DSIAC JOURNAL

A Quarterly Publication of the Defense Systems Information Analysis Center

Volume 5 • Number 4 • Fall 2018

ADDITIVE MANUFACTURING IN THE DoD

DSIAC JOURNAL

VOLUME 5 | NUMBER 4 | FALL 2018

Editor-in-Chief: Brian Benesch
Copy Editor: Maria Brady
Art Director: Melissa Gestido

On the Cover:
Cleaning activity on an additive deoiler (photo courtesy of Avio Aero - a GE Aviation business).

The *DSIAC Journal* is a quarterly publication of the Defense Systems Information Analysis Center (DSIAC). DSIAC is a DoD Information Analysis Center (IAC) sponsored by the Defense Technical Information Center (DTIC) with policy oversight provided by the Office of the Under Secretary of Defense (OUSD) for Research and Engineering (R&E). DSIAC is operated by the SURVICE Engineering Company with support from Georgia Tech Research Institute, Texas Research Institute/Austin, and The Johns Hopkins University.

ISSN 2471-3392 *(Print)*
ISSN 2471-3406 *(Online)*

CONTENTS

CONTACT DSIAC

Ted Welsh
DSIAC Director

DSIAC HEADQUARTERS
4695 Millennium Drive
Belcamp, MD 21017-1505
Office: 443.360.4600
Fax: 410.272.6763
Email: contact@dsiac.org

Brian Benesch
DSIAC Technical Project Lead

WPAFB SATELLITE OFFICE
704 TG/OL-AC/DSIAC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.3828
DSN: 785.3828
Fax: 937.255.9673

DSIAC CONTRACTING OFFICER REPRESENTATIVE
Peggy M. Wagner (COR)
704 TG/OL-AC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.6302

DSIAC PROGRAM MANAGEMENT ANALYST
Emese Horvath
IAC Program Management Office (DTIC-I)
Office: 571.448.9753

MESSAGE FROM THE EDITOR

By Brian Benesch

Every month, DSIAC processes 1,000 scientific and technical reports. This is the average monthly rate at which we upload new scientific and technical information (STI) to the Defense Technical Information Center's (DTIC's) Research and Engineering (R&E) Gateway. When you conduct a literature search with DTIC's R&E Gateway, newly available information is available because of our continual uploads.

We are chartered with the mission of collecting STI and populating DTIC's R&E Gateway to benefit knowledge reuse amongst the entire Department of Defense (DoD) community. We research, obtain, and upload unclassified and classified STI, specifically STI related to defense systems or any of our nine focus areas. We do this with both new and old STI.

NEW STI

The majority of our new STI comes from three main sources—technical area tasks (TATs), core analysis tasks (CATs), and open sources. TAT contracts are large efforts designed with the sole purpose of producing late-breaking STI for the larger defense community. CATs have the same design as TATs but are simply smaller in scope. From these TATs and CATs, DSIAC receives reports, documents, findings, etc., and fully catalogues each STI element as it is entered into DTIC's R&E Gateway.

Open-source STI consists of documents generally captured from public sources and other non-CAT/TAT-related sources. These pieces of STI may come from DoD or Department of Energy research labs, universities, industry, etc. Our open-source STI often represents recent research but, in some cases, is a record of old work.

> We are chartered with the mission of collecting STI and populating DTIC's R&E Gateway to benefit knowledge reuse amongst the entire DoD community.

OLD STI

To ensure that old STI is not lost, we are always on the lookout for historical STI so we can archive it for posterity.

We regularly support the defense systems community by receiving their aging reports or documents, digitizing them, and uploading them to DTIC's R&E Gateway. This keeps the information forever available for future researchers, engineers, and scientists.

YOUR STI

Our STI upload services are available for your STI as well. If you have any newly-generated STI that defense researchers will benefit from, let us add it into DTIC's R&E Gateway. If you have physical STI documents that are starting to fade away or a set of digital STI stored in only one location and at the risk of being lost, let us put it into the Gateway. The more STI that is accessible through DTIC's R&E Gateway, the better resource it becomes for defense researchers. Please contact us to help get your STI uploaded in support of maximizing knowledge reuse for the DoD community. ■

OVERCOMING THE BARRIERS TO HUMAN-MACHINE TEAMS

By Katherine Hendrickson

(Source: U.S. Navy, John F. Williams)

INTRODUCTION

One of the inescapable features of the modern technical landscape is the ubiquity with which human-machine interactions occur. In warfighting, these interactions are often characterized by huge benefits and grave consequences, placing strain on the critical relationship between man and machine. This has necessitated a framework shift from machines as tools to machines as peers. Illustrating this point, Lange et al. stated that "the most critical aspect of automation is not the engineering behind the automation itself, but the interaction between any automation and the operator who is expected to work together with it" [1]. Military professionals and academics have identified a lack of trust as a critical challenge to human-machine teaming [2, 3]. A study of team learning in a military context found, "Interpersonal trust is especially important when team tasks require considerable collaboration and team situations entail risk, uncertainty and vulnerability" [4]. Obstacles to trust must be navigated and overcome to achieve even a base level of effectiveness in human-machine teams.

Enhancing interaction and trust with autonomous systems is a core mission of the U.S. Air Force [5]. The U.S. Department of Defense is already applying machines to vastly different teams—from drone swarms for reconnaissance (Figure 1) to explosive ordinance disposal (Figure 2). However, the Air Force has identified key technical challenges that include a "lack of robust and reliable natural language interfaces…fragile cognitive models and architectures for autonomous agents and synthetic teammates…[and an] insufficient degree of trust calibration and transparency of system autonomy" [5]. Ultimately, a requisite level of trust can be severely impaired by all three of these challenges—communication, comprehension, and control. Each of these will be discussed in detail, along with suggested improvements to increase trust.

Figure 1: Defense Advanced Research Projects Agency's (DARPA's) OFFensive Swarm-Enabled Tactics Program Envisions Future Small-Unit Infantry Forces Using Small Unmanned Systems in Swarms of 250 Robots or More *(Source: DARPA).*

COORDINATION

At the center of team coordination and success is communication [6]. In covert, high-stakes military combat missions, communication becomes crucial. Unfortunately, communication among human-machine teams is not yet as technically efficient or effective as human-human or machine-machine teams [7]. The U.S. Air Force Research Laboratory's vision for human-machine teams involves transitioning from a tool-user framework to a peer-peer framework, with a shared common language and understanding [8]. Two-way, peer-to-peer communication is at the center of trusting relationships, including human-machine teams [9]. There are three primary approaches to improving human-machine communication: (1) reducing translation, (2) encouraging useful member feedback, and (3) establishing common ground.

Figure 2: A Navy Explosive Ordnance Disposal Technician Conducts Counter Improvised Explosive Device Training With a Robot During Cobra Gold 2016 in Thailand, 17 February 2016 *(Source: U.S. Navy Petty Officer 2nd Class Daniel Rolston).*

A tool-user framework generally necessitates translating commands into the native language of the autonomous system through code, joystick commands, or simple phrases. To foster human-machine trust, however, personnel and machines must be peers who communicate in real-time through a common language. In a military operation, there is no time for personnel to translate inputs to a machine and interpret complex machine outputs. The mental burden of translating and interpreting orders among various human-machine members is too great a task; the mental load must shift to the machines to be effective. For example, the Atlas robot in Figure 3 must perform routine tasks such as cutting through a wall without direct personnel guidance. Autonomous systems must understand, interpret, and reply to personnel in a way that requires no lengthy translation.

It is also imperative that machines provide feedback to personnel that is easily understood and useful. In efficient teams, members "self-repair." They identify, clarify, and recover from potential miscommunications. A 2016 study of effective team collaboration found that "teams that used more self-repairs may have been able to minimize collaborative effort by clarifying and adjusting their utterances to their partner's perspective" [6]. Kozlowski et al. suggest that such feedback mechanisms be considered early in an autonomous system's design process, allowing engineering design teams to incorporate communication concerns in parallel with other system goals [10]. By including such social constructs in artificial intelligence, human-machine teaming will more closely resemble human-human teams and increase collaboration and trust.

Gervits et al. found that the most important factor of team collaboration was "the ability to efficiently establish and maintain common ground with one's teammate through task-oriented dialog" [6]. Effective directors accomplish this by supplying information for team members to confirm. By establishing common ground, all parties ensure they are heard and understood. This requires members be given the ability to frame questions and information through their different perspectives, posing a unique challenge to machines as they do not intrinsically understand differences in human perspective and behavior. Artificial intelligence should include considerations for building rapport and common ground with human team members from a myriad of backgrounds.

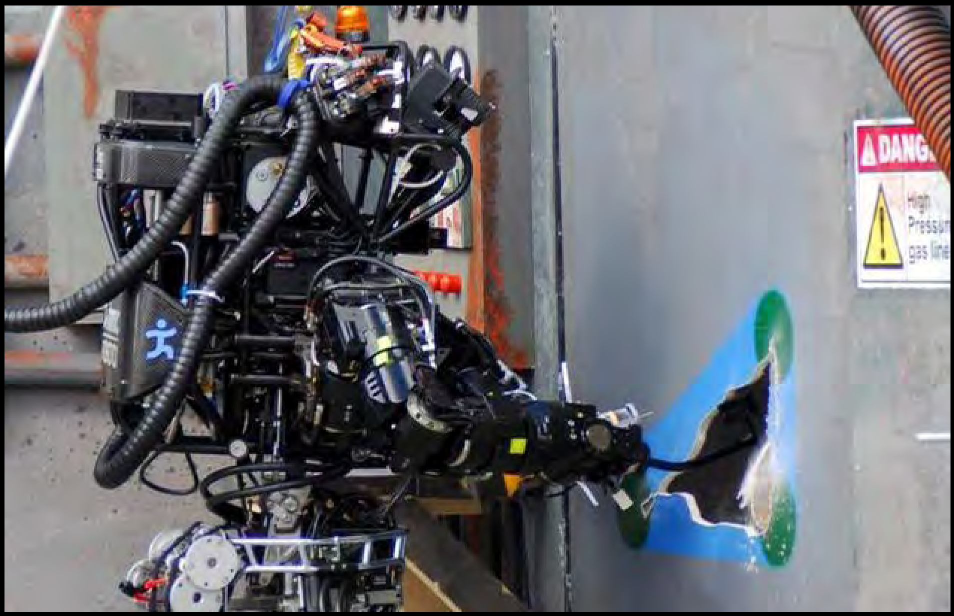


Figure 3: An Atlas Robot Is Hard at Work During the Second Round of DARPA's Robotics Challenge in 2013 (*Source: DARPA*).

To foster human-machine trust, personnel and machines must be peers who communicate in real-time through a common language.

Transferring the burden of translation from personnel to machine will greatly improve the efficiency of human-machine communication. For personnel to believe that this improved communication is accurate, however, machines must also provide feedback and establish common ground. This, in turn, will increase trust between team members. Such social developments in artificial intelligence must be considered and incorporated in human-machine teams. Ultimately, "People will trust AI systems when systems know users' intents and priorities, explain their reasoning, learn from mistakes, and can be independently certified" [11].

COMPREHENSION

Another result of the paradigm shift from user-tool to peer-peer is the need for autonomous systems. Increasing the autonomy and number of machine members creates comprehension challenges to human and machine members. This asymmetric comprehension adversely impacts trust—how can personnel trust something that they neither understand nor are understood by? According to Lewis, "The asymmetry between what we can command and what we can comprehend has been growing" [12]. Personnel must grasp the way artificial intelligence operates while trusting the machine's ability to perform assigned tasks. Artificial intelligence must understand complex environments and incorporate collaborative and combative frameworks, allowing teams to consider members' weaknesses and focus on their strengths.

Combining different perspectives and their effects on outcomes should be evaluated and incorporated into autonomous methodologies [10]. Veestraeten et al. studied team-learning behaviors in a military context and found that a "cognitive awareness of who knows what allows team members to coordinate knowledge, tasks, and responsibilities in an organised and efficient way" [4]. It is important that personnel can conceive with reasonable accuracy what machine team members know and act upon. In special operations missions, specialized and individual roles are extremely well-defined. For example, while clearing a building, the point man must know and *trust* that the other team members are monitoring their respective zones of awareness, freeing him or her to focus entirely on individual roles in the mission. This is also true in human-machine teams. Personnel must focus on their own tasks and trust that autonomous systems will perform as expected. This can be accomplished by a two-fold approach. First, autonomous systems should incorporate and encourage a reciprocal cognitive awareness among team members without overburdening personnel. They can do this through better communication and artificial intelligence that incorporates the socially complex aspects of the military team. Second, personnel can be trained with machine team members. It is important that personnel understand autonomous decision-making criteria and predict how autonomous systems should behave. By increasing the exposure and experience of personnel with machines, their understanding and cognitive awareness of each other will improve.

Improving a machine member's comprehension of movement, environments, and crowd behavior will also increase the efficiency of human-machine teams. The challenge of dense crowd maneuvering was studied by Trautman et al. by proposing incorporating crowd cooperation into the AI's decision algorithms [13]. They found that machines, when presented with a dense crowd of people, either took a highly inefficient, evasive path or froze altogether due to decision paralysis. The algorithm change incorporated a probabilistic predictive model that assumed other participants would cooperate to avoid collision with the robot. When the model also included multiple goals and stochastic movement duration, they found that it performed similarly to human teleoperators with a crowd density of 0.8 humans per square meter. Conversely, models that did not consider cooperation were 3x as likely to exhibit unsafe behavior. When generalizing to combat situations or hazards in unexpected environments, however, much more work in machine comprehension is needed. This is critical for systems such as the Shipboard Autonomous Firefighting Robot (SAFFiR) (Figure 4), which will most likely need to navigate dense crowds fleeing from the scene of the fires it must extinguish. By including collaborative and combative assumptions, artificial intelligence can better understand and navigate complex environments.

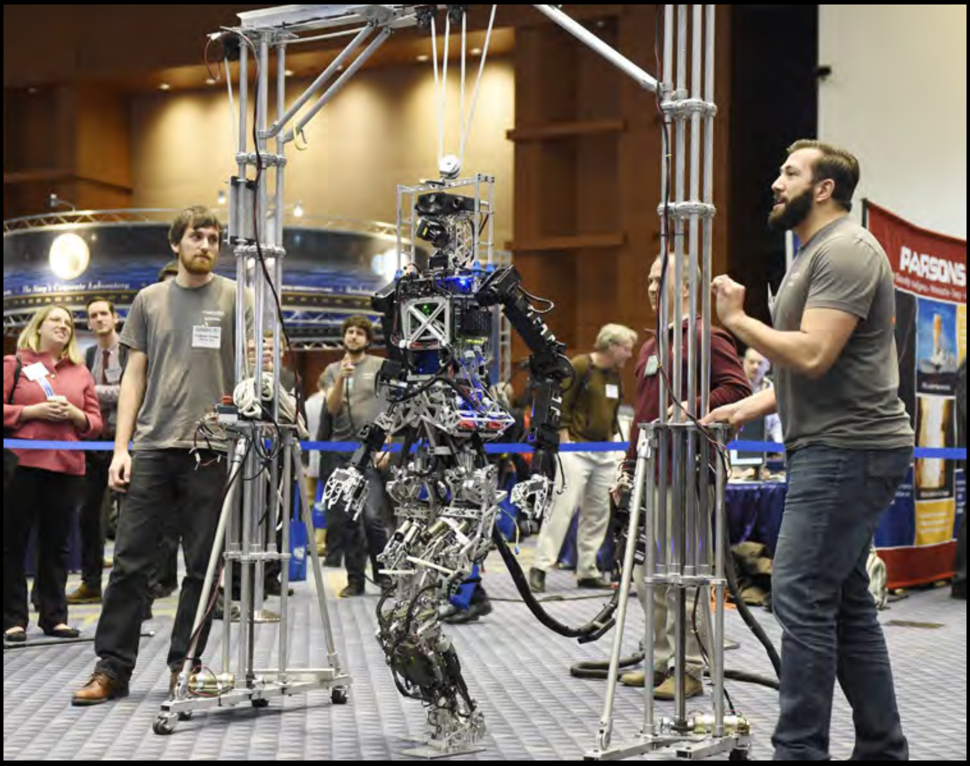


Figure 4: Graduate Students From Virginia Tech Demonstrate the Capabilities of the Office of Naval Research-Sponsored SAFFiR in the Exhibit Hall During the Naval Future Force Science and Technology Expo *(Source: U.S. Navy, John F. Williams).*

One of the greatest benefits of human-machine teams is integrating a machine's ability to perform computations far more quickly and accurately than humans. This could be used in a plethora of ways, including the arduous tasks of spatial reasoning and coordinating transformations. The National Aeronautics and Space Administration developed a spatial reasoning agent as part of their early Human-Robot Interaction Operative System [14]. The agent creates a mental simulation of an interaction and assigns it multiple frames of reference. Information is then referenced by frame and location, and the desired perspective is assigned to the world, allowing the spatial reasoning agent to connect local and global coordinates of an interaction. By assigning spatial reasoning tasks to machines, personnel can coordinate among their own reference points and let the machines do the work of translating to all team members. Studies should be conducted to construct teams in a way that highlights each member's strengths and accounts for their weaknesses.

Government and industry are working on explaining the varying levels of comprehension and capabilities. In 2016, DARPA created the Agile Teams program, which focuses on developing mathematical models that enable the optimization of human-machine teams. The model will be generalized, allowing the input of team specifics that would result in applicable abstractions, algorithms, and architectures. The goal is to create a new teaming methodology that will "dynamically mitigate gaps in ability, improve team decision making, and accelerate realization of collective goals" [15]. This will improve the control of human-machine teams by ensuring the team structure is most efficient and realistic.

One of the greatest benefits of human-machine teams is integrating a machine's ability to perform computations far more quickly and accurately than humans.

Human-machine trust and efficiency will continue to improve as comprehension and experience increase. Division of roles and transparency in decision making is critical for personnel to understand autonomous team members. Personnel must understand artificial intelligence and assigned roles. As artificial intelligence improves and accounts for complex environments, trust will also improve. As IBM summarized, "To reap the societal benefits of AI, we will first need to trust AI. That trust will be earned through experience, of course, in the same way we learn to trust that an ATM will register a deposit, or that an automobile will stop when the brake is applied. Put simply, we trust things that behave as we expect them to" [11]. After this trust is established, teams can be constructed to capitalize on the benefits provided by machine members.

CONTROL

Human-machine teams require that machine members operate with a high level of autonomy. However, personnel must retain a certain level of control for ethical considerations and team effectiveness. A study conducted by the Florida Institute for Human and Machine Cognition found that "increases in autonomy may eventually lead to degradations in performance when the conditions that enable effective management of interdependence among the team members are neglected" [16]. They emphasized that while autonomy is required, machines must also remain somewhat dependent and collaborate and participate in interdependent joint activity. Thus, there is a fine balance to achieve—too much control reduces team efficiency, while too little control increases the potential for error. There are three ways that control can be addressed: (1) new command techniques, (2) error checking artificial intelligence, and (3) continued oversight.

To maintain efficient teams while increasing the autonomy of machine members, better control interfaces must be established. Lange et al., with the Space and Naval Warfare Systems Center, stated that while autonomy is needed for very large teams, "autonomic strategies must also be made more adaptable and in doing so also maintain the property of being recognizable by a commander" [1]. DARPA's OFFensive Swarm-Enabled Tactics (OFFSET) program attempts to address this challenge by combining new communication techniques and virtual reality training (Figure 5). Because personnel will need to monitor and direct a large swarm of unmanned systems, the program is developing "rapidly emerging immersive and intuitive interactive technologies (e.g., augmented and virtual reality, voice-, gesture-, and touch-based) to create a novel command interface with immersive situational awareness and decision presentation capabilities" [17]. The Office of Naval Research's Battlespace Exploitation of Mix Reality Laboratory is already seeking to apply commercial-mixed

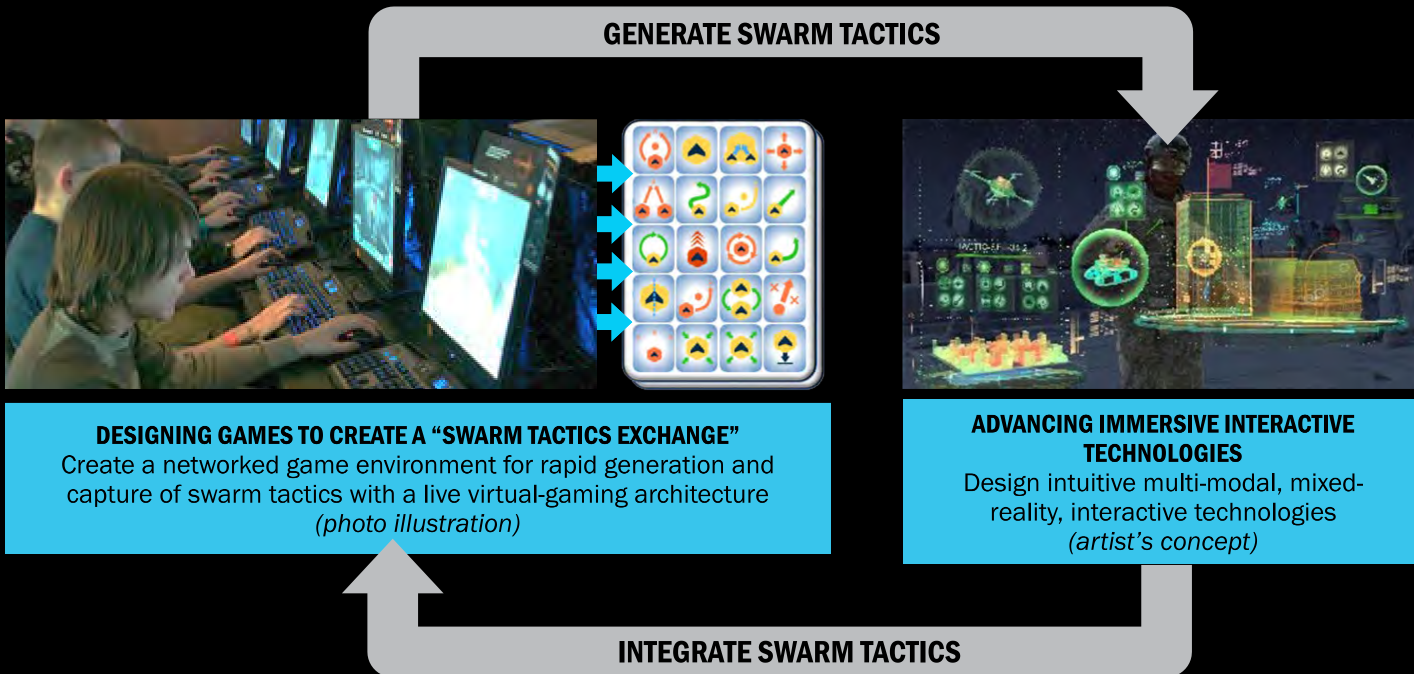


Figure 5: OFFSET Approach to Command Interfaces and Training *(Source: DARPA).*

reality, virtual reality, and augmented reality technologies (Figure 6); the scope could also be widened to include autonomous systems. By focusing on ease of communication and virtual reality immersion, controlling a swarm might be much more intuitive, reducing personnel's mental workload.

Humans excel at making decisions on limited data and sense when data has been compromised. Artificial intelligence must mimic this decision-making and real-time data analysis with extremely large data sets. As IBM reported, "Training and test data can be biased, incomplete, or maliciously compromised. Significant effort should be devoted to techniques for measuring entropy of datasets, validating the quality and integrity of data, and for making AI systems more objective, resilient, and accurate" [11]. This will allow machine team members to remain autonomous when gathering data and performing calculations. By passing off data responsibilities and error checking

Figure 6: Navy Lt. Jeff Kee Explores the Office of Naval Research-Sponsored Battlespace Exploitation of Mixed Reality Laboratory at Space and Naval Warfare Systems Center Pacific, San Diego, CA, 14 September 2015 *(Source: U.S. Navy, John F. Williams).*

to machine members, personnel can focus their control on those truly critical elements.

As there is a significant gap between human inherent understanding of the environment, test data, and human behavior, there must still be an element of personnel oversight and control. The U.S. Army Research Laboratory found that too much trust could pose a danger. According to Schaefer et al., "An over-trusting operator is more likely to become complacent and follow the suggestions of the automation without cross-checking the validity against other available and accessible information" [18]. More efficient human-machine teams require increased levels of trust. However, personnel must still actively manage machine team members when necessary. Hancock et al. characterized a complete lack of control as neglect and found that "neglect tolerance should be appropriate to the capabilities of the robot and the level of human-robot trust" [19]. It is important that personnel be reminded of the capabilities and shortcomings of machine members. Machines must remain dependent on personnel, and personnel must retain a certain level of distrust. This continued oversight and interdependence will strengthen the bonds between man and machine and prevent dangerous complacency.

This tension between autonomy and control must exist to have highly effective human-machine teams where personnel still retain ultimate control. Virtual reality and improved interfaces make controlling autonomous systems and human-machine teams easier. As artificial intelligence improves, machines will use compromised and limited data to make decisions comparable to their human peers. For practical and ethical reasons, the ultimate responsibility for actions taken by the team must still rest with a human leader. Relinquishing too much control results in a team that may be ineffective and possibly dangerous. Effective human-machine teams reside in this balance between autonomy and interdependence.

As artificial intelligence improves, machines will use compromised and limited data to make decisions comparable to their human peers.

CONCLUSION

Significant advances are being made in artificial intelligence, autonomy, and human-machine teaming. At the heart of effective teams, however, are interpersonal relationships built on understanding and trust. For human-machine teams to overcome the barriers of communication, comprehension, and control, more work is needed. Through improving communication, feedback, and understanding common ground, coordination among team members will improve. Asymmetrical comprehension inherent in autonomy necessitates a deeper understanding of decision making, roles, and human-machine team frameworks. Finally, a balance must be found when controlling autonomous team members. Control interfaces must be more efficient and natural to allow machines to control certain areas. However, maintaining control and challenging complacency are required to avoid mistakes when autonomous systems operate outside their design. By continuously tweaking these areas for efficiency, human-machine teams will not only exist but thrive. ■

REFERENCES

[1] Lange, D. S., P. Verbancsics, R. Gutzwiller, and J. Reeder. "Command and Control of Teams of Autonomous Units." Presented at the 17th International Command and Control Research and Technology Symposium, Space and Naval Warfare Systems Center, San Diego, CA, June 2012.

[2] DeLaughter, J. "Building Better Trust Between Humans and Machines." *MIT News*, 21 June 2016.

[3] Gillis, J. "Warfighter Trust in Autonomy." *DSIAC Journal*, vol. 4, no. 4, 2017.

[4] Veestraeten, M., E. Kyndt, and F. Dochy. "Investigating Team Learning in a Military Context." *Vocations and Learning*, vol. 7, issue 1, pp. 75–100, April 2014.

[5] Tangney, J., P. Mason, L. Allender, K. Geiss, M. Sams, and D. Tamilio. "Human Systems Roadmap Review." Technical Report DCN# 43-1322-16, Office of Naval Research, Arlington, VA, February 2016.

[6] Gervits, F., K. Eberhard, and M. Scheutz. "Team Communication as a Collaborative Process." *Frontiers in Robotics and AI*, vol. 3, article 62, October 2016.

[7] MacDonald, M. "Human-Machine Teams Need a Little Trust to Work." *AIAA Communications*, 11 January 2018.

[8] Overholt, J., and K. Kearns. "Air Force Research Laboratory Autonomy Science & Technology Strategy." 88ABW-2014-1504, U.S. Air Force Research Laboratory, 711 HPW/XPO, April 2014.

[9] Lockheed Martin. "Machines Evolve to Help, But Not Replace, Humans." *Washington Post WP Brand Studio*, October 2015.

[10] Kozlowski, S. W. J., J. A. Grand, S. K. Baard, and M. Pearce. "Teams, Teamwork, and Team Effectiveness: Implications for Human Systems Integration." In D. Boehm-Davis, F. Durso, and J. Lee (Eds.), *The Handbook of Human Systems Integration*, pp. 555–571, Washington, D.C.: American Psychological Association.

[11] IBM. "Preparing for the Future of Artificial Intelligence." IBM Response to the White House Office of Science and Technology Policy's Request for Information, 2016.

[12] Lewis, M. "Human Interaction with Multiple Remote Robots." *Reviews of Human Factors and Ergonomics*, vol. 9, ch. 4, pp. 131–174, 2013.

[13] Trautman, P., J. Ma, R. M. Murray, and A. Krause. "Robot Navigation in Dense Human Crowds: Statistical Models and Experimental Studies of Human-Robot Cooperation." *The International Journal of Robotics Research*, vol. 34, no. 3, pp. 335–354, 2015.

[14] Fong, T., L. M. Hiatt, C. Kunz, and M. Bugajska. "The Human-Robot Interaction Operating System." In Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction, pp. 41–48, Salt Lake City, UT: Association for Computing Machinery, 2016.

[15] Defense Advanced Research Projects Agency. "Designing Agile Human-Machine Teams." *Program Information,* 28 November 2016, https://www.darpa.mil/program/2016-11-28, accessed 10 April 2018.

[16] Allen, J. "Process Integrated Mechanism for Human-Computer Collaboration and Coordination." AFRL-OSR-VA-TR-2012-1071, The Florida Institute for Human and Machine Cognition, Pensacola, FL, December 2012.

[17] Chung, T. "OFFensive Swarm-Enabled Tactics (OFFSET)." Defense Advanced Research Projects Agency, Program Information, https://www.darpa.mil/program/2016-11-28, accessed 17 April 2018.

[18] Schaefer, K., D. Billings, J. Szalma, J. Adams, T. Sanders, J. Chen, and P. Hancock. "A Meta-Analysis of Factors Influencing the Development of Trust in Automation: Implications for Human-Robot Interaction." ARL-TR-6984, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, July 2014.

[19] Hancock, P., D. Billings, K. Oleson, J. Chen, E. De Visser, and R. Parasuraman. "A Meta-Analysis of Factors Influencing the Development of Human-Robot Trust." ARL-TR-5857, U. S. Army Research Laboratory, Aberdeen Proving Ground, MD, December 2011.

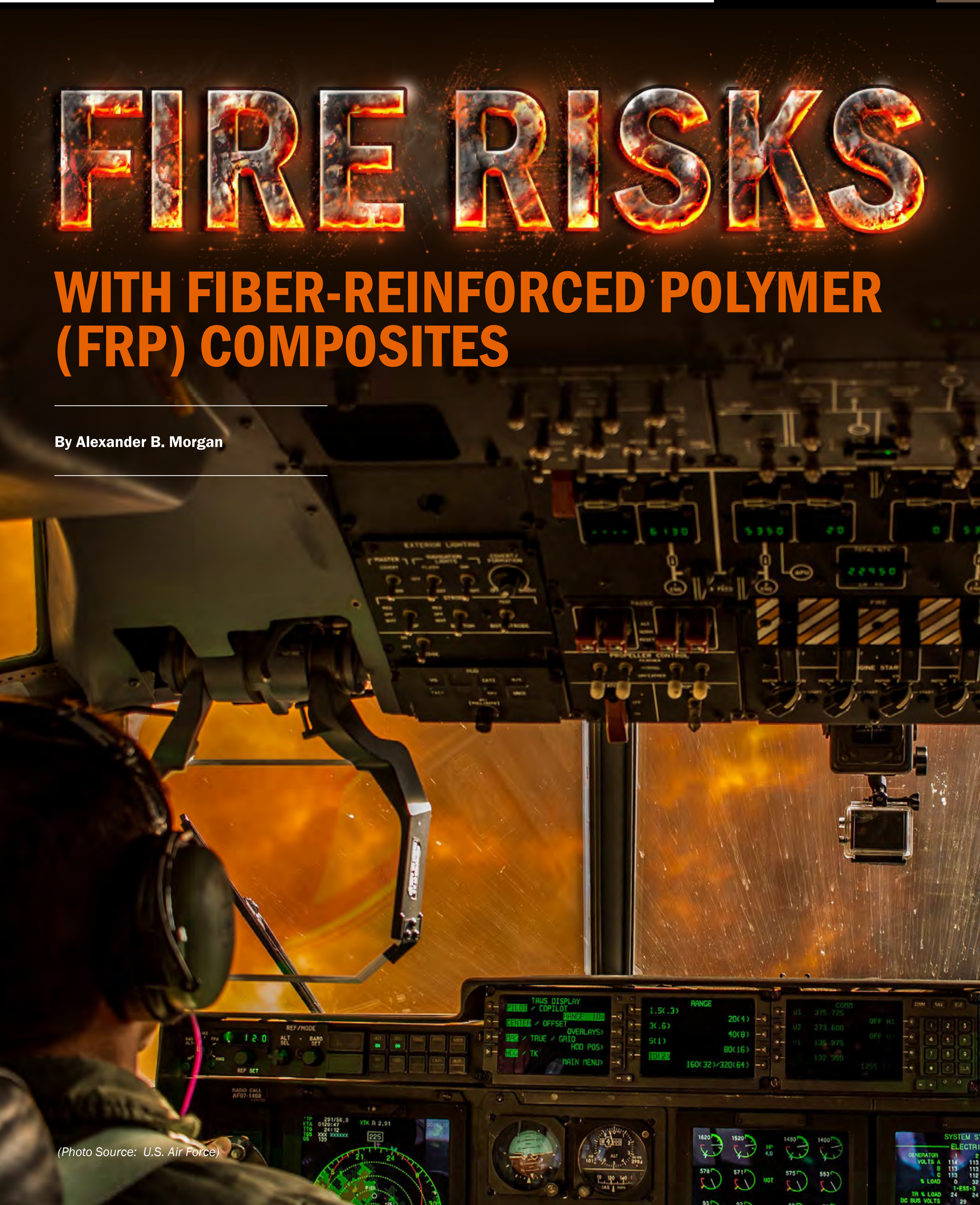
BIOGRAPHY

KATHERINE HENDRICKSON is a survivability analyst with SURVICE Engineering's Gulf Coast Operation. She currently utilizes tools such as AJEM, COVART, FASTGEN, BRL-CAD, and TurboPK to perform vulnerability and lethality analysis for a variety of customers under the mentorship of Mr. Ben Osborne and Dr. Kevin McArdle. As an undergraduate, she also published research in sociology and recently co-authored a paper in physics. Ms. Hendrickson holds a B.S. in pure mathematics from Auburn University and an M.S. in industrial and systems engineering from the University of Florida.

FIRE RISKS

WITH FIBER-REINFORCED POLYMER (FRP) COMPOSITES

By Alexander B. Morgan



(Photo Source: U.S. Air Force)

SUMMARY

Fiber-reinforced polymer (FRP) composites have a wide range of use in military applications, including portable shelters, aircraft structures, ship structures, and some ground vehicle components. These composites bring major advantages over metals, including resistance to corrosion and lighter weight for increased mission range. However, they present a very different fire risk scenario (chance of fire loss) than what is seen with metals. Specifically, they are not easily extinguished with foams, can structurally fail well before the fire grows large, and can present survivability and vulnerability challenges. This article will focus on how composites burn, give an overview of known hazards and their effects on equipment and personnel, and describe possible ways of addressing composite flammability. Best practice firefighting measures for dealing with composite fires will be discussed, along with fire protection measures compatible with composites. With this information, readers will be better equipped to deal with composite fire risk scenarios and can start using some of the known fire protection measures to design fire-hardened military equipment.

INTRODUCTION

Composites, materials composed of more than one material, are increasingly used in military applications due to their high performance over existing single-material components. Many of us are familiar with carbon-fiber epoxy composites used in high-performance sports cars or golf clubs and even with epoxy + fiberglass composites in circuit boards. Composites can be made of a wide range of materials, including carbon-carbon composites (used for brake pads and reentry shields), ceramic matrix composites (reinforced ceramics for very high-temperature applications such as engines), and metal matrix composites (two different metals, not alloyed, used in high-performance applications such as landing gear). One of the more common composites used today are FRP composites like the epoxy/carbon fiber and epoxy/fiberglass materials just mentioned. The polymer in the composite can be highly varied depending upon the synthetic polymer used. The fibers can also vary, from the common fiberglass and carbon fiber to Kevlar, silicon carbide, quartz, metal, and other strong fibers in select composite applications. For military applications, FRP composites are present in ships (structure and bulkheads), aircraft (fixed and rotary wing), portable hard-wall shelters, some handheld military gear and weapons, electronic components, and ground vehicles (structural and nonstructural parts and spall liners). FRPs are used because they bring lighter weight (improved mission range), good mechanical properties, resistance to corrosion, and other benefits that may not be achievable or practical with existing metal or ceramic materials. Some well-known examples of polymer composites in military use today are shown in Figure 1.

FRP properties are prized in the civilian world, where some of the same military applications are mirrored in ships, aircraft, ground transportation (trains, subway, cars, and trucks), and electronics. FRPs are also used for building materials, wind turbine blades, electronics, and train/rail/subway cars. There is a continued desire for new uses for FRPs in civilian markets due to their performance and cost benefits. While FRPs bring many advantages to their widespread use, they do have limitations. Temperature is their main limitation [1]. Specifically, all polymers in FRPs have a “glass transition” temperature where the material begins to soften and deform with force applied.

Figure 1: FRPs in Military Applications *(Sources: [Left] U.S. Air Force MSgt Donald R. Allen and [Right] General Dynamics Bath Iron Works).*

This happens before the material melts and is effectively the "use temperature" for the material. The use temperature will vary depending upon the chemistry of the polymer used to make the FRP. Some FRPs can be used up to 300 °C (572 °F), while others will begin to notably soften in temperatures as low as 40 °C (104 °F). Certainly, metals have use temperatures and performance limits, but usually, metals can withstand heat much better than FRPs. Along with this temperature limitation is a key survivability/vulnerability concern, which is how polymer composites burn. This limitation is very different than most military-grade metals. Some metals can burn quite spectacularly (e.g., magnesium alloys). But it is how FRPs burn when exposed to fire that presents challenges from the perspectives of force protection and structural durability, when the FRP may structurally fail early in a fire and lead to catastrophic losses. While these thermal properties can present notable survivability and vulnerability threats for military equipment, they can be overcome and shielded. This article discusses known historical events where FRPs in fires caused structural failure and military equipment loss. From those examples, details on how to protect FRPs against fire will be discussed, including their specific hazards and how military firefighters should approach FRP fires.

EXAMPLES OF COMPOSITES POTENTIALLY EXPOSED TO FIRE IN MILITARY USE

Fire protection engineers look at the fire hazard (damage caused by a fire) and fire risk (chance of fire occurring) to create a fire risk scenario. Once that fire protection scenario is defined, it becomes possible to protect against the fire in that scenario should a fire occur. Fire risk scenarios are not universal, and the fire threat for an aircraft will be different than for a ship or a ground vehicle; the same is true for FRPs.

Our first fire risk scenario begins with fires on ships. There are two examples of FRPs in naval fires that have led to complete loss of the ship—the Royal Norwegian Navy minesweeper "Orkla" and the Indonesian littoral combat ship "Kri Klewang" (to be discussed in the following paragraphs). These examples serve as a warning to not ignore FRP fire behavior in typical naval fire risk scenarios.

Fire onboard ships is not a new phenomenon and has been thoroughly studied since the dawn of naval surface warfare. When navies of the world moved to metal hulled ships, the main fire risk scenario of a wooden ship "burning to the waterline" and capsizing was replaced by compartment fires due to fuel spills and munition-induced damage. However, with the advent of composite hulls, the scenario of the hull burning has returned but in a somewhat different manner. In two reported cases, ships with composite hulls were involved in fires. In both cases, the ships had notable structural fires while burning, resulting in the ships capsizing and sinking.

The first example is the Royal Norwegian Navy minesweeper "Orkla," which developed a fire in a propulsion room [2, 3]. As the composite hull and structure of the minesweeper ignited, it quickly overwhelmed the firefighting crew who were forced to abandon ship. The ship burned for just over 24 hours before capsizing, breaking apart, and then sinking. A post-mortem analysis found that the fire suppression system on the ship failed, indicating that due to the flammability of the composites that made up most of the ship structure, additional passive fire protection for the composites was needed.

Another example of a composite ship catching fire and resulting in total loss of the ship was the Indonesian littoral combat ship "Kri Klewang." This ship caught fire due to an electrical short while docked and getting fitted for sea trials (see Figure 2). Again, the fire protection system did not activate (it

Figure 2: In September 2012, the Indonesian Navy's Kri Klewang Suffered Major Fire Damage *(Source: http://www.tribunnews.com/regional/2012/09/28/kapal-siluman-kri-klewang-625-ludes-terbakar).*

had not yet been installed). The fire was quite large, and the entire ship was lost [4, 5]. Note in both cases, the fires were so intense that ship firefighting measures were not enough to overcome them. Clearly, both incidents support the need for secondary fire protection of the composites to ensure no loss of structure and, more importantly, that the fires do not get out of control from the beginning.

Acceptable secondary fire protection for composites can include using flame-retardant polymer in the FRP. Ceramic fiber fire protection blankets and wraps are commonly used onboard U.S. Navy/Coast Guard ships with composite structures as well as onboard civilian maritime ships with composite materials. However, these ceramic blankets have their own issues, such as installation/maintenance. But they are proven to work as a backup fire protection system in the event fire suppression systems and fire protection crews are unable to address the fire in a timely manner.

Another fire risk scenario for FRPs in military applications is in ground vehicles. Setting aside highly complicated fire risk scenarios such as incendiary and high-explosive rounds, compartment fires are a known fire risk scenario that can kill the crew of the vehicle if it gets out of control. In the past, halon extinguishers and self-sealing fuel bladders, combined with a mostly all-metal vehicle hull and interior components, would address most of the nonmunition-based fires in vehicles. More recently, high-performance FRPs are inserted into vehicles such as mine-resistant, ambush-protected vehicles, namely as spall liners capturing fragments from mines and other munition threats. Work conducted by this author, through U.S. Army funding, found that the composition of the FRP spall liner great affected its flammability [6]. In some cases, the spall liner's flammability was low enough that the crew could grab an extinguisher and put out the fire. But in other cases, the flammability of the FRP was so high that a hand-held extinguisher was insufficient, and immediate exiting of the vehicle was recommended. Older technology S-2 glass + phenolic polymer FRPs showed very low flammability, while newer lightweight, ultrahigh molecular weight polyethylene FRPs showed very high flammability when studied by a cone calorimeter [7]. The cone calorimeter measures the inherent flammability of materials. The higher the heat release rate (HRR) of the material, the higher the fire hazard for that material (Figure 3) [6]. Both spall liners provide their expected protection against fragmentation threats, but only the phenolic polymer FRP provides low-heat release and fragment protection. This further supports the importance of understanding FRP inherent flammability and how selecting the wrong FRP can have unintended consequences from a fire protection perspective.

> The higher the heat release rate (HRR) of the material, the higher the fire hazard for that material.

A notable incident of how composites have burned in aircraft and some of their specific hazards that resulted in different firefighting measures occurred in February 2008. A B-2 bomber (mostly all composite; see Figure 4) crashed onto the runway shortly after takeoff, resulting in a large fire and complete loss of the $1.4B aircraft [8]. Since the aircraft was recently fueled, the tank likely exacerbated the fire upon crashing. The resulting fire and guidance from aircraft manufacturers on how to put out FRP fires are worth discussing as well as the hazards to ground crews and how firefighting changes when dealing with FRPs.

SPECIFIC HAZARDS OF COMPOSITES IN FIRE

Mostly carbon-based, FRPs can be considered eventual "fuel" in a fire, unlike ferrous metals. Therefore, just about all the FRP can be involved in the

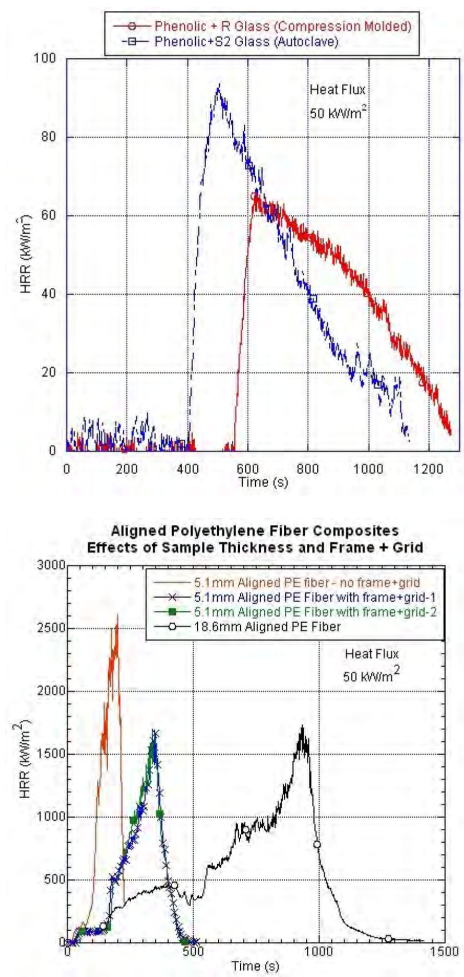


Figure 3: HRR Curves for Phenolic + S-2 Glass FRP Spall Liners (Top) and Ultrahigh Molecular Weight Polyethylene Spall Liners (Bottom) *(Source: Morgan [6])*.

Figure 4: B-2 Bomber Aircraft Performing a "Touch and Go" *(Source: U.S. Air Force Airman 1st Class Stephen Linch, http://www.af.mil/News/Photos/igphoto /2000430108/).*

fire and contribute to fire growth. If the FRP matrix material is a "thermoplastic" polymer (it can melt and flow under heat), then once the fire is underway, the material can greatly deform during a fire. This can lead to delamination (increased surface area for accelerated burning) or melt pool formation, which may create an effect like a gasoline-pool fire and rapidly accelerate a fire to ignite other nearby objects or send a compartment to flashover. Flashover means the compartment is completely engulfed in flame (fills all volume of the space) and spills out of the compartment opening, resulting in total fire loss and death to anyone trapped in the compartment. If the FRP matrix material is a thermoset polymer (once it is made, it will not melt again), fire damage can also result in delamination during the fire; however, melt pool formation does not occur. Along with the obvious flame and heat release from a burning FRP (whether thermoplastic or thermoset) and the structural failure of the FRP as it goes past its use temperature, smoke release is often common with these materials, and the smoke can be generated in large amounts. Depending on the chemistry of the matrix polymer in the FRP, the smoke can be black and highly sooty. It can contain other gases, presenting toxicity to crew in the compartment and/or corrosive gases damaging electronics as well as causing breathing issues for the crew. Some high-performance polymers for FRPs can have the right chemistry such that their heat and smoke release and toxic gas emissions are quite low in a fire due to how the polymer in the FRP chars (coverts to thermally stable carbon) rather than burns. While these high-performance polymers are preferred for fire protection, their higher costs limit their use to extreme applications such as engine compartments, mission critical hardware, submarines, and spacecraft. Even with submarines, FRP use is highly limited as fire underwater is a highly undesirable event because any gases from the fire must be scrubbed out until the submarine can surface and get fresh air. Depending upon the mission, this may not be an option until some time after the fire occurs. For spacecraft, the issues are even more severe as there is nowhere to escape from fire in a spacecraft, and the emissions must be scrubbed out and fresh oxygen flushed into the compartment. Close attention must be paid to selecting polymer for FRP in a military application because picking the wrong one may result not just in fire issues, but collateral damage to vehicle electronics and crew.

Another FRP component to consider in a fire is fiber reinforcement. While inorganic fibers in FRPs are not combustible, carbon fibers in military FRPs contribute their own unique hazards to a fire. Specifically, carbon fibers conduct heat—they can drive heat from the fire source deeper into the composite structure, causing the entire composite to heat up. Further, carbon fibers oxidize and release needle-like fragments in fires [9], suggesting further health concerns for crew exposed to smoke from the fire and firefighters

Close attention must be paid to selecting polymer for FRP in a military application because picking the wrong one may result not just in fire issues, but collateral damage to vehicle electronics and crew.

and repair crews tending to the fire afterwards. National Fire Protection Association 1971 compliant breathing protection gear is strongly recommended for firefighters involved in fighting FRP fires.

COMPOSITE FIREFIGHTING MEASURES

With the specific hazards mentioned, firefighting measures when dealing with FRPs are somewhat different than those used for putting out traditional fuel-based fires in military scenarios. Typical military firefighting extinguishments include water, foams, CO_2, halon, and powders for metal fires. Most aircraft fires with large jet fuel pool fires upon crashing (such as the B-2 crash) utilize foam to smother the fuel pool fire so it extinguishes. For metal-based aircraft, once the fuel pool fire is smothered with foam, the metal rapidly cools and the entire fire is out. This is not the case for FRPs. Once FRPs ignite, the foam will simply put out the fuel pool fire, but the FRP will remain hot and will reignite, which may, in turn, reignite the fuel pool fire. Although foam is needed for dealing with a combination FRP/fuel pool fire, it has almost no effect on the FRP itself. While halon will rapidly snuff out the fire of a FRP, the underlying FRP will remain hot and reignite once the halon gas cloud extinguishes. Therefore, to extinguish a burning FRP, the FRP must be cooled with either CO_2 or water. To further complicate the scenario, the water which cools the FRP may interfere with the foam on the fuel pool fire. As a result, careful and mindful firefighting must be conducted. Boeing has released special guidance for dealing with fires of their mostly all-composite airlines, the Boeing 787. They issued instructions to airport fire departments on how to extinguish the FRP and what tools to use to fully extinguish the fire. Since carbon fibers in aircraft FRPs are quite strong, Boeing recommends special fuselage-piercing tools and diamond/carbide blade saws to cut through the fuselage to insert hoses to put out the fire and, where appropriate, remove the structure to get at other parts of the aircraft where fire may have spread [10].

Each FRP in specific military applications will present its own fire threats that may or may not be easily dealt with using existing firefighting equipment on hand.

Each FRP in specific military applications will present its own fire threats that may or may not be easily dealt with using existing firefighting equipment on hand. For fire risk scenarios that represent unique military threats (incendiary rounds, high explosives, and napalm), how FRPs will behave can only be speculated in this article. Most likely, the FRP will ignite. Depending on the exact event and how the FRP and military threat interact, as well as the chemistry of the FRP itself, there could be cases where the FRP does not ignite because the FRP did not encounter enough heat to undergo significant decomposition. Based on the intensity of the military threat, the FRP may ignite and contribute to a growing fire, resulting in the loss of the vehicle and/or crew. For more traditional fire risk scenarios, however, FRP should be considered as a fire hazard that requires fire protection and specific guidance on firefighting measures when the FRP ignites.

COMPOSITE FIRE PROTECTION APPROACHES

Since polymers have been well known to be flammable, there are many solutions available for fire protection of polymers for many different nonmilitary fire risk scenarios. Likewise, these same solutions can be leveraged for FRPs in military applications. However, for the unique military threats just mentioned, some of the fire protection solutions for FRPs may or may not be appropriate. Live-fire testing to verify protection may be needed. For more traditional fire threats (post-crash fuel pool fires, short circuits, and open flame threats), proven fire protection approaches exist.

Active Fire Protection Systems

Active fire protection systems in military vehicles and buildings are one of the most common methods of fire protection. Examples of this include sprinkler systems or other extinguishers that react in a fire. Usually, these systems are heat activated. In some cases, they can be manually activated by personnel inside or outside the compartment where the fire is located. When FRPs are involved in the compartment, active fire protection systems that use water are preferred. Halon-type or CO_2–based extinguishers will work as well. However, these gases may only snuff out the fire, not cool the FRP and prevent it from reigniting. If the extinguisher puts out the fire quickly, the FRP may never heat up enough to reignite after the extinguishing agent has dissipated. Foam-based sprinkler systems may not always be appropriate for extinguishing FRP-based fires. It should be noted that for mixed material fires (e.g., FRP aircraft inside a hangar with jet fuel), multiple extinguishing systems may be required to ensure all fire threats are addressed. In cases where the compartment containing FRPs is manned, some extinguishing systems may not be allowed and passive fire protection systems may be required.

Passive Fire Protection Systems

Fire Protection Barriers

Fire protection barriers are among the more common solutions for protecting FRPs. The general concept behind the barriers is to make them out of something noncombustible to provide thermal protection to the underlying FRP, thus preventing it from getting hot enough to decompose and ignite. Typical barriers for FRPs include ceramic fiber blankets and metal plates (Figure 5). Where appropriate, some densified ceramic plates may be included where the ceramic plate also serves as an armor tile. Other barriers include intumescent paints. Upon exposure to fire, these paints produce a carbon-based "foam" which slowly combusts but provides good thermal protection. While barriers are common, their weak link is their connection to the FRP and any gaps that may form in the fire protection barrier. If the barrier falls off or is penetrated, cut, or damaged in any way, then that opening is where the fire can directly interact with the FRP, resulting in fire damage at the exposure site.

Newer concepts for fire protection barriers for FRPs include intumescent systems directly bonded to the FRP as a top coat (also known as "gel coat") to the composite such that the coating cannot be easily damaged/removed from the composite because it is integral to the outer composite layers [12–15]. Another newer concept, although perhaps not as robust to damage, is to create metallized infrared reflective layers reflecting heat away from the sample, thus preventing or slowing ignition of the underlying polymer [16]. While this later concept has not been tested for electromagnetic (EM) interference capabilities, these metallized layers may also provide some unique protection to electronic enclosures or other components sensitive to EM warfare that also need fire protection.

Flame Retardants

Another common solution to providing fire protection to FRPs is to incorporate flame-retardant chemistry directly into the polymer used to make the FRP. There are several flame retardants available for polymers typically used for FRPs, such as epoxies, vinyl esters, and other thermoset polymers. In some cases, the FRPs can be made out of polymers which have inherently low flammability due to their chemical structure. There are numerous review papers on flame-retardant polymers to guide the FRP user on what chemistry to select [17–22]. Ultimately, a balance of properties is required. Specifically, fire safety performance, manufacturability, use temperature (i.e., glass transition temperature), durability, and cost all must be factored into flame-retardant choices for this approach to be successful. Note that flame retardants can be combined with fire protection barriers to give a better balance of properties in the final FRP and provide a more robust fire safety performance as a "defense in depth" should the fire protection barrier be breached.

Structural Reinforcement

Considering the issues mentioned about composites under structural load failing when exposed to heat and fire, sometimes high-temperature

Figure 5: Example of Fire Protection Barriers – Ceramic Fiber Blankets (Left) and Metal Skins Enabling Composites to Pass the Room Corner Test (Right) *(Source: Morgan and Toubia [11]).*

metal reinforcement is used to serve as structural support for the FRP in event of a fire. Examples of this include metal superstructure for the fuselage/hull of a vehicle where the FRPs are connected to the superstructure and do not provide main structural support but rather as secondary vehicle "skins" or compartment walls. When this approach is put in place, fire protection for the FRP and the metal is needed (as is done with metal support structure in buildings today) to prevent the metal from heating up and softening/melting under load.

CONCLUSIONS

FRPs do have an important role in military systems, as they bring good enhancements in properties over metal materials, thus enabling new missions and increased mission range. We should not assume that FRPs and metals can be easily exchanged for one another, as FRPs present their own fire hazards and fire risk scenarios. Further, new firefighting approaches and post-fire hazards with FRPs can be very different than what has been seen with older generation military equipment, where FRPs were only minor components and not typically structural materials. The fire hazards associated with FRPs can be dealt with through understanding the fire threat, paying careful attention to polymer chemistry, and designing the system accordingly. Through a combination of the right polymer chemistry selection as well as active and passive fire protection measures, FRPs can be used in military environments without compromising mission effectiveness or survivability. ■

REFERENCES

[1] Correia, J. R., Y. Bai, and T. Keller. "A Review of Fire Behavior of Pultruded GFRP Structural Profiles for Civil Engineering Applications." *Composite Structures*, vol. 127, pp. 267–287, 2015.

[2] Mouritz, A. P. and A. G. Gibson (editors). *Fire Properties of Polymer Composite Materials*. Springer-Verlag, The Netherlands: Springer-Verlag, p. 16, 2006.

[3] Wikipedia. "Alta-Class Minesweeper." https://en.wikipedia.org/wiki/Alta-class_minesweeper, accessed 22 May 2018.

[4] Foxtrot Alpha. "Dear US Navy: The Futuristic X3K Is What Littoral Combat Ships Should Be," by Tyler Rogoway. https://foxtrotalpha.jalopnik.com/dear-us-navy-the-futuristic-x3k-is-the-littoral-combat-1644205558, accessed 22 May 2018.

[5] Wikipedia. "North Sea Boats." https://en.wikipedia.org/wiki/North_Sea_Boats, accessed 22 May 2018.

[6] Morgan, A. B. "Flammability of Fiber-Reinforced Polymer Composites for Vehicles." Fire and Materials 2009 Proceedings, San Francisco, CA, 26–28 January 2009.

[7] ASTM International. *Cone Calorimeter.* ASTM E1354, 27 September 2013.

[8] Wikipedia. "2008 Anderson Air Force Base B-2 Accident." https://en.wikipedia.org/wiki/2008_Andersen_Air_Force_Base_B-2_accident, accessed 22 May 2018.

[9] Eibl, S. "Potential for the Formation of Respirable Fibers in Carbon Fiber Reinforced Plastic Materials After Combustion." *Fire Mater.*, vol. 41, pp. 808–816, 2017.

[10] Boeing. "787 Aircraft Rescue & Firefighting Composite Structure April 2013." http://www.boeing.com/assets/pdf/commercial/airports/faqs/787_composite_arff_data.pdf, accessed 22 May 2018.

[11] Morgan, A. B. and E. Toubia. "Cone Calorimeter and Room Corner Fire Testing of Balsa Wood Core / Phenolic Composites Skin Sandwich Panels." *J. Fire Sci.*, vol. 32, pp. 327–344, 2014.

[12] Kandola, B. K. and W. Pornwannachai. "Enhancement of Passive Fire Protection Ability of Inorganic Fire Retardants in Vinyl Ester Resin Using Glass Frit Synergists." *J. Fire Sci.*, vol. 28, pp. 357–381, 2010.

[13] Kandare, E., A. K. Chukwunonso, and B. K. Kandola. "The Effect of Fire-Retardant Additives and a Surface Insulative Fabric on Fire Performance and Mechanical Property Retention of Polyester Composites." *Fire Mater.*, vol. 35, pp. 143–155, 2011.

[14] Kandare, E., C. Chukwudole, and B. K. Kandola. "The Use of Fire-Retardant Intumescent Mats for Fire and Heat Protection of Glass Fibre-Reinforced Polyester Composites: Thermal Barrier Properties." *Fire and Materials*, vol. 34, pp. 21–38, 2010.

[15] Morgan, A. B. and S. Putthanarat. "Use of Inorganic Materials to Enhance Thermal Stability and Flammability Behavior of a Polyimide." *Polym. Degrad. Stab.*, vol. 96, pp. 23–32, 2011.

[16] Schartel, B., U. Beck, H. Bahr, A. Hertwig, U. Knoll, and M. Weise. "Sub-micrometre Coatings as an Infrared Mirror: A New Route to Flame Retardancy." *Fire Mater.*, vol. 36, pp. 671–677, 2012.

[17] Morgan, A. B. and A. Z. Worku. "Flame Retardants: Overview." *Kirk Othmer Encyclopedia of Chemical Technology*, Hoboken, NJ: John Wiley & Sons, 2015.

[18] Morgan, A. B. and C. A. Wilkie (editors). *Non-Halogenated Flame Retardant Handbook*. Hoboken, NJ: Scrivener Publishing LLC, 2014.

[19] Wilkie, C. A. and A. B. Morgan (editors). *Fire Retardancy of Polymeric Materials*, 2nd edition. Boca Raton, FL: Taylor and Francis, 2010.

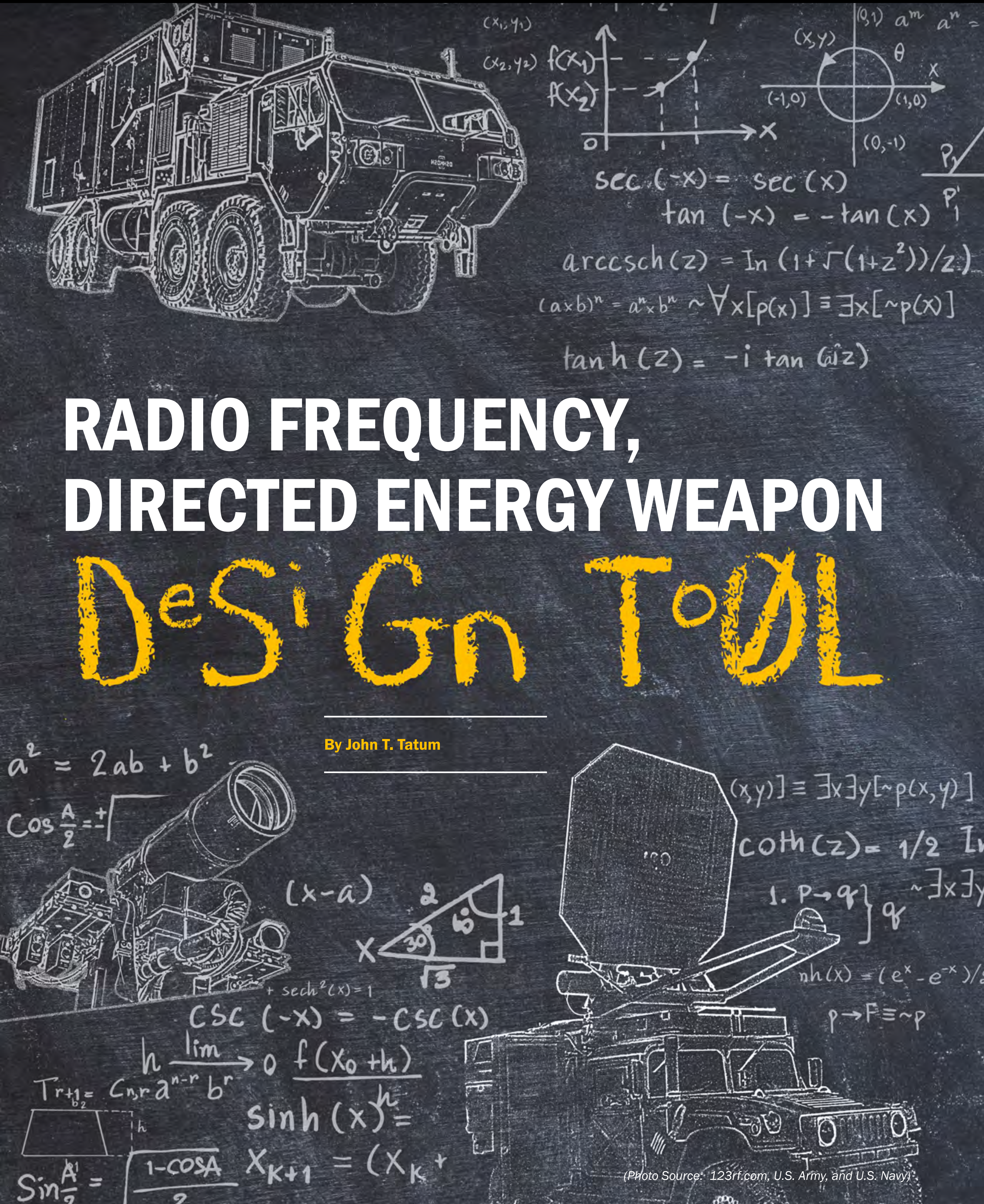
[20] Weil, E. D. "Fire-Protective and Flame-Retardant Coatings – A State-of-the-Art Review." *J. Fire Sci.*, vol. 29, pp. 259–296, 2011.

[21] Levchik, S., A. Piotrowski, E. Weil, and Q. Yao. "New Developments in Flame Retardancy of Epoxy Resins." *Polym. Degrad. Stab.*, vol. 88, pp. 57–62, 2005.

[22] Levchik, S. V. and E. D. Weil. "Thermal Decomposition, Combustion and Flame-Retardancy of Epoxy Resins – A Review of the Recent Literature." *Polym. Int.*, vol. 53, pp. 1901–1929, 2004.

BIOGRAPHY

ALEXANDER B. MORGAN is a distinguished research scientist with the University of Dayton Research Institute and is a group leader of the Applied Combustion and Energy group. He has over 22 years' experience in material flammability and fire safety requirements and supports government and industrial customers on practical fire safety needs. Dr. Morgan is the Editor-In-Chief for the Journal of Fire Sciences and is a member of Sigma Xi, American Chemical Society, ASTM, and the International Association of Fire Safety Scientists. Dr. Morgan holds a Ph.D. in chemistry from the University of South Carolina and a B.S. in chemistry from the Virginia Military Institute.



RADIO FREQUENCY, DIRECTED ENERGY WEAPON DESIGN TOOL

By John T. Tatum

(Photo Source: 123rf.com, U.S. Army, and U.S. Navy)

INTRODUCTION

High-power microwave (HPM), radio frequency (RF), directed energy weapons (DEWs) provide the Warfighter with several advantages over conventional kinetic energy weapons. Due to a relatively wide beam, HPM DEWs can engage multiple targets at the speed of light and with a high probability of hit. They can produce a range of effects that vary from long-term electronic upset to permanent damage, depending upon the target's vulnerability level and range. Most importantly, they have a relatively unlimited supply of "low-cost ammo" (i.e., a "deep magazine of RF/microwave pulses"), limited only by the power and fuel capacity of the host platform/vehicle, which can lead to less logistics and costs.

The first step in evaluating the feasibility of an HPM DEW concept is to determine how much power is required for the weapon system to produce the desired effect at the desired range. Once we know the power required, we can compare this to the power available on the weapon platform to see if it is within its limits.

This article is divided into two basic sections. The first section describes the methodology, physics, and mathematics required to calculate the power requirements of an HPM DEW system. The process and equations described herein have further been integrated into an easy-to-use Excel™-based tool known as the Radio Frequency, Directed Energy Weapon Design Tool (RFDEDT).

HPM DEWs can engage multiple targets at the speed of light and with a high probability of hit.

The second section of this article walks through a fictional example using the RFDEDT. The RFDEDT allows a user to specify the power density required at the target for an effect (i.e., the target effect/vulnerability level) and range, and the tool computes the effective radiated power (ERP) required for an HPM DEW system. The tool then computes the peak transmitter power required based on other user inputs, such as the antenna size and efficiency. The tool works backward to compute the total prime power required for the weapon system based on user inputs for the modulation needed to affect the target (i.e., pulse width and pulse repetition frequency [PRF]) and the efficiencies of the transmitter, modulator, and prime power supply. Once the user knows the total power required for the HPM DEW, he or she can compare the power available from the host platform/vehicle to determine if the HPM DEW concept is feasible from a power standpoint.

METHODOLOGY

The overarching approach to develop an HPM DEW system is shown as a five-step block diagram in Figure 1 [1].

The first step is to define the targets of interest and desired engagement range for those targets. Second, HPM power density required on the target to produce an effect, either electronic upset or damage, must be estimated. Third, the power/system requirements are developed. Fourth, the HPM DEW system is designed. And finally, the HPM DEW system is built and tested.

Given the desired targets and engagement range, we then need to estimate the required target effect level from our HPM DEW system. HPM typically enters a target through some port of entry and travels to the critical components. If the power at the component is greater than the component's effect level, then there is a probability of effect. Ideally, if the target system is available for HPM effects experiments, we should determine the target effect level distribution based on experimental data and use the data to develop probability of target effect curves as a function of the incident HPM power density on the target. However, if this is not possible, we can roughly estimate the target effect level, S, by estimating the power required for component effect, P_c, the effective area of the HPM POE, A_e, and the HPM loss along the path from POE to the component, as shown in Figure 1 and equation 1.

$$S = Pc / Ae\ L. \qquad (1)$$

Once we know the target effect level, S, and the desired engagement range, R, we can compute the HPM DEW's peak

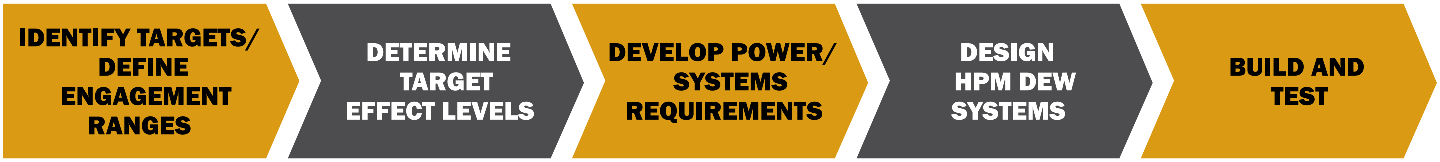


Figure 1: Methodology for Developing an HPM DEW System *(Source: SURVICE Engineering Company).*

ERP, ERP_p, required to produce a target effect, as shown in equation 2.

$$ERP_p = 4\pi R^2 S. \qquad (2)$$

This equation is a variation on the transmission equation and assumes that the HPM DEW is irradiating into free space and experiences no atmospheric losses. For frequencies from 1 to 10 GHz, this is a reasonable assumption unless the range is very large (i.e., tens of kilometers). The ERP is defined as the product of the transmitter's power, P, and antenna gain, G, as shown in equation 3.

$$ERP = PG. \qquad (3)$$

Therefore, based on this equation, we can compute the transmitter power required for the HPM DEW by dividing the ERP by the antenna's gain.

HPM DEWs typically need very high gain antennas to direct the HPM at the target and reduce the amount of power out of the transmitter. For RF/microwave frequencies, this means the antennas need to be large compared to the wavelength of the radiation they are transmitting. Typically, antennas that can handle high power use a circular of rectangular aperture that is large relative to the radiation wavelength. The gain of an aperture-type antenna is based on the physical area of the aperture, A, its antenna efficiency, N, and the radiation wavelength, λ, as shown in equation 4.

$$G = 4\pi AN/\lambda^2. \qquad (4)$$

For a circular aperture, with diameter, D, the gain is given by $G = (\pi D/\lambda)^2 N$.

Related to an antenna's gain is its beam width. The half power beam width in degrees, B, of a circular aperture antenna with a radius, D, in meters is given in equation 5.

HPM DEWs typically need very high gain antennas to direct the HPM at the target and reduce the amount of power out of the transmitter.

$$B = k\lambda/D, \qquad (5)$$

where k is a factor which varies depending on the shape of the reflector and the illumination pattern of the antenna feed. For a uniformly illuminated parabolic reflector, k is typically about 57 (the number of degrees in a radian). For a "typical" parabolic antenna without uniform illumination, k is approximately 70.

The radiation spot size (diameter), d, at a target is related to the antenna's beam width, B, and target range, R, as shown in equation 6.

$$d = 2R \tan (B/2). \qquad (6)$$

Another important parameter for an antenna is its far field boundary, which is defined as the distance from an antenna at which the RF radiation is essentially a plane wave and the power density from an HPM DEW decreases proportional to the inverse square of the distance. The minimum far field boundary of an antenna, FF, depends upon the largest dimension of the antenna aperture, D, and the wavelength being radiated, λ, as shown in equation 7.

$$FF = 2D^2 / \lambda. \qquad (7)$$

Once we know the gain of the antenna, we can compute the peak transmitter power, P_p, required for an HPM DEW by dividing the peak ERP by the antenna gain, as shown in equation 8.

$$P_p = ERP_p /G. \qquad (8)$$

Since we are eventually interested in determining the total average prime power required for the HPM DEW, we convert the peak transmitter power required to average power, P_a, by multiplying the peak power by the HPM source's pulse width, τ, and PRF, f_r, as shown in equation 9.

$$P_a = P_p \tau f_r. \qquad (9)$$

The product of the pulse width and PRF is known as the duty cycle of the HPM DEW system.

Unfortunately, transmitters are typically not 100% efficient due to internal losses, so some of the input power (power provided by the modulator) does not produce HPM radiation and is wasted as heat. The wasted power for a transmitter, P_{TW}, can be estimated by equation 10.

$$P_{TW} = P_a (100 - E_T)/100, \qquad (10)$$

where P_a is the average input power of the transmitter and E_T is the transmitter's efficiency. Here, we define the transmitter's efficiency as the transmitter's output power divided by the input power.

Now that we know the total average power required for the transmitter, P_a, and the transmitter's efficiency, we can compute the output power required from the modulator to drive the transmitter, P_M, as follows:

$$P_M = P_a / E_T. \qquad (11)$$

As with the transmitter, modulators are typically not 100% efficient due to internal circuit losses, so some of the power is wasted in the form of heat. The power wasted in the modulator, P_{MW}, can be estimated by equation 12.

$$P_{MW} = P_M (100 - E_M)/100, \quad (12)$$

where E_M is the efficiency of the modulator.

Once we know the modulator power, P_M, we can compute the power required of the prime power system, P_{PR}, to drive the modulator as follows:

$$P_{PR} = P_M / E_M, \quad (13)$$

where E_M is defined as the efficiency of the modulator.

Prime power supplies for an HPM DEW are also not 100% efficient and waste some of the power. The total power needed to produce HPM, P_{HPM}, is given by equation 14.

$$P_{HPM} = P_{PR} / E_{PP}, \quad (14)$$

where E_{PP} is defined as the efficiency of the prime power supply.

The power wasted by the prime power supply, P_{PPW}, is given by equation 15.

$$P_{PPW} = P_{RF} (100 - E_{PP})/100. \quad (15)$$

Equation 14 represents the total prime power required for the HPM DEW to produce sufficient power at the target for an effect, but it is not the total prime power required for the HPM DEW system. Since the HPM DEW has other subsystems requiring power, we must include them in our power budget calculations. For example, an HPM DEW will most likely use vacuum tubes for the high-power transmitter, such as magnetrons and klystrons. These tubes require power for their filament and high-voltage power supplies. This is known as the transmitter's "house-keeping power," P_H. Further, the transmitter may require a vacuum pump to prevent voltage breakdown within the tube; this also requires power, P_{VP}. Finally, the HPM DEW will probably need power for the antenna control system, P_{AC} (to point the antenna toward the target), power

> Prime power supplies for an HPM DEW are also not 100% efficient and waste some of the power.

for a sensor to detect the target, P_s, and power for other auxiliary subsystems, P_{AUX}.

Therefore, the total power required for an HPM DEW system, P_{Total}, is given by the sum of the power required for each of the subsystems as follows:

$$P_{Total} = P_{HPM} + P_H + P_{VP} + P_{AC} + P_{AC} + P_{AUX}. \quad (16)$$

The total wasted power that must be removed by the thermal management cooling, P_{TotalW}, is the sum of the waste power from each of the major HPM DEW subsystems as given by equation 17.

$$P_{TotalW} = P_{TW} + P_{MW} + P_{PPW}. \quad (17)$$

USING THE RFDEDT

All the equations discussed in the Methodology section have been built into the RFDEDT to quickly compute the total power required for a notional HPM DEW system. Figure 2 shows the main screen for the RFDEDT, along with fictional example values. In this section, we will walk through a fictional example to demonstrate use of the RFDEDT. All the numbers used in the example are totally fiction and meant only to demonstrate how to use the tool.

We start with the "Target" block shown on the lower right of the main screen. The inputs to the tool are shown in green and the calculated values shown in black. For the Target block, the user inputs are the target effect level required and the target range. Based on equation 2, the tool calculates that we would need 50 GW of *ERP* to affect a target at 2000 m, with a target effect level of 0.1 W/cm^2. Next, we input the HPM DEW's pulse width, *PRF*, and the dwell time on target for effect. For an HPM DEW that produces 1-μs pulses at 100 Hz, the duty cycle would be 1 X 10^{-4}. The average ERP required to affect the target would be 5 MW.

Next, we go to the "Antenna" block shown in the upper right corner of the main screen. Here, we calculate the antenna gain based on the user inputs of antenna size/diameter, the antenna efficiency, and the HPM frequency/wavelength. Based on equations 4 and 5, we see that a circular, 3-m diameter antenna with an efficiency of 60% and radiating at a frequency of 1000 MHz would provide a gain of 592 (or 27.7 dB). Further, the antenna's beam width would be about 7 degrees, producing a beam spot size diameter of 236 m at the target range of 2000 m. The far field boundary for such an antenna is estimated to be about 60 m.

The "Transmitter" block to the left of the Antenna block will calculate the peak and average transmitter power required for the HPM DEW to affect the target. Based on equation 3, the peak transmitter power required to produce a peak *ERP* of 50 GW is 85 MW. With this peak power, the average transmitter output power would be about 8.5 kW, based on the duty cycle assumed. The primary user input for the Transmitter block is the efficiency of the transmitter. For our example, we have assumed a transmitter efficiency of about 50%, which is a reasonable number for very high-power tubes [2]. Based on equation 11, we see that for a transmitter with an efficiency of 50% to produce 8.5 kW of average power, the modulator must provide at least 17 kW

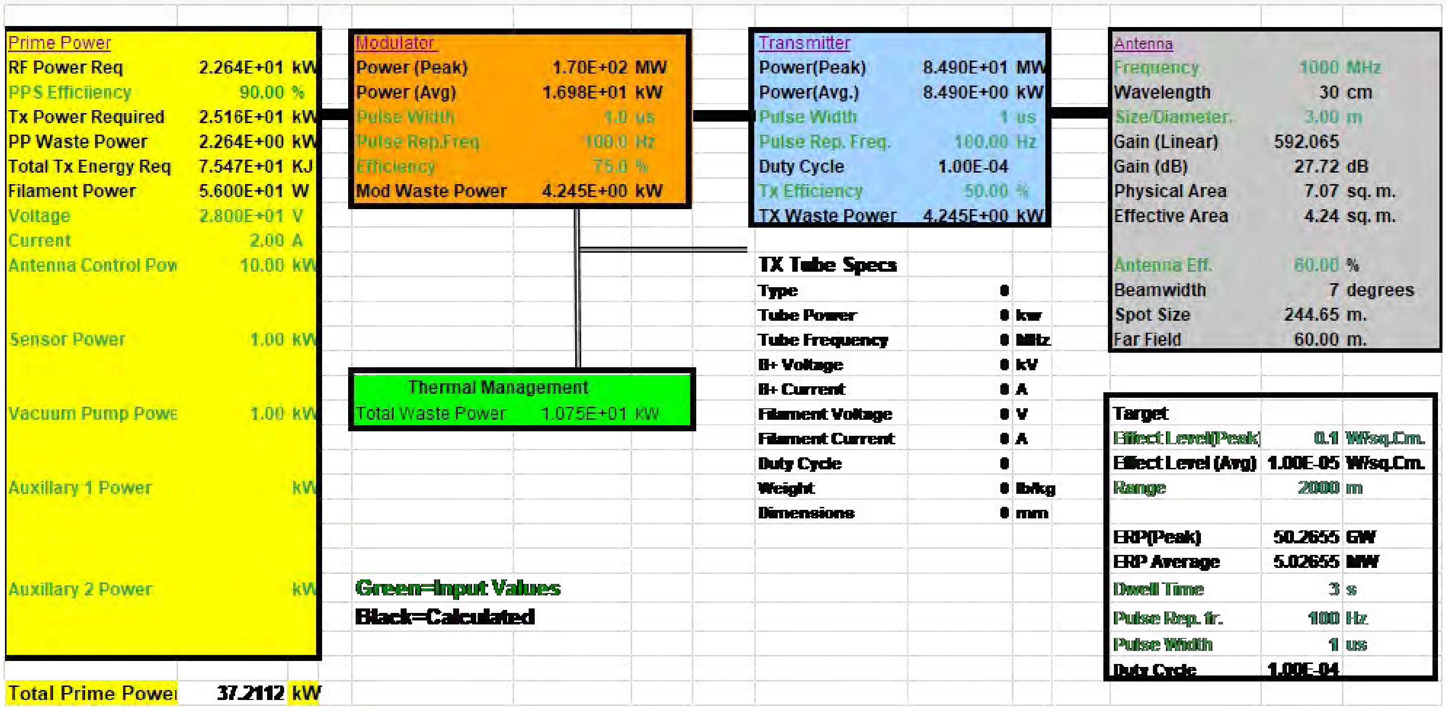


Figure 2: Screen Shot of the RFDEDT With Fictional Values Shown *(Source: SURVICE Engineering Company).*

into the transmitter. Since not all the transmitter's input power is converted to HPM, based on equation 10, the wasted power is estimated to be about 4 kW.

The "Modulator" block will determine how much power is required from the modulator to drive the transmitter. For the modulator, the primary user input is the efficiency. For our example, we have assumed a modulator efficiency of 75%, which is a typical efficiency for a modulator based on a pulse-forming network made from inductors and capacitors [2]. With a modulator efficiency of 75%, the prime power required to drive the modulator is estimated to be about 23 kW, with a waste power of about 4 kW.

Finally, we go to the "Prime Power Supply" block on the main screen. For the prime power supply, the primary user input is the efficiency of the prime power supply. For our example, we have assumed a prime power supply efficiency of 90%, which is reasonable for prime power supplies such as generators [3]. Based on equation 14, the total prime power required for an HPM DEW to affect the target is estimated to be about 25 kW. Since we assumed that we must irradiate the target for a dwell time of 3 s, this means we must have at least 75 kJ of energy.

It must be emphasized that this is the power/energy needed just to produce the HPM energy necessary to affect the target at range. We must also consider the power requirements for other parts of the HPM DEW system. For our example, we have assumed that we will need about 56 W of filament power for the transmitter, 10 kW for the antenna control system, 1 kW for the sensors, and 1 kW for the vacuum pumps to prevent voltage breakdown in the tube. Therefore, the total power required to drive the HPM DEW system is estimated to be about 37 kW, and the total waste power is estimated to be about 10 kW.

At this point, the user can compare the total power estimated to be required for an HPM DEW concept to the power available from the proposed platform. If the power required is less than the available power, the concept may be feasible from a power budget standpoint. If the power available is less than the power required, then the concept may not be feasible or require a larger prime power generator.

CONCLUSION AND FUTURE PLANS

The RFDEDT tool is meant to only provide an estimate of the total power required for an HPM DEW and is very dependent upon the user inputs and assumptions. For an actual HPM system design, one should add a safety power margin to the computed value to ensure that the weapon has a high probability of target effect.

To fully evaluate the feasibility of an HPM DEW concept, it is also important to perform a technology survey to determine if there is commercially available equipment that meets the HPM DEW requirements or whether new technology must be developed. To assist in this problem, the RFDEDT also has subscreens for the transmitter, the modulator, and the prime power supply that provide some of the available commercial equipment. In the future, we hope to add size and weight for each of the subsystems to estimate the total size, weight, and power (and cooling) required for an HPM DEW concept. In the interim, we hope this design tool will be useful to HPM weapon concept developers to quickly and easily determine the power requirements. It has been reviewed to ensure correct calculations for the inputs used, but it is not a commercial application. HPM concept developers should follow the basic design methodology that has been presented and are encouraged to take advantage of the RFDEDT. Please contact the author for more information and/or to obtain a copy of the RFDEDT. ■

ACKNOWLEDGMENTS

The author would like to thank Dr. Tom Podlesak of the U.S. Army Communication Electronics Command (formerly with the U.S. Army Research Laboratory) for his valuable contributions to the RFDEW design tool—specifically, in developing some of the main screen graphics and developing the transmitter, modulator, transformer, and prime power supplies subscreens.

REFERENCES

[1] U.S. Department of Defense. "Methodology Guidelines for High Power Microwave (HPM) Susceptibility Assessments." Office of the Secretary of Defense HPM Effects Assessment, Methodology Sub-Panel, Chairman - Anthony Pesta, Rome Air Development Center (RADC), January 1990.

[2] Hovanessian, S. A. *Introduction to Sensor Systems.* Norwood, MA: Artech House, 1988.

[3] Skolnik, M. *Introduction to Radar System-2nd Edition*. Chapter 2, New York: McGraw-Hill, 1980.

BIOGRAPHY

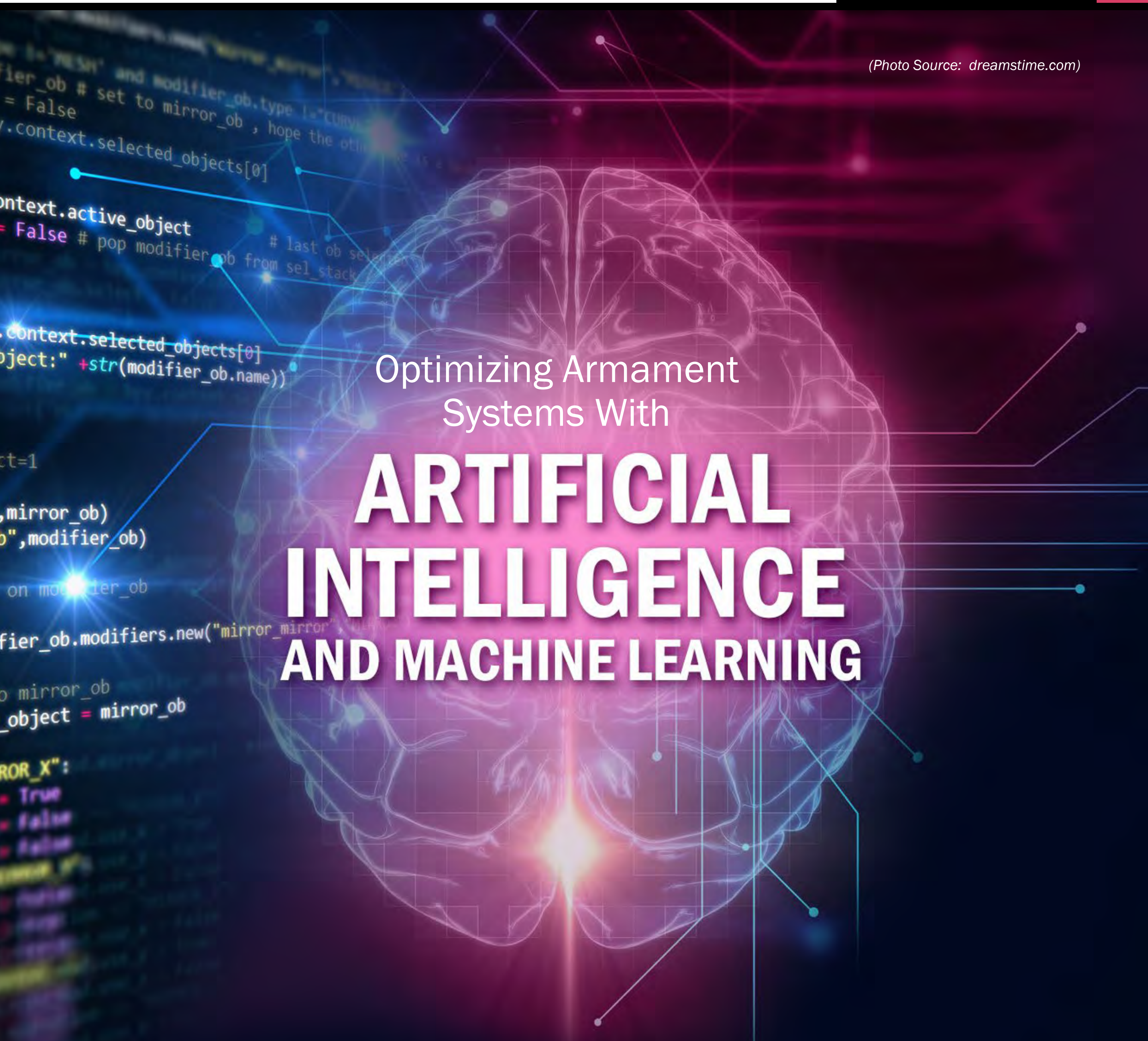
JOHN T. TATUM is an electronic systems engineer with the SURVICE Engineering Company. His area of expertise is electronic warfare (EW) and radio frequency, directed-energy weapons (RF DEWs). He worked more than 36 years at the U.S. Army Research Laboratory's RF Electronics Division in radar/EW, where he directed and participated in electromagnetic/RF effects investigations on military systems and supporting infrastructure. He served as the chairman of the Army's RF DE Joint Munitions Effectiveness Manual Working Group and the RF Effects Panel for the Office of the Secretary of Defense's Technology Panel on DEW. Mr. Tatum is a fellow of the Directed Energy Professional Society. He holds a B.S. in electrical engineering from the University of Maryland and has completed graduate courses in communications and radar at the University of Maryland and The John Hopkins University.

LONGTIME APG SCIENTIST PASSES AWAY

It is with great sadness that we received news about the sudden passing of Dr. Brad Forch. Brad served the U.S. Army Research Laboratory as a senior research scientist in ballistics, where we had the opportunity to work with him as DSIAC's first Contracting Officer's Representative. Brad maintained regular contact with DSIAC ever since its beginnings and has been a tremendous supporter and advocate. His dedicated work ethic and genuine concern for DoD research is a testament to him as a person and his passions as a scientist . He will most certainly be missed.

https://www.dsiac.org/resources/journals/dsiac/summer-2014-volume-1-number-1/message-cor ▸

(Photo Source: U.S. Army)



(Photo Source: dreamstime.com)

Optimizing Armament Systems With ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

By Ralph Tillinghast, Michael Wright, and Myron Hohil

INTRODUCTION

In the war of buzz words, artificial intelligence (AI) and machine learning (ML) currently rank among the top listed. This is due to the obvious potential impact these technologies have on almost every market sector. Based on a review of multiple predictive reports [1] and with an estimating growing market cap between $5 billion to $8 trillion by 2020, it is imperative to ask how these technologies are applied and can they continue to be utilized to optimize our armament systems. The purpose of this article is to give a high-level review of how AI and ML can optimize weapon platforms. This includes a base discussion on the benefits and concerns of having AI and ML become a part of our integrated weapon and fire control systems. The importance of how our Warfighter is “in-the-loop” will always be a talking point, particularly as AI and ML continue to move closer to reaching singularity. For this reason, some discussion will focus on identifying levels of autonomy for armaments systems to ensure control is never compromised. AI and ML are not new concepts for the Army to adopt for their armament systems. Utilizing fire control platforms that provide multiple examples of AI and ML already in the field or being developed will be included. Finally, ethical and moral issues with AI and ML utilized for weapon platforms should be addressed.

BENEFITS

The ability to process information quickly and effectively stands as one of the fundamental benefits of AI and ML, as it has been proven for computer systems. There are increasing advantages as the deep learning and complexity of the information increases. AI and ML have the potential to allow processing information at a higher volume and speed than possible for our Warfighters. The ability to identify patterns advantageous to the Warfighter also lie within this processing. This has multiple benefits, not only in accuracy and speed, but also in lightening the cognitive load on our Warfighter. Allowing the Warfighter to focus and process a more complex strategy and real-time decision making is critical during an operation. If utilized properly, using AI and ML can also aid in reducing errors that occur due to the often stress-dependent human element.

SINGULARITY AND CONCERNS

The point of singularity is described as the convergence of human intelligence and machine intelligence; the computer and its software will have reached the same level and pattern of recognition and awareness that our species enjoy. Arguments as to whether this will ever be possible continue. Nevertheless, based on world gross domestic product (GDP) and processing power (i.e., budget and how many transistors can troubleshoot), Ray Kurzweil asserts that we will reach singularity in the 2050-2060 timeframe based on this model [2].

AI and ML have the potential to allow processing information at a higher volume and speed than possible for our Warfighters.

This will create a new species on the planet. Linked into armaments systems, this opens the imagination to many different possibilities that have been played out throughout many sci-fi movies and has built a base of distrust for this type of development. On a positive note, humans have always won in these scenarios, but reality may not be so kind. A result of Ray Kurzweil's assertion was an open letter to the United Nations signed by many of the greatest thinkers and leaders who want to ensure humanity's growth continues by asking for a ban on developing "killer robots" or Lethal Autonomous Weapon Systems (LAWS) [3]. This directly links into the armaments community who will need the proper safeguards in place while still utilizing the benefits of AI within armament solutions by controlling the levels of autonomy as machines are weaponized. A fundamental dilemma is the possibility that other "actors" will develop these types of capabilities and put us at a disadvantage. In other words, the rules of engagement will be forced to shift as these types of systems are deployed. Therefore, any leading military must develop platforms with these capabilities and have them ready for use if an adversary begins to deploy them to ensure an overmatch is maintained.

This does not fully elevate the operational and ethical concerns. Further discussions need to occur to fully understand the ethical ramifications of developing fully autonomous weapon platforms that integrate high AI and ML capabilities. Schroeder's research in the ethics of war as it relates to autonomous weapons systems identifies multiple fundamental considerations that need to be addressed as these types of systems are developed [4]. One major concern is that designers will not be able to 100% predict how these systems will operate, opening the possibility for misconduct on the battlefield by LAWS. This links directly to the 2001 Responsibility of States for International Wrongful Acts published by the International Laws Commission that identifies states operating LAWS-based systems would be responsible for the acts of these systems when employed with their forces [5]. Some have argued that autonomous systems will not perform acts out of fear or aggression and would have video evidence to back up their actions [4, 6].

It is difficult to predict how the law and ethics for a LAWS-based system will be established and upheld, as the systems do not yet fully exist. Using weaponized platforms such as LAWS will alter the way battles will be fought.

The use of these systems may get more complex when dealing with different cultures' opinions on the importance or placement of robotic platforms within society. Some cultures value robotic systems in their culture more than others. As singularity is achieved at a humanitarian level, it can be argued that humans have created a new species on the planet that deserves the same rights and protections as themselves and other species. As the platforms get closer to singularity [7], there is debate on human rights vs. robot rights. Sending a fully weaponized robot that is "aware" or reached singularity but has not chosen to fight on its own might be conceived as another form of forced labor or slavery. Fortunately, there will be a few years before this point is reached to allow in-depth discussions and debate. Understanding and classifying the levels of autonomy for weaponized platforms are part of this discussion.

LEVELS OF AUTONOMY

These levels of autonomy establish clear stages of how AI, ML, and robotic platforms are controlled and supervised based on their roles and scenarios. The U.S. Army's Armaments, Research, Development and Engineering Center (ARDEC) has internally developed a draft set of autonomy levels for weaponized platforms to track and make development decisions [8]. Because of the strong systems engineering practices utilized by ARDEC, understanding each of these levels and how they interact with all stakeholders is critical. The draft levels are illustrated in Table 1.

Applications that could impact the Warfighter's armaments capability can be identified at all levels. Understanding these levels is critical so we ensure control is maintained throughout each level of autonomy. Countermeasures for these capabilities also need developed as adversaries develop weapon platforms within these outlined levels. Questions remain on how AI and ML are currently utilized within existing armament systems, as armaments consist of three basic subsystems—the weapon, munition, and fire control.

> Sending a fully weaponized robot that is "aware" or reached singularity but has not chosen to fight on its own might be conceived as another form of forced labor or slavery.

FIRE CONTROL APPLICATIONS

Modern fire control is typically digitized in nature, making it an obvious choice to utilize AI and ML for this subsystem. AI and ML have great impact and future potential to support fire control and its kill chain. This is not surprising because the computer was invented for and first used to calculate fire control ballistic trajectories of artillery shells in the 1940s [9]. To see the potential utilization within fire control, the fire control kill chain [10] that is the doctrinal base for most armament systems must first be reviewed. This kill chain is broken into six stages, as shown in Figure 1.

Moving through the chain, one can see that the target is identified and tracked and means of engagement identified. Once this is accomplished, the weapon platform is aimed and fired. From that point, the munition is tracked and/or guided to the target, which is then assessed for further action. As mentioned before, the very first computer program was used to calculate how the munition would fly, allowing the artillery gun to be pointed in the correct direction. This capability to exceed human calculations continues to be a theme within fire control and may be considered a low-level AI capability.

This leads to a currently fielded system that provides ballistic calculations for mortar platforms. The Mortar Fire

Table 1: Proposed Levels of Autonomy for Armament Systems

LEVEL	DESCRIPTION
Level 1	The indirect and direct retransmission of imagery and/or data (e.g., target information) from a remote system.
Level 2	The receipt of imagery and/or data directly from the unmanned system (UMS)/remotely operated system and the functionality of previous levels.
Level 3	The control of the unmanned system (UMS) manned systems/remotely operated system's (RMS's) mission equipment packages, sensors, or payloads (i.e., weapons) and the functionality of previous levels (synonymous to teleoperation).
Level 4	Full functionality and control of the UMS/RMS and the functionality of previous levels; less program-specific special authorization, such as safety and security related (e.g., supervised autonomy).
Level 5	All inclusive, full functionality, and control of a UMS from start through completion.
Level 6 (Full Autonomy)	Fully aware and making own functional decisions (e.g., complete autonomy, human/strategic thinking, etc.).

Figure 1: Fire Control Kill Chain *(Source: ARDEC)*.

Control System (MFCS), utilized for 120-, 81-, and 60-mm mortar platforms, is currently fielded on multiple devices depending on the platforms (Figure 2). Within this software, the ballistic calculations are developed based on multiple variables that affect the projectile during the armaments operation. The software algorithm adjusts the weapon by using distance, wind, air pressure, and other factors such as propellant temperature. This is like how a human archer would adjust the bow before releasing an arrow. Today, some may not consider this AI compared to the early definitions put forth by John McCarthy in 1956—“the science and engineering of making intelligent machines” [11]. One can see how this was an early adoption of AI principles for armament systems.

As image processing is currently a large focus area within AI development, it is easy to link to the first step in the fire control kill chain—”identify and track” the potential target. Many systems have been developed that will classify and track objects within a visual area.

> The capability to exceed human calculations continues to be a theme within fire control and may be considered a low-level AI capability.

Orientation and pointing continues to be one of the most difficult areas to develop solutions within the fire control kill chain. Currently, laser ring or fiber optic gyros are the go-to solutions for identifying north within the accuracy needed to ensure successful weapon pointing. The issue with this type of technology is directly linked to SWaP (size, weight, and power) and cost. Typical laser ring gyros capable of 1-mil accuracy are approximately ~16 lbs, at least ~5x7x8.5”, and cost between $50 and $100 K, depending on volume being purchased. This size and cost does not make it applicable to smaller caliber weapon platforms such as the 60- and 81-mm mortar system previously referenced. To overcome this, the Weaponized Universal Lightweight Fire (WULF) control system (Figure 3) was developed.

Figure 2: M150/M151, 120-mm Mortar Fire Control System *(Source: U.S. Army).*

WULF is a solution that has been transitioned to PEO Ammo for fielding in 2022. This system utilizes multiple low-cost, miniature electrical mechanical switch-based sensors (such as accelerometers, magnetometers, and inclinometers) in conjunction with a camera to give pointing solutions for weapon systems. Using multiple sensors integrated together gives an advantage. By understanding the strengths and weaknesses of each of these sensors, a robust solution was developed. The WULF system can point at a ~3-mil accuracy at a cost of ~$10 K and weight of ~1.8 lbs. The way this relates to AI and ML is that the integrated sensors have more than 130 variables or sources of errors that could influence the accuracy of the WULF pointing device. These variables include variances in the weapon platform connected to variations in orientation of sensor chips when soldered to the base circuit board. To optimize the system, an ML algorithm was adopted that considers all 130+ variables and allows the fire control sensor to teach itself how to be more accurate based on the situation it is operating in. This resulted

Figure 3: Weaponized Universal Fire Control *(Source: U.S. Army).*

in an increased accuracy from ~3 mils to ~2 mils. Within the orientation and pointing community, this is considered a significant accomplishment.

The fourth example directly links to the ability for algorithms to process and make complex decisions faster and more accurately than humans. The Flexible Fire Control System (F2CS) (Figure 4) was developed to allow a full integrated fire control solution that can adapt to incoming threats. The F2CS system utilizes an AI algorithm to link existing threat detection systems to armaments systems that can defeat an incoming threat. This is accomplished by integrating multiple threat detection systems into the AI algorithm. If a threat is detected and classified, it utilizes the database of connected weapon platforms, selects the best weapon or weapons to defeat the target, and slews/aims the weapon(s) to engage. In less than a second, this is presented to the Warfighter for engagement approval. Without this AI algorithm, the processing/decision-making time may not allow the threat defeat. The importance of understanding the levels of autonomy discussed before is illustrated in this example. As the fire control system goes through the kill chain process to identify, classify, slue, and engage the target, time is critical. Due to these time limitations, the only way to ensure Warfighter survivability and defeat the threat may be to build in this type of autonomy. An example methodology for this is to have preapproved engagement air space to expand if an incoming threat enters a preselected area around a base. The fire control will have authorization to engage that object.

These last four examples are all organic Army-developed programs. However, we are not the only countries developing armament systems with AI and ML capabilities. As an example, the SGR-A1 [12] is an autonomously firing weapon platform capable of executing all stages of the fire control kill chain. Developed to maintain/monitor the demilitarized zone between North and South Korea, the SRG-A1 is an example of level 5/6 of weaponized autonomy with AI systems (Figure 5). If activated, it is given full authority to execute the kill chain autonomously on any object that moves within the space, whether that is an armored vehicle or a squirrel. This naturally pivots the mind toward the ethical considerations and levels of trust with armament systems that utilize AI/ML and have high autonomy levels. These considerations come full

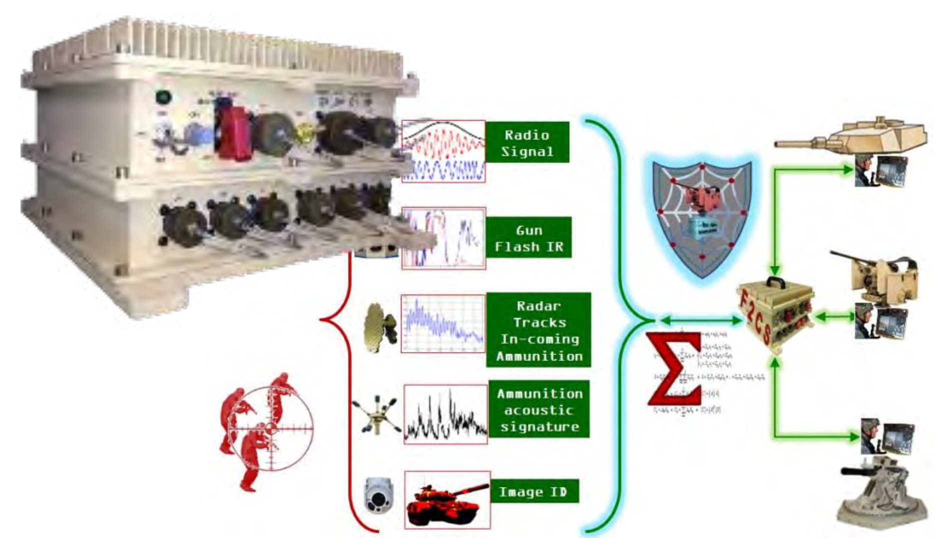


Figure 4: F2CS *(Source: U.S. Army Research, Development and Engineering Center).*

Figure 5: SRG-A1 Autonomous Weapon *(Source: SGR-A1 [12]).*

circle in trying to understand the ethical considerations of these types of systems and how our War Fighters will trust and operate with these platforms.

TRUST

These efforts are a method to support our Warfighters and ensure that they continue to have an overmatch during operations. As AI-based systems are further integrated into our platforms, the interface between humans and machines becomes more critical. One question is the level of trust that will be established between these platforms and our Warfighter. The initial inclination is our Warfighter will distrust system; however, research by the Georgia Institute of Technology has found that humans overtrust robots in some situations [13]. The bond between AI-based systems and the Warfighter will need to be further explored and understood to make sure decisions in real-time, high-stress situations are not compromised. Research has been conducted in this area on EOD operators and their field robots [14]. Patterns were identified, but further research is needed to fully understand how trust will play in the operational environment.

CONCLUSION

Overall, the benefits and advantages of AI and ML are already being capitalized within our armaments systems, as shown by the examples provided. These benefits are just a small sampling focused on weapon platforms. As these technologies are expanded across the entire U.S. Department of Defense logistical footprint, it is easy to see the potential impact. The balance that must be maintained is the control over the technology, in both development and use. AI and ML will no doubt increase the effectiveness of weapon platforms. This impact is multiplied when combined with other emerging technologies, including sensor saturation through the Internet of Things, massive data analytics through deep learning and big data methods, modern cognitive science, social network technologies, and other technologies that allow a wider and deeper understanding of how integrated complex systems operate. These advancements still must navigate through the growing ethical concerns surrounding these systems and align with and adopt to the Law of War (legal) obstacles that still exist. ■

REFERENCES

[1] Faggella, D. "Valuing the Artificial Intelligence Market, Graphs and Predictions," March 2018, www. TechEmergance.com, accessed 1 June 2018.

[2] Kurzweil, R. "Timing the Singularity." *The Futurist*, http://www.singularity2050.com/2009/08/timing-the-singularity.html, accessed 1 June 2018.

[3] Sample, I. (editor). "Ban on Killer Robots Urgently Needed, Say Scientists." *The Guardian*, https://www.theguardian.com/science/2017/nov/13/ban-on-killer-robots-urgently-needed-say-scientists, accessed 1 June 2018.

[4] Schroeder, T. W. "Policies on the Employment of Lethal Autonomous Weapon Systems in Future Conflicts," 2016.

[5] United Nations. "Responsibility of States for International Wrongful Acts 2001." International Law Commission, Articles 30–31, pp. 34-39, 2008.

[6] Lubell, N. "Robot Warriors: Technology and the Regulation of War." TEDxUniversityofEssex, YouTube.com 13:44, 2014.

[7] Robertson, J. "Human Rights vs. Robot Rights: Forecasts From Japan." *Critical Asian Studies* 46.4, pp. 571–598, 2014.

[8] Tillinghast, R., et al. "Guns, Bullets, Fire Control and AI." NDIA, Armaments Systems Forum, 2018.

[9] Computer History Museum. "ENIAC." http://www.computerhistory.org/revolution/birth-of-the-computer/4/78, accessed 1 June 2018.

[10] Tillinghast, R., et al. "Fire Control 101." National Fire Control Symposium, 2017.

[11] McCarthy, J. "Artificial Intelligence." *Science Daily*, https://www.sciencedaily.com/terms/artificial_intelligence.htm, accessed 13 April 2018.

[12] SGR-A1. www.wikipedia.org/wiki/SRG-A1, accessed 2 June 2018.

[13] Robinette, P., et al. "Overtrust of Robots in Emergency Evacuation Scenarios." Human-Robot Interaction (HRI), 11th ACM/IEEE International Conference, 2016.

[14] Carpenter, J. "The Quiet Professional: An Investigation of US Military Explosive Ordnance Disposal Personnel Interactions With Everyday Field Robots." Dissertation. 2013.

BIOGRAPHIES

RALPH TILLINGHAST, a subject matter expert in digitized fire control, is the science and technology advisor for the Fire Control System & Technology Directorate at the U.S. Armament Research, Development and Engineering Center (ARDEC) and the director of the Collaboration Innovation Laboratory. He began his career outside the DoD designing and developing medical and industrial endoscopic devices. He started working in Mortar Fire Control Systems at ARDEC in 2003. During this time, he held various roles as design engineer, lead system engineer, project lead, and Army Project Officer. As an adjunct professor for the Armaments Graduate School, he currently instructs a class on fire control and is a strong advocate for STEM outreach, visiting schools monthly. Mr. Tillinghast holds undergraduate degrees in electrical and mechanical engineering and a master's degree in manufacturing engineering from Worcester Polytechnic Institute. He is currently pursuing a doctorate in system engineering from Stevens Institute of Technology.

MICHAEL THOMAS WRIGHT, a subject matter expert in fire control for mortars and artillery, works at the Mortars and Common Fire Control Division of the U.S. Army Armament Research, Development & Engineering Center, Picatinny, NJ. He is responsible for the Azimuth Testing Laboratory and is APO for the Weaponized Universal Lightweight Fire Control system. He plans, directs, and coordinates technical programs related to the design, development, and application of advanced north finding and fire control systems. His efforts include developing a broad range of fire control systems, software applications, and north finding sensors. Mr. Wright holds a B.S. in computer engineering from New Jersey Institute of Technology and an M.S. in management and an MBA from the Florida Institute of Technology.

MYRON HOHIL is the senior associate for technology at the Munitions Engineering Technology Center at ARDEC and a faculty member of the Armament's University. At ARDEC, he served as the Director of Technology, the Associate Director for Technology within the Fuze and Precision Armaments Technology Directorate, and the competency manager for the Acoustic and Networked Sensors Division. As a faculty member of the Electrical and Engineering Department at Stevens, he taught courses in electrical engineering. His academic/professional research has generated over 50 journal and conference publications. Serving on national and international conference committees, his interests include artificial intelligence, neural networks, deep learning, and digital signal processing. Dr. Hohil received his Ph.D. in electrical engineering in 1997 from Stevens Institute of Technology.

ADDITIVE MANUFACTURING IN THE DoD

(Courtesy of Avio Aero - a GE Aviation business)

By Amanda M. Schrand, Ph.D.

INTRODUCTION

The global advancements in additive manufacturing (AM) are far reaching. From a U.S. Department of Defense (DoD) perspective, all the Services (U.S. Air Force, Army, Navy, and Marine Corps) are working to advance AM materials, processes, and manufacturing technologies. The investment is substantial. Progress is being systematically made through a variety of means including, but not limited to, the following: (1) dedicated DoD Service AM implementation plans, (2) a Federally-funded national network of manufacturing institutes with an increasing number of research programs, and (3) successful AM efforts, including repairs and parts production for noncritical and flight/submarine-critical parts. An update on the status of AM in the DoD is presented, as opportunities are exploited and challenges overcome.

THE VALUE AND PROMISE OF ADDITIVE MANUFACTURING

Much has been written on the future value of AM, and several recent publications highlight the unique opportunity areas for the defense sector [1–4]. In 2014, Deloitte Consulting LLP [1] envisioned and imagined the real-world impact of AM in the DoD Maintenance Enterprise to deliver weapon systems faster and with improved platform designs. The following spring of 2015, the Defense Systems Information Analysis Center (DSIAC) covered the "Opportunities and Challenges of Additive Manufacturing in the DoD" to include major outcomes of enhancing Warfighter capability while reducing the current logistical footprint and total life cycle system costs [2]. In the fall of 2016, *Strategic Studies Quarterly* published "Additive Manufacturing: From Form to Function" [3], which provided a perspective for future joint efforts by exploring the status and shaping of AM capabilities through the strategic framework contained within key U.S. Air Force (USAF) reports, planning documents, and other relevant resources within the DoD. The article explored the growth of AM within the military, the role of AM in logistics and sustainment, and its impact on the acquisition process and concluded with future opportunities and challenges.

The December 2016 issue of the *Defense Acquisition, Technology and Logistics (AT&L) Magazine* [4] was a special issue on additive manufacturing, with contributions from Deloitte Consulting LLP; the U.S. Navy; USAF; Lockheed Martin; Raytheon; Defense Acquisition University (DAU); Youngstown State University; Defense Logistics Agency (DLA); U.S. Army Armament Research, Development and Engineering Center (ARDEC); and several others. The 16 articles spanned topics ranging from "The Digital Thread as a Key Enabler" to "Challenges of Enterprise-wide AM for Air Force Sustainment." The opening article addressed the trade-off between quality and time from the perspective of rapid defense acquisitions. For example, some AM products can be made quickly, inexpensively, and of low quality for form-and-fit checks or attributable assets. By comparison, other defense products demand high reliability, maintainability, and operation in a wide range of climates/terrains, modularity, the prospect of being upgradable, having well-designed user interfaces, and having built-in cybersecurity protection measures, etc. Therefore, the complexity of the threat will ultimately dictate our product requirements [5].

Some of the greatest benefits of AM can be categorized into time and cost, complexity and customization, and novelty compared to challenges in quality, workforce development, and trust in meeting the demanding requirements of many DoD applications (Figure 1). Although AM cannot answer all the toughest defense challenges, the status of AM in the DoD is on its way up the slope of enlightenment according to Gartner's hype cycle (Figure 2; [6]). Some of the greatest momentum can be seen in the following selected AM defense efforts listed as subsections in this article: (1) DoD AM Implementation Plans Unique to Each Service, (2) DoD AM Research Ecosystem: Manufacturing USA, and (3) DoD AM Headline Accomplishments: From Repairs to Point Insertions.

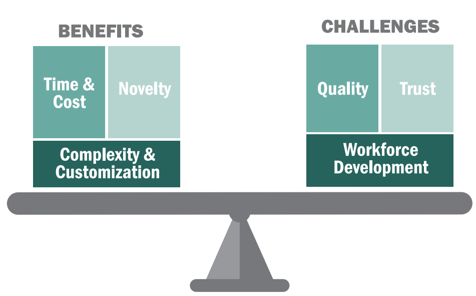


Figure 1: Opportunities and Challenges Presented by AM With Relevance to the DoD *(Source: Morris [6])*.

DoD AM Implementation Plans Unique to Each Service

Strategic implementation plans for AM have been independently produced by the USAF [7] and the U.S. Department of the Navy (DON) [8]. The U.S. Army has also developed a draft AM technology report [9].

In the USAF AM Strategic Implementation Plan, the development of AM is based upon a crawl, walk, run strategy described in now, near, and long terms [7]. The following nine key challenges were identified to move from the current state of AM to the desired implementation of AM:

1. Material standards and availability
2. Part selection
3. Skillset development
4. Configuration control
5. Reproducibility
6. Cybersecurity
7. Part validation and qualification
8. Process validation and qualification
9. Reverse engineering

Currently, AM in the USAF is primarily decentralized and consists of polymer and metal-based technology (Figure 3 [7]). Therefore, as a near-term goal, selective AM capabilities will be developed in a centralized manner to qualify target, noncritical parts. This will allow standard AM equipment, training, processes,

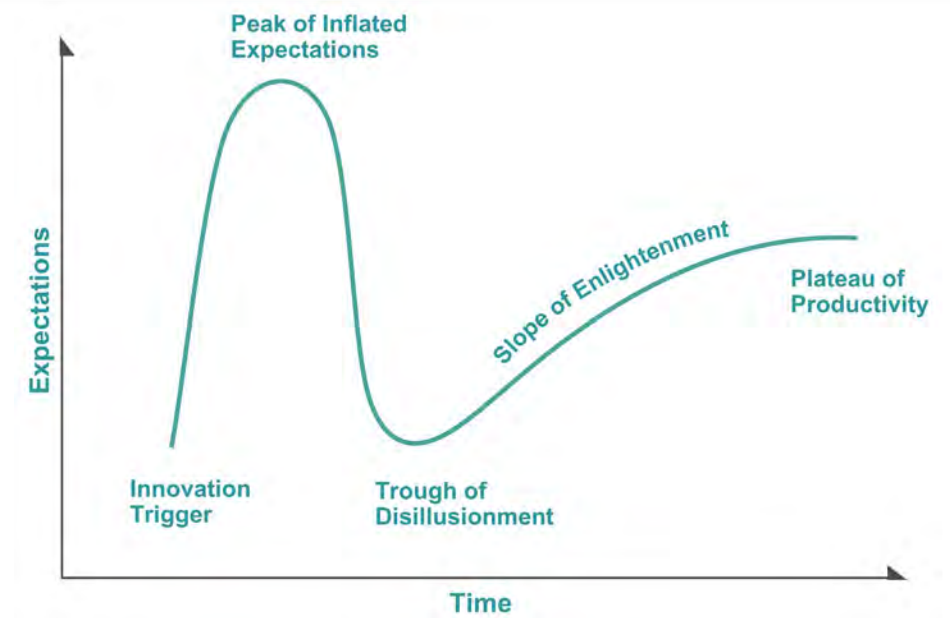


Figure 2: Gartner's Hype Cycle Showing the Phases of Innovation; AM Is on the "Slope of Enlightenment" *(Source: Gartner Methodologies).*

guidelines, tools, and post-processing procedures to be vetted, shared, and expanded across the DoD enterprise. Once these advancements have been made, the long-term vision is to place these established AM capabilities within the context of a global manufacturing network to enable on-demand printing. Other aspects of the future global AM network include a cybersecure parts library tied to the end user's viewpoint or concept of operations. These goals are in the context of ensuring agility and flexibility for the Warfighter by improving readiness while reducing cost.

The DON has a developed structure for promoting and addressing AM. The Naval Additive Manufacturing Executive Committee, consisting of the Deputy Assistance Secretary for the Navy for research, development, test and evaluation; Deputy Chief of Naval Operations for Fleet Readiness and Logistics (OPNAV N4); and Deputy Commandant, Installations and Logistics, has developed and released multiple DON AM implementation plans (IPs). The first plan was developed in 2016 in accordance with the Secretary of the Navy's 3 September 2015 memo "Additive Manufacturing/3-D Printing" and later revised in Version 2.0 (V2.0) released in 2017 [8]. The DON AM IP V2.0 identifies the following five objectives for the DON to move toward:

1. Increase development and integration of AM systems.
2. Develop the ability to qualify and certify AM parts.
3. Standardize the digital AM

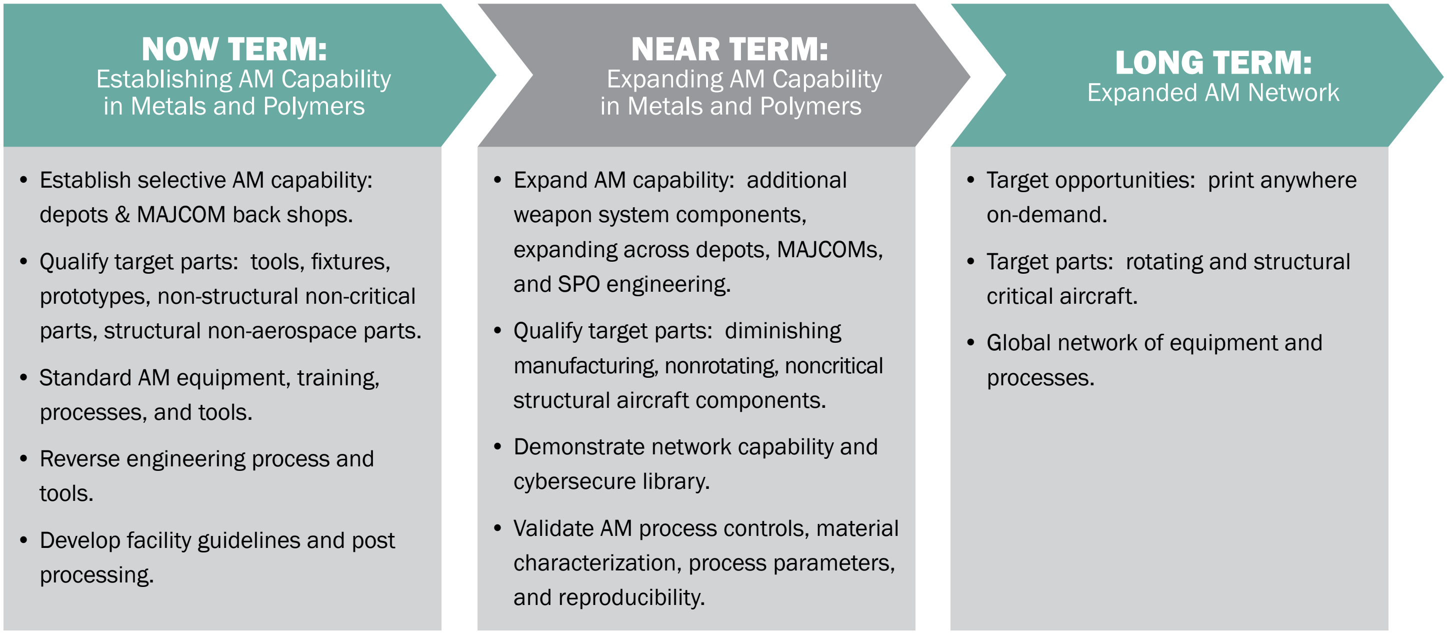


Figure 3: USAF Vision for AM Divided Into Now-, Near-, and Long-Term Capabilities *(Source: Naguy [7]).*

framework and tools and enable end-to-end process integration.

4. Establish the DON's advanced integrated digital manufacturing grid.
5. Formalize access to AM education, training, and certifications for the DON workforce. Beyond these broad objectives, the DON AM IP V2.0 breaks down specific focus areas and implementation challenges to overcome while also showing progression milestones and demonstrations spanning 2017 through 2021+.

Although the Army AM implementation plan is currently under development by the U.S. Army Materiel Command, the Army AM Technology Roadmap (AAMTR) [9] comprises 15 technical objectives, 65 sequenced activities, and 241 requirements across four primary AM focus areas, or "swim lanes"— design, material, process, and value chain— based upon the America Makes DoD Roadmap framework [10, 11]. The Army plan calls out specific AM application areas, including (1) maintenance and sustainment, (2) new part/system production and acquisition, and (3) AM at the point of need and in expeditionary environments. Further, the Army plan elaborates on several other nontechnical key enablers that must be addressed for the successful implementation of AM, including cultural change, workforce development, data management, and policy change.

DoD AM Research Ecosystem: Manufacturing USA

Although each Service has its own unique ecosystem of AM research, all the Services are members of the National Manufacturing Institutes, more recently renamed "Manufacturing USA" (Figure 4). Here, an update on the status of the manufacturing institutes most closely tied to AM will be discussed. These institutes are part of a larger and growing AM research ecosystem of federally-funded manufacturing efforts that include the Office of the Secretary of Defense (OSD) and Service-specific programs such as the Air Force Office of Scientific Research for basic (6.1) efforts, Commander's Research and Development Fund for basic/applied (6.1/6.2) research, and the Small Business Innovative Research Program. As of 2018, the federal government committed over $1 billion, which has been matched by more than $2 billion in investment by industry, academia, and state and local governments. A

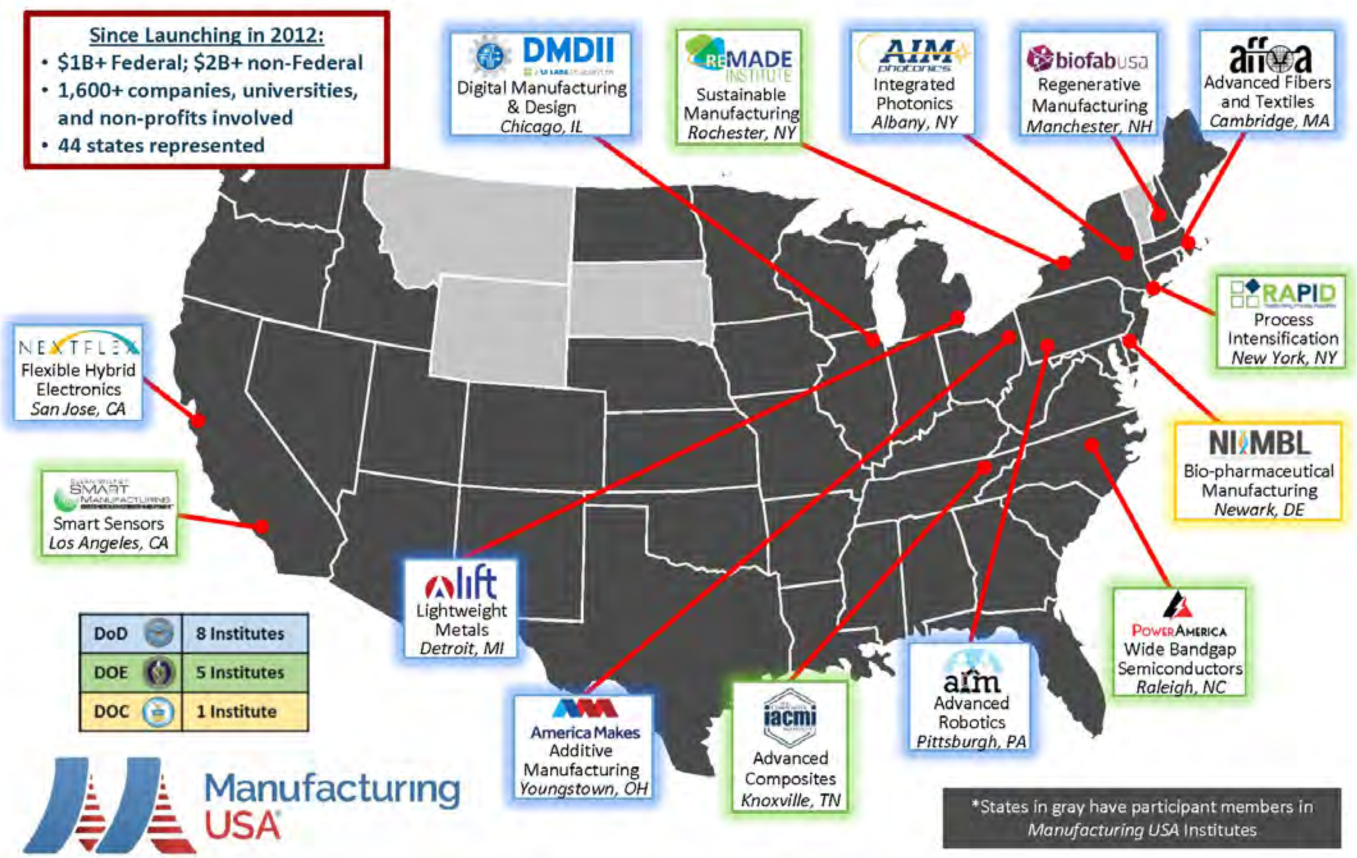


Figure 4: Map of the National Manufacturing Innovation Institutes, Also Known as "Manufacturing USA" *(Source: DoD [12]).*

variety of institutes have focused on technologies such as biofabrication, photonics, fibers and textiles, recycling, lightweight metals, digital manufacturing and design, process development, biopharmaceuticals, power, advanced composites, clean energy, and flexible hybrid electronics (Figure 4 [12]). The most recent institutes launched in 2017 were the Advanced Regenerative Medicine Institute, also known as ARMI's BioFabUSA, and Advanced Robotics for Manufacturing Institute.

The primary center of AM institute activities at America Makes in Youngstown, OH, was founded in 2012 and has since funded over 60 projects [10–12]. Recently, America Makes worked with each DoD Service/agency (USAF, Army, Navy, and Defense Logistics Agency) and had over nine workshop sessions to generate a public-releasable AM roadmap for the systematic development of AM technology. The roadmap was divided into design, materials, processes, and value chain technical focus areas. The design area covers technological advancements in new design methods and tools. The materials area builds the body of knowledge for benchmark AM property characterization data and eliminates variability in "as-built" material properties. The process area drives technological advancements that enable faster, more accurate, and higher detail resolution AM machines. The value chain area encourages technological advancements that enable step change improvements in end-to-end value chain cost and time to market for AM-produced products. Other recent notable accomplishments for America Makes include coordinating and publishing a national roadmap for standards and specifications in collaboration with the American National Standards Institute and launching the digital storefront to digitally represent the live AM roadmap and index project data to the roadmap. Data was integrated from external sources to provide a fuller picture of the progress made against AM technical challenges as a community.

Recent AM successes in the USAF, Navy, and Army include repairs, flight and submarine critical parts, locally certified parts, printed armament, AM cast, and the addition of functionality through AM.

Another institute focusing on AM is NextFlex, America's Flexible Hybrid Electronics (FHE) Manufacturing Institute, based in San Jose, CA. To date, projects in the NextFlex portfolio range from next generation digital printing systems to flexible medical devices. NextFlex currently has 40 projects underway, 16 of which have been funded directly by government agencies, in addition to the core OSD funding. Part of the Institute's long-term sustainability plan is a technology hub in San Jose, which will combine digital printing with traditional electronics manufacturing services tools to create a prototyping and low-volume manufacturing capability for FHE devices.

DoD AM Headline Accomplishments: From Repairs to Point Insertions

Recent AM successes in the USAF, Navy, and Army include repairs, flight and submarine critical parts, locally certified parts, printed armament, AM cast, and the addition of functionality through AM. The first set of AM repair examples involves a cold spray technology with a significant impact on tri-Service systems, including nonrepairable/nonprocurable components. This is important because new repair technologies are not systematically incorporated into the maintenance supply processes due to organizational barriers that prevent implementing new technology into aging weapon systems and lack of funding for developing repair processes on legacy weapon systems [13]. For example, the B1 plane has undergone cold spray repair on forward equipment bay (FEB) panels (Figure 5 [13]). These parts were cracking due to chafing wear of the lightweight Al2024 composite bonded, stiffened skin panels upon repeated opening and closing for

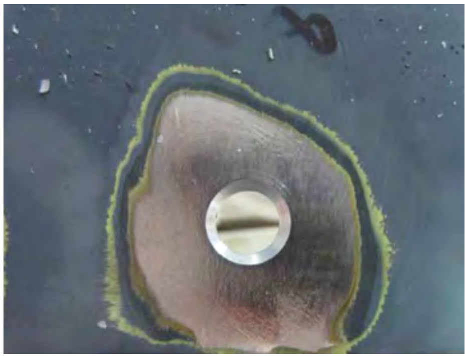


Figure 5: Example of Cold Spray Repair of B-1 Bomber Aircraft FEB Panel Showing Chafing Wear on Fastener Hole (Left) and Then After Grit Blasting, Cold Spray Repair, Grinding, Polishing, and Final Hole Machining (Right) *(Source: Widener [13]).*

general maintenance. These external access panels are typically secured to the airframe with steel fasteners, which are designed to sit flush with the panel to enable laminar flow over the fastener head. However, after repeated access to the panels, the hole become enlarged around the fasteners and below the surface of the panel, resulting in turbulent airflow, vibration, and eventual pull-through and loss of the fastener in flight. The material developed to repair the FEB panels was Al6061, which was tested in 2014 for adhesion, tensile strength, and impact resistance, with additional tests in 2016 for wear, corrosion, and additional impact. Figure 6 shows that there is a strong interface between cold spray and original material [13].

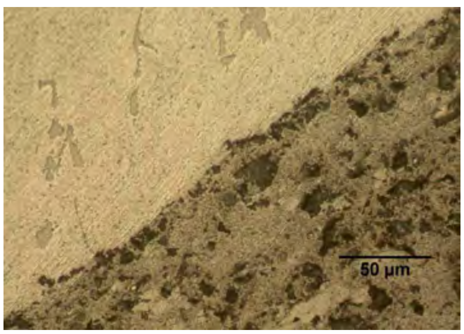


Figure 6: Strong Interface Between Cold Spray and Original Material *(Source: Widener [13]).*

There are currently three B-1's flying with cold sprayed components, including an upper FEB panel and landing gear hydraulic brake lines. Most recently, the USAF 28th Bomb Wing Maintenance Group received authorization from the Change Evaluation Team in January 2018 for repairing nonsafety critical, nonstructural repair of aluminum (6061 Al) on magnesium (ZE41A-T5, AZ91C-T6, and EV31-T6) parts and is currently repairing FEB panels on additional B-1 planes.

Several additional success stories for cold spray repair include hydraulic

Cold spray AM dramatically improved readiness for DoD systems by decreasing repair time and cost for a variety of routinely damaged metal parts.

aircraft tubing, a helicopter sump, and submarine actuator. For the titanium (Ti) hydraulic tubing in the B-1 that interfaces with the main and nose-landing gear, cold spray repair was used from 2009 to 2011 to prevent chafing wear. This was a notable achievement because the hydraulic Ti tubing is customized to each unique airframe, and when it goes out of tolerance, it must be individually addressed. Tests performed on the tubing included adhesion, hardness, wear, burst, hydraulic impulse, and pressurized rotating beam.

The UH-60 Blackhawk helicopter sump located at the bottom of the aircraft is traditionally cast out of a large piece of magnesium (Mg) and holds liquids such as hydraulic fluid. Subject to corrosion, its repairs have become backlogged due to the large number of damaged sumps. To address this, the Army instituted an aluminum (Al) cold spray process to coat the Mg, thereby returning the part's integrity. Due to the huge scrap rate of large-cast Mg parts accounting for a greater economic impact to business, industry adopted the cold spray technique in the field and the factory rather than repairing previously damaged parts.

The U.S. Navy Seawolf TD-63 actuator was also repaired with an Al -based cold spray AM technology. The TD-63, a valve actuator body for the periscope, experienced corrosion and required sealing the surface to prevent water leakage. Damage to the original material included corrosion pits in the box structure of the actuator; however, the lead time for replacement parts was approximately a year. As a result, cold spray AM dramatically improved readiness for DoD systems by decreasing repair time and cost for a variety of routinely damaged metal parts.

Naval Air Systems Command's successful flight critical AM part, the MV-22B Osprey nacelle link (Figure 7 [14]), was flight tested in July 2016 at the Naval Air Station in Patuxent River, MD. The nacelle link was chosen due to its history as a legacy part, its incorporation of redundancy (configured with three other nacelles to ensure that if the AM part broke, backups would keep the engine fastened to the wing), and the suitability of printing in a technically mature material—Ti-6Al-4V

Figure 7: Examples of NAVAIR's Printed Ti Flight Critical Nacelle Link as Printed (Top) and With Associated Electronics (Bottom) *(Source: Newman [14]).*

[14]. The development process took 18 months and included developing four different production designs and fitting the printed link with instrumentation to ensure its safety and performance. (Done in a traditional way, this would have taken years.) Multiple V-22 components, built by Naval Air Warfare Center Aircraft Division (NAWCAD) in Lakehurst, NJ, and Pennsylvania State University Applied Research Laboratory, were tested at Patuxent River to validate performance. The final part was printed at the NAWCAD. Another Navy example is the NAVSEA AM cast for the PL8/9 tail piece on a Seawolf class submarine, which showcases the ability of AM to quickly produce casts for a submarine critical part.

The Army has printed functional armament such as an M-4 rifle, M203 grenade launcher, and 40-mm rounds [15, 16] (Figure 8 [16, 17]). The Army's grenade launcher called "Rapid Additively Manufactured Ballistics Ordnance" (RAMBO) includes a standalone kit with printed adjustable buttstock, mounts, grips, and other modifications. More than 90% of the components in the prototype grenade launcher (Figure 8, top right) were printed with AM in just 35 hours and on a single build plate. The M781 components were 3-D-printed during a 6-month collaborative effort that involved the Research, Development and Engineering Command (RDECOM), ManTech, and America Makes. The Army also fielded a portable manufacturing lab dubbed the "Rapid Fabrication via Additive Manufacturing on the Battlefield" (R-FAB), which is linked to a database for 3-D printable files called the Repository of Additive Parts for Tactical and Operational Readiness [17]. Additionally, some parts locally certified for experimental flights by the Army included a sensor fairing on the front

> The future of AM materials for defense continues to grow and includes high-temperature polymer composites made with carbon fiber-infused polymer resin and selective laser sintering.

of the Bell 407 helicopter and cooling ducts for the UH-60 Blackhawk.

With added functionality, the USAF demonstrated a direct-write Cu plasma antenna on an MQ-9 Reaper remotely piloted aircraft (Figure 9, top left [18–20]). Mesoscribe, established in 2002 as a spin-off company at Stony Brook University and the Long Island High Technology Incubator, commercialized the technology. In this case, by structurally integrating the electronics onto a servo cover, they demonstrated improvements in aerodynamic efficiency and reductions in susceptibility to damage compared with conventional blade/pod approaches. An additional benefit to the direct-write technology was relocating antennas to enable greater navigational precision. The U.S. Air Force Research Laboratory (AFRL) continues to look for ways to retrofit servo cover caps with conformal antennas to use Link 16, a military tactical data exchange network used by fourth-generation fighter jets such as F-15 Eagles and F-16 Fighting Falcons [18].

The future of AM materials for defense continues to grow and includes high-

Figure 8: Examples of Printed Rifle (Top), Grenade Launcher (Bottom Left), and Printed Rounds (Bottom Right) *(Source: Szondy and Lopez [16, 17]).*

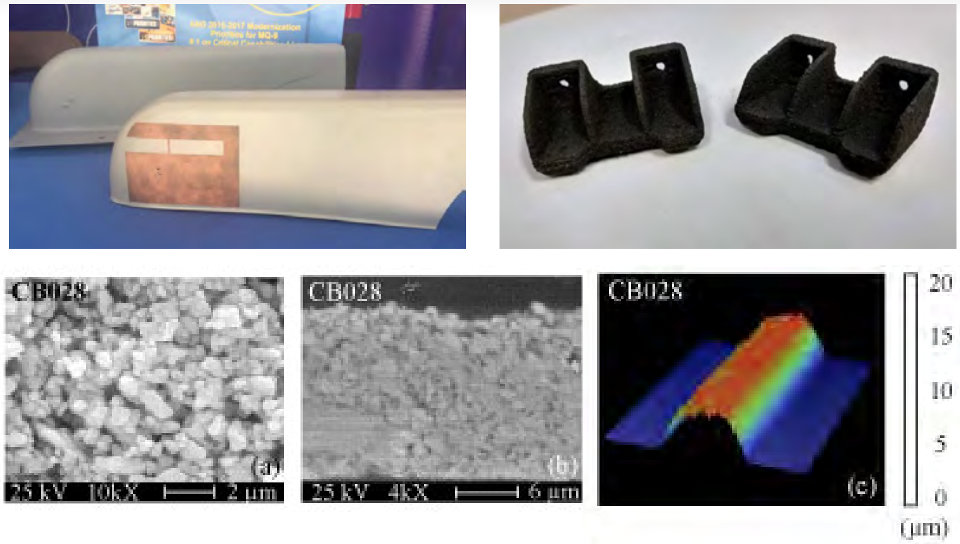


Figure 9: Examples of USAF AM Technologies for Functional and Extreme Environments: Direct-Write Plasma Technology to "Print" a Cu Antenna on an MQ-9 Reaper (Top Left), Printed High-Temperature Carbon Fiber Composite (Top Right), and Images of Silver Ink Used to Print Resilient Hybrid Electronics Onto PEEK (Bottom) *(Sources: Pawlyk, Neff et al., and AFRL [18-20]).*

temperature polymer composites made with carbon fiber-infused polymer resin and selective laser sintering. These materials for extreme environments have potential use in engine components and on the leading and tail edges of next generation fighter jets (Figure 9, top right). Other materials considered for resilient hybrid electronics include silver inks (Figure 9, bottom) and high-temperature/chemically-resistant polymers such as poly ether ether ketone (PEEK) [19].

CONCLUSIONS

Additive manufacturing has gained a lot of attention for improving defense systems. In the DoD, AM is gaining momentum, as witnessed by the Service-specific AM implementation plans, growth in National Manufacturing Institutes, and an increasing number of parts and technologies that substantiate and raise the anticipation of revolutionary outcomes. ■

ACKNOWLEDGMENTS

The author would like to thank the following people for their contributions to this article: LJ Holmes (University of Delaware), Debora Naguy (USAF/Air Force Life Cycle Management Center [AFLCMC]), Michael Froning (USAF/AFLCMC), Brian James (USAF), Dan Berrigan (USAF/AFRL), Ben Leever (USAF/AFRL), Tracy Frost (OSD), Dennis Butcher (America Makes), Caroline Vail (Naval Surface Warfare Center Carderock Division).

REFERENCES

[1] Louis, M. J., T. Seymour, and J. Joyce. "3D Opportunity in the Department of Defense: Additive Manufacturing Fires Up." Deloitte University Press, 20 November 2014, https://www2. deloitte.com/content/dam/insights/us/articles/additive-manufacturing-defense-3d-printing/DUP_1064-3D-Opportunity-DoD_MASTER1.pdf.

[2] Lein, P. "Opportunities and Challenges of Additive Manufacturing in the DoD." *DSIAC Journal*, vol. 2, no. 2, Spring (March) 2015, https://www.dsiac.org/resources/journals/dsiac/spring-2015-volume-2-number-2/opportunities-and-challenges-additive.

[3] Schrand, A. "Additive Manufacturing: From Form to Function." *Strategic Studies Quarterly*, pp. 74-90, Fall 2016, http://www.airuniversity.af.mil/Portals/10/SSQ/documents/Volume-10_Issue-3/Schrand.pdf.

[4] Defense Acquisition University. "Special Issue on Additive Manufacturing (3D Printing)." *Defense Acquisition, Technology and Logistics (AT&L) Magazine*, December 2016, https://www.dau. mil/library/defense-atl/p/Defense-ATandL---November-December_2016.

[5] Kendall, F. "When and When Not to Accelerate Acquisitions." *Defense AT&L*, pp. 2–4, November–December 2016, https://www.dau.mil/library/defense-atl/DATLFiles/Nov-Dec2016/Kendall.pdf.

[6] Morris, K. "Driving Innovation to Support the Warfighter." *Defense AT&L*, pp. 44, November–December 2016.

[7] Naguy, D. A. "United States Air Force Additive Manufacturing Strategic Implementation Plan (AMSIP)." Air Force Life Cycle Management Center Product Support Engineering Division (AFLCMC/EZP), October 2016.

[8] U.S. Department of the Navy (DON). "Additive Manufacturing (AM) Implementation Plan V2.0," 2017. www.dtic.mil/dtic/tr/fulltext/u2/1041527.pdf.

[9] U.S. Defense Systems Information Analysis Center. U.S. Army Additive Manufacturing Technology Report (AAMTR), DSIAC-EN-TR 2017-11, draft.

[10] Manufacturing USA. America Makes. https://www.manufacturingusa.com/institutes.

[11] U.S. Defense Systems Information Analysis Center. "DoD Releases Additive Manufacturing Roadmap," 16 December 2016. https://www.dsiac.org/resources/news/dod-releases-additive-manufacturing-roadmap.

[12] U.S. Department of Defense. Map of National Manufacturing Institutes. http://www. businessdefense.gov/Programs/Manufacturing-USA-Institutes/

[13] Widener, C., Hrabe, R., James, B., Champagne, V. "B1 Bomber-FEB Panel Repair by Cold Spray." CSAT Meeting: WPI, Worcester, MA , 21 October 2012, http://www.coldsprayteam. com/files/CSAT_2012WidenerB1_Bomber_FEB_Panel_Repair.pdf

[14] Newman, J. "Additive Manufacturing Promises to Boost Naval Aviation Readiness." *Naval Aviation News*, 17 October 2016, http://navalaviationnews.navylive.dodlive.mil/2016/ 10/17/printing-the-future/.

[15] Burns, S. K., and J. Zunino. "RAMBO'S Premiere." Army online article, 1 March 2017,

https://www.army.mil/article/183465/rambos_premiere.

[16] Szondy, D. "US Army fires 3D-printed grenade launcher." *News Atlas*, 11 March 2017.

[17] Lopez, E. "To Support Readiness, Army Team Demonstrates Ability to Make Essential Parts with 3D Printing." Army online article, 2 November 2017, https://www.army.mil/article/197455/to_ support_readiness_army_team_demonstrates_ability_to_make_essential_parts_with_3_d_printing.

[18] Pawlyk, O. "Air Force Works on Liquid Antennas for Aircraft Adaptability." *DefenseTech News*, 1 June 2013, https://www.military.com/defensetech/2 z017/06/13/air-force-research-lab-works-on-liquid-antennas-for-aircraft-adaptability.

[19] Neff, C., E. Elston, M. Burfeindt, N. Crane, and A. Schrand. "A Fundamental Study of Printed Ink Resiliency for Harsh Mechanical and Thermal Environmental Applications." *Additive Manufacturing*, vol. 20, pp. 156–163, 2018.

[20] U.S. Air Force Research Laboratory. "AFRL Researchers Push Limits in High-Temperature, Polymer Additive Manufacturing." Defense visual information distribution service (DVIDS), 9 March 2018, https://www.dvidshub.net/image/4231694/afrl-researchers-push-limits-high-temperature-polymer-additive-manufacturing.

BIOGRAPHY

DR. AMANDA SCHRAND currently serves as principal investigator for additive manufacturing of resilient hybrid electronics at the Fuzes Branch of the U.S. Air Force Research Laboratory Munitions Directorate, Eglin Air Force Base, FL. Prior to moving to Florida, her research career was established at Wright Patterson Air Force Base in Ohio and spanned multidisciplinary fields, including molecular biology, nanotoxicology, nanomaterials characterization, and materials science & engineering. She has two patents submitted related to additive manufacturing of survivable materials. Dr. Schrand has authored over 60 literary products, including a strategic studies quarterly article that is a required reading for the USAF Air War College Rapid Global Mobility module for senior leaders. She holds a B.S. in biological sciences and an M.S. in molecular biology from Wright State University and a Ph.D. in materials science and engineering from the University of Dayton.

CORROSION PROTECTION

FOR COST SAVINGS ON PACIFIC BASES

By Julie Holmquist

(Source: U.S. Marines)

INTRODUCTION

Mission readiness at a U.S. Air Force base involves more than just the aircraft. It encompasses everything involved in getting the aircraft and airmen successfully off the ground, including maintaining the airfield damage repair (ADR) vehicles used to keep runways in good condition. These ADR vehicles include hundreds of vehicles associated with street repair—front-end loaders, graders, dump trucks, street sweepers, water trailers, forklifts, and asphalt and concrete spreaders. Though not needed on a regular basis, they must be kept in ready-to-use condition. The challenge is maintaining ADR vehicles stored in open fields in highly corrosive conditions on bases throughout the Pacific. In these environments, sea spray, dust, high winds, and other harsh elements take a toll on the ADR fleets, multiplying repairs and shortening vehicle service life.

BACKGROUND

Equipment preservation was once part of the vehicle maintenance budget throughout the Pacific. However, when budget cuts hit, preventative maintenance also suffered, leaving bases to deal with the resulting corrosion. In general, this meant more repairs, more downtime, and more labor and material costs. It is not uncommon for vehicles to start rusting after just a few months on base. According to Technical Sergeant Justin Petty in charge of the 18th Logistics Readiness Squadron at the Kadena Air Force Base in Okinawa, Japan [1], if these vehicles are not treated for corrosion, they will need repair within a year after painting (5–7 years are usually needed for full repainting). Often, corrosion repairs must be performed on vehicle bodies for them to reach their 17-year life expectancy.

Because of the high costs and toll corrosion takes on ADR fleets, TSgt. Petty began a search several years ago to find a corrosion-preventative solution for the $20 million ADR vehicle fleet recently purchased by the base. A successful search would result in a product or system that would protect ADR vehicles during their constant exposure to harsh environments, ward off the costly and debilitating effects of corrosion, and leave the vehicles ready for use at a moment's notice.

It is not uncommon for vehicles to start rusting after just a few months on base.

Petty's research brought him into contact with Larry Mudd, a retired U.S. Air Force vehicle maintainer turned senior project manager of preservation and field services at a company specializing in corrosion-inhibitor manufacturing and application [2]. Mudd was familiar with vehicle corrosion problems faced by the Pacific Air Forces (PACAFs) and helped them tailor an appropriate solution for their needs. The system was designed to slow vehicle corrosion in the aggressive Pacific atmosphere while maintaining the ADR fleet in mission readiness. The preservation program aroused much interest not only at Kadena but at other PACAF bases as well.

DEVELOPING A MISSION-READY CORROSION CONTROL PLAN

TSgt. Petty's main concern other than corrosion protection was that the chosen product and/or system would allow the equipment to start up and be used at a moment's notice without unwrapping film. Mudd helped the base develop a strong corrosion protection plan [2] within Petty's mission-ready requirements. Rather than wrapping the vehicles in anticorrosion film, the new plan implemented a clear water-based coating that left a very thin and unnoticeable protective layer over the equipment's original finish. Two other temporary water-based coatings and one solvent-based, anticorrosion coating were strategically designated for other vehicle components, such as wheel wells and grader buckets.

In addition to protecting vehicle bodies, the preservation system also focused on details—keeping smaller components, such as electronics, electricals, and moving parts, in good condition. Applying corrosion inhibitors to these less-obvious systems helps minimize future repair and failures from, for instance, an electrical wire shorting out and needing replacement.

The new plan would allow the base to maintain a mission-ready system while reducing the amount of repair and labor costs required when the equipment is otherwise allowed to deteriorate. Due to the nature of the products, no extra work would be needed to get a vehicle back into circulation. Mudd explained, "All the suggested or recommended products will allow them to just go out and . . . get in it and drive it away with no prep, no cleanup, no preparation to be mission ready—you just turn the key and go" [3].

THE MISSION-READY PRESERVATION SYSTEM

Protecting Electronics and Electricals

Heavy equipment contains many electronic or electrical components and sometimes even their own electrical control boxes. To discourage premature failure from the corrosive environment, a corrosion-inhibiting electrical spray that dries quickly into a thin, dry film was designated for metal electrical components, such as wiring, battery connections, sensors, relays, and electrical motors. Vapor corrosion inhibitor (VCI) emitting devices (see figure 1) that release a corrosion-inhibiting vapor were assigned for fuse boxes or electrical enclosures under dashboards. When left in an enclosed space, the VCIs form an invisible protective film on metal surfaces. The invisible film discourages the normal corrosion reaction of metal with air, moisture, and chlorides from taking place. The VCIs also have the advantage of protecting intricate and hard-to-reach spaces that a spray-on film might miss.

Figure 1: VCI Emitters Contain Corrosion Inhibitors That Vaporize and Condense in a Protective Layer on Metal Surfaces When Placed Inside Enclosures Such as Electrical Cabinets *(Source: Cortec Corporation).*

Protecting Moving Parts, Lubrication Points, and Fuel Systems

Standard lubricants and greases naturally provide a degree of corrosion protection by protecting the metal surface from direct interaction with air and moisture. However, in extreme conditions like those on Pacific bases, a more powerful strategy is to use lubes and greases enhanced with corrosion inhibitors for additional protection. The new preservation program at Kadena includes applying a wet film corrosion-inhibiting lubricant to all moving parts—hinges, lift cylinders, pintle hooks, etc.

The VCIs also have the advantage of protecting intricate and hard-to-reach spaces that a spray-on film might miss.

Extra pressure lithium grease enhanced with corrosion inhibitors was selected for grease zerks. Fuel systems are treated with a corrosion-inhibiting additive that protects at a low dose and provides a degree of protection to spaces above the fuel level.

Protecting Equipment Bodies

To protect heavy equipment bodies and paint jobs without impeding use, a special water-based, corrosion-inhibiting, permanent coating that dries to a thin, clear, matte film was selected. The coating, which could be applied directly over the original vehicle paint, contains special organic corrosion inhibitors that enhance the corrosion protection of the water-based coating and increase the overall protection of the vehicle coating system. The clear coating is expected to provide protection for several years and minimize the frequent need for repainting while allowing free movement of the vehicles, which could be turned on at any moment and driven away for airfield repair work. According to Mudd [3], touch-up work or coating reapplication may be needed at times; however, overall corrosion maintenance should be significantly reduced.

A separate clear but removable, corrosion-inhibiting, water-based coating would be applied to wheel wells, firewall surfaces, and underneath the engine compartment. The coating can be left on or removed with an alkaline wash. Dump truck beds, forklift tines, grader blades, and similar surfaces were designated for protection with a corrosion-inhibiting coating that leaves a peelable layer with a texture like fruit leather. This coating provides some abrasion protection in addition to being corrosion resistant. If necessary, the coating can be peeled off and simply thrown in the trash as solid waste.

Where equipment already started to rust, rust removal or using a primer that converts rust into a passive layer was recommended before applying the protective coating.

APPLYING THE MISSION-READY PRESERVATION SYSTEM

Before implementing the new program, the suggested products had to first pass a long review process with the Hazardous Materials Office to permit their use on the island base. This was approximately 1 and 1/2 years from the time the base contacted Mudd in November of 2015 to the time he came on base for hands-on training in the spring of 2017 [3]. Since the system was already reviewed at Kadena, implementations at other bases should be much quicker.

Mudd conducted a 2-day training to introduce the materials and provide application instruction for achieving the best possible protection on the 200-plus vehicle fleet. The base supplied two pieces of equipment—a front-end loader and a compact track loader—for the hands-on training. Mudd showed how to apply products correctly, demonstrated good spray techniques for the coatings, and stressed proper use of personal

Figure 2: Personal Protective Equipment and Good Surface Prep Are Two Important Aspects of a Safe and Effective Coatings Application *(Source: Senior Airman Omari Bernard, 18th Wing Public Affairs).*

protective equipment where designated by product safety data sheets (see figure 2).

Before applying the corrosion inhibitors, Mudd performed a walk-around inspection to make sure everything was clean, masked off, or accessible. The next step was to pressure wash the vehicles with an alkaline cleaner containing flash rust inhibitors (a clean surface free of debris is critical to achieving good coatings performance). After the vehicles dried, Mudd did another walk-around and showed how to apply the electrical coating on electrical components and the anticorrosion lube to grease zerks. All moving parts were then sprayed with the corrosion-inhibiting lubricant. After all these products were dry, the clear, nontacky, temporary coating was applied to appropriate surfaces in the engine compartment (see figure 3), around firewalls, and on wheel wells and allowed to dry. All windows, hoses, fittings, registration numbers, and other critical areas were masked off (note masked areas in figure 4) before applying the thin matte finish, anticorrosion, clear coat over the equipment's vehicle paint. The clear coatings were applied directly over the vehicle finish to provide corrosion protection while leaving the vehicle unencumbered and ready to use. Representatives of several other air bases, such as Andersen in Guam and Misawa in Japan, were also present to observe the new protective strategy training. Where appropriate, equipment parts, such as buckets and grader surfaces, were coated with a peelable coating. Additional protection was later added to the electrical boxes, near fuses, and underneath dashboards by sticking VCI emitter cups into the enclosed areas.

Figure 3: Spraying Coatings Inside Engine Compartment to Provide Extra Protection Against the Corrosive Environment *(Source: Senior Airman Omari Bernard, 18th Wing Public Affairs).*

PROJECTED RESULTS OF THE NEW PROGRAM

It is estimated that the corrosion control project could save more than $20 million and extend equipment service life by 5–7 years [4]. The squad will go out every 6 months for a full inspection and reapply the system as needed. This maintenance work is expected to require far fewer labor hours and repair costs than frequent vehicle rework required when no corrosion prevention is applied. Because of the program's corrosion-protection and cost-savings potential, TSgt. Petty decided to create a technical application manual for future reference for squads who want to apply the anticorrosion system. The program has also been shared with other Pacific air force bases, such as Andersen; Misawa; and Yokota, Tokyo, where the corrosive Pacific environment also begs for a mission-ready corrosion protection program. The preventative maintenance

Table of Contents

Figure 4: Two Members of the 18th Logistics Readiness Squadron Prepare to Apply Corrosion Inhibitor Coatings After Having Masked Off Critical Areas *(Source: Senior Airman Omari Bernard, 18th Wing Public Affairs).*

> The corrosion control project could save more than $20 million and extend equipment service life by 5–7 years.

aspect of the program also makes it a good candidate for implementing stateside to preempt corrosion before vehicles are shipped out to the corrosive Pacific base environments. ■

ACKNOWLEDGMENTS

Special thanks to Larry Mudd of Cortec Corporation for relating his experience of designing and implementing a corrosion control system for Kadena's ADR fleet. Thanks also to Cortec Tech Service Engineer John Wulterkens for technical review of this article.

REFERENCES

[1] Bernard, A. O. "Corrosion Control: Kadena Airmen save Air Force millions." DVIDS, 12 May 2017, https://www.dvidshub.net/news/233597/corrosion-control-kadena-airmen-save-air-force-millions, accessed 12 June 2018.

[2] Cortec Corporation. "Case History 557: Military Equipment Preservation." Cortec Case Histories, August 2017, http://www.corteccasehistories.com/?s2member_file_download=access-s2member-level1/ch557.pdf, accessed 15 August 2018.

[3] Mudd, L. Personal communication. Cortec Corporation, St. Paul, MN, 2017.

[4] KadenaAirBase. "Brainstorming." Facebook video, 30 April 2017, https://www.facebook.com/KadenaAirBase/videos/1887653657927281, accessed 15 August 2018.

BIOGRAPHY

JULIE HOLMQUIST is a Content Writer for Cortec Corporation. Since joining the company in 2015, she has been researching and writing about corrosion problems and treatments, with a special focus on vapor corrosion inhibitor technology. Her work on corrosion control has been published in dozens of industry magazines in a variety of sectors, including metalworking, oil and gas, electronics, water treatment, packaging, and construction. Ms. Holmquist holds a bachelor's degree in biblical studies from the University of Northwestern - St. Paul.

CONFERENCES AND SYMPOSIA

DARPA Launch Challenge (DLC)
16 April 2018–31 December 2019
http://www.darpalaunchchallenge.org

NOVEMBER 2018

SOFWERX: Next Generation Information and Identification Awareness (NGIA)
31 October–1 November 2018
https://www.sofwerx.org/ngia

The 2018 OSA Laser Congress
4–8 November 2018
The Westin Boston Waterfront
Boston, MA
https://assl.osa.org/home/about-assl

Aircraft Survivability Symposium 2018
6–8 November 2018
Naval Postgraduate School
Monterey, CA
http://www.ndia.org/events/2018/11/6/9940-2018-aircraft

2018 Workshop on Space Environment Applications, Systems, and Operations for National Security (SEASONS)
7–9 November 2018
The Johns Hopkins University Applied Physics Laboratory Kossiakoff Center
Laurel, MD
http://seasons.jhuapl.edu

Military Standard 810G (MIL-STD-810G) Testing
12–15 November 2018
National Technical Systems
Chicago, IL
https://equipment-reliability.com/training-calendar/military-standard-810g-mil-std-810g-testing-nts-chicago-il

I/ITSEC 2018
26–November 2018
Orlando, FL
http://www.iitsec.org

3-Day Mechanical Shock Testing & Data Analysis
27–29 November 2018
Denver, CO
http://hitestlabs.com/shock-course/?mc_cid=a81f453fd6&mc_eid=22a13551cc#mechanical-jump

Army Autonomy and Artificial Intelligence Symposium and Exposition
28–29 November 2018
COBO Center
Detroit, MI
https://www.ausa.org/army-autonomy-ai-symposium

DECEMBER 2018

2018 Defense Manufacturing Conference
3–6 December 2018
Nashville Music City Center
Nashville, TN
http://www.dmcmeeting.com/index.html

Joint Army-Navy-NASA-Air Force (JANNAF) Meeting
10–14 December 2018
Portland, OR
https://www.jannaf.org/mtgs/2018Dec/pages/index.html

Military Standard 810G (MIL-STD-810G) Testing
10–13 December 2018
National Technical Systems
Fullerton, CA
https://equipment-reliability.com/training-calendar/military-standard-810g-mil-std-810g-testing-nts-fullerton-ca

35th International Test and Evaluation Symposium
11–14 December 2018
Embassy Suites Mandalay Beach Hotel & Resort
Oxnard, CA
https://www.itea.org/event/35th-international-test-and-evaluation-symposium

2019

AHS Autonomous VTOL Technical Meeting and Electric VTOL Symposium
29–31 January 2019
Sheraton Mesa Hotel
Mesa, AZ
https://vtol.org/events/autonomous-vtol-technical-meeting-and-evtol-symposium

Defense Strategies Institute's 3rd Annual Military Additive Manufacturing Summit & Tech Showcase
6–7 February 2019
CAMLS Center
Tampa, FL
http://militaryam.dsigroup.org

Air Warfare Symposium
27 February–1 March 2019
Rosen Shingle Creek
Orlando, FL
https://www.afa.org/events/aws/technology-exposition

AUVSI XPONENTIAL 2019
29 April–2 May 2019
McCormick Place
Chicago, IL
https://www.xponential.org/xponential2019/public/enter.aspx

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

Defense Systems Information Analysis Center

4695 Millennium Drive
Belcamp, MD 21017-1505

DSIAC ONLINE

www.dsiac.org

DSIAC PRODUCTS AND SERVICES INCLUDE:

- Performing literature searches.
- Providing requested documents.
- Answering technical questions.
- Providing referrals to subject-matter experts (SMEs).
- Collecting, electronically cataloging, preserving, and disseminating Defense Systems scientific and technical information (STI) to qualified users.
- Developing and deploying products, tools, and training based on the needs of the Defense Systems community.
- Fostering and supporting the DSIAC technical Communities of Practice.
- Participating in key DoD conferences and forums to engage and network with the S&T community.
- Performing customer-funded Core Analysis Tasks (CATs) under pre-competed IDIQ Delivery Orders.

DSIAC SCOPE AREAS INCLUDE:

- Advanced Materials
- Autonomous Systems
- Directed Energy
- Energetics
- Military Sensing
- Non-Lethal Weapons
- Reliability, Maintainability, Quality, Supportability, and Interoperability (RMQSI)
- Survivability and Vulnerability
- Weapon Systems

CONNECT WITH US ON SOCIAL MEDIA!