Hornet and Super Hornet, F-35 Lightning II, P-3 Orion, P-7, P-8 Poseidon, C-130 Hercules, C-27 Spartan, KC-46 Pegasus, V-22 Osprey, H-53 Stallion and King Stallion, H-46 Sea Knight, AH-1 Cobra, UH-1 Huey, H-60 Blackhawk and Seahawk, and
Survivability tests at WSL range from full-scale U.S. and foreign aircraft and subsystems to smaller-scale developmental hardware, simulators, replicas, components, and materials.

MQ-9 Reaper.

In addition, the kinds of testing performed at WSL includes:

- Full-scale operational aircraft/rotorcraft
- Structural response to ballistic impacts (projectile and warhead fragments)
- Hydrodynamic (hydraulic) ram pressure effects
- Aircraft fire-detection and fire extinguishing systems
- Fuel-ingestion investigations of engines under full-up operating conditions
- Warhead detonations/fragments against airframes or running engines
- Thermal and structural tests of advanced composite materials/airframes
- Infrared signature tests (using a 360° rotatable mount)
- Critical systems armor
- Propulsion systems
- Simulated in-flight and carrier-deck pool fires
- Static and simulated in-flight canopy and crew ejections
- Communication link payout studies
- Aerodynamic studies (40–600 knots), including flutter, fuzing, aircraft stores separation, parachute systems.

Likewise, WSL’s efforts have contributed to the development, testing, and implementation of numerous vulnerability reduction technologies onboard U.S. military aircraft, including:

- Fire Suppression Technologies (including active fast-acting extinguishing systems [fixed-wing/rotary-wing] and passive fire suppression systems [rotary-wing])
- Critical systems armor protection (rotary-wing)
- Fuel tank ullage inerting technologies (fixed-wing)
- Flammable fluid leak detection and shut off (fixed-wing)
- Self-sealing and self-healing leak mitigation technologies (rotary-wing).

**UNIQUE TESTING EXAMPLES**

Over the years, as threats and the enemy’s use of them have evolved, WSL has adapted and expanded its capabilities, approach, and methods. The following are a few examples of particularly unique WSL test and threat capabilities.

**Remoted Hover Operation/Dynamic Rotor Blade Targeting**

In 1996, engineers developed and demonstrated the capability to fire live munitions at a AH-1 Cobra helicopter’s rotor system while operating in a hover in-ground effect condition (see Figure 7). The effort added the ability to evaluate the helicopter’s component and system responses to a hit while in-flight (hover). This remote control capability allowed the helicopter to be flown in self-powered hover, while steadying its position in space to ensure accurate aiming of the gun system onto rotor component (e.g., blades, pitch links, pitch beam, swashplate).

**METS MANPADS Testing**

Prior to 2008, live fire testing of aircraft against a man-portable air defense system (MANPADS) threat required setting up a one-time-use test at a remote area of NAWCWD land ranges (see Figure 8). The testing included positioning the aircraft on top of an elevated tower and mounting infrared (IR) heating elements at the desired hit point for acquiring MANPADS missile lock and track. The MANPADS missile was typically launched 1.5 miles away, with the missile then tracking toward the IR signal source (hit point) located down range. Firing a MANPADS missile at a nonmoving target near the ground was risky, challenging, and often resulted in the missile missing its intended target. In addition, the remote setup required relocation of WSL equipment and capabilities, which added complexity and cost to the overall...
operation, as well as created many test limitations that ultimately resulted in reduced instrumentation, aircraft monitoring, data collection, and choice for the engagement scenario tested. Finally, firing the MANPADS using the standard method for delivery to the target created a fixed condition for velocity (intercept) and was not suitable for replicating other aircraft-to-MANPADS threat engagements.

Accordingly, from 1994 through 2008, in an attempt to address the aforementioned deficiencies, WSL engineers established the capability to fire MANPADS threats at aircraft with pinpoint accuracy, required approach angles, and intercepting speed. WSL first developed a Missile Engagement Threat Simulator (METS) composed of a high-pressure gas gun to propel items such as missiles, liquids, and other objects, including engine fragments (see Figure 9). In addition, a MANPADS firing capability from the METS gun was added, allowing for close proximity firing of the MANPADS threat at an aircraft that is operational, controlled, monitored, fully instrumented, and under HIAS airflow.

**RPG Launching**

Until recently, the LFT&E of an RPG required moving the aircraft in closer, which created issues in replicating some threat-encounter conditions, as well as possible effects on aircraft vulnerability results. To address this limitation, WSL engineers in 2016 developed the capability to deliver an RPG (with a live warhead) on target with pinpoint accuracy and up to its maximum fly-out speed within 10 m of launch (see Figure 10). The new RPG launcher provides live fire testers with the capability to replicate all threat conditions.
encounter and engagement conditions needed to support the DoD and the survivability community.

CONCLUSION

Since its establishment a half century ago, WSL has experienced ongoing and significant change and expansion. As new threats and needs have continued to emerge and develop, the laboratory has likewise continued to adapt and innovate to provide the DoD with the most modern and capable LFT&E facilities. And WSL leaders are committed to building on this 50-year legacy to help ensure the survivability and effectiveness of U.S. air and weapons systems for many more years to come.

ABOUT THE AUTHOR

Mr. Marty Krammer is an aircraft vulnerability engineer at the Naval Air Warfare Center Weapons Division in China Lake, where he currently leads LFT&E activities for multiple Navy aircraft programs. With more than 29 years of experience, he has supported numerous aircraft vulnerability reduction and testing programs, including AV-8B, F-15, F-14, F/A-18, JSF, AH-1, UH-1, H-60, V-22, and CH-53; and he has provided many recommendations to reduce the vulnerability of these aircraft. In particular, Mr. Krammer specializes in aircraft fire, fuel tank self-sealing, and explosion protection. He also serves as the Navy co-chairman of the Joint Aircraft Survivability Program Office'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.

2020 AIRCRAFT COMBAT SURVIVABILITY SHORT COURSE

7-9 April 2020 | San Diego, CA

SAVE THE DATE

This 3-day short course in aircraft combat survivability is designed to provide an overview of the aircraft combat survivability discipline. The course is intended for Department of Defense (DoD), active duty military, and government contractors who need to better understand how to increase the survivability and combat effectiveness of air platforms, both manned and unmanned systems.

For more, please visit: https://www.dsiac.org/events/2020-aircraft-combat-survivability-short-course
2019 NDIA AIRCRAFT SURVIVABILITY SYMPOSIUM AWARDS

by Robert A. Gierard

Each year, the National Defense Industrial Association (NDIA) Combat Survivability Division (CSD) recognizes superior contributions to combat survivability by presenting awards for leadership, technical accomplishment, lifetime achievement, and excellence in a young professional. This year’s awards, which were part of the annual NDIA Aircraft Survivability Symposium on 5–7 November 2019, were once again presented at the Naval Postgraduate School’s historic Herrmann Hall in Monterey, CA.

PROFESSOR ROBERT E. BALL
YOUNG PROFESSIONAL AWARD FOR COMBAT SURVIVABILITY

The Young Professional Award is presented to an early- to mid-career person (35 years of age or younger at the time of award) who has made a significant technical, analytical, or tactical contribution to any aspect of aircraft survivability.

This year’s award was presented to Ms. Laura M. Ross, a young engineer and system analyst at MIT Lincoln Laboratory, who has made significant contributions to the Air Force Red Team’s Air Vehicle Survivability program. Ms. Ross applied her data analysis and signal processing skills to bring numerous field and flight test lessons learned to Red Team aircraft survivability and operational effectiveness analyses. Her early work involved designing and implementing key signal processing algorithms for the Red Team’s “White Box” digital radio frequency memory (DRFM) jamming system. Ms. Ross became a national expert on DRFM jamming, with a focus on evaluating...
the effectiveness of U.S. fire control radar and missile seeker electronic protection via flight testing. She also applied her skill sets to the testing and design of B-2 global positioning system (GPS) antijam antennas; as well to the design and integration of real-time beam-forming, adaptive nulling and dual polarization multichannel array processing for a prototype low-VHF threat surrogate radar system; and, most recently, to serving as team leader for the integration, verification, and aircraft susceptibility testing of a new passive radio frequency (RF) surveillance system.

COMBAT SURVIVABILITY AWARD FOR TECHNICAL ACHIEVEMENT

The Technical Achievement Award is presented to a person who has made a significant technical contribution to any aspect of survivability. It may be presented for a specific achievement or for exceptional technical excellence over an extended period. Individuals at any level of experience are eligible for this award.

Mr. James E. Rhoads, currently a research staff member of the Institute for Defense Analyses (IDA), was honored for his more than 25 years of contributions to the aircraft survivability discipline. Mr. Rhoads is well known and respected as one of the pre-eminent vulnerability analysts of his generation. Recognized early in his career at the SURVICE Engineering Company as an expert vulnerability analyst performing fixed- and rotary-wing assessments, he also had a long and successful history at Lockheed Martin Aeronautics, leading numerous vulnerability analyses and the streamlined Live Fire Testing & Evaluation (LFT&E) for the F-35 program. He then joined IDA in 2010, supporting the LFT&E of several rotary- and fixed-wing aircraft programs for the Office of the Secretary of Defense Director of Operational Test & Evaluation. His most recent work has been the groundbreaking analysis of aircraft combat data from the wars in Afghanistan, Iraq, and Syria. His analyses have been widely briefed to Department of Defense, Service, and field leadership and flight crews, effectively impacting operational tactics while also definitively illustrating the value of early vulnerability design work.

RADM ROBERT H. GORMLEY COMBAT SURVIVABILITY AWARD FOR LEADERSHIP

The Leadership Award is presented to a person who has made major leadership contributions to combat survivability. The individual selected must have demonstrated outstanding leadership in enhancing overall combat survivability or played a significant role in a major aspect of survivability design, program management, research and development, test and evaluation, modeling and simulation, education, or the development of standards. The emphasis of this award is on demonstrated superior leadership over an extended period of time.

Mr. Gary C. Wollenweber, the Consulting Engineer for Infrared (IR) and Thermal Design at General Electric (GE) Aviation, was recognized this year for his more than 42 years of sustained leadership in aircraft engine thermal design, specializing in exhaust nozzle cooling and IR signature control technologies. Mr. Wollenweber established the GE design practice for IR survivability analysis, design, and measurement, while serving as a major contributor or key designer for numerous fixed-wing, rotary-wing, and commercial-derivative aircraft exhaust systems. These systems include the B-2, A-12, ATF, F-16, F-18, E-3, C-5, A330 and B-767 tanker, H-60, H-1 and H-46, and CSAR-X. In addition, he has numerous patents related to gas turbine engines and is recognized within GE, industry, and academia as a leading expert in propulsion IR signature technology. He has also focused on the development of next-generation IR design professionals, serving as a mentor to numerous GE engineers, as an adviser to many Air Force graduate students, and as an author/instructor of multiple survivability/IR short courses. Finally, Gary has been an active and valued member of the Combat Survivability Division Executive Board for more than 19 years.

COMBAT SURVIVABILITY AWARD FOR LIFETIME ACHIEVEMENT

The Lifetime Achievement award is presented to a person who has made significant technical and leadership contributions throughout his/her professional career, spanning many or most of the numerous facets of aircraft combat survivability. This award is nominated by the CSD Executive Board and is intended to recognize an individual’s lifetime of accomplishments and dedication to the aircraft survivability community and to the aircrews we serve.

Mr. Neal W. Brune, Vice President for Countermeasures Business
Development at Amtec Countermeasures Company, was recognized this year for his more than 50 years of leadership and prolific development within the national technology industrial base as a technical champion for the development of expendable countermeasures and aircraft survivability equipment. He has led the research and development, conceptual design, flight test, engineering and manufacturing development, and production of numerous chaff and flare systems, including everything from Vietnam-era chaff-dispensing pods and chaff roll sets tuned for the Hanoi air defenses; to generations of conventional chaff and flare cartridges; to advanced aerodynamic, kinematic, and pyrophoric IR expendables; to aerosol and ultrafine chaff technologies; to active RF expendable concepts. In addition, Mr. Brune has selflessly volunteered in many community roles, such as serving on the NATO Industrial Advisory Committee on Countermeasures Interoperability, as a Chairman of the Military Sensor Symposium on IR Countermeasures, and as a co-author on countless papers and several books on aircraft survivability, including chapter 4 of The Infrared & Electro-Optical Systems Handbook (volume 7) and the EW Handbook. His most significant contributions, however, have resulted in the many flare and chaff cartridges that continue to protect U.S. and allied pilots and aircrews.

BEST POSTER PAPER AWARD

This year’s NDIA Survivability Symposium Best Poster Paper Award was presented to an Air Force Research Laboratory/Materials Directorate (AFRL/RX) and industry team who developed a novel, nondestructive, noncontact capability to measure coating thicknesses without requiring a coupling agent. The system displayed at the symposium applies THz wavelengths, achieving submillimeter-level thickness accuracies. The development team includes Dr. Bryan Foos, Mr. Juan Calzada, and Capt. James O’Keefe from the AFRL Material State Awareness Branch (AFRL/RXCA); Mr. Tyler Zicht of the SURVICE Engineering Company’s Dayton Operation; and Dr. David Zimdars of TeraMetrix.

Congratulations to all of the 2019 Combat Survivability awardees for their many accomplishments and contributions.

LOOKING AHEAD TO 2020

As always, it’s not too early to consider who among our ranks is deserving of recognition next November at the 2020 NDIA Aircraft Survivability Symposium in Monterey. Is there someone in your own staff/organization who has demonstrated technical or leadership achievement in the survivability community? Also, is there someone among your early-to-mid career staff who has demonstrated a flair for the survivability discipline and is deserving of early recognition?

The CSD will publish award nomination deadlines and submission procedures later in 2020, but there is no need to wait. Those interested in making a nomination, gaining more information, or discussing the nomination process should contact Mr. Robert Gierard at robert.gierard@raytheon.com or 310-200-1060 or Ms. Jessica Lewton at jlewton@NDIA.org or 703-247-2588.

ABOUT THE AUTHOR

Mr. Robert Gierard is Chairman of the NDIA CSD Awards Committee.
MARCH

IEEE Aerospace Conference
7–14 March in Big Sky, MN
https://aeroconf.org/

Directed Energy Science and Technology Symposium
9–13 March in West Point, NY

23rd AIAA International Space Planes and Hypersonic Systems and Technologies Conference
10–12 March in Montreal, Canada
https://casica.event 352392

JMUM
10–12 March in Atlanta, GA
https://www.dsiac.org/events/2020-jasp-model-users-meeting

WSL 50 Year Open House
13 March in China Lake, CA

Hypersonic Weapons Summit
31 March to 2 April in Arlington, VA
https://www.xgta.org/events-hypersonic-weapons-spring?utm_medium=portal&mac=TOPCCORP

APRIL

Marine South
2–3 April in Camp Lejeune, NC
https://www.marinemilitaryexpo.com/marine-south/home/

Aircraft Combat Survivability Short Course
7–9 April in San Diego, CA
https://www.dsiac.org/events/2020-aircraft-combat-survivability-short-course

Precision Strike Annual Review
14–15 April in Arlington, VA
https://www.precisionstrike.org/events-listing/2020/4/14/psar2019

21st Annual Science and Engineering Technology Conference
15–17 April in Miami, FL

Army Aviation Mission Solutions Summit
22–24 April in Nashville, TN
https://a2zinc.net/clients/AAAA/AAAA20/Public/Enter.aspx

IEEE International Radar Conference
27 April to 1 May in Washington, DC
https://radar2020.org/

JCAT TWE
28–30 April in Hurlburt Field, FL
https://www.dsiac.org/events/twe

MAY

SAMPE 2020 Conference and Exhibition
4–7 May in Seattle, WA
https://www.nasampe.org/events/EventDetails.aspx?id=1204840&group=

63rd Annual Fuze Conference
11–13 May in Kansas City, MO
https://www.ndia.org/events/2020/5/11/fuze-2020

JASP Proposal Review
12–14 May in Albuquerque, NM

2020 JANNAF Meeting
18–22 May in Pittsburgh, PA

Vertical Flight Society's 76th Annual Forum and Technology Display
19–21 May in Montreal, Canada
http://vtol.org/forum

JUNE

35th Annual National T&E Conference
1–5 June in Aberdeen Proving Ground, MD
https://www.ndia.org/events/2020/6/1/35th-annual-national-test-and-evaluation-conference

2020 AVIATION Forum
15–19 June in Reno, NV
https://www.aiaa.org/aviation

Note

The inclusion of an event in this calendar does not necessarily reflect the endorsement of that event or its sponsoring organization(s) by the Joint Aircraft Survivability Program Office or the Defense Systems Information Analysis Center.