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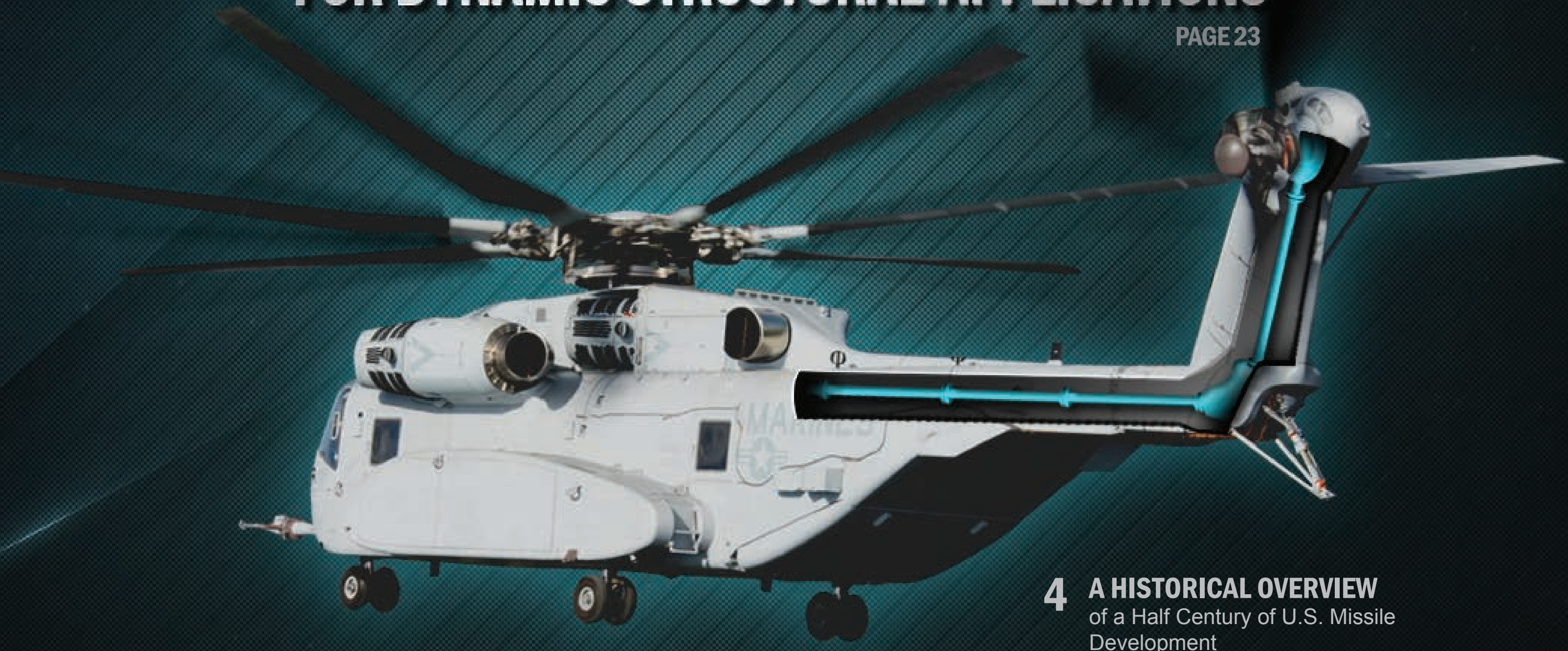
ADVANCED COMPOSITE SOLUTIONS

FOR DYNAMIC STRUCTURAL APPLICATIONS

PAGE 23



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On the Cover:
First CH-53K test aircraft achieves
120 knots in West Palm Beach, FL
Sikorsky Photo

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MESSAGE FROM THE EDITOR

ERIC FIORE

Systems engineers earn their keep by translating performance requirements of tactical systems into affordable and optimal design solutions, solutions that often must meet particularly challenging operational requirements. The risk of inserting new technology into a system is often traded against cost until a substantial improvement to operation capability that outweighs the associated risks is achieved.

In our feature article this quarter, Rick Luzetsky discusses one such scenario with the selection and application of advanced composite material technology (based on fiber-reinforced thermoplastic materials) that not only improves helicopter system performance but also significantly improves the aircraft's survivability. Mr. Luzetsky discusses how a U.S. Naval Air Systems Command Small Business Innovation Research program was leveraged to provide a lighter weight, more durable, and highly reliable composite drop-in replacement helicopter drive shaft design solution. The developmental risk reduction measures employed as part of the verification and validation process for this effort are a textbook example of the correct way to insert new technology into a fielded system.

Such new technology is not only helping to improve systems performance and operational capability; it is also helping to improve the operational availability of tactical systems. Additive manufacturing, more commonly referred to as 3-D printing, has received a lot of attention recently and is showing promise as a tool that can be used to economically create one-of-a-kind or limited availability parts. The technology has advanced to the point that it is no longer limited to plastic parts. Ceramic and metal parts are now being 3-D printed using a variety of different techniques. But just how good are these parts? In our article on the nondestructive inspection of additive-manufactured parts, Michael Mazurek and Russell Austin discuss techniques for inspecting such parts to answer that question.

Ensuring our high-performance tactical systems remain operational is no easy task, especially when these systems are involved in a fight. In our article on self-sealing fuel tank technology, Kyle Bates discusses an interesting technology that does just that. Self-sealing technology has been around for many years. In fact, you may have experienced similar technology first-hand if you have ever discovered a nail in your tire. However, the concept of self-sealing technology in fuel tanks has evolved considerably over the last five decades. Mr. Bates details the latest evolution of a newly developed technology that is ensuring our tactical systems remain as survivable as possible.

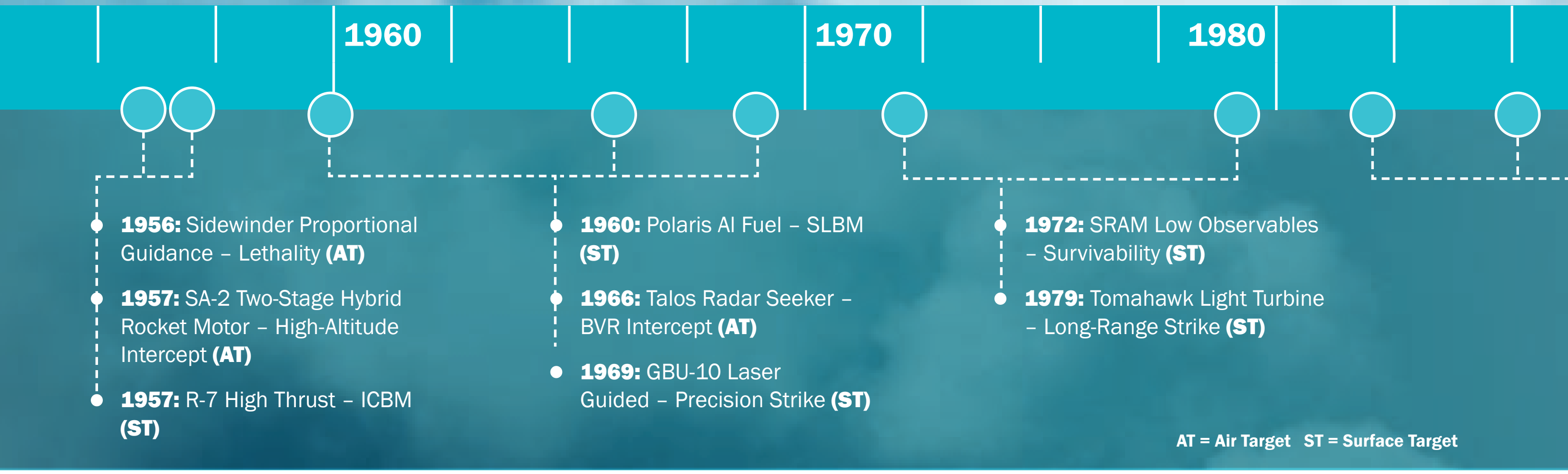
And you don't have to be a rocket scientist to appreciate Eugene Fleeman's and Ralph Teague's nostalgic review of the evolution of missile technology. There is no clearer example of how technology has changed warfare. Missiles today can now fly further and faster and strike with greater precision than was ever imagined a few decades ago. While the U.S. currently maintains an advantage with tactical performance that is periodically advanced with block upgrades, new hypersonic technology is looking to once again disrupt the status quo and transform warfare.

Finally, Bruce Simon provides a review of the 17th Annual National Defense Industrial Association (NDIA) Science & Engineering Technology Conference that was held in Tampa, FL, this past April. During the conference, Government leaders shared their visions for maintaining technological superiority during this period of financial austerity. The call for action has been sounded, and the need for industrial defense innovation has never been greater. And, as always, DSIAC stands ready to support your research and development analysis needs. ■

DSIAC ANNOUNCES DEFENSE SYSTEMS NEWS DIGEST

DSIAC is pleased to announce the biweekly release of the *Defense Systems News Digest.* The digest is intended to provide readers with a compilation of the latest defense systems-related information and technological developments in the nine DSIAC scope areas. As a recipient of *DSIAC Journal* notifications, you will be automatically subscribed to receive the digest. We hope that you enjoy this information service, and please contact us at www.dsiac.org with any questions or comments you have about this or any other DSIAC product. We look forward to hearing from you.

A HISTORICAL OVERVIEW OF A HALF CENTURY OF U.S. MISSILE DEVELOPMENT



- **1956:** Sidewinder Proportional Guidance – Lethality **(AT)**
- **1957:** SA-2 Two-Stage Hybrid Rocket Motor – High-Altitude Intercept **(AT)**
- **1957:** R-7 High Thrust – ICBM **(ST)**
- **1960:** Polaris Al Fuel – SLBM **(ST)**
- **1966:** Talos Radar Seeker – BVR Intercept **(AT)**
- **1969:** GBU-10 Laser Guided – Precision Strike **(ST)**
- **1972:** SRAM Low Observables – Survivability **(ST)**
- **1979:** Tomahawk Light Turbine – Long-Range Strike **(ST)**

AT = Air Target ST = Surface Target

Figure 1 (above). Transformed Capabilities via Transforming Missile Technologies. AT: Air Targets/ST: Surface Targets

By Eugene Fleeman and James Ralph Teague

INTRODUCTION

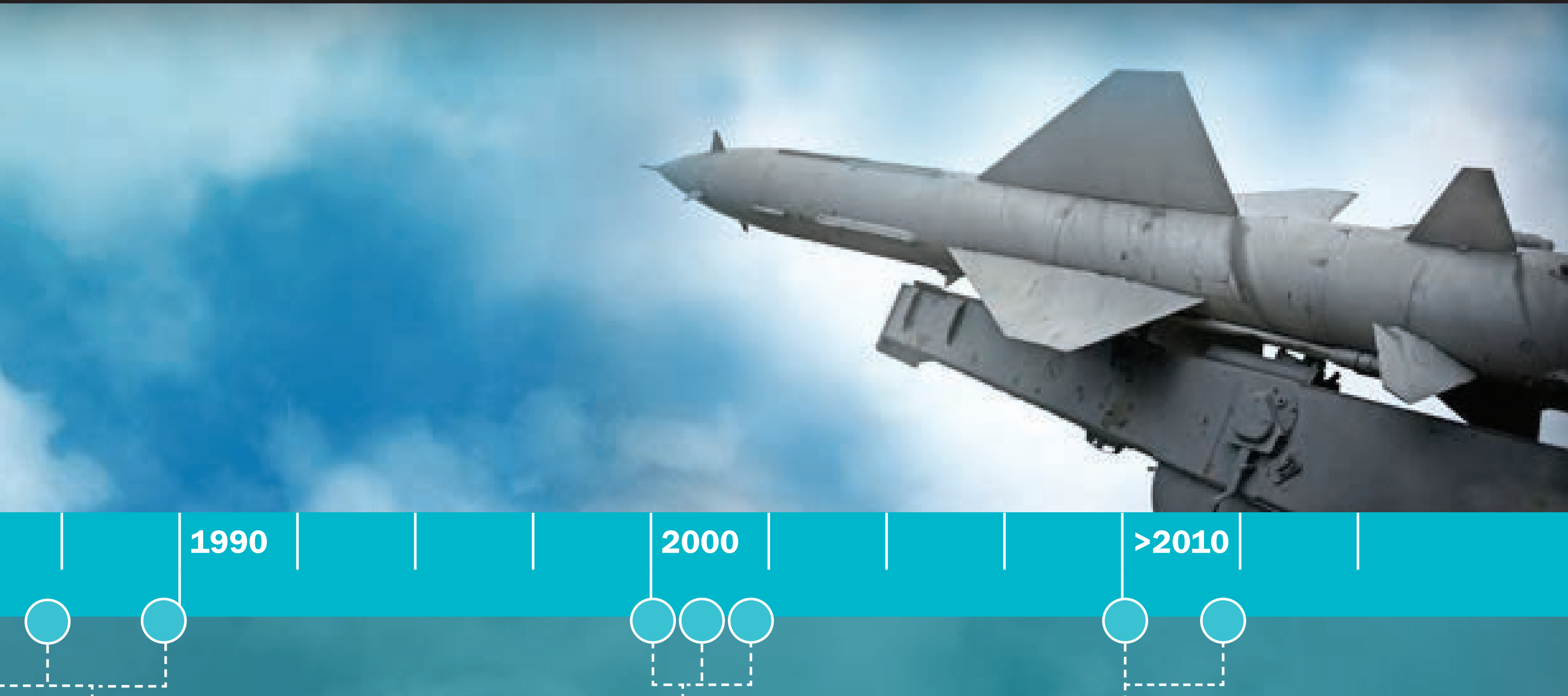
Over the last 60 years or so, ongoing developments in missile technology have provided the Department of Defense (DoD) with a transformation in operational capability. With ever-improving range and accuracy, these missiles have largely replaced unguided weapons in numerous military applications—air-to-air (ATA) missiles have largely replaced aircraft guns, air-to-surface (ATS) missiles have largely replaced dumb bombs, surface-to-air (STA) missiles have largely replaced anti-aircraft artillery, and surface-to-surface (STS) missiles have largely replaced artillery. This article, much of which is based on previous author texts [1–3], provides a brief overview of missile development over the past half century and examines some notable examples of how technology has driven the evolution of these systems and how advances in new materials and technologies might shape the systems of tomorrow.

A HISTORY OF TRANSFORMING MISSILES TRANSFORMING WARFARE

As illustrated in Figure 1, missile technology has experienced steady and dramatic development since the 1950s, which has in turn helped to transform the ways in which combat is fought. The following examples touch on some of the most noteworthy missile advancements.

In 1956, the proportional guidance accuracy of the AIM-9 Sidewinder led to higher lethality and a higher exchange ratio in air-to-air combat. A real-world demonstration of these improvements was provided on the Sidewinder's first combat application in September 1958, when Republic of China F-86 aircraft destroyed four People's Republic of China MIG-17 gun-only aircraft, with no losses.

In 1957, the development of the Russian R-7 high-thrust rocket motor provided the capability for the world's first intercontinental ballistic missile (ICBM), a capability that brought within reach virtually any target (or any threat) around the world.



- **1982:** Sunburn Ramjet – Time-Critical Strike **(ST)**
- **1985:** Stinger Two-Color Seeker – Target Acquisition in Clutter **(AT)**
- **1987:** Archer TVC – Off Boresight Lethality **(AT)**
- **1989:** Hellfire Digital Processor – Multi-Purpose & High Reliability **(ST)**

- **2000:** JDAM GPS/INS – Low-Cost X Weather Strike **(ST)**
- **2001:** PAC-3 Accuracy – Ballistic Missile Defense **(AT)**
- **2002:** SM-3 Accuracy – High-Alt Missile Defense **(AT)**

- **> 2010:** Meteor Ducted Rocket – Standoff **(AT)**
- **2012:** APKWS Guidance Kit – Low-Cost, Light-Weight Strike **(ST)**

In 1960, the SA-2 Guideline (V-77) two-stage high-performance rocket motor provided the capability for high stratospheric altitude intercept. The capability was demonstrated during the famous international incident in May of that year, when the Soviet Union used an SA-2 to shoot down an American high-altitude U-2 reconnaissance aircraft being flown by pilot Gary Powers. Also in 1960, the application of solid aluminized propellant allowed the development of a safe high-performance rocket motor for the Polaris submarine-launched ballistic missile (SLBM).

In the late 1960s, developments in radar seekers led to the first combat demonstration of a beyond visual range (BVR) surface-to-air missile. In 1968, Talos missiles were launched from the missile cruiser *USS Long Beach* and successfully shot down two North Vietnam MIG aircraft at a range of more than 50 nautical miles.

In addition, proven semi-active laser-precision guidance accuracy of the Guided Bomb Unit-10 (GBU-10) reduced the number of required aircraft sorties, providing higher aircraft survivability. One example of the value of precision-guided weapons occurred in May 1972, when the United States attacked the Thanh Hoa Bridge in Vietnam. Over the previous 6 years, a staggering 871 aircraft sorties had dropped unguided bombs on the bridge (resulting in the loss of 11 aircraft) but had failed to close it. However, the first operational application of laser-guided bombs (dropped in four sorties) resulted in direct hits on the supporting piers, successfully closing the bridge with no loss of aircraft. More recent examples of the growing use of precision strike weapons are their applications in Operation Desert Storm (1991), where 9% of the strike weapons were guided weapons; Kosovo (1998–1999), where 35% of the strike weapons were guided

> Missile technology has experienced steady and dramatic development since the 1950s, which has in turn helped to transform the ways in which combat is fought.

weapons; and Operation Enduring Freedom (2002), where 69% of the strike weapons were guided weapons.

Also in 1972, the development of low observables Short Range Attack Missile (SRAM) provided a higher capability for missile survivability, a greater number of targets killed per bomber, and enhanced bomber survivability. SRAM provided the B-52 and B-1 bombers with enhanced survivability for standoff attack against defended targets.

In 1979, the Tomahawk's lightweight turbine led to a long-range standoff and relatively small size cruise missile, making the Tomahawk a weapon of choice for long-range strikes. In fact, during Operation Desert Storm (1991), 297 Tomahawks were fired at long-range standoff, destroying more than 90% of their targets.

The introduction and development of Ramjet propulsion in 1982 of SS-N-22 Sunburn led to the capability of time-critical attack of ship targets, with enhanced missile survivability from high-speed flight, high stratospheric altitude flight, and long-range standoff.

The initial operational capability (IOC) in 1985 of the ground-to-air Stinger's two-color infrared/ultraviolet (IR/UV) seeker led to better target acquisition in clutter and better countermeasure resistance. Introduced in Afghanistan in 1986, Stingers shot down more than 200 fixed-wing aircraft and helicopters.

In 1987, the proven thrust vector control (TVC) of the AA-11 Archer led to large off-boresight, reduced time for firing, and enhanced capability against maneuvering aircraft. This capability provided a high lethality and exchange ratio in short-range air-to-air combat, as well as made the U.S. AIM-9L Sidewinder aerodynamic control missile obsolete.

In 1989, demonstration of Hellfire's digital processor led to flight trajectory flexibility and a multi-mission missile with higher reliability. In the opening salvo of Operation Desert Storm, Apache helicopters used Hellfire missiles to destroy Iraqi low-frequency early warning radar sites, clearing the way for F-117 aircraft.

> In the late 1960s, developments in radar seekers led to the first combat demonstration of a beyond visual range (BVR) surface-to-air missile.

The proven global positioning system/ inertial navigation system (GPS/INS) guidance of the Joint Direct Attack Munition (JDAM) led to a low-cost adverse weather fire-and-forget precision strike weapon in 2000. And as of 2013, more than 250,000 JDAMs have been produced, with more than 20,000 dropped in combat.

In 2001, kinetic hit-to-kill accuracy of the Patriot Advanced Capability-3 (PAC-3) led to high lethality for terminal ballistic missile defense, and PAC-3's were used to successfully destroy threat ballistic missiles during Iraqi Freedom in 2003.

Likewise, the exo-atmospheric accuracy of the Standard Missile-3 (SM-3) led to a capability for long-range/high-altitude missile defense in 2002, and the SM-3 demonstrated the capability to destroy a satellite, with limited debris, in 2008.

In 2010, the advent of meteor-ducted rocket air-breathing propulsion demonstrated a standoff air-to-air capability with more than twice the range of the Advanced Medium Range Air-to-Air Missile (AMRAAM), which has conventional rocket propulsion.

Finally, the development of the lightweight, low-cost Advanced Precision Kill Weapon System (APKWS) in 2012 showed the accuracy and range of the Hellfire missile at a fraction of the Hellfire's weight and cost.

U.S. TACTICAL MISSILE FOLLOW-ON PROGRAMS

As shown in Figure 2, the frequency of a follow-on program is every 24 years or so for most U.S tactical missiles. Once a missile is in production, it usually has a long lifetime, including block upgrades. Block upgrades often incorporate the emerging new technologies in electronics, sensors, and propulsion and are also often necessary for new launch platform integration. However, eventually a capability is needed that is not easily achievable through a block upgrade, requiring a new competitive follow-on missile development.

Examples are shown in Figure 2 of the driving requirements for ATA, ATS, STS, and STA follow-on missile programs. The driving requirements are the improved maneuverability of AIM-9X; the autonomous seeker, lighter weight, higher speed, and longer range of the AIM-120 AMRAAM; the higher speed and longer range of the AGM-88 High Speed Anti-Radiation Missile (HARM); the improved response, logistics, and safety

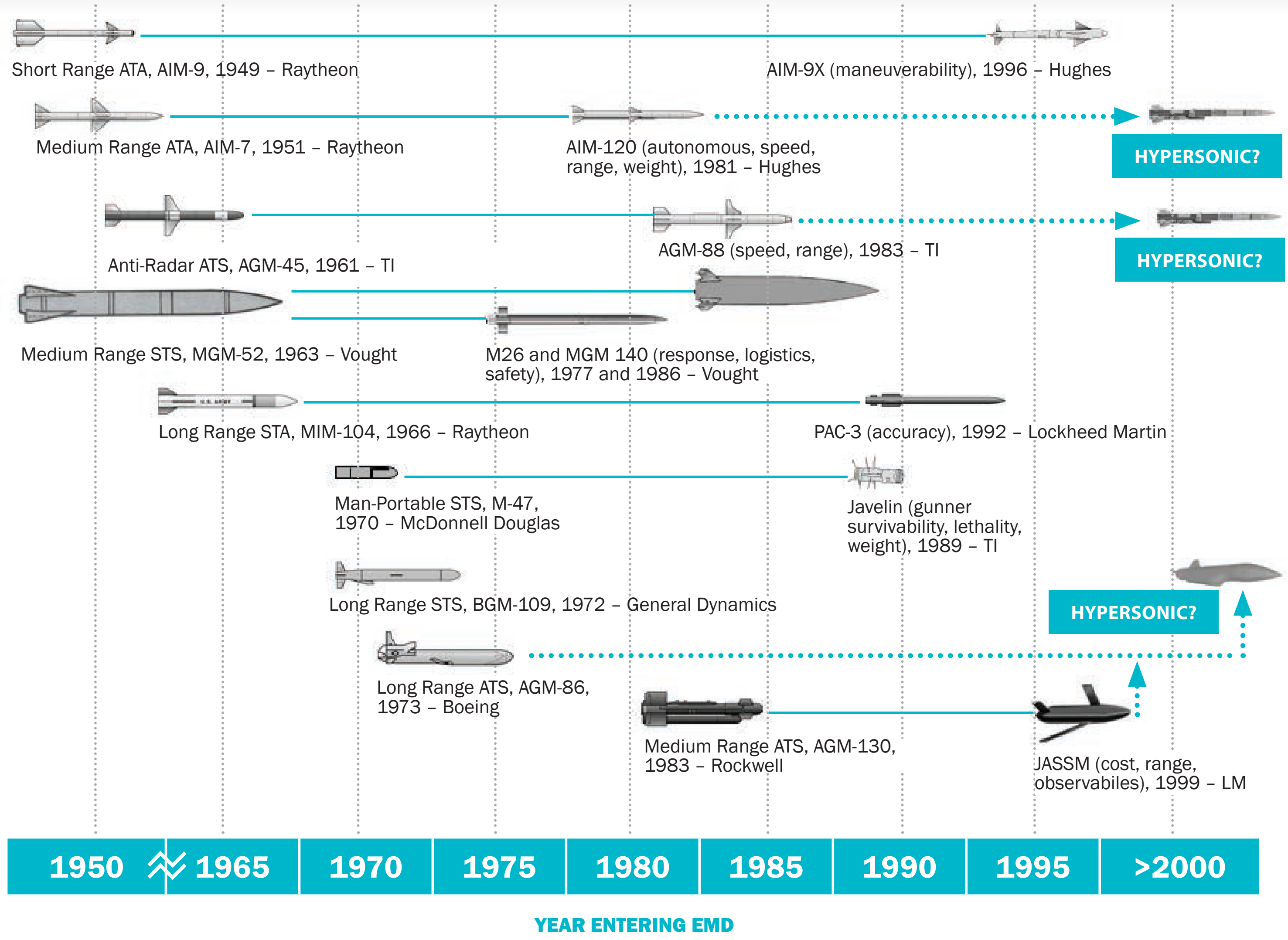


Figure 2. U.S. Tactical Missile Follow-On Programs.

of the solid propellant M26 Army Tactical Missile System (ATACMS) and the MGM-140 Multiple Launch Rocket System (MLRS) tactical ballistic missiles; the improved accuracy (hit-to-kill) of the PAC-3; the higher gunner survivability (lower observables, launch-and-leave), lethality, and lighter weight of Javelin; and the combined robustness of lower cost, longer range, and reduced observables of the Joint Air-to-Surface Standoff Missile (JASSM). It is interesting to note that in almost no case does a U.S. missile follow-on program go to the incumbent contractor of the current missile.

Unguided-to-guided missile conversion kits have offered great promise for reducing the cost per precision strike engagement by as much as 75% for a certain class of targets. However, because of industry circumstances, only international customers have ordered the systems so far and only one new U.S. missile program has been able to surpass the engineering and manufacturing development (EMD) acquisition milestone between 2000 and 2016. This missile, the APKWS II, is manufactured by BAE and comprises a guidance package added to a converted 70-mm unguided rocket that has been in use since the 1960s.

Other companies, such as Lockheed Martin (Dager), Orbital ATK (GATR), and Raytheon (Talon), have invested heavily in developing comparable technology, but none of these systems has a U.S. program of record.

Opportunities exist for a new start for a U.S. hypersonic air-breathing missile program in the post-2016 time frame. A hypersonic air-breathing missile would provide faster time-to-target and may also provide longer range. Examples of possible hypersonic missile opportunities include a ducted rocket missile follow-on program for the air-to-air AIM120 AMRAAM, a ducted rocket missile follow-on program for the air-to-surface defense suppression AGM-88 HARM, and a liquid fuel ramjet missile follow-on program for the current cruise missiles (BGM-109 Tomahawk, AGM-86 CALCM, RGM/UGM 84 Harpoon, and JASSM).

Current supersonic/hypersonic air-breathing missiles are shown in Figure 3. Except for the SS-N-19 Mach 2.5 turbojet, the missiles use either ducted rocket or liquid fuel ramjet propulsion. Current missiles use either a nose inlet or aft inlets. Missiles with a nose inlet are the United Kingdom Sea Dart, the Russian SS-N-19 and SS-N-26, and India BRAHMOS. Missiles with aft inlets are the United Kingdom Meteor; French Anti Navire Supersonique (ANS) and Air Sol Moyenne Portee (ASMP); Russian AS-17/Kh-31, Kh-41, SS-N-22/3M80, and SA-6; Chinese C-101 and C-301; and the Taiwan Hsiung Feng III. Notably, the United States has no high-speed air-breathing missiles.

COLD WAR U.S. STRATEGIC MISSILES AND FOLLOW-ON PROGRAMS

As shown in Figure 4, the United States did have numerous strategic missile follow-on programs during the Cold War. The liquid propellant Atlas and Titan ICBMs were replaced by the solid propellant Minuteman, which has faster launch response time and higher survivability. Minuteman also has better guidance accuracy. The Polaris SLBM was replaced by Poseidon, which had higher firepower, using multiple independent reentry vehicles (MIRVs). Poseidon was replaced by Trident, which has longer range and better accuracy.

In the area of naval strategic cruise missiles, the relatively small-size/high-firepower, high-readiness, and high-accuracy BGM-109 Tomahawk replaced the Regulus missile. In addition, there may be opportunities for a new start for a U.S. strategic cruise missile in the post-2016 time frame. Possible examples include a liquid fuel ramjet missile, which would provide faster time-to-target and potentially improved survivability over the current subsonic cruise missiles (BGM-109, AGM-86).

For a strategic missile, the time interval to a follow-on program is likely

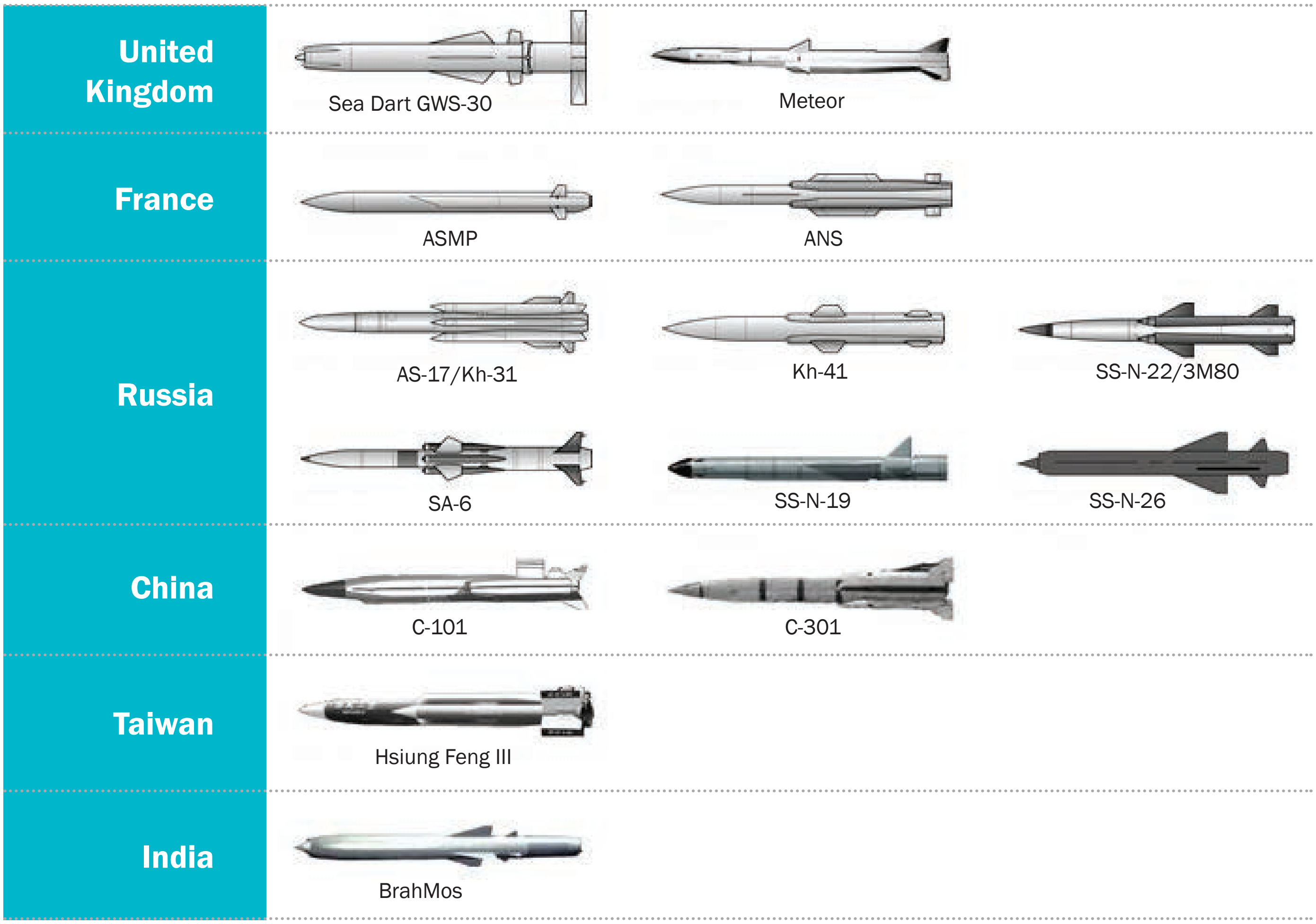


Figure 3. Examples of High-Speed Air-Breathing Missiles.

to be longer than that of a tactical missile (and is often influenced by political considerations). For example, Minuteman III (EMD year 1966) and Trident (EMD year 1968) have not yet had follow-on programs. A partial follow-on to AGM-86 ALCM, the AGM-129 reduced radar cross section (RCS) missile, was terminated.

CHALLENGES TO U.S. MISSILE DEVELOPMENT PROGRAMS

As shown in Figure 5, current U.S. defense funding (as a fraction of total U.S. federal funding) is the lowest it has been since just before World War II. This low emphasis on spending and development poses a significant challenge for DoD development programs, including missile development programs.

> It is interesting to note that in almost no case does a U.S. missile follow-on program go to the incumbent contractor of the current missile.

Another challenge is the relatively low number of current U.S. missile system contractors. Figure 6 shows the U.S. missile contractor consolidations, falling from 12 contractors in 1985 to 3 contractors in 1997. Implications of the consolidations include less competition, less creativity, and more vertical integration (fewer suppliers).

ENABLING TECHNOLOGIES FOR MISSILES

Going forward, there are numerous high-payoff, enabling technologies that are now, and will likely continue to be, critical to ongoing missile system development. These technologies are summarized in Figure 7 and detailed in the paragraphs that follow.

- ***Seeker Dome*** - Faceted/window and multi-lens seeker domes have reduced dome error slope, resulting

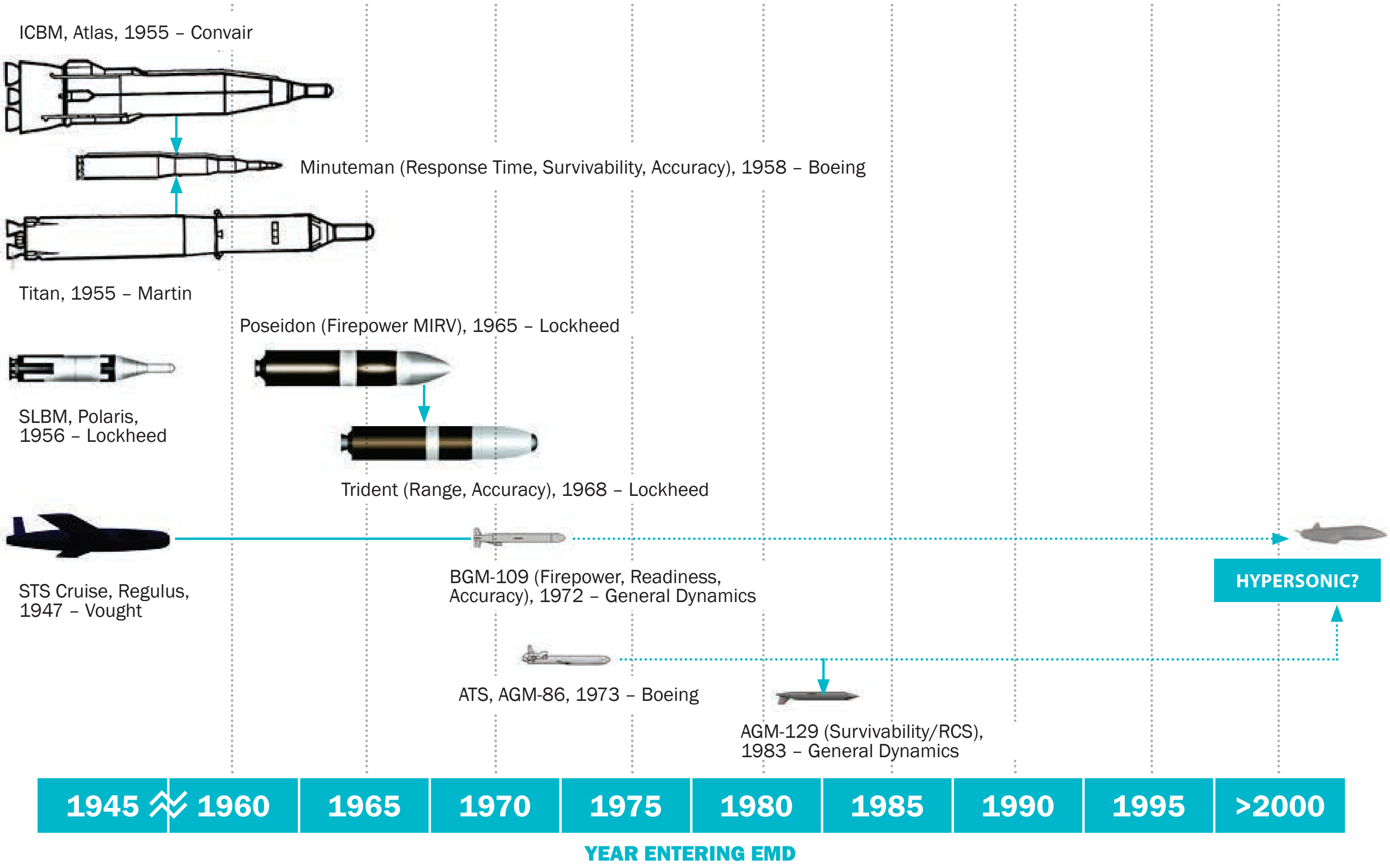
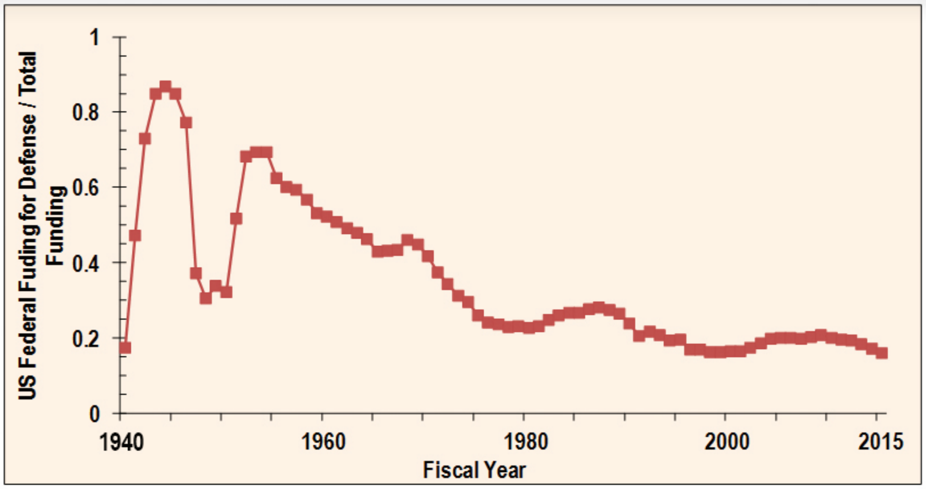
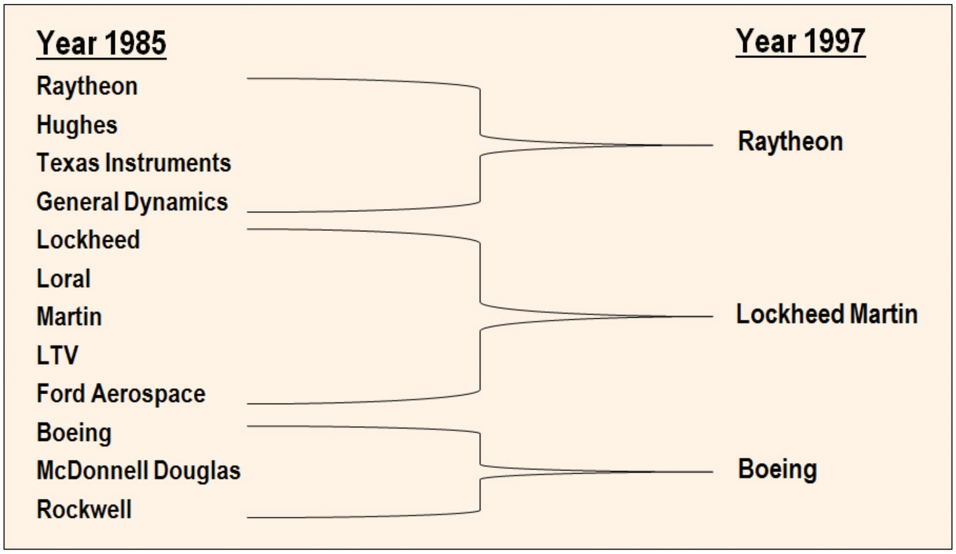


Figure 4. Cold War U.S. Strategic Missiles and Follow-On Programs.



Source: US Office of Management and Budget, FY 2015 Budget, Table 6-1

Figure 5. The Relatively Low Emphasis on Funding U.S. Defense Programs.



Source: US Defense Science Board, May 1997

Figure 6. Major U.S. Missile Contractor Consolidations (1985–1997).

in improved guidance accuracy, low observables, and low drag at supersonic speed. Multi-mode, multi-spectral, and multi-lens domes are also being developed.

- ***Seeker*** - Multi-spectral/multi-mode imaging seekers enhance performance for automatic target recognition (ATR) in countermeasures and clutter. Synthetic aperture radar (SAR) seekers have good effectiveness against surface targets in adverse weather and ground clutter. Strap-down and uncooled imaging infrared (IIR) seekers provide reduced parts count and lower cost. High gimbal seekers enhance off-boresight capability. Phased array enhances resolution and response time.
- ***Guidance, Navigation, & Control (GN&C)*** - Integrated GPS/INS permits precision guidance of a low-cost seekerless missile against fixed targets. Multi-mode (command/inertial/autonomous terminal homing) guidance provides a balance of missile effectiveness and launch platform survivability. Using in-flight digital prediction of the trajectory flight and derived flight conditions (e.g., angle of attack, angle of sideslip) from the GPS/INS, missiles will continuously optimize the flight trajectory to maximize performance parameters. Advancements in ATR technology will provide new capabilities of near real-time ATR and lower false-alarm rates. Hit-to-kill guidance accuracy is also being improved.
- ***Electronics*** - Processing capability is ceasing to be a limitation for the application of processors to sensor data fusion and near real-time trajectory optimization to missiles. Commercial off-the-shelf (COTS) electronics, a single central processor, and micro-electromechanical systems (MEMS) provide lower cost.
- ***Airframe*** - Lifting body airframes provide enhanced maneuverability and efficiency. Enhancements are also provided by configurations that maintain near-neutral static margin over the flight envelope. Split canard control and free-to-roll tails also enhance maneuverability. Aerodynamic surface planform shaping can reduce the shift of static margin aerodynamic center with Mach number and minimize flight control hinge moment. Lattice fins have advantages of smaller hinge moment and higher control effectiveness. Compressed carriage aerodynamic surfaces provide higher volumetric effectiveness for internal carriage. Inlets with low-drag and low-pressure oscillation are in development for hypersonic missiles. Increased usage will be made of castings, 3-D printed/additive manufacturing, vacuum-assisted resin transfer molding (VARTM), pultrusion, extrusion, and filament winding to reduce parts count and cost. High-temperature composite and titanium materials will

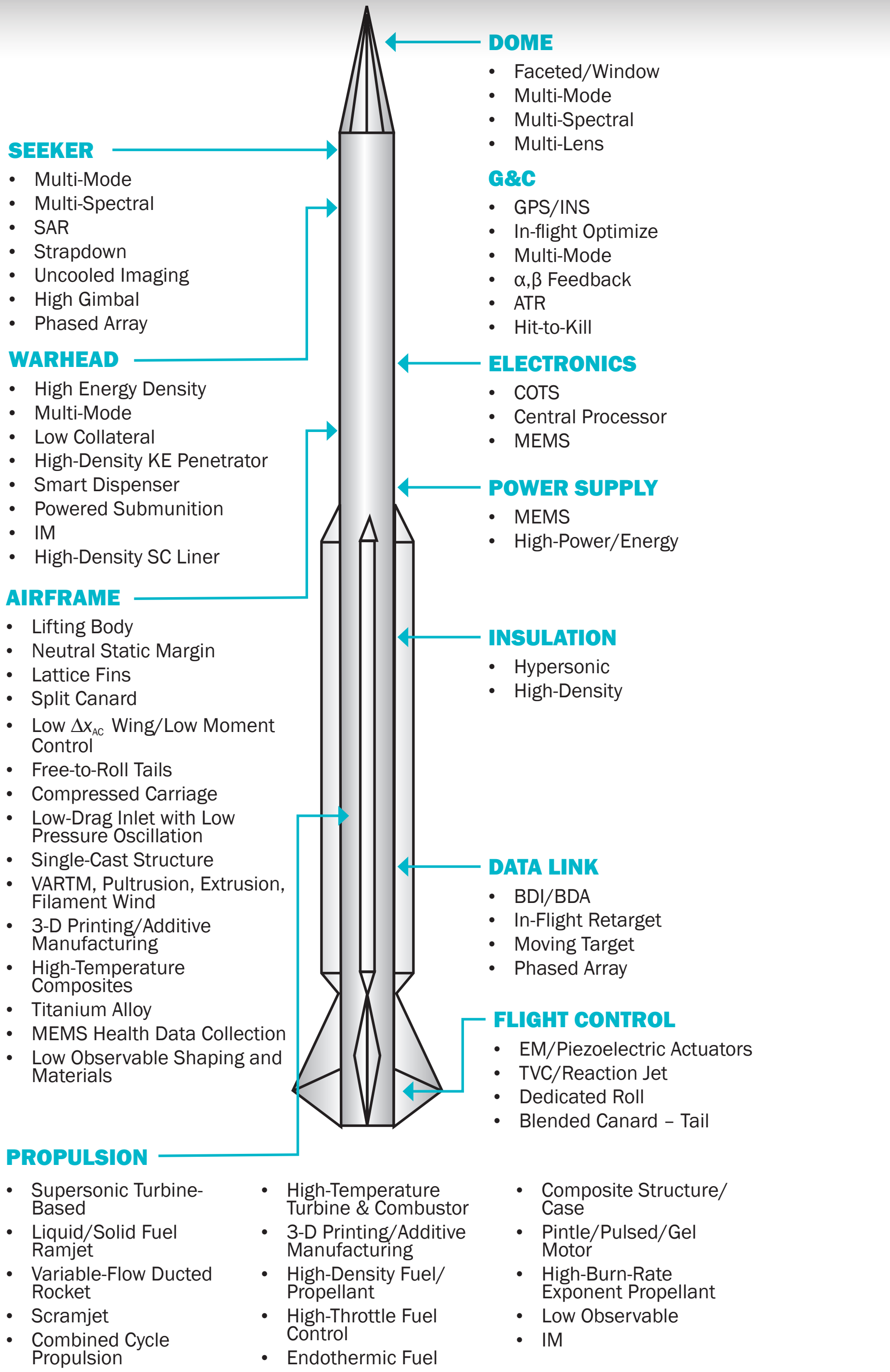


Figure 7. Enabling Missile Technologies.

be used in hypersonic missiles. Low-cost/small-size MEMS sensors will reduce the cost of development test data collection and logistics health monitoring. Also, airframe shaping and composite materials technology will provide reduced observables.

- ***Power Supply*** - Development of MEMS micro turbine generators and advanced lithium-air batteries will provide a large reduction in the weight of the power supply.

- ***Warhead*** - Higher energy density explosive charges, such as the U.S. Navy China Lake CL-20, will be developed. Modular multi-mode warheads will be developed that tailor the type of kill mechanism (e.g., blast, kinetic energy) to fit the target. Low-collateral-damage warheads that confine lethality to the target area will be developed. Kinetic energy (KE) warheads with higher density and boosted penetrators will be developed for defeating hard and deeply buried targets. High-density liners that provide greater penetration will be developed for shaped charge (SC) warheads. Reduced collateral damage submunition dispensers and autonomous submunitions will counter mobile, time-critical targets. Improved insensitive munition (IM) warheads will also be developed.

- ***Insulation*** - Higher density insulation will be developed to improve the volumetric efficiency of hypersonic missiles.

- ***Propulsion*** - Turbojet, air turbo-rocket, ramjet, and ducted rocket propulsion will be developed for high-speed air-breathing missiles. In the longer term, scramjet and combined cycle (ramjet/scramjet) propulsion may also be developed. However, the risk is high for scramjets because of their low thrust margin, low combustion efficiency, and the requirement for a large/heavy booster. High-temperature turbines and combustors will be developed for turbojet and turbofan missiles. The leveraging of 3-D printing/additive manufacturing will be used to reduce the development time, parts count, and cost. High-density fuels and propellants will provide higher volumetric performance. Endothermic fuels will provide higher specific impulse, shorter combustor length, and cooling for scramjets. Composite motor cases will provide reduced weight. Thrust management technologies will be developed for pintle, pulse, and gel rocket motors. In the case of a pintle motor, high-burn-rate exponent propellants will be developed to maintain high specific impulse over a broad range of thrust. Reduced observable propellants will be developed with higher specific impulse and greater safety. Higher thrust motors to quickly accelerate missiles to hypersonic speed will be developed for kinetic kill missiles. Finally, improved IM propulsion will be developed.

- ***Data Link*** - Battle damage indication/battle damage assessment (BDI/BDA) will be enhanced by continued development of data links with target imagery. In-flight retargeting by a high bandwidth data link will be developed for mobile and moving targets. High-bandwidth data links will allow a seekerless missile with a hit-to-kill capability against moving targets. Phased array antennas will be developed for higher data rate and mission flexibility.
- ***Flight Control*** - High-power density electromagnetic (EM) and piezoelectric actuators will provide high bandwidth and high rate performance with reduced weight. Thrust Vector Control (TVC) and reaction jet control performance will be enhanced for highly maneuverable and hit-to-kill missiles. Dedicated roll control surfaces will provide higher control effectiveness at high angle of attack and simplify the autopilot design. Finally, blended canard-tail flight control will provide divert maneuvering at low angle of attack to minimize radome error slope miss distance, facilitating hit-to-kill accuracy.

CONCLUSION

If the U.S. military is to continue the capability transformation that missile development has provided over the last half century or so, it must continue to invest in the research and development of technologies to enhance the speed, accuracy, and destructive power of these weapons. System engineering trades will continue to be important for missile concept development—including all the aforementioned technologies—and must be unbiased, creative, and iterative with defined evaluations.

In addition, the conceptual development effort should have a mission/scenario/system definition, weapon system requirements trade studies and sensitivity analysis, launch platform integration, weapon concept design synthesis, and technology assessment and development roadmap. Moving to a 3- to 9-month design development cycle is also recommended, with the development effort determining the driving parameters for each missile figure of merit. This determination will involve translation of customer requirements to engineering design characteristics.

Finally, hardware experiments must be designed to efficiently evaluate the aforementioned technologies used in the weapon design. Evaluation of emerging missile technologies will also require advanced modeling and simulation to provide a cost-effective method that supports missile maturation throughout the weapon system's life cycle. Ultimately, the main attributes of a new or enhanced missile system concept will be lethality, survivability, agility, versatility, deployability, and affordability for defense against both current and future threats. ■

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BIOGRAPHIES

EUGENE FLEEMAN has more than 50 years of government, industry, academia, and consulting experience in the design and development of missile systems. Formerly a manager of missile programs at the U.S. Air Force Research Laboratory, Rockwell International, Boeing, and Georgia Tech, he is an international lecturer on missiles and the author of more than 200 publications, including three textbooks. His textbooks and short courses on missile design and system engineering emphasize physics-based prediction methods for enhanced insight, speed, and accuracy of the conceptual design process. Mr. Fleeman holds a B.S. in aerospace engineering from the University of Cincinnati and an M.S. in aerospace engineering from the University of Dayton.

JAMES "RALPH" TEAGUE is a principal research scientist at the Georgia Tech Research Institute (GTRI) with more than 44 years of experience in sensor and related technologies, encompassing material science to large-scale sensor system integration. Dr. Teague currently serves as a technology specialist supporting DSIAC, responding to technology inquiries from the military and homeland defense sensing communities. He provides short courses to the sensor community in detection and tracking systems; laser systems; missile seeker design; EO/IR payloads; self-defense systems; chemical, biological and explosion detection systems; and required sensor-related technologies, such as detectors, image processing, and optics. Dr. Teague is also active as a technology advisor, consultant, and expert witness and has also been an Associate Editor for the *IEEE Aerospace and Electronic Systems* magazine, responsible for sensors, EO, and radar content. He holds a B.A. from the University of North Carolina, an M.S. from New Mexico Highlands University, and a Ph.D. in experimental physics from the University of Missouri-Rolla.

DTIC SEARCH TERMS:

Missile Development Technology

RESULTS: 293,000

- Other (9,800+)
- Guided Missiles (2,740+)
- Weapons (2,348+)
- Antimissile Defense Systems (2,099+)
- Directed Energy Weapons (1,318+)
- Computer Programming and Software (1,300+)
- Weapons Technologies (1,300+)
- Export Control (1,213+)
- Ammunition and Explosives (1,200+)
- Electrical and Electronic Equipment (1,200+)

*See page 30 for explanation ▸

NONDESTRUCTIVE INSPECTION

OF ADDITIVE MANUFACTURED PARTS IN THE AEROSPACE INDUSTRY

By Michael Mazurek and Russell Austin

INTRODUCTION

Recent advancements in additive manufacturing (AM) have allowed the technology to move from simple prototyping using plastics to creating fully formed metallic components that can be integrated into modern aerospace systems. AM presents a revolution in traditional manufacturing methods by removing the limitations of traditional casting subtractive manufacturing processes. AM also provides designers and engineers the freedom to create parts that not too long ago would have been considered either too costly or nearly impossible to machine. Consequently, the adoption and expansion of AM in the aerospace industry is leading to new structural concepts as well as a re-evaluation of established part design.

The 2014 Wohlers Report found that the AM market reached $3.07 billion in 2013, representing a 34.9% growth rate, the highest growth rate in 17 years. And over the past 26 years, the average growth rate in worldwide revenue from AM was 27% [1]. In 2013, the McKinsey Global Institute released a report naming AM as among the technologies most likely to transform the world [2]. Without a doubt, AM is quickly becoming a strong segment of the manufacturing economy on a global scale; however, market penetration of AM products, specifically in aerospace markets, is limited by the lack of robust and mature inspection and validation technologies compared to traditional subtractive manufacturing parts.

Recently, NASA has been promoting the development of AM as a tool for the next generation of space flight. In fact, astronauts aboard the

International Space Station (ISS) have already begun printing parts, such as threads, springs, clamps, buckles, and containers using a 3-D ABS printer [3]. The use of 3-D printing in space overcomes a large logistics hurdle, removing the need to be reliant on launch facilities on Earth and the requisite launch window opportunities and risks associated with supplying replacement parts to astronauts aboard the ISS. But more than just replacing a broken screw, NASA wants to push for even more AM in space, which could remove size and weight restrictions placed on satellites and structures built on the Earth.

The current process of launching material into space must take into account the tremendous forces applied by the cargo, and because satellites and probes can cost millions of dollars, there is an onus on the engineer to overdesign to ensure launch survival. But the overdesign comes at a cost of a higher launch weight, and at the going rate of $10,000/lb to launch an object into space, adding extra material just to survive launch can quickly increase one's launch cost. NASA believes that AM in space can circumvent this issue by needing only to transport bulk material (such as that shown in Figure 1) used to build a structure in space that is optimized for the space environment, not the launch environment. Nevertheless, due to the lack of ability to certify AM parts and critical structures, there is no desire to take a chance in the risk-averse world of space flight.

But NASA is making efforts to close the gap to take advantage of the benefits of AM. NASA created its Nondestructive Working Group (NNWG) to help coordinate interagency cooperation on developing standards for AM inspections, including new standards produced by ASTM. The NNWG helps researchers target information and technology gaps and directs resources to bridge these gaps.

Figure 1. Titanium "Tube in a Tube" for a Cryo-Thermal Switch on ASTRO-H. Traditional Manufacturing Would Cost up to $20,000 and Take 3 Months to Build, While AM Can Drop the Cost to $1,200 and the Wait Time to 2 Weeks [4].

FACTORS FOR DETERMINING INSPECTIBILITY

Design Complexity

Before discussing the state of inspection technologies, let us first examine the types of parts that can be produced through AM, as well as different AM techniques and the defects seen in the AM process, all of which guide the inspection selection process. Todorov et al. [5] defines a five-step evolution of design complexity that is based on the skill growth and increased technological comfort of the engineer designing a part.

Figure 2 charts the growth of the designer as he/she becomes more comfortable with AM. Group 1 sees relatively simple parts that can typically be fabricated using traditional machining. Parts produced in this group have surface features that can be easily accessed and can be served through traditional nondestructive evaluation (NDE) technology. Often, parts in this group are produced as a proof-of-concept or rapid prototype, and because of the simplicity of the manufacturing techniques, these parts are not seen as economically viable when compared to traditional subtractive manufacturing parts.

Figure 2. Examples of the Increasing Complexity in Design That AM Allows.

Group 2 parts begin to take advantage of AM's ability to produce more complex shapes and designs than traditionally fabricated parts without the need for complicated tooling processes. The example in Figure 3 comes from a 2013 GE Aviation crowd-sourced competition to find ways to reduce the weight of a standard forged titanium engine mounting bracket [6]. The original bracket weighed 2,033 g (4.48 lbs), but the AM redesign was able to reduce the weight by 84% while maintaining an equivalent performance in lab tests. Group 2 parts mark the start of cost savings from subtractive manufacturing by reducing the need for excess materials and complex tooling. However, the addition of complexity comes with the cost of narrowing the technologies available to perform NDE on the part unless specifically made for the part. Generally speaking, Groups 1 and 2 are not dissimilar enough from subtractive manufactured parts that they require any new or specialized inspection technologies from what is already available.

Group 3 AM components are defined as parts that cannot be manufactured through traditional subtractive manufacturing. These parts feature internal structures such as tubes or channels that previously would have necessitated the part to be made through casting. In a traditional setting, these parts would have multiple individual subcomponents manufactured and then an assembly phase to produce the final component.

Figure 4 shows an injection molding tool (note especially the cooling channels moving through the component). The tight channels within the part increase the cooling efficiency of the tool, allowing for faster production rates. However, these embedded features represent a challenge to the inspectibility of the part and reduce the NDE technologies to those that can image the interior features.

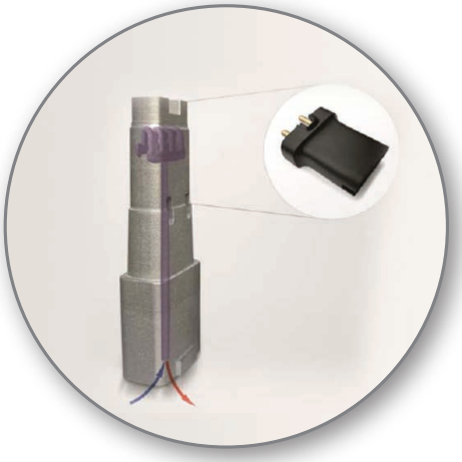

Figure 4. Tool Insert and Injection-Molding Component. Because of the Internal Conformal Cooling Channels, the Manufacturer Was Able to Reduce Cooling Time From 14 to 8 s (Source: EOS and Salcomp) [7].

Group 4 parts can potentially be produced through traditional methods; however, the cost and skill required to produce the designs make the operation economically unfeasible. The engineer begins to incorporate organic and nonlinear shapes that place emphasis on performance rather than producibility. In addition, the internal structure of these parts (as shown in Figure 5) can be complicated and produced without the need for traditional "line of sight" to create the features. And the ability to inspect these parts is greatly reduced due to the presence of highly detailed and embedded features.

Group 5 parts, which are almost entirely produced through AM, consist of extremely fine features. Examples of these parts include metallic lattice structures (as shown in Figure 6). These lattice structures can be tailor made to suit specific purposes and can include thousands of individual

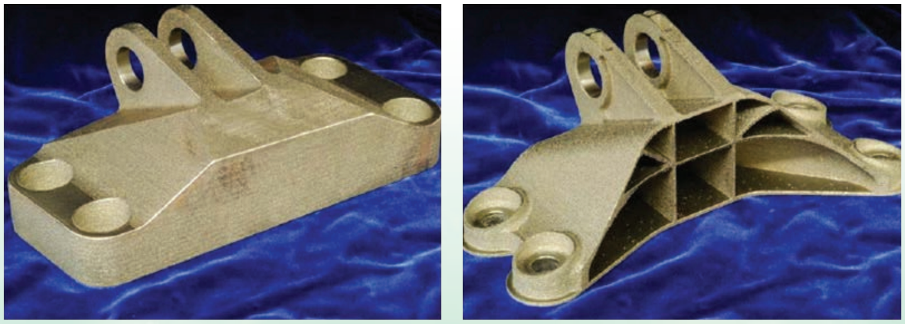

Figure 3. Side-by-Side Comparison of a Traditionally Made Engine Mount (left) and the Optimized AM-Produced Design (right) [6].

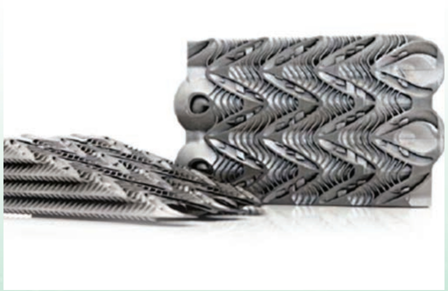

Figure 5. A Heat Exchanger Produced Through Laser Powder Bed Fusion (L-PBF), Demonstrating the Complexity of a Group 4 Part [5].

Figure 6. Group 5 Part Complexity Includes Structures Such as Metallic Lattices, Which Cannot Be Produced Through Traditional Means. The Titanium Lattice Ball Shown Here Has a Hollow Interior and a Complex Internal Geometry (ESA Photo) [8].

nodes in a relatively small space. The complexity of these structures requires a long fabrication time, but this fact is offset by the structures' potential to reduce material costs while maintaining the strength-to-weight ratio of bulkier forbearers. A byproduct of the increased complexity of these parts is the lack of NDE technology that can provide a reliable validation of the part for use in larger systems. Developing NDE technology for Group 5 parts would allow the parts to reduce costs overall at a system level, meaning the cost of manufacturing the entire final deliverable is reduced even with the increased cost of fabricating the Group 5 part.

AM Processes

AM covers a wide range of processes, depending on what type of material one is using. Simple, inexpensive in-home 3-D printers tend to use spools of polymer wire that are melted and deposited layer by layer. The plastic parts formed in these machines are often the only experience the general public has with AM. Although these parts are certainly novel and exciting, they are not well suited for industrial or structural use. For industrial purposes, the main form of AM for metals comes in the way of powder bed fusion (PBF) systems, with the layers being joined either through the use of selected laser melting (SLM) or electron beam melting (EMB). In both instances, layers of metal powder are deposited on the printing platform and then melted by either the laser or the electron beam, with the process repeating itself over and over until the part is completed.

While the two processes are similar, the subtle differences between SLM and EBM can impact the final product. EBM has a higher energy density and scanning rate, and thus a faster build rate, with the tradeoff coming in the form of a poorer surface finish as compared to SLM. Because EBM also requires the printing tray to be preheated prior to use, the thermal gradient in the part is minimized, resulting in a lower residual stress in the final product. However, EMB is limited to standard metallic materials, while SLM‘s range of materials includes metals, ceramics, and polymers. Table 1 provides additional comparisons between the two systems.

Defects Found in AM Parts

The PBF approach, whether laser-based or electron beam-based, is the most common form of AM manufacturing seen in the aerospace industry. In PBF-manufactured parts, there are typically four classes of defects that can occur: (1) volumetric defects, (2) cracking and delaminations, (3) balling, and (4) surface roughness. These defects are typically the result of poor process controls, process parameters, or even the geometry of the part to be produced, though it should be noted that even the most stringent of process controls will not entirely prevent the formation of defects in AM parts. As with traditional subtractive manufacturing, these defects can be detrimental to the performance of the part, and therefore there is a great importance placed on the inspection process to find the defects before the part becomes compromised. Understanding the nature of the defect types is necessary to

Table 1. Comparison of Electron Beam Melting and Selective Laser Melting Traits [5]

Characteristic	Electron Beam Melting	Selective Laser Melting
Thermal Source	**Electron Beam**	**Laser**
Atmosphere	**Vacuum**	**Inert Gas**
Energy Absorption	**Conductivity Limited**	**Absorptivity Limited**
Scan Speed	**Extremely Fast, Magnetically Driven**	**Limited by Galvanometer Inertia**
Energy Costs	**Moderate**	**High**
Surface Finish	**Poor to Moderate**	**Moderate to Excellent**
Feature Resolution	**Moderate**	**Excellent**
Materials	**Conductive Metal**	**Polymers, Metals, Ceramics**
Beam Size	**100–500 μm**	**100–150 μm**
Powder Size	**45–100 μm**	**20–50 μm**

implementing the proper quality monitoring process and inspection technique for the finished part.

The most common defects seen in AM parts are volumetric defects, either porosity (as shown in Figure 7) or a lack of fusion of the powder material. Generally speaking, porosity is described as being spherical in shape while defects formed by a lack of fusion can be more irregularly shaped and may have unmelted powder material within them. Gong et al. [9] found that beam power and scanning speed are the main drivers of porosity and lack of fusion in AM parts. They discovered that at a given beam power level, a low scanning speed will produce porosity, while an excessively high scanning speed will produce a lack of fusion in the material. Thus, to minimize the occurrence of volumetric defects in AM parts, operators must find the "Goldilocks" zone of scanning speed for a specific beam power and a specific material. Fortunately, powder suppliers have conducted extensive research in this area and provide the necessary parameters to manufacturers to mitigate the risk of volumetric defects.

Cracks and delaminations make up the second class of defects. These defects are more in line with the traditional defects seen in subtractive manufacturing and are the result of internal thermal stress gradients produced through the additive process (as shown in Figure 8). As each layer of powder heats and cools, the thermal stresses can grow, leading to the AM part delaminating from the substrate or cracks growing between the layers. This type of defect is more readily seen in structures with low geometrical stiffness, such as thin-walled tubes. Of the two processes, delaminations and cracks are more often seen in SLM parts, as EBM systems use a heated production tray to reduce the thermal gradient in the part as it is being constructed.

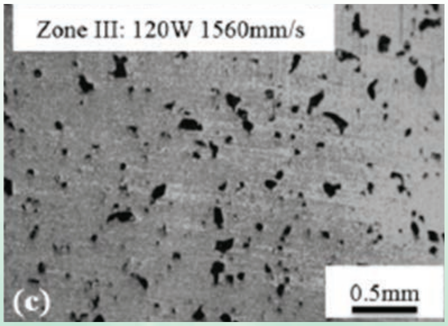

Figure 7. Low-Energy Input Causes a Lack of Fusion Between Layers, Resulting in Porosity Issues [5].

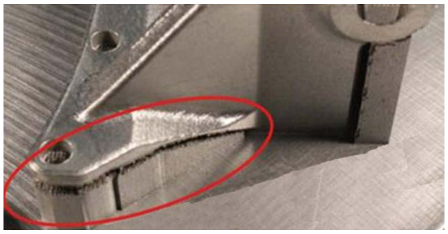

Figure 8. Cracking and Delamination Can Be the Result of Residual Stresses in the Part During the Build Process (CAD Design of Test Article Provided by Honeywell) [10].

Balling, the third class of defect (shown in Figure 9), occurs when instabilities cause the melt pool to break into thin spherical droplets. This defect derives from problems of the liquid metal wetting in its solid form [11]. In these cases, the surface tension of the newly melted powder exceeds the wettability of the underlying layer, in much the same way that water beads up on a hydrophobic surface. Because the molten powder resolidifies on the order of milliseconds, subsequent layers are built around the balling defects, leading to compounded defects as the part grows. Moreover, layers built around the balling can experience interlayer loss of adhesion due to the reduced surface contact, while the volume occupied by the sphere itself can grow into a volumetric defect.

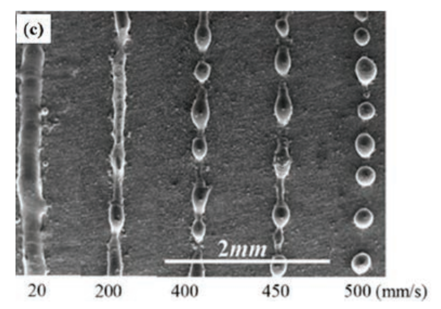

Figure 9. The Formation of Balling Defects as the Laser Scanning Speed Is Increased [5].

Although the last class of defect, surface roughness, is not inherently considered a defect in AM, it does have a bearing on the types of NDE that can be performed on finished parts. AM parts are built by taking computer-aided design (CAD) models and then slicing them into consecutive layers, which are translated into reality through the 3-D printer itself. Due to this layer stacking, any nonhorizontal, nonvertical face will be rough and give a stair-step-like appearance. And the junctures of the stair step features can create sharp corners, which are ideal for stress concentrations that can lead to part failure. Figure 10 compares SLM- and EBM-produced specimens to a traditional cast specimen.

Stroffregen et al. [13] found that when comparing AM parts against traditionally made test specimens of steel, the rougher surface of AM parts can be the site of initiation of fatigue cracks and the primary reason for fatigue failure in those parts (as shown in Figure 11).

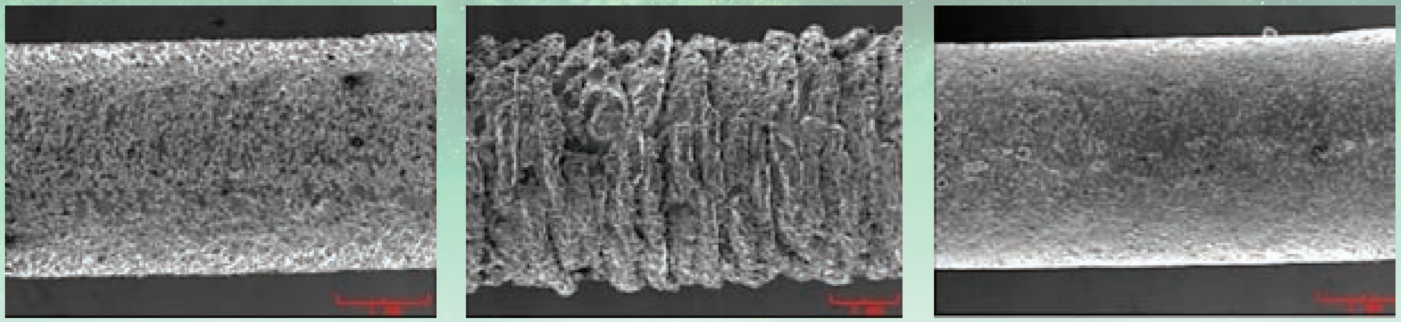

Figure 10. Surface Roughness Comparison Between SLM (left), EBM (middle), and Cast Ti-6AL-4V ELI (right). Higher Levels of Surface Roughness Can Produce Stress Concentrations, Resulting in Crack Formation [12].

Stroffregen also found that the mean deviation for surface roughness for AM parts (Ra) averaged 13.7 µm and the maximum height of the roughness profile (Rz) was 80 µm, compared to machined parts having respective roughness parameters of 0.2 µm (Ra) and 1.7 µm (Rz). At 10^7 cycles, the AM parts had a max stress of 219 MPa while the machined parts had a max stress of 49a MPa. Surface roughness is a byproduct of the build process, and Figure 11 illustrates how much of an effect the build process can have on the overall performance of the final part. Care must therefore be taken to minimize the surface roughness of AM parts, whether through tight process controls and slow build times or by post-production machining to refine the surface and eliminate crack initiation points.

INSPECTING AM PARTS

In-Situ Monitoring

The NDE of AM parts occurs in two forms, in-situ monitoring and post-production inspection. In-situ monitoring is important as a first-look capability for process control. Unfortunately, in-situ monitoring is fairly limited in the types of systems that can be used. The most widely used in-situ monitoring system involves using near infrared (NIR) cameras to capture the temperature gradient between the newest layer of melted material and the previously formed layers. NIR cameras are able to detect areas where insufficient beam energy imparted on the powder bed has resulted in a “cold” spot where the powder has not completely melted. As discussed previously, these locations of poor melt can produce volumetric defects in the finished parts. NIR camera systems can be improved to include multiple cameras, real-time tracking, and feedback algorithms, which can help improve the weld consistency in AM (as has been seen in the manufacturing of stainless steel straight wall samples) [3]. Going beyond simple monitoring, the parametric information provided by the NIR cameras (temperature, shape, and cooling rate) can be analyzed in real time to create metrics for feedback and real-time control of the system.

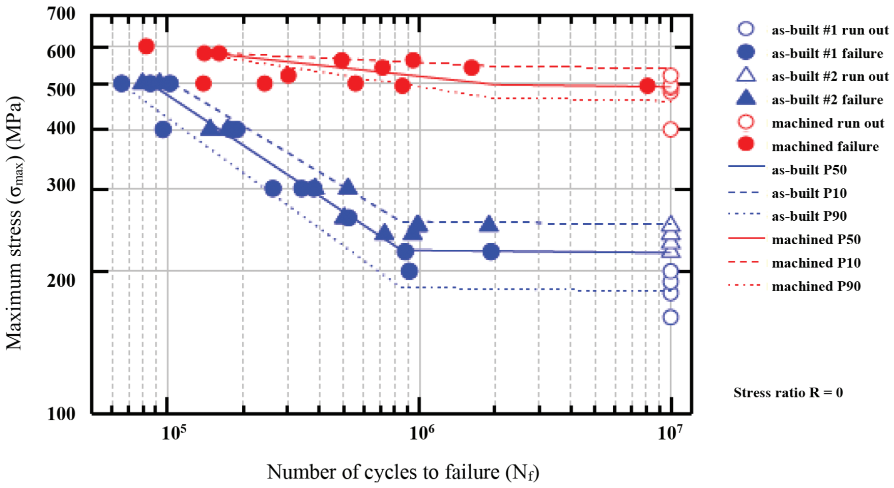

Figure 11. S-N Curves for As-Built AM Parts (Blue) Compared to Machined Parts (Red) [13].

Recently, researchers at Penn State have examined the use of optical image analysis to perform layerwise in-situ monitoring of AM [10]. The research team focused on using the layerwise monitoring as a means to correlate the anomalies seen in post-production 3-D X-ray computed tomography (CT) scans to features seen in the images between layer melts.

Figure 12 demonstrates how the individual layer images can be stacked to produce a 3-D CAD model that maps the locations of defects. This type of in-situ monitoring is useful in improving the process controls by identifying where in the build the defects generate, and therefore measures can be taken to eliminate the source of defects before they can affect the build process.

Moving beyond imagery techniques, one of the more promising techniques being developed is in-situ ultrasonic (UT) monitoring of the build process. In-situ UT can be used to monitor the laser power in SLM machines, with the A-scans allowing an inspector to infer conclusions about the quality of the SLM process. Reider et al. [14] describe the process of using in-situ UT when producing Inconel 718, a nickel alloy used for aero engine components. The UT monitoring system used a four-channel transmitter and receiver system with a bandwidth ranging from 400 kHz up to 30 MHz, a sampling rate of 250 MHz and 14-bit resolution, the ability to perform 1,000 A-scans every second, and a temporal resolution of 4 ns. The SLM process was monitored in a layerwise fashion with simultaneous visualization of the radio frequency (RF) signals. Because in-situ monitoring is still a relatively recent development, the parts manufactured for testing were simple test cylinders, with each one having intentional defects added to the build process in the form of spherical and half spherical voids made of nonmelted powder. During the build, the voids were clearly seen in the scans, thus indicating that the SLM process can be used to fabricate calibration blocks.

In-situ UT can also be used to monitor the single-layer fusion process by comparing the time-of-flight of the ultrasonic signal and the build time. This technique takes advantage of the ability of AM to produce nominally consistent layer thicknesses during the build time. In this instance, the average layer thickness was 40 µm (see Figure 13), meaning that for a part with a total thickness of 20 mm, the build time is approximately 90 min.

In another test, the researchers varied the laser power to monitor the effects on the microstructure of the Inconel test part. Taking advantage of the high numbers of A-scans the system could record, researchers plotted the scans against the build time to view areas of low beam power, which resulted in areas of high and low porosity.

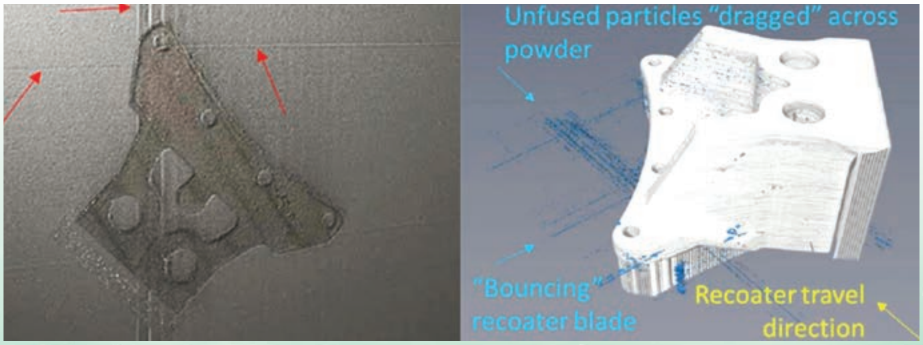

Figure 12. As Individual Images Are Collected of Each Build Layer, a 3-D Model Can Be Generated and Correlated With CT Scans (CAD Design of Test Article Provided by Honeywell) [10].

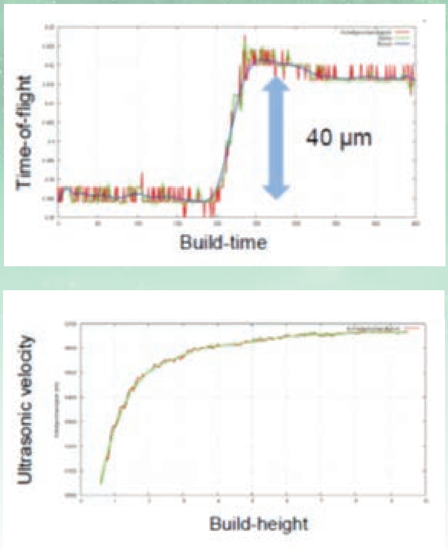

Figure 13. A Single-Layer Measurement of the Ultrasonic Signal (top), Showing a Direct Correlation With the Welding Process and Allowing a Determination in the Changes of the Ultrasonic Velocity as a Function of Build Height (bottom) [14].

Verification of the in-situ UT monitoring was conducted in the post-build phase using CT scans. As seen in Figure 14, the aberrations seen in the UT B-scan align neatly with the porosity imaged by the CT scan.

A newer form of UT in-situ inspection is also in development using laser ultrasonics (LUT). LUT works by using a pulsed laser beam to generate a transient ultrasonic wave in the solidified layer. The waves then interrogate the layer for defects and arrive at the point of detection. The resulting surface displacement is then detected with a separate laser-based receiver. As the beams scan along the layer during production, the signal detected at each position is acquired, and the signals are combined to form a B-scan image that can be interpreted

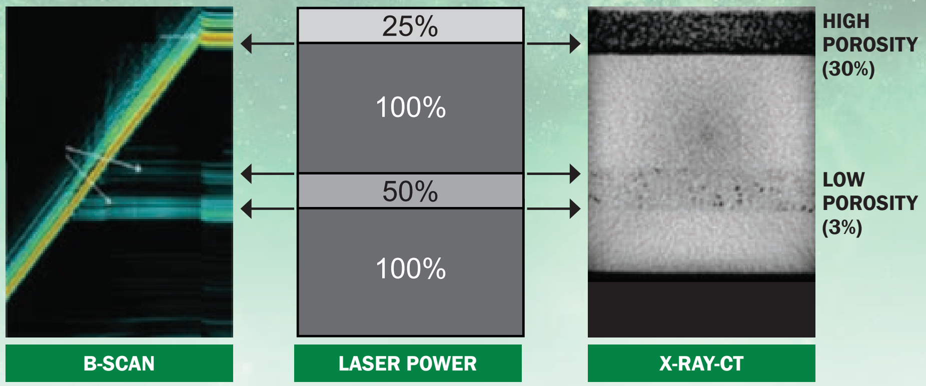

Figure 14. The B-Scan (left) Shows a Clear Indication of the Drop in Laser Power During the Build Time, With the Resulting Porosity Verified Through a Post-Build CT Scan [14].

with advanced, automated signal and image processing algorithms to determine the integrity of each layer [15].

Figure 15 shows a defect and the corresponding signal used to create the defect profile. By applying a threshold level, seen as the yellow line in the right image, the detection of defects can be an autonomous process. LUT in-line monitoring is still in development, but if the technology is able to mature, it has the potential to ensure that all finished AM parts will be qualified without the need for further inspections.

Post-Production Inspection

In-situ monitoring can be a powerful tool for monitoring process control and preventing large-scale batch poor builds; however, this monitoring does negate the need for post-build inspection of parts. While most of the post-build inspection of AM parts is identical to the inspection processes of subtractive manufacturing, the method of inspection is often found to be a greater function of the complexity of the AM part. For instance, penetrant dye testing (PT) (such as shown in Figure 16) is often used to find surface cracks in traditionally made parts. However, because AM relies on the stepwise layer slice build-up of the part, the surface roughness is often greater than with subtractive manufacturing.

PT is based on using capillary action to draw the dye into the crack, whereby the excess dye is removed from the surface and an ultraviolet light is shone on the part, illuminating any dye that has become trapped in the cracks. The surface roughness of the AM part presents multiple opportunities for small cracks to form between the layers as the part is built up, thus making it an almost insurmountable task to use PT on an as-built part, at least without first performing post-processing machining and polishing.

Beyond examining surface cracks with PT, AM parts can be inspected using Process Compensated Resonance Testing (PCRT). PCRT is used in the automotive, aerospace, and power generation industries. To conduct the test, the AM part is excited at its resonance frequency and the frequency shift is analyzed to determine whether or not the part is

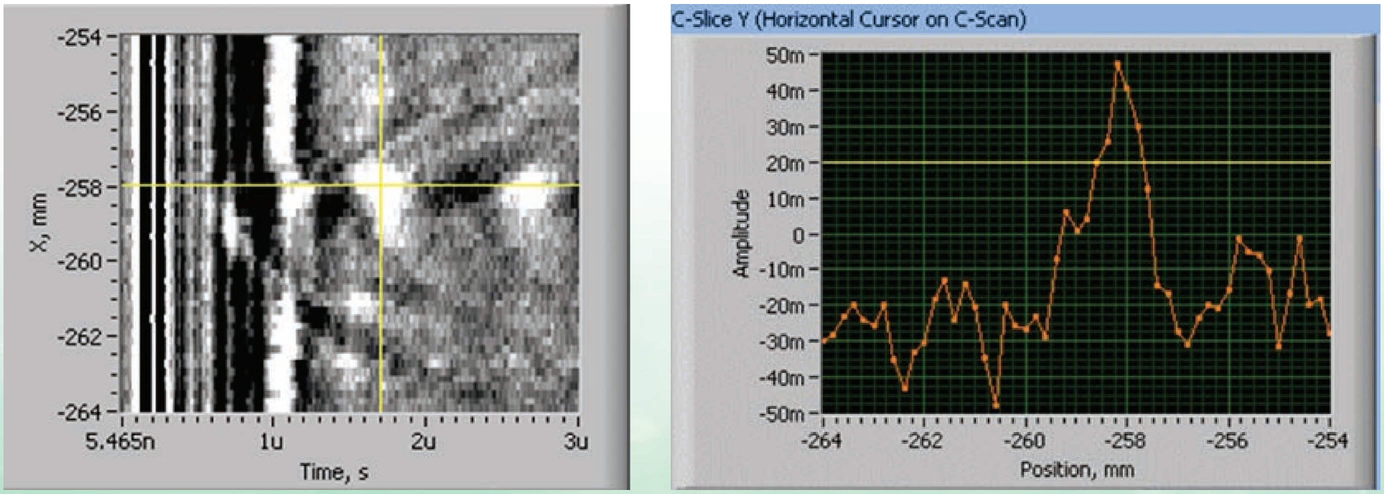

Figure 15. B-Scan of a Sample Specimen (left) With a Defect Located at Position -258. A Defect Profile Can Be Generated From the Returned Laser Ultrasound Signal (right) [15].

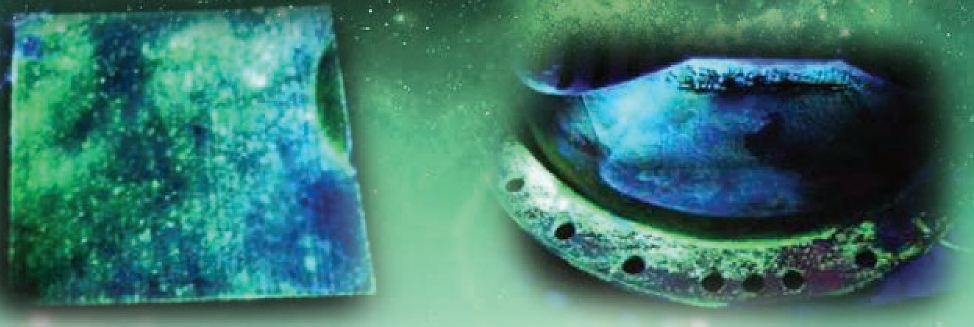

Figure 16. Penetrant Testing of Ti-6Al-4V for a Liquid Rocket Gaseous Hydrogen/Liquid Oxygen Injector (left) and a POGO-Z Baffle (right) Showing High Levels of Noise Due to the Surface Roughness of the Parts [3].

acceptable. PCRT has been employed in evaluating in service engine blades. If the mass and the stiffness of the part is known, the process is fast and reliable. However, PCRT is considered a global test and does not provide the location of any defects, thus making it a good gatekeeper test with the ability to identify the parts that have no defects or the parts that need additional inspections.

The need for fast first-look testing is important given that the most widely used inspection method is X-ray CT. Industry has been using CT inspections since 1972, and this method has proven its effectiveness by allowing inspectors to detect the exact position of the defect within the body of the part. In a CT scan, a radiation source transmits X-rays through the part to a collector, where the images are compiled and reconstructed by a computer to create a 3-D image. CT scans can be a powerful tool, able to reach further into a part than other NDE methods, no matter the complexity. The resolution of the CT scan is dependent on the power of the scanner. As the power of the beam increases, the depth of the beam penetration increases, which means that a more powerful beam is able to scan a denser part. This is not to say, however, that a low-powered scanner should not be used in the inspection process. Inspection of less dense parts can employ a low-powered scanner with a radiation source with a small emitter size and can achieve resolutions down to the submicrometer scale [5]. For AM parts produced through powder beam methods, defects are expected to be on a smaller scale, and therefore submicrometer detection is a powerful asset.

Figure 17 shows an example of the power of CT scans. Inspectors are able to detect and locate all instances of porosity in the test cube. CT scans are considered the best post-production inspection method for AM parts up to Group 4 complexities; and if microfocused CT scans are employed, even Group 5 complexity parts can be inspected by this method. However, the higher inspection capabilities do come at a cost. CT scanning equipment is expensive and needs a radiation source to power the beam. CT scans also produce high volumes of data and therefore need intense computing power to return results in a timely and useful manner. A Group 2 part might take 10 min to process a few gigabytes of data using dual multicore processors, but as the parts become more complex and the number of welds becomes higher, the scan analysis quickly becomes an operation that can take hours to perform. If complex AM parts are to become more prevalent in everyday use, the ability to inspect the parts quickly and accurately is going to be the limiting factor.

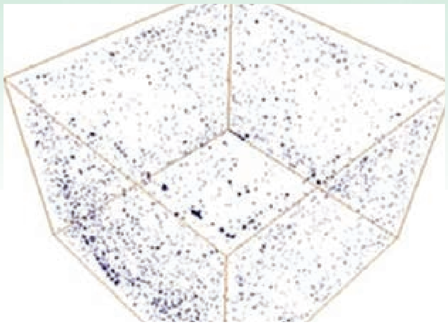

Figure 17. 3-D View Generated by a CT Scan of the Porosity in a Ti-6Al-4V Cube Produced by Electron Beam Melting [5].

As with in-situ monitoring, LUT is also showing promise in post-production inspections. The benefit of the LUT as opposed to CT devices is the lack of a radiation source and the subsequent infrastructure needed to support it. This means the LUT systems can be less expensive and therefore more available to manufacturers.

Figure 18 demonstrates the work performed by Levesque et al. in applying LUT to post-production inspection of AM parts. The Inconel piece was scanned from the substrate underside in the span marked by the arrows. The scans detected a slight

Heat Affected Zone (HAZ) as well as indications of possible discrete porosities in the thicker areas of the part. LUT is still being developed but has the potential to work in conjunction with in-situ processes and other post-production inspection methods to decrease the time needed to perform inspections on complicated AM parts.

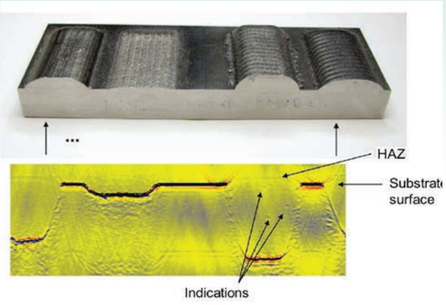

Figure 18. Laser Ultrasound B-Scan of a Coupon of Inconel 718 Showing Indications in the Build [16].

CONCLUSION

AM has not been widely adopted in the aerospace industry because there is a lack of standards and methods for easily and quickly qualifying parts for flight. Simple AM parts can be qualified by the same methods as traditionally made parts; however, as the complexity of the part grows, the ability to inspect it becomes limited. Current developments for in-situ monitoring seek to impose stricter process control as a first step to mitigating the formation of defects, while post-production inspections can provide a final certification of the part for use. As more improvements in the methods are developed, the aerospace industry will be more likely to employ AM parts in greater numbers and increase the economic impact of 3-D printing through new and innovative designs and less material needed to produce those designs. ■

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BIOGRAPHIES

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RUSSELL AUSTIN is a senior engineer at Texas Research Institute/Austin, focusing on nondestructive inspection technology development and condition-based maintenance. His background includes low-frequency ultrasonics/acoustic emission to detect and locate damage in large structures, microwave/millimeter-wave inspection of thick and/or lossy polymer materials, and development of miniature embedded structural health monitors. He started his career operating the infrared thermography laboratory at Argonne National Laboratory. He has a B.S. in materials engineering from the New Mexico Institute of Mining & Technology.

DTIC SEARCH TERMS:

Nondestructive Inspection NDE Additive Manufactured Parts

RESULTS: 2,020

- Symposia (265)
- Laminates and Composite Materials (264)
- Composite Materials (258)
- Nondestructive Testing (216)
- Aircraft (172)
- Materials (161)
- Mechanics (151)
- Information Science (139)
- Manufacturing (135)
- Export Control (128)

*See page 30 for explanation ▸

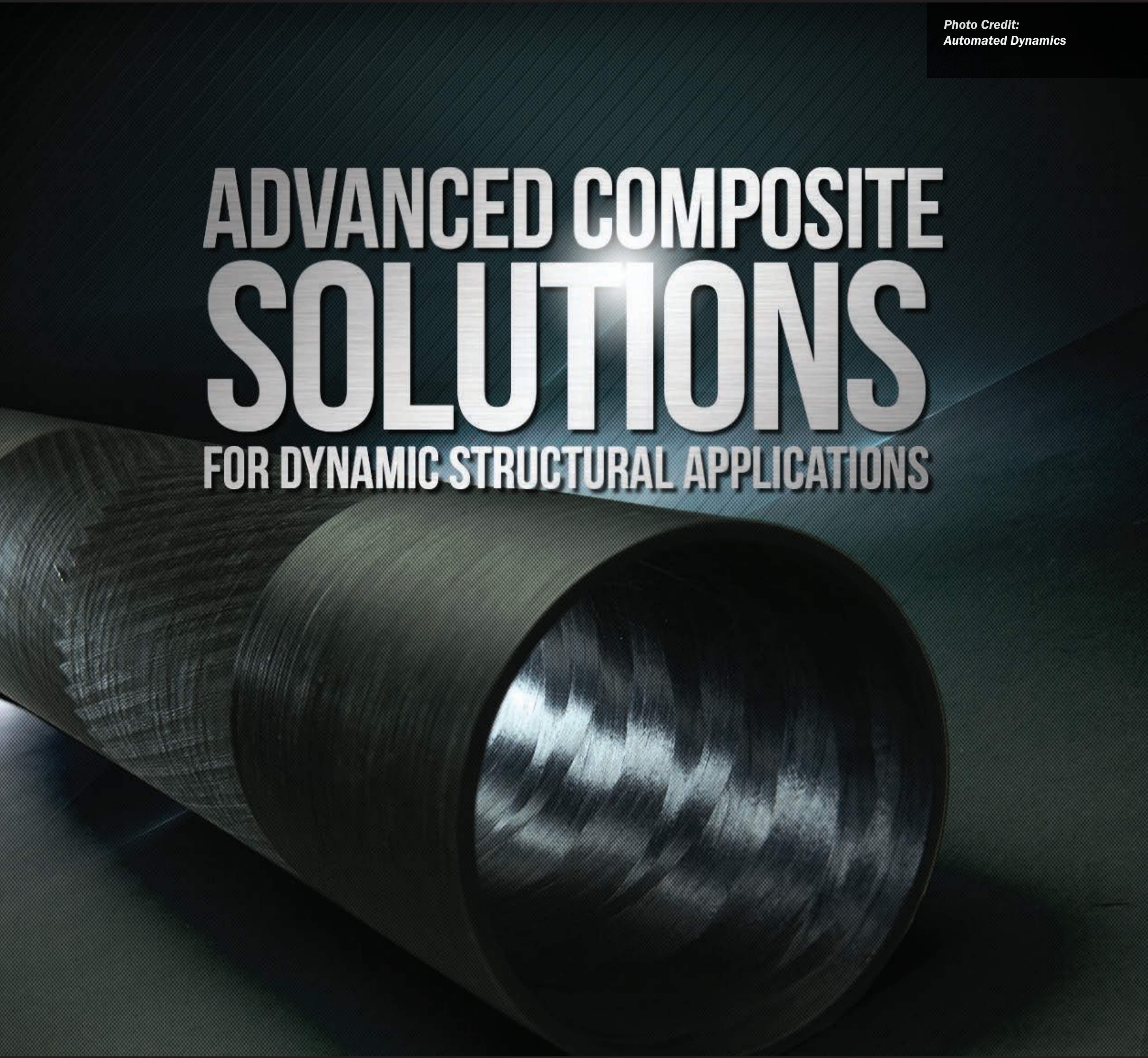


Photo Credit: Automated Dynamics

ADVANCED COMPOSITE SOLUTIONS

FOR DYNAMIC STRUCTURAL APPLICATIONS

INTRODUCTION

By Harry R. Luzetsky

The selection and application of advanced composite materials play a critical role in the quest for improving performance of air and ground vehicles to meet ever-changing requirements. Unique properties of composites provide designers with the capability to customize structural characteristics of components and structures while yielding a reduction in weight over metallic counterparts. Initial application of composites to vehicles was applied to secondary structures, but as these composites and applications have matured, they have been expanded to primary structures. One of the most challenging applications has been to dynamic components, such as transmission drive shafts associated with rotary-wing aircraft. The development of composites with high levels of damage tolerance, coupled with unique manufacturing processes, has made their application to drive shafts a reality.

The use of an IM7/polyetheretherketone (PEEK) composite using in-situ tape placement fabrication technology has

demonstrated the ability to construct a composite damage-resistant, ballistic-tolerant rotary-wing drive shaft. Through an evolutionary process, design data and techniques were developed to support this application. Test shafts were designed and fabricated, and their performance was validated. In addition, design/material data were evaluated to identify any data gaps that would obstruct transition of the technology to a production environment. Through a building-block approach, shafts were developed, design tools were validated, and test shafts were created for a ground test vehicle to support system design tests. In addition, an expansion program has been designed to transition the developmental shafts to a production configuration. This expansion program includes addressing identified design and data gaps, developing inspection processes, and developing manufacturing support processes and techniques required for the production of a flight-critical drive shaft.

HISTORICAL PERSPECTIVE

The first significant application of composites material to a military helicopter was made by Boeing Helicopters in the 1980s with its experimental technology demonstrator medium-lift tandem-rotor cargo helicopter, the Boeing Model 360. While Boeing and other aircraft companies were pursuing potential applications of composites to existing and future platforms, the number and types of composites being made available were rapidly increasing.

In 1981, International Chemicals Industry (ICI) introduced a PEEK thermoplastic under the name of Victrex. This material was a semi-crystalline polymer with a maximum 48% degree of crystallinity. The counterpart composite material was introduced a year later as APC-1 with a 52% fiber volume, and it was optimized to yield APC-2 with a 63% fiber volume. The fiber adhesion properties of APC-2 resulted in superior impact and crack resistance compared to the APC-1, as well as existing epoxy-based composites. With a concerted effort by ICI Fiberite to develop manufacturing processes, in-situ tape placement was developed. The process, when coupled with the material properties, provided an ideal composite material for a drive shaft application.

To support various developmental activities, material data were created and used to develop preliminary design allowables and methodologies that were applicable to the design of drive shafts. From this work, shaft designs were ultimately developed to support the RAH-66 Comanche program, and the tail rotor drive shaft was planned to be constructed out of IM7/PEEK. When the Comanche program was cancelled in 2004, however, this work was suspended.

In 2010, work on an IM7/PEEK drive shaft was reborn via a U.S. Navy Naval Air Systems Command (NAVAIR) Small Business Innovation Research (SBIR) program, with the CH-53K as the target platform. Prior to initiating this program, it was necessary to reconstruct the design processes and design allowables from previous Army research programs and available data. The results of this program have demonstrated the feasibility of a highly survivable (i.e., ballistic-tolerant) thermoplastic composite drive shaft and have illustrated the ability to customize the design to meet unique shaft properties, such as frequency, thus raising the technology readiness level (TRL) to a point that would support transition to production.

NAVAIR SBIR

The 2010 NAVAIR SBIR (titled “Innovative Material Design and

Manufacturing Development for a Lightweight, Low Cost, Highly Survivable Drive Shaft") picked up on the initial industry research leveraging lessons learned and material characterization efforts of IM7/PEEK thermoplastic and furthered the technology to produce a highly survivable drive shaft. There were two phases for this program demonstrating the survivability capability of the IM7/PEEK drive shaft, as well as the ability to customize its properties to meet stringent design requirements. Supplementing this initial research is an expansion program designed to transition the work from Phases 1 and 2 to a production shaft with the required level of material characterization (i.e., design allowables and material properties), manufacturing process development, inspection techniques, and process validation through analysis and test.

While conducted in two phases, the shaft development work has consisted of the following three distinct elements:

1. Design Allowable Evaluation and Verification
2. Design Process/Analysis Development and Expansion
3. Ballistic Design, Test, Evaluation, and Demonstration.

Design Allowable Evaluation

B-basis design allowables (90% probability with 95% confidence) recreated from data used in previous Army experimental programs were evaluated to determine viability in supporting a drive shaft design and to identify any data gaps that would require resolution to support technology transition to a production application. While a large database of material information is required for establishing B-basis design allowables, the database for the IM7/PEEK allowables was limited. In addition, ongoing processing improvements designed to reduce void content meant that the material property values would be changing with the process evolution. To account for the limited property database, advanced statistical regression techniques were used in accordance with MIL-HBDK-17 (CMH-17) guidelines for pooling daza where insufficient data from a single fiber/resin configuration are available (as long as all the pooled data possess the same resin matrix).

> Composites provide the capability to customize structural characteristics of components and structures while yielding a reduction in weight over metallic counterparts.

Due to limited data availability, it was necessary to pool data from AS4, IM6, and IM7 PEEK to develop a material database of adequate size to develop B-basis allowables. In addition, the available data used in this process were taken from different fabrication processes and were not exclusively representative of the in-situ tape placement process used for drive shaft fabrication. The data were grouped as determined appropriate by batch analysis studies. The justification for this approach relies on the resin-dominated properties being the same coupled with an understanding of the fiber contributions to the overall material properties.

Because autoclaving and press curing were used to manufacture the test specimens to develop the design allowables, it was necessary to cross-walk these values against the material properties produced using the in-situ tape placement process used to fabricate the drive shafts. From this evaluation, it was determined that the existing design B-basis design allowables were acceptable for development of prototype shafts as they tended to underpredict performance. However, to support transition to production, the allowables would have to be refined to better account for the in-situ tape process-generated properties. This conclusion came from comparison of properties developed through a series of material property tests configured to provide a material property comparison between the in-situ process and data used to create the B-basis allowables. The in-situ developed data were compared with the preliminary B-basis allowables and the respective database. From this comparison, it was determined that while shear-dominated properties require additional refinement, the current B-basis allowables are adequate to support initial design of a drive shaft and represent a conservative approach.

Design Process Development

To facilitate the laminate design of the shaft, a process was required to quickly evaluate different ply orientations and layups for their ability to meet the program objectives. This evaluation process was achieved by using classical laminate theory with the Tsai-Wu failure criteria. Relationships were developed in an engineering calculation software package. They were developed in a manner permitting simple modification of the laminate orientation and applied torsion load to determine torsional load capability. The analysis evaluates the shaft configurations for torsional buckling and strength in the undamaged configuration, as well as torsional strength in the damaged configuration. The damaged configuration is developed by introducing elliptical damage into the calculation meant to simulate the amount of damage expected from a ballistic event. This degree of damage was developed from previous test data and represents an estimate of expected damage from the ballistic threat defined for this program.

Analysis assumptions used Kirchhoff hypotheses, which assume all normals remain straight (do not bend), unstretched (keep the same length), and normal (always make a right angle to the neutral plane). In addition, perfect bonding is assumed for the laminate. This means the bonding itself is infinitesimally small (there is no flaw or gap between layers), it is non-shear-deformable (no lamina can slip relative to another), and the strength of bonding is as strong as it needs to be (the laminate acts as a single lamina with special integrated properties). From this analytical approach, it was possible to quickly assess different fiber orientations for weight, torsion capability (with and without ballistic damage), lateral stiffness, and frequency.

Drive Shaft Design Parameters and Fabrication

As mentioned, drive shaft design parameters were derived from the CH-53K helicopter platform. The goal of the composite design was to determine the architecture required for a thermoplastic composite driveshaft to be a direct replacement for the existing aluminum shaft. A minimum 15% weight reduction over that of the aluminum shaft, which equates to approximately 0.213 lb/unit inch of shaft length, with no reduction in performance was required. The composite shaft was required to possess the same geometry as the existing shaft with an inner diameter (ID) of 6.25 inches and an outer diameter (OD) of 6.5 inches. The drive shaft configuration would have to experience temperatures of -40 °C (-40 °F) to +50 °C (+122 °F) during continuous operation and of -54 °C (-65 °F) to +71 °C (+180 °F) in a nonoperating or storage and transport capacity. The natural frequency cannot exceed 15% of 118% of 4,269 rpm. Torsional loads must be fully reversible, and unbalanced forces must be constrained to 2.8 g_m-in at operating speed.

Several design configurations were developed for this program to evaluate the effect of fiber orientation on the mechanical properties and optimize the design (greatest properties for least weight). A typical IM7/PEEK composite drive shaft is shown in Figure 1, which was processed with the in-situ tape placement process shown in Figure 2.

Figure 1. IM7/PEEK Drive Shaft.

Figure 2. Driveshaft Fabrication Using Automated Dynamics In-Situ AFP Process.

In the in-situ tape automated fiber placement (AFP) process, the thermoplastic composite tape (i.e., IM7/PEEK) is applied to a mandrel via an automated process that first heats the raw material using a hot gas torch stream and then consolidates/compacts the laminate with a rigid steel roller. The heating agent is nitrogen gas, which is heated as it passes through an electrically resistive heating element to elevate the raw material temperature up to its melting point. The material is then passed between a rigid steel roller and the processing tool to consolidate the material. The first layer of material is placed onto a cold tool. Subsequent layers are placed on top of the previous layers to form the laminate of desired thickness and fiber orientation. Each new layer is melt-bonded to the previous layer. The laminate is built to the desired specifications and then removed from the tooling. At this point, the laminate is considered complete. There is no post-processing needed. The part is then trimmed to the desired geometry and is ready for use.

Drive Shaft Design Verification

The ballistic and static torsion properties were validated through a series of ballistic and static tests that used a test fixture (shown in Figures 3 and 4) supplied by the NAVAIR China Lake Test Facility. Torque was applied through a rotation disc via actuators, and a digital inclinometer was used to support measurement of shaft rotational angular deflection.

The test fixture was modified to accept a composite driveshaft, and the appropriate actuator arrangement (actuators, pump, and controls) to support the loads (introduction rates and magnitude) required for both the ballistic and post-damage torsion-to-failure tests was included. In addition, a data acquisition system (DAQ) was designed and fabricated to record readings from the load cells (used to measure applied torque) and a digital inclinometer (used to measure shaft angle). To exercise the capabilities of the fixture prior to beginning the test sequence, a test shaft was used to evaluate the fixture functionality.

The range configuration illustrated in Figure 5 shows the orientation of the test fixture in the range with the hydraulics nearest the gun barrel to minimize damage potential, and Figure 6 shows the actual test setup.

The ballistic test fixture design incorporated an actuator system to apply and maintain a predefined torsion load during test and to increase loading at a 20,000 in-lb$_f$/min rate until failure of the test shaft occurred. Throughout the load application, the angular deflection of the shaft was measured. A plot was generated comparing reacted torque as a function of angular deflection to characterize the performance of the shaft. Of the tests conducted, all but two tests were conducted at room temperature dry (RTD) conditions. The two exceptions required thermal conditioning prior to the ballistic event. One shaft was conditioned at +180 °F and the other at -40 °F. Thermocouples were used to verify that the appropriate conditions were achieved and present during the ballistic event.

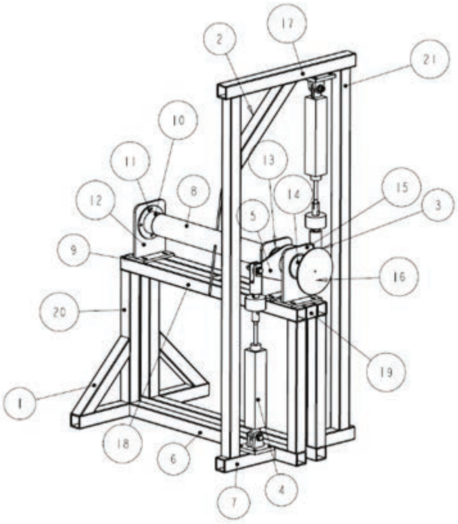


Figure 3. Schematic of Test Stand With Shaft.

Figure 4. Actual Test Stand With Shaft.

Design verification testing of the ballistic damaged shafts included the following:

1. The ballistic impact load was set at 32,000 in-lb$_f$ of torque to simulate the worst-case flight scenario during an impact event, with the load application set in the direction that would cause the damage from the event to close on itself. Testing on a slotted shaft realized lower torsion levels with the load applied so as to close the slot as compared to one in which the slot would open.

2. The extent of ballistic damage was characterized by a nondestructive inspection (NDI) coin tap methodology.

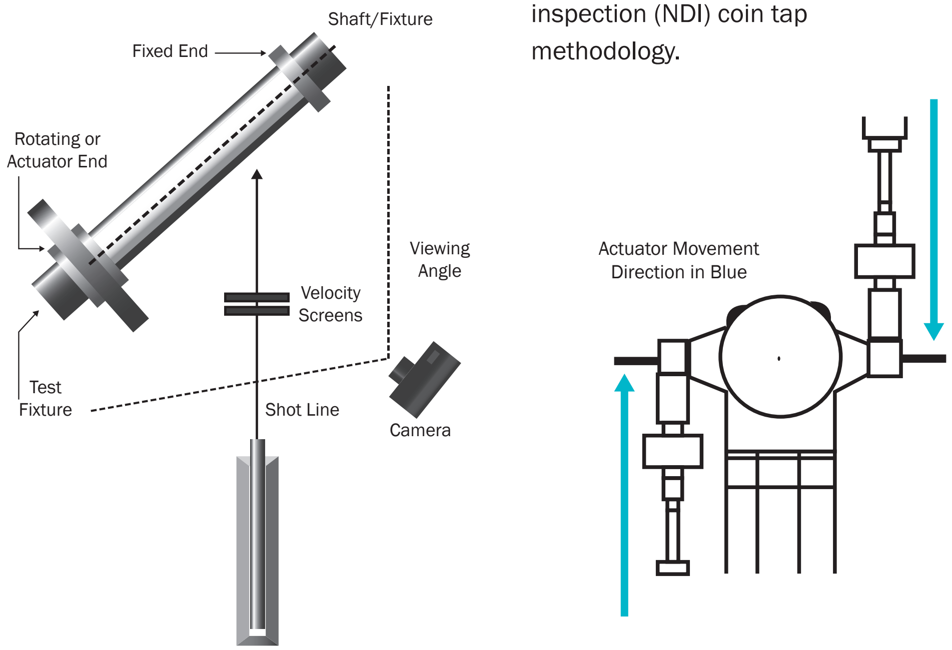
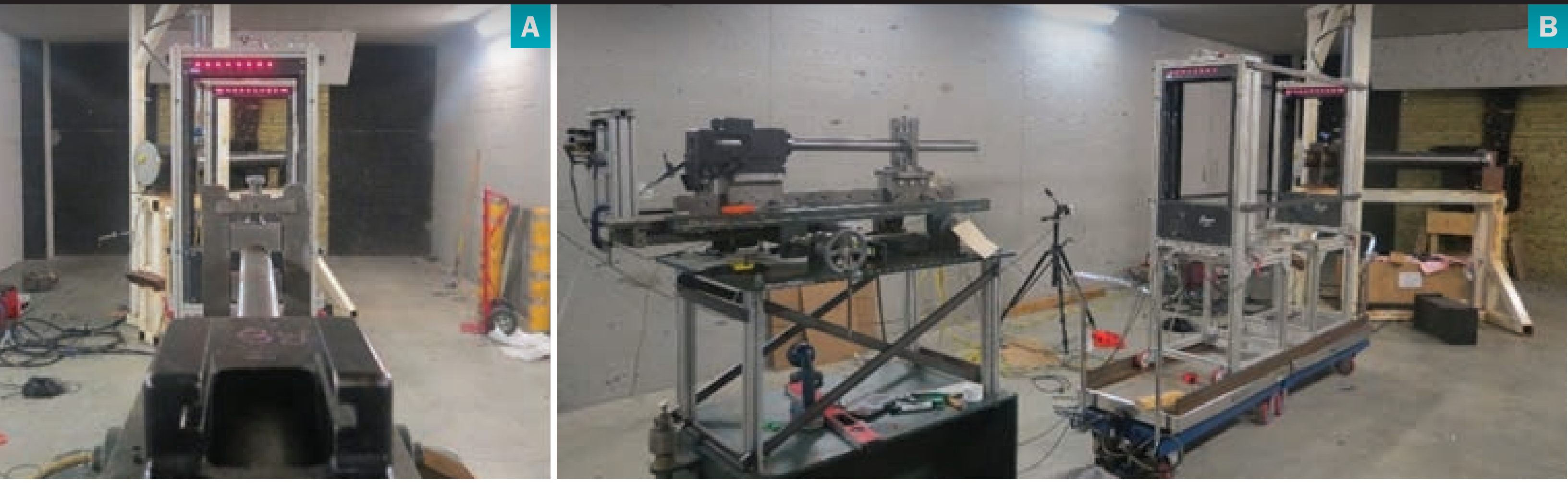


Figure 5. Schematic of Range Setup.



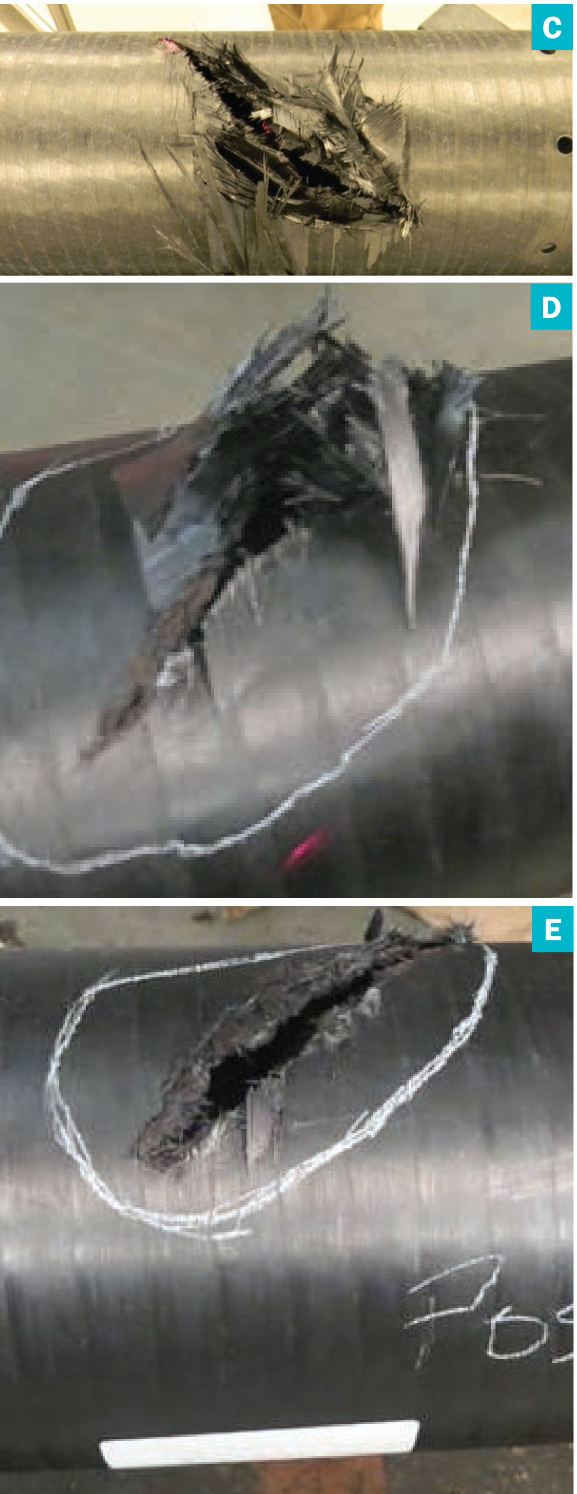


Figure 6 (A and B). Typical Range Setup.
Figure 7 (C, D, and E). Ballistic Test Results for Normal (C) and Tumbled (D and E) Impact Events.

3. Thermal measurements for conditioned specimens were taken at several intervals prior to test, including at removal from the conditioning chamber, at installation into test fixture (start and end), and prior to the ballistic event.
4. The weight of the shafts was measured to the hundredth of a pound before and after the ballistic event to determine approximate weight reduction due to material loss from the ballistic impact, which was used to determine potential shaft out-of-balance.
5. The post-damage shaft was tested with a 20,000 in-lb$_f$/min loading rate until failure of the test shaft.
6. Drive shaft lateral stiffness was measured by the angular inclination of the fixture load application moment arm before, during, and after the ballistic impact event.
7. Post-impact stiffness was measured using the angle of inclination as captured by the inclinometer and was recorded continuously during the post-damage test as a function of applied load.
8. Both normal and tumbled projectile events were used to damage the test shafts. Figure 7 shows typical damage for each event type although the degree of damage varied for the test events.

In each of the developed designs, the measured properties of the test drive shafts were greater than that calculated in the design process. As shown in Table 1, the calculated properties for the drive shafts underestimated the actual test results by approximately 50%.

When considering specimens with similar degrees of damage (TP3, 4, 5, 6, and 8) the calculated properties consistently underpredicted by approximately 31%. Those with a lesser degree of visible damage were capable of supporting an even greater torsion load, resulting in a larger deviation between the calculated properties and test data.

Several factors attributed to the differences between the model and test results. These include:

- Conservatism built into the B-basis design allowables.

Table 1. Design/Analysis Correlation

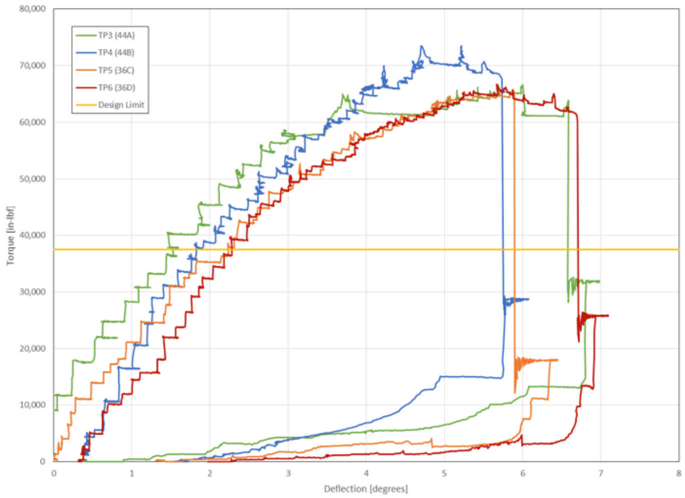
Test Specimen Designation	Number Of Plies	Specimen Type (Layup)	Calculated Torque Undamaged (in-lbs)	Calculated Torque Damaged (in-lbs)	Measured Torque Undamaged (in-lbs)	Measured Torque Damaged (in-lbs)	Delta (%)
TP3	44	A	258,500	49,200	NA	63,814	30%
TP7	44	A	258,500	49,200	NA	110,664	125%
TP8	44	A	258,500	49,200	NA	53,603	9%
TP12	44	A	258,500	49,200	NA	86,630	76%
TP11A	44	A	258,500	49,200	NA	92,555	88%
TP4	44	B	287,800	53,200	NA	67,639	27%
TP5	36	C	197,600	41,700	NA	64,616	55%
TP6	36	D	229,100	44,300	NA	58,543	32%
TP1	44	A (Spare)	258,500	49,200	338,000	NA	31%
TP10	44	A (Spare)	258,500	49,200	NA	NA	NA

- The application of the Tsai-Wu first-ply failure approach to define the torsion failure point for the shaft. In reality, composite laminates often can support greater loads than that which may initiate failures in the laminates on an individual ply basis.
- The estimate of the damage in the analytical model. As the actual damage deviates from this condition, so does the torsional load from the calculated value.
- The degree at which the B-basis design allowables represent the mechanical properties produced using the in-situ tape placement process.

The effect of elevated and depressed shaft temperature did not adversely affect the torsion performance of the shafts. As with the room temperature tested shafts, both cases tested above the design limit torque. There was no apparent degradation in mechanical performance for either conditioned shaft. In considering the various design architectures, all of the shaft configurations performed above their respective design limits, and the failure modes were extremely similar (as illustrated in Figure 8).

As illustrated in Figure 9, drive shafts impacted with tumbled projectiles (TP11A and TP12) exhibited a higher static ultimate torque than a similar shaft shot straight on. The visible damage for both tumbled round shafts was more localized to the impact zone than the straight shot shafts although the nonvisible delaminated region (as defined by the tap test) was larger. Note that TP11A experienced an initial decrease in load-carrying capacity at approximately 4.5° of deflection. Even after this decrease, the shaft still easily carried between 60,000 and 70,000 in-lbs although at this point the shaft entered progressive failure where every increase in applied load resulted in increasing deflection and lessening reacted torque.

In torsion testing of an undamaged shaft (no damage present), the failure occurred at the bolt pattern at a static ultimate torque level of more than 338,000 in-lb_f. There was no apparent damage to the body of the shaft, and this measured failure level was 31% greater than that predicted by the analytical process.



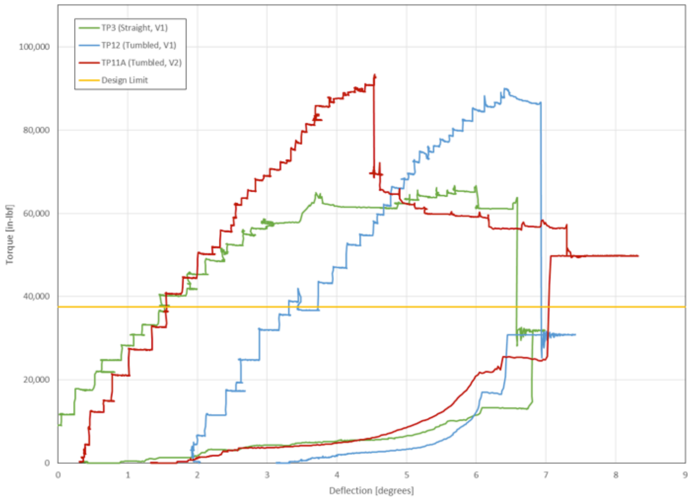


Figure 8 (left). Damaged Shaft Torque-to-Failure vs. Layup.
Figure 9 (right). Damaged Shaft Torque-to-Failure vs. Projective Configuration.

During evolution of the designs, it became necessary to modify shaft properties for frequency response to improve overall drive train properties. This modification required reduction of the margin of safety associated with the shaft design in favor of developing the proper frequency response. Using the same analytical process for the ballistic shafts, a balanced design was developed and the frequency response of the resultant fabricated shaft was correlated against the analytical predictions using both stiffness and rap testing.

CONCLUSIONS

The NAVAIR SBIR program validated the potential of an IM7/PEEK drive shaft for application to a helicopter drive train. The program met all performance and gate requirements as defined in the statement of work and supporting documentation. A number of candidate shaft designs were fabricated based on coupon-level test data. These shafts successfully withstood a ballistic event under load and continued to meet performance requirements when they were torqued to failure afterwards. The effect of varying the layup, manufacturing process, projectile configuration, and temperature were examined in these tests. The candidate shaft designs all far exceeded the minimum weight reduction (15%) exhibiting weight reductions of up to 33%. In addition, it was demonstrated that the frequency response of the composite drive shaft, unlike its metal counterpart, could be tailored.

With these results, prototype shafts were delivered to support operation of a ground test vehicle and an expansion program was designed to produce the necessary data to transition the technology to a production variant for the CH-53K. Furthermore, the success of this program and previous research work has laid the groundwork for IM7/PEEK and its derivatives to be considered in numerous air and ground vehicle applications, both static and dynamic, offering advances in performance at lower weights than offered by traditional materials. ■

BIOGRAPHY

HARRY "RICK" LUZETSKY is a subject-matter expert at the SURVICE Engineering Company, with more than 30 years of experience in composites and more than 20 years of experience in survivability. With a specific expertise in design, test, and research and development, Mr. Luzketsky has helped develop and assess survivability features for numerous aircraft and has been active in composite design for vehicle performance and survivability improvements. He is the lead engineer for SURVICE's role in the development of the thermoplastic drive shaft and is a co-author of a pending patent on an advanced fuel containment technology, and fiber reinforcement structural composite faraday cage enclosure for electronics. Mr. Luzetsky holds a B.S. in materials engineering from Drexel University.

ACKNOWLEDGMENTS

The author wishes to acknowledge the following organizations and individuals for their invaluable involvement in this program: NAVAIR for its sponsorship of SBIR N101-097 (especially Ms. Leslie Leigh for her leadership and guidance in the execution of the program); Automated Dynamics for its program management and fabrication efforts to turn engineered designs into viable composite drive shafts; and Sikorsky Aircraft and United Technology Aircraft Systems (UTAS) for their general support and guidance. In particular, UTAS is acknowledged for its performance of frequency measurements and preparation of the shafts for use on the ground test vehicle.

DTIC SEARCH TERMS:

Fiber-Reinforced Thermoplastics

RESULTS: 6,170

- Laminates and Composite Materials (1,819)
- Composite Materials (1,440)
- Plastics (993)
- Polymers (836)
- Fiber-Reinforced Composites (747)
- Mechanical Properties (681)
- Symposia (527)
- Mechanics (525)
- Laminates (486)
- Thermoplastic Resins (470)

*See box below for explanation ▸

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NDIA

SCIENCE AND TECHNOLOGY CONFERENCE REVIEW

By Bruce Simon

This past April, DSIAC attended the 17th Annual National Defense Industrial Association (NDIA) Science & Engineering Technology Conference in Tampa, FL. Presenters included Department of Defense (DoD) policymakers and science and technology (S&T) community leaders, who discussed issues and initiatives to move S&T capabilities forward and to bring together industry, academia, and the Services to face emerging challenges presented by U.S adversaries.

NDIA S&T Chairman James Chew, the Director of Strategic Development for General Atomics, opened the conference by stating that although the DoD S&T program remains strong, there is a lack of coordination between private sector innovations and DoD needs. In particular, there is no obvious outlet for innovations to get into the military market from the private sector. One of the conference's goals, therefore, was to bring together DoD planners, the Combatant Commands (CCMDs) and their requirements, and the communities of interest (COIs) to streamline and make available opportunities for cooperation and collaboration.

Dr. Melissa Flagg, Deputy Assistant Secretary of Defense for Research, OASD(R&E), framed the issues further by stating that, as we come out of 15 years of war, many ask what S&T is doing for us. We need to change what we fight with and how we fight as our adversaries close our 40-year technological superiority gap (see the technological superiority trends in Table 1).

We must bring in young engineers and reject the idea of decline. Our vision is sustaining U.S. technological superiority through S&T, preparing for an uncertain future, and accelerating delivery of technical capabilities to the warfighter. Our mission is to create technological surprise through S&T to ensure technological superiority, mitigate current and anticipated threats, win the current and future fight, and provide affordable options. As the global access to technology and talent by competitors is challenging U.S. cost and cycle time, we must assure that our military retains superior and global access to these critical assets.

The issues outlined by Dr. Flagg are supported by the DoD's Better Buying Power Initiatives. In particular, Better Buying Power 3.0 is making sure, in the words of Dr. Flagg, that "we get the most for our buck." We must plan more jointly and include the COIs in the process. And bringing together the laboratories, private sector, and academia is crucial. We have to ensure that what we do is more efficient, with less spending on overhead and more on actual research.

Likewise, the Honorable Stephen Welby, Assistant Secretary of Defense for Research and Engineering, discussed the crossroads we are at today as well as the offset strategies that require big change, such as the third offset strategy.

Table 1. Technological Superiority Trends Relative to Competitors

	Near Term (2020)	Mid Term (2025)
Air Domain	↓	↓
Maritime Domain	↓↓	↓↓
Undersea Domain		↓
Electromagnetic Spectrum	↓	↓
Space Domain	↓↓	↓↓↓
Resilient Comm, ISR, PNT	↓↓	↓
Resilient Basing	↓↓	↓↓

The first of these offset strategies, Mr. Welby noted, occurred in the 1950s, when President Eisenhower sought to overcome the Warsaw Pact's numerical advantage by leveraging U.S. nuclear superiority to introduce battlefield nuclear weapons—thus shifting the axis of competition from conventional force numbers to an arena where the United States possessed an asymmetrical advantage. This approach provided stability and offered the foundation for deterrence.

The second of these offset strategies arose in the late 1970s and 1980s with the recognition that the Soviet Union had achieved nuclear parity. This strategy, informed by studies such as the 1973 Long Range Research and Development Planning Program, sought to create an enduring advantage by pursuing a new approach to joint operations—leveraging the combined effects of conventional precision weapons; real-time long-range intelligence, surveillance, and reconnaissance (ISR) sensor capabilities capable of supporting real-time precision targeting; and the joint battle networks that permitted these capabilities to be synchronized and executed over the full breadth of the battlespace. These integrated systems-of-systems provided a significant force multiplier by improving the efficiency and effectiveness of conventional strike systems, creating opportunities for synergistic effects across warfighting domains, and permitting U.S. forces to more effectively and rapidly project conventional power globally with reduced forward presence.

Mr. Welby went on to note that neither of these two original offset strategies was solely about technological advantage. In each case, it was the right combination of technology-enabled operational and organizational innovation that provided decisive strategic and operational advantage and therefore bolstered conventional deterrence.

So what has changed? Mr. Welby pointed out that today's competitors, such as Russia and China (and countries to which these nations proliferate advanced capabilities), are pursuing and deploying advanced weapons and capabilities that demonstrate many of the same technological strengths that provide the technological basis for U.S. advantage. This growing symmetry between U.S. technical capabilities and near-peer potential competitors is particularly seen in the capabilities demonstrated during Russian power-projection operations in Syria. Mr. Welby also explained that the emergence of increasing symmetry in the national security environment suggests that it is again time to begin considering the mix of technologies, system concepts, operational concepts, and military organizations that might shift the nature of the competition to U.S. advantage. Such a set of capabilities would provide the basis for a third offset strategy.

> The Defense Innovation Unit - Experimental (DIUx) should serve as a nexus between innovating ecosystems and the DoD.

As was true of previous offset strategies, a third offset strategy, Mr. Welby stated, would seek, in a budget constrained environment, to maintain and extend U.S. competitive technological and operational advantage by identifying asymmetric advantages that are enabled by unique U.S. strengths and capabilities. A third offset strategy would also ensure that our conventional deterrence posture remains as strong in the future as it is today and would establish the conditions to extend that advantage into the future.

The DoD anticipates that the capabilities delivered through a third offset strategy will enable the Joint Force to:

- Fight and deliver effects from a distributed posture at extended ranges.
- Leverage range, precision, and speed to seize and maintain the initiative.
- Leverage dispersal and new forms of operational sanctuary to increase survivability.
- Achieve mass in the form of ensembles of many low-cost, collaborating "effectors."
- Develop new forms of distributed maneuver and close combat techniques that combine kinetic, electronic warfare, and cyber-enabled operations.
- Operate battle networks much less vulnerable to cyber and electronic attack.

Mr. Welby concluded that we must engage all parties, including industry, academia, Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), and global partners, to rapidly advance new technology development, innovation, speed, and agility and ultimately ensure technological superiority. The DoD labs are the centers for driving science and technology ideas. There are 63 labs and engineering centers that provide expertise and enhance our warfighting capabilities. There must be more industry partnerships. And the newly formed Defense Innovation Unit - Experimental (DIUx) should serve as a nexus between innovating ecosystems and the DoD.

Mr. Robert Baker, Deputy Director, Plans and Programs, OASD (R&E), addressed the President's FY17 budget submission to Congress. He said that S&T is 2.7% of the DoD's top line budget. He also said that the S&T budget submission has 0% growth and that this is a good thing because the rest of the defense budget has dropped. S&T investment is $12.5 billion, and we need to protect it. Mr. Baker also spoke to the need for technological superiority, noting that the five main challengers today are Russia, China, North Korea, Iran, and ISIL. We must mitigate current and anticipated threat capabilities and work more affordably. We must create technological surprise. Through the third offset, we must concentrate on anti-access area denial systems, robotics, biotechnology, autonomous learning systems, human machine collaboration, and unmanned and autonomous systems; and we must make critical finance decisions.

Mr. Earl Wyatt, Deputy Assistant Secretary of Defense, Emerging Capabilities & Prototyping, OASD (R&E), spoke about using prototyping to accelerate the adoption of transformative capabilities and bringing ideas to DIUx. He explained that prototyping is a set of design and development activities intended to reduce technological uncertainty to improve the quality of subsequent decision-making. Better Buying Power talks about prototyping, cost, and how we make decisions. The offset strategy is how to offset a cost disadvantage with a force multiplier that we can employ. Mr. Wyatt also identified the focus areas for FY17, which include asymmetric force application, the electromagnetic spectrum, autonomous systems, and the integration of operations and analysis.

Col. Steve Butow, representing the Lead National Guard Element, DIUx, discussed how disruptive technologies that were once safely possessed by advanced nations have proliferated widely and are now being sought or acquired by unsophisticated militaries and terrorist groups. Other competitor nations are closing the technology gaps by pursuing and funding long-term modernization programs. DIUx seeks and supports the innovation of disruptive technology that sustains and extends U.S. strategic advantage.

In addition, the respective Services presented their S&T program overviews, with a common emphasis on the importance of defining future needs and capabilities, the challenges of the current budget, and the need to protect the S&T budget.

Mr. Kurt Kratz, Deputy Administrator of the Defense Technical Information Center (DTIC), spoke of the tools of the information analysis centers (IACs), including DSIAC. He explained that the IACs are a collection of subject-matter experts (SMEs) from industry, government, and academia that provide resources for partnerships. For industry, the IACs are a way to get an in-depth look at government needs across warfighting labs and program managers. For the industry defense and innovation marketplace, there is a portal that covers the CCMDs' unclassified needs (see www.dtic.mil). Mr. Kratz also urged industry conference participants (with proper clearances) to use the combatant commanders' reading room at DTIC to learn about classified needs.

Mr. Dale Ormond, Principal Director, Research, OASD (R&E), explained the needs of the CCMDs and the roles of the COIs. He discussed the complicated acquisition process and the need to meet the needs of the CCMDs quickly. He also explained the process that the Joint Chiefs and Services use to procure capabilities on behalf of the CCMDs. Mr. Ormond stated that the S&T community needs to have demonstrations and put developmental items into the hands of operators to help adjust to their needs. He advised industry to be tied to the labs and to work with the joint staff to have demonstrations.

Mr. Ormond also discussed Reliance 21, the overarching framework of DoD's S&T joint planning and coordination process, as well as the issues of S&T oversight, emerging threat mitigation, affordability generation, joint coordination, and the S&T executive committee (led by Steve Welby). He stated that one role of the COIs is to defend S&T investments—that is, to identify opportunities and efficiencies that provide data to ensure that warfighters are receiving the greatest benefit from S&T resources and efforts. As far as Better Buying Power goes, he said that we must eliminate duplication and explore collaborative opportunities. Industrial engagement is crucial.

DSIAC is continuing to collaborate with the organizations and representatives who participated in this year's NDIA Science & Engineering Technology Conference. In particular, ongoing discussions with Col. Butow, Mr. Chew, Mr. Wyatt, Mr. Ormond, Dr. Michelle Atchison (the University of Texas System's Associate Vice Chancellor for Federal Relations), and others will help continue to advance DSIAC integration with these and other organizations in the community. ■

TECHNICAL MONOGRAPHS NOW AVAILABLE ON THE DSIAC STORE

DSIAC is pleased to announced that five Technical Monographs are now available from the DSIAC Store (at **www.dsiac.org/store**). The Technical Monograph initiative was started in 2013 by the SURVICE Engineering Company under the sponsorship of the former Survivability/Vulnerability Information Analysis Center (SURVIAC). The purpose was to develop and document unique (and potentially perishable) technical information, insights, and experiences from senior-level subject-matter experts to support personnel/community development, technical training, and/or information archiving. This effort continues today under the sponsorship of DSIAC.

The five SURVICE/DSIAC Technical Monographs now available are as follows:

- **"An Overview of Blast and Its Effect on Combat Systems,"** *SURVICE Monograph 13-001, by James Walbert, May 2013 (distribution authorized to U.S. Government agencies and their contractors).*

  The use of large explosive charges detonated under ground combat systems has long been a source of concern for those responsible for developing, analyzing, and improving these systems. And this concern has only increased in recent years as the use and size of these charges have markedly increased in modern combat zones. This monograph is intended to provide survivability analysts, designers, testers, and field assessors with a more complete understanding of the subject by defining pertinent terminology, describing the fundamental physics of blast and other detonation products, examining various aspects of mitigation, and dispelling myths that surround these phenomena.

- **"Projectile Aerodynamic Approximations Derived in Closed Form From Limited Data,"** SURVICE *Monograph 13-002, by Fred Malinoski and James Walbert, September 2013 (approved for public release; distribution is unlimited).*

  The approximations in this monograph provide simple, easy-to-calculate one-dimensional values for various aerodynamic functions for projectiles, such as range as a function of velocity, time as a function either of range or velocity, and drag as a function of velocity, assuming there are data on any one of them. In the absence of actual data or full three-dimensional computational methods, these approximations enable trajectory calculations not otherwise possible.

- **"Time Series Analysis and Its Application to Ballistic Data,"** *SURVICE Monograph 14-001/DSIAC-TR-2014-001, by James Walbert, August 2014 (approved for public release; distribution is unlimited).*

  This monograph is intended to serve as an introduction to the topic of time series analysis, documenting numerous methods for analysis of ballistic data, such as pressure and acceleration. The methods have applicability beyond ballistic data as well.

- **"An Introduction to Ground Combat System Ballistic Vulnerability/Lethality Analysis,"** *SURVICE Monograph 14-002/DSIAC-TR-2014-002, by James Walbert, August 2014 (approved for public release; distribution is unlimited).*

  Based on a training course developed and taught by the author, this text focuses on the fundamental methodologies, approaches, models, tools, and practices that are (or should be) used in conducting ground combat system vulnerability/lethality studies. Extensive coverage is also given to mathematical counterexamples and statistical anomalies, as well as common misuses and misinterpretation of data, mathematical and statistical methods, and the natural variability inherent in physical processes.

- **"Ballistic Equations: A Compilation of Equations and Methods for Evaluation of Parameters Relevant to Penetration, Blast Effects, and Crater Formation,"** SURVICE *Monograph 15-001/DSIAC-TR-2015-001, by James Walbert, August 2015 (distribution authorized to U.S. Government agencies and their contractors).*

  Critical to combat system survivability analysis is the ability to estimate the effects of threat-target interactions. However, this ability is particularly challenging given the inherent variability in the fundamental physical processes of detonation physics, fracture mechanics, and penetration mechanics. Thus, the analyst must seek to bound the problem and its solution set (e.g., using first-order estimates) and find a range of possible outcomes given a range of initial conditions. This document is a compilation of equations and methods that form the basis for a number of analytical tools designed to provide first-order estimates of the effects of ballistic-related penetration and blast.

To obtain copies or find out more about these and other publications available from DSIAC, please visit **www.dsiac.org**. ■


U.S. Navy

ADVANCES
IN SELF-SEALING FUEL TANK TECHNOLOGY

By Kyle Bates

INTRODUCTION

Pilots of World War I often called the aircraft they operated "flying coffins" (as shown in Figure 1). The grim nickname was a reflection of aircraft technology that was previously untested in combat and barely a decade old. By World War II, however, aircraft technology had become far more advanced in virtually every way. The new generation avoided enemy fire by flying higher and faster, and it also survived combat damage far more effectively. Stories abound of World War II pilots returning with aircraft so thoroughly perforated by enemy gunfire that they had to be scrapped after landing safely. One significant component that was largely responsible for this leap in survivability (and that is so commonplace in aircraft today that it is often taken for granted) is the self-sealing fuel tank [1].

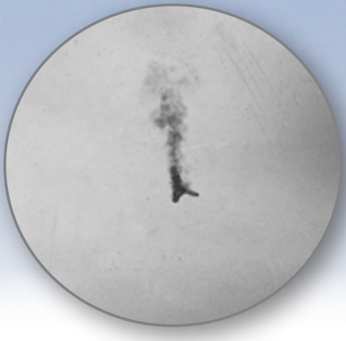
Figure 1. World War I Aircraft in Flames Falls From the Sky (Source: National Wold War I Museum).

Although the earliest iterations of self-sealing fuel containment date back to World War I, it was not until a concerted effort started in the late 1930s that a truly effective and reliable self-sealing design was established. And some designs that resulted from this effort can still be seen in the fuel tanks of today's military aircraft. The fundamental elements, including the self-sealing mechanism, are largely unchanged. However, over the last decade, during the wars in Afghanistan and Iraq, there has been a renewed effort to improve self-sealing fuel containment technology. This article reviews self-sealing fuel containment technology from its inception through select examples of modern advanced designs.

AN ELEGANTLY SIMPLE AND ENDURING DESIGN

The inception of effective self-sealing technology was enabled by advances in rubber material processing. These innovations coincided with a rise in the demand for rubber materials in commercial and military applications leading up to World War II. In 1940, the U.S. Naval Proving Ground at Dahlgren, VA, began testing fuel tank designs provided by each of the four largest rubber manufactures at the time: Firestone Tire and Rubber Company, B. F. Goodrich Company, Goodyear Tire and Rubber Company, and U.S. Rubber Company [1]. Each of these companies, and several smaller ones, committed significant resources toward the research and development of self-sealing fuel containment technology (see Figure 2). It is therefore not surprising that two of the companies that currently produce many of the fuel tanks for modern military aircraft, Zodiac Aerospace and Meggitt, started out as spin-off companies from Firestone and Goodyear, respectively.

The self-sealing technology that was developed through that effort and that has persisted through multiple wars—and despite dramatic changes in the employing aircraft—is elegantly simple. The fundamental design consists of a layer of soft rubber "sealant" that swells in the presence of fuel and that is sandwiched between two polymer layers that are impervious and insoluble to fuel. When a bullet perforates the composite lay-up and fuel begins to leak through, the sealant layer swells into the hole and stops the flow.

This simple composition and design, which are inexpensive, lightweight, and easily produced in large volumes, confronts the deceptively complex ballistic dynamics of a bullet perforating a fuel tank. When a normally oriented bullet pierces a fuel tank, it leaves a small residual hole less than the diameter of the projectile. But this small hole is just the beginning of the challenge. The bullet, travelling at 3,000 ft/s, begins to unload its tremendous kinetic energy on the fuel inside. This unloading generates a high-velocity wave of pressure in the fuel that is reflected back on the wall milliseconds after the bullet tears through. This pressure wave, known as hydrodynamic ram, blasts a jet of fuel back through the entrance wound. The bullet, still moving at a high velocity, and now followed by the same pressure wave, begins to tumble as it travels through the fuel. When it reaches the back wall of the tank, the bullet erupts sideways through the material and leaves an elongated gash that is often torn further by the trailing wake of hydrodynamic ram.

> An ever-present desire to reduce aircraft system weight has pushed current self-sealing fuel tanks to their physical limits.

Initial fuel tank prototypes tested by Navy engineers were discouraging

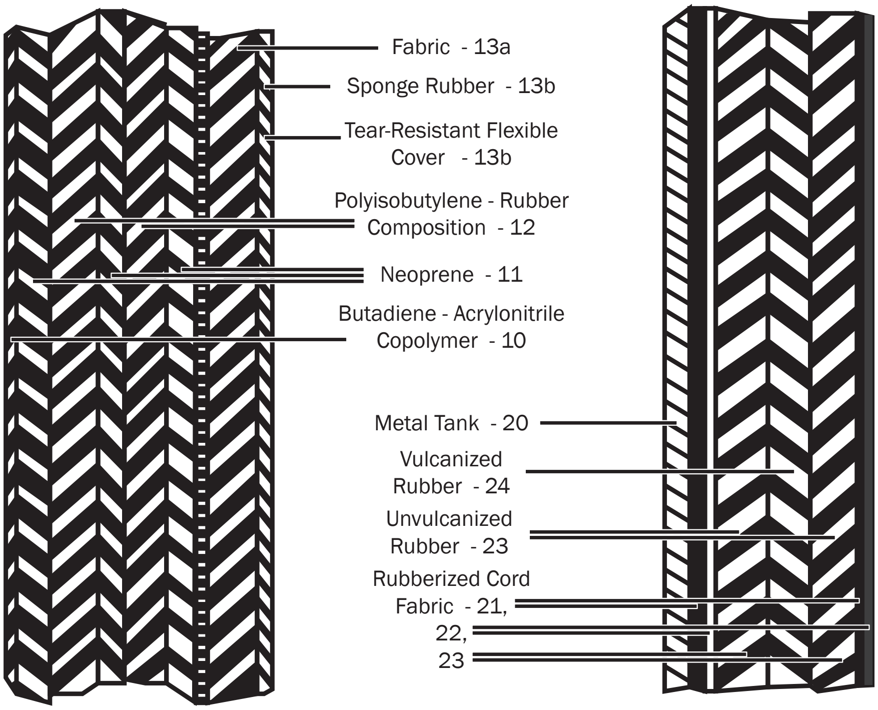

Figure 1

Figure 2

Figure 2. Figures From a 1941 Patent for a "Self Sealing Fuel Tank." Assigned to B. F. Goodrich [2].

failures. Engineers had not anticipated the challenging dynamics, and often the entire back walls of prototype tanks were blown out by the hydrodynamic pressure wave. However, these early development tests shed some light on the mechanisms that brought down so many pilots and aircraft during the World War I. The Navy and rubber company engineers persisted and established remarkably effective design features and manufacturing processes that ultimately saved untold lives not just in World War II but in each of the armed conflicts since then.

INCREMENTAL CHANGES

Over the years, manufacturers have made incremental improvements to the fabrication processes and materials used in self-sealing fuel tanks. In the 1950s and '60s, during the South East Asia conflict, new survivability measures were implemented to reduce the likelihood of fire as a result of a ballistic impact or vehicle collision. An Air Force investigation team identified that the single most important cause of aircraft losses was fuel system fire or explosion. This finding led to key changes in aircraft fuel tank design [3].

The first change addressed the volatile fuel vapor that resides in the ullage space within the fuel tanks. The vapor can be ignited by incendiary rounds or sparks caused by impacts to metal components. The combustion of the fuel vapor can result in catastrophic structural damage as the burning vapor rapidly expands. Engineers determined that the risk of fuel vapor deflagration was effectively reduced by filling fuel tanks with low-density reticulated polyurethane foam. The foam material promotes condensation of the fuel vapor and disrupts the combustion propagation within the tank.

Engineers also significantly improved vulnerability by establishing standards to make fuel tanks "crashworthy"—meaning that the fuel tank can withstand the force of impact associated with a modest crash of 65 ft. Fuel tank manufacturers were able to meet the standards by improving their fabrication processes and incorporating layers of woven fiber reinforcement within the fuel tank wall composite lay-ups. Crashworthy fuel system design and the guiding requirements were pioneered by Dr. Harry Robertson and documented in the Military specification MIL-DTL-27422, which remains today as the guiding document for crash-resistant and ballistic-tolerant fuel tank requirements and verification testing protocols [4].

NEW APPROACHES

A new wave of fuel tank design innovation has occurred over the last two decades in response to a number of factors. The wars in Iraq and Afghanistan have highlighted the vulnerability of fuel systems in some ground vehicles. In response, ground vehicles are increasingly requiring self-sealing and blast-resistant fuel tanks for improved survivability. Department of Defense (DoD) initiatives to use more synthetic and renewable fuels are also driving innovations away from the traditional self-sealing approach. Unfortunately, these changes in fuel chemistry can diminish the efficacy of the traditional sealant materials. In addition, an ever-present desire to reduce aircraft system weight has pushed current self-sealing fuel tanks to their physical limits. Rather than trying to squeeze weight out of fuel tank designs that have been optimized over the course of 60 years, any additional lightweighting may depend upon the invention of completely novel designs.

When the first self-sealing fuel tanks were created, they employed the most advanced materials available at the time. Much has changed since 1939 in the way of materials science, particularly in the realm of polymers. High Impact Technologies LLC (HIT) has developed a design that reimagines the classic self-sealing approach with modern materials to achieve a similar self-sealing function. The technology, called BattleJacket® (shown in Figure 3), consists of layers of a custom polyurethane elastomer that sandwich a middle layer containing small fuel-imbibing beads. The beads readily swell as they absorb leaking fuel and expand to seal ballistic perforations. This self-sealing function is analogous to one provided by the soft rubber sealant in traditional self-sealing fuel tanks. A differentiating feature of the HIT design is that the system is applied by spray coating. This unique production process enables application onto the exterior of existing fuel tanks. The system has been successfully deployed in theater on fuel tanker trucks and Mine Resistant Ambush Protected (MRAP) vehicles.

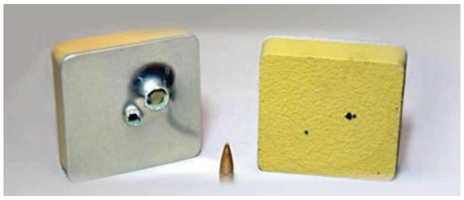

Figure 3. Exit Holes Through an Alumininum Substrate (left) and Entrance Holes Through the Opposite Side Spray-Coated With BattleJacket Material (right) [5].

Another (patent pending) approach, recently developed by the SURVICE Engineering Company, abandons the traditional principle that relies on swelling from the absorption of fuel. The sealing mechanism is self-contained and functions independently of fuel or air exposure.

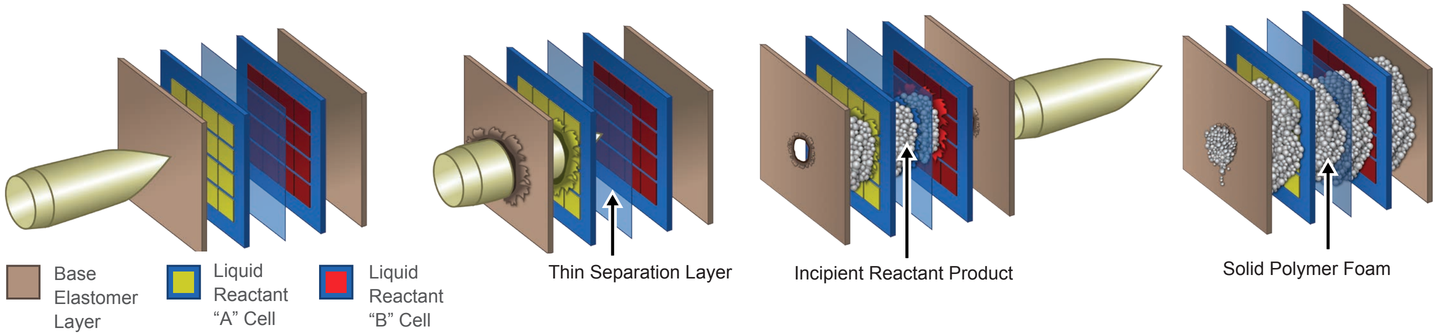

Figure 4. Functionality of SURVICE's Autonomous Self-Sealing System. Layers Are Depicted in an "Exploded" View for Visibility [6].

As illustrated in Figure 4, two liquid reactants are contained separately in discrete cells that are embedded within the wall of the fuel tank. When a ballistic impact breaks the cells, the reactants flow together and begin to rapidly polymerize. The reaction forms a solid foam material that expands within seconds to seal the damaged area. Because the mechanism operates independently from the contained fuel type, it is effective for use with nontraditional fuels that can undermine the self-sealing capabilities of conventional self-sealing systems. Recent ballistic and crash impact testing of prototype specimens built to MIL-DTL-27422 standards has confirmed the technical feasibility, but it has also indicated the need for continued development. The test specimens demonstrated an ability to seal normally oriented and tumbled small- and medium-caliber threats typically encountered by aircraft, but repeatability has not yet been fully achieved. The Joint Aircraft Survivability Program Office (JASPO) is sponsoring continued development for the promising technology.

CONCLUSIONS

The self-sealing fuel tanks developed prior to World War II were a landmark in aviation survivability. Their simple and reliable technology has endured for more than 60 years, even while the aircraft that use them have changed radically. But the legacy self-sealing approach is increasingly seen as an old technology that is ripe for innovation. The next generation of self-sealing fuel tanks will need to combine the steadfast reliability of the original designs while providing warfighters with critical increased survivability in air and ground vehicles as well as project managers (who must now count every fraction of an ounce) with critical weight reduction. ■

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BIOGRAPHY

KYLE BATES is a senior engineer at the SURVICE Engineering Company. He has worked in the area of self-sealing fuel tank research, development, and testing since 2008. He serves as the lead engineer for SURVICE's autonomous self-sealing fuel containment system and is a co-author of a pending patent on the technology. Mr. Bates holds an M.S. in materials science engineering from Johns Hopkins University and a B.S. in Engineering Science from Loyola University in Maryland.

DTIC SEARCH TERMS:

Self-Sealing Fuel Tank Technology

RESULTS: 2,840

- Helicopters (476)
- Aircraft (412)
- Vulnerability (314)
- Survivability (246)
- Fuels (184)
- Test and Evaluation (180)
- Military Operations, Strategy and Tactics (164)
- Transport Aircraft (160)
- Fuel Tanks (141)
- Attack and Fighter Aircraft (137)

*See page 30 for explanation ▸

CONFERENCES AND SYMPOSIA

JULY 2016

2016 MSS Tri-Service Radar
11–14 July 2016
Venue TBD
Boulder, CO
https://www.sensiac.org/external/mss/meetings/list_meetings.jsf ▸

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7th Annual Integrated Air and Missile Defense Symposium
14 July 2016
Johns Hopkins University
Laurel, MD
http://www.ndia.org/meetings/6100/Pages/default.aspx ▸

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Automated Vehicles Symposium 2016
18–22 July 2016
Hilton San Francisco Union Square
San Francisco, CA
http://www.auvsi.org/emevents/event-description?CalendarEventKey=2725786f-db61-43ab-bfc9-643eee0fc5d4&Home=/events1aa/events ▸

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AIAA Propulsion and Energy Forum and Exposition (AIAA Propulsion and Energy 2016)
25–27 July 2016
Salt Palace Convention Center
Salt Lake City, UT
http://www.aiaa-propulsionenergy.org/?_ga=1.166006270.1106410592.1462975418 ▸

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Military Helicopters 2016
25–27 July 2016
Venue TBD
Enterprise, AL
http://www.militaryhelicoptersusa.com/ ▸

For more events, visit:
dsiac.org/resourses/events ▸

AUGUST 2015

Global Explosive Ordnance Disposal (EOD) Symposium & Exhibition
2–3 August 2016
Bethesda North Marriot Hotel & Conference Center
Bethesda, MD
http://www.ndia.org/meetings/6950/Pages/default.aspx ▸

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NDIA Annual CBRN Defense Conference and Exhibition
2–4 August 2016
Building 4516
Aberdeen Proving Ground, MD
http://www.ndia.org/meetings/6300/Pages/default.aspx ▸

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19th Annual Space & Missile Defense Symposium
16–18 August 2016
Von Braun Center
Huntsville, AL
https://smdsymposium.org/ ▸

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AM3D Additive Manufacturing + 3D Printing Conference & Expo
21–24 August 2016
Charlotte Convention Center
Charlotte, NC
https://www.asme.org/events/am3d-conference ▸

SEPTEMBER 2015

Insentive Munitions and Energetic Materials Technology Symposium
12–15 September 2016
Gaylord Opryland Hotel & Convention Center
Nashville, TN
http://www.ndia.org/meetings/6550/Pages/default.aspx ▸

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Additive Manufacturing Conference
13–14 September 2016
McCormick Place
Chicago, IL
http://www.additiveconference.com/events/additive-manufacturing-2016/event-summary-04cbcb98aa8348da801c1ace803b853b.aspx ▸

2016 Joint Undersea Warfare Technology Fall Conference
19–21 September 2016
U.S. Naval Submarine Base New London
Groton, CT
http://www.ndia.org/meetings/6240/Pages/default.aspx ▸

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SAE 2016 Aerospace Standards Summit
20–21 September 2016
Crowne Plaza Washington National Airport
Arlington, VA
https://www.sae.org/standardsdev/summit/ ▸

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3rd Annual Additive Manufacturing for Defense and Aerospace
26–28 September 2016
Venue TBD
Washington, DC
http://www.additivemanufacturingfordefense.com/
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2016 MSS Active E-O Systems
26–29 September 2016
Venue TBD
Springfield, VA
https://www.sensiac.org/external/mss/meetings/list_meetings.jsf ▸

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The Composites and Advanced Materials Expo (CAMX)
26–29 September 2016
Anaheim Convention Center
Anaheim, CA
http://www.thecamx.org/ ▸

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2nd Annual Integrated Air and Missile Defense
28–30 September 2016
Venue TBD
Washington, DC
http://www.airmissiledefenseevent.com/ ▸

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- Non-Lethal Weapons
- Reliability, Maintainability, Quality, Supportability, and Interoperability (RMQSI)
- Survivability and Vulnerability
- Weapon Systems