

# DSIA JOURNAL

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## SPACE TRAVEL AIDED BY PLASMA THRUSTERS

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Editor-in-Chief: Ted Welsh

Copy Editor: Eric Edwards

Art Director: Melissa Gestido

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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 >

WPAFB SATELLITE OFFICE
96 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 REPRESENTATIVES
Peggy M. Wagner (COR)
96 TG/OL-AC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.6302

DSIAC PROGRAM MANAGEMENT ANALYST
Marisiah Palmer-Moore
IAC Program Management Office (DTIC-I)
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218
Office: 703.767.9109

Brad E. Forch (ACOR)
U.S. Army Research Laboratory
RDRL-WM
Aberdeen Proving Ground, MD 21005
Office: 410.306.0929

## MESSAGE FROM THE EDITOR



**H**ave you been wondering lately about space exploration developments since the completion of the final space shuttle

mission on 21 July 2011? Well the National Aeronautics and Space Administration (NASA) continues to plan for further exploration, such as manned journeys to Mars, leveraging evolving space travel technologies.

In our feature article this quarter, Albert DeFusco, Christopher Craddock, and Wesley Faler discuss the merits of plasma thruster technology as an electric propulsion alternative to chemical propulsion. Hundreds of electric thrusters are presently deployed on communication satellites orbiting the earth and are also used to conduct deep-space probe missions. In these applications, where high fuel efficiency with exceptionally long operational times is required, electronic propulsion is more desirable than chemical propulsion, which typically exhausts stored energy in a matter of seconds or minutes. Advancements in plasma thrust design variants of electrical propulsion, such as fusion-assisted plasma thrusters, have the potential to drastically reduce space transit times. With these types of enhancements to plasma thruster technology, it is conceivable that the travel time for a Mars Transportation Orbiter could be reduced from upwards of a year to just a matter of days.

The use of unmanned aerial systems (UASs) and drones has boundless applications in both commercial and military applications. This journal issue includes two articles specific to related Department of Defense (DoD) concerns. The first article, by George Hansen and Frank Zeller, considers various reliability enhancement factors, such as integrated computational materials engineering (ICME), multiple-stress accelerated life testing (ALT), and the Design for Reliability (DFR) approach, along with their associated impact on reliability.

The DoD rapid acquisition and deployment of UASs since the mid-1980s are attributable to their ability to accomplish comparable missions to those performed by piloted aircraft assets without the potential risk to pilot life. Therefore, the use of UASs to perform combat missions has become the reconnaissance system of choice. The question then becomes whether or not the reliability of this technology has kept pace with the proliferation of its use.

With the ever-increasing UAS technology accessibility and use of UASs in combat situations, the DoD is challenged to have sufficient deployable counter-UAS solutions. The use of UASs for surveillance is an established practice, but the emergence of weaponized UASs and the threat they present, especially to dismounted troops, are significant concerns. This situation is driving government science and technology developers, academia, and industry

technology innovation to address the need for technical solutions to counter UAS threats.

Our second article, by Joseph Schuman and Edward Hall, explores the use of programs that promote collaboration of diverse and nontraditional stakeholders to address ever-emerging UAS threats.

Military ground vehicle underbody blast (UBB) detonation is a key concern for the survivability and vulnerability community. Given the extensive use of improvised explosive devices (IEDs) by enemy forces in Iraq and Afghanistan in the early 2000s and the resultant threat to occupants within armored ground vehicles, the U.S. military has been faced with developing effective countermeasures. The Joint Light Tactical Vehicle (JLTV) program was established in 2006 to address this threat and combines the agility of the traditional High-Mobility Multipurpose Wheeled Vehicle (HMMWV) with the UBB protection of the Mine Resistant Ambush Protected (MRAP) truck. In our article on JLTV UBB protection, Brian Benesch discusses the design features of the JLTV that draw on lessons learned in UBB protection to result in enhanced vehicle survivability and mitigation of occupant injuries. ■



# RELIABILITY OF UAVs AND DRONES

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By George Hansen, Frank Zeller, and Russell Austin

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## INTRODUCTION

**D**rones and unmanned aerial vehicles (UAVs), such as those pictured in Figure 1, have been the subject of active development and use by the Department of Defense (DoD) for reconnaissance since at least the mid-1980s. Unfortunately, the need for

information on combatant locations and capabilities has often been so urgent, these machines were first employed before full development and testing could be completed. In fact, so successful and useful were they in initial applications (and the demand for them so high), low-level production ensued after just one or two deployments to areas of interest [1]. These reconnaissance systems did not put pilots' lives at risk, and thus were operable in situations and conditions

normally viewed as dangerous or harsh to humans. Not only was this capability a high motivating factor for UAV use within the DoD, it may have been the primary reason that initial transition and acquisition were accelerated before system reliability could be fully investigated and characterized. In the words of Secretary of Defense William Perry in 1996, "If Predators save one soldier's life, they are worth deploying now."



Figure 1: An MQ-1 Predator (Left) and MQ-9 Reaper (Right), Which Provided Intelligence, Surveillance, and Reconnaissance During Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) (U.S. Air Force Photo/Lt. Col. Leslie Pratt).

Over the past 15 years, drone designs have rapidly proliferated [2]. Early designs resembled traditional aircraft in general shape and size. Today, much smaller morphologies are proliferating on the market, ranging from meter-sized quadcopters down to “birds” and potentially even minute “insects” and “spiders” that can easily rest on a palm. A video demonstration developed by the University of Pennsylvania’s General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory showing current capabilities in tandem aerobatics, three-dimensional (3-D) flight formation, and obstacle circumlocution for a series of 20 “nano” quadroters is available on the Internet [3]. In addition, two recent *DSIAC Journal* articles surveyed the state-of-the-art in drone fleet coordination [4, 5]. Consider also the photograph of a mosquito-sized drone mock-up model sitting on a person’s fingertip (Figure 2). Though nonfunctional, this prototype indicates what developers are considering for potential next steps and a future avenue this technology will be taking. Of course, with new developments such as these come new challenges as well, particularly in the areas of miniaturization, aerodynamics, quality, reliability, and cost-effective production.

Thus, it appears that today we are standing on the threshold of a new

technological age, where drones have the potential to become commonplace in public life, with smaller models mass-produced rapidly, and likely with a haste that seems to belie any focus on quality and reliability. Whereas public interest in drone use has centered mainly on potential encroachments on individual privacy and the weaponization of this technology, defense development interests have remained focused on reliability and equipment safety.

This article surveys the lengthy reliability evolution of this technology with the objective to pinpoint successful approaches that yield improved initial reliability of emerging technologies. Our specific focus is on what past records, our cumulative body of engineering knowledge, integrated



Figure 2: A Mock-Up Prototype of a Drone “Insect” [6].

computational materials engineering (ICME), and multiple-stress accelerated life testing (ALT) can do to achieve high reliability (especially when the pace of development and transition to acquisition is as high as current trends suggest it will be).

## UAV FAILURE PATTERNS

Public interest and support are particularly important because the public opinion tends to influence the Federal Aviation Administration’s inclinations to allow these unmanned vehicles into public airspace. Because public interest is guided by what it sees in the various broadcast media, our investigation started with a drone crash database compiled and maintained by the *Washington Post* starting in 2007 [7]. The data in this link are provided mainly in summary format. Access to the full, detailed records can be obtained at a website titled UK Drone Wars [8]. Almost 260 records can be found therein, providing details on specific dates, models, locations, country of origin, and in many cases details of the failure modes found to have caused the crash. Many of these documents were obtained from the DoD through the Freedom of Information Act. Using this drone crash database, our initial UAV failure trend analyses are noteworthy, especially when viewed

against the backdrop of the DoD's own summary reports, which are reviewed in following text.

Figure 3 summarizes the records archived in the *Washington Post* database. The top graphic shows how the crash distributions spread through time for the models involved in most accidents. Seven models are specifically named, and then numerous others involved in only one or two accidents were grouped together in the class "Other Models." While it may appear from these plots that these unmanned aircraft are prone to accidents, the numbers of incidents are actually within an order of magnitude of those from manned military aircraft.

These graphics are actually more reflective of the use frequency of equipment than the equipment's inherent reliability. The accident rates are proportional to equipment use rates. For instance, Predator is the most frequently deployed UAV, and it is most frequently flown in Afghanistan, the United States, and Iraq. Predator is also the model with the highest crash record, and these crashes have occurred principally in these same three countries, as the graphics indicate. Though the *Washington Post* database goes no further back than 2007, we augmented our records with mishap records found in other sources as we encountered them in our investigations. Records for Global Hawk accidents, for instance, were found in defense reports predating 2007, and these records were included when appropriate in the data reflected in Figure 3. Incidentally, the Global Hawk is operated primarily by the U.S. Navy, and public awareness of its mishaps may be obscured by the fact that they occur predominantly over an ocean and thus evidence is quickly lost.

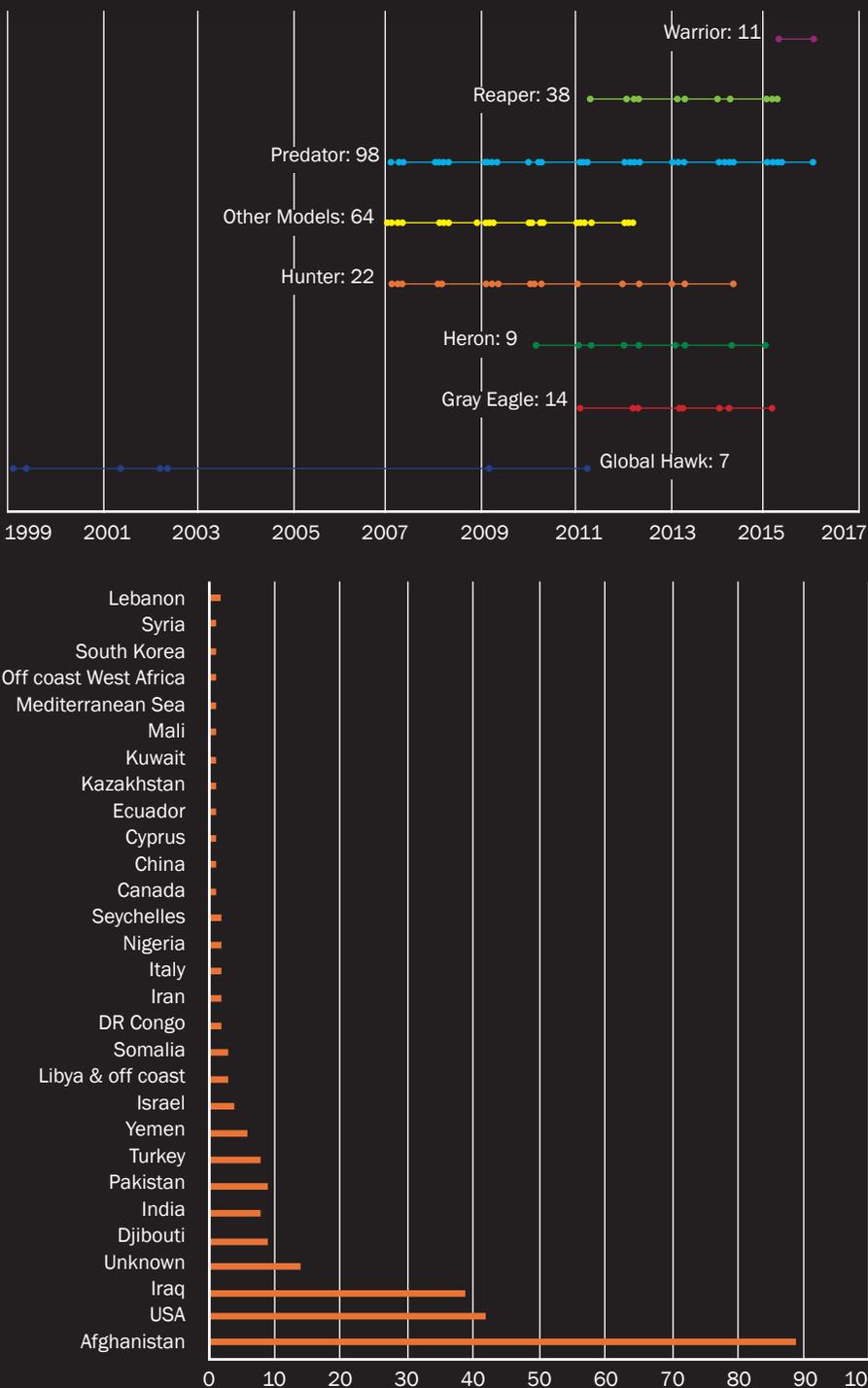


Figure 3: UAV Crashes by Temporal Incidence (Top) and Geographic Incidence (Bottom).

Looking at the data from a different perspective, the crash incidents are split by model types shown in the pie chart in Figure 4. In this graphic, the "Other Models" category in Figure 3 can be seen to be represented by dozens of smaller slices roughly on par with cumulative records for Global Hawk.

Not surprisingly, frequent practice and familiarity increase success rates. As the military flew drones in Iraq, Afghanistan, and elsewhere during the past 15 years, accident rates declined to 5.13 per 100,000 flight hours in fiscal year 2011, as opposed to 62.06 in 2001. Specifically, the

Predator's accident rate fell to 4.86 in 2011, compared with the F-16 Fighting Falcon's 3.89 rate when that fighter jet was at the same point in its service life [9]. On the other hand, with apparently less time aloft, Global Hawk had an accident rate of 15.16 per 100,000 flight hours, almost three times that of the Cold War-era U-2 spy plane it has been replacing.

## FACTORS FOR INCREASED RELIABILITY

In 2003, the Office of the Secretary of Defense (OSD) conducted a review of UAV reliability to assess the state of the technology at that time [10]. This report, which is available on the web, is informative of the development histories, operational tempos, and reliability conditions for several of the models used by the DoD. A second report issued in 2007 (and further discussed in following text) provides additional data on operational tempos as well as investments in the reliabilities of two UAV models [11]. Of particular interest here are the operational tempo data compiled in both of these documents.

Figure 5 (top) shows data compiled from both reports. The plot represents the length of each flight (sortie) in thousand hours per year on the vertical axis and the increasing number of sorties (also in thousands per year) on the horizontal axis. These data come from earlier and later blocks of time, though there is considerable overlap between the two sets. The operational tempo of the earlier set was governed mainly by flights associated with developmental testing and training. The later block of data represents deployment and increased use of the Predator model in OIF and OEF. Increased slope of the later plot corresponds to longer flights; and data plotted on the right end of the horizontal

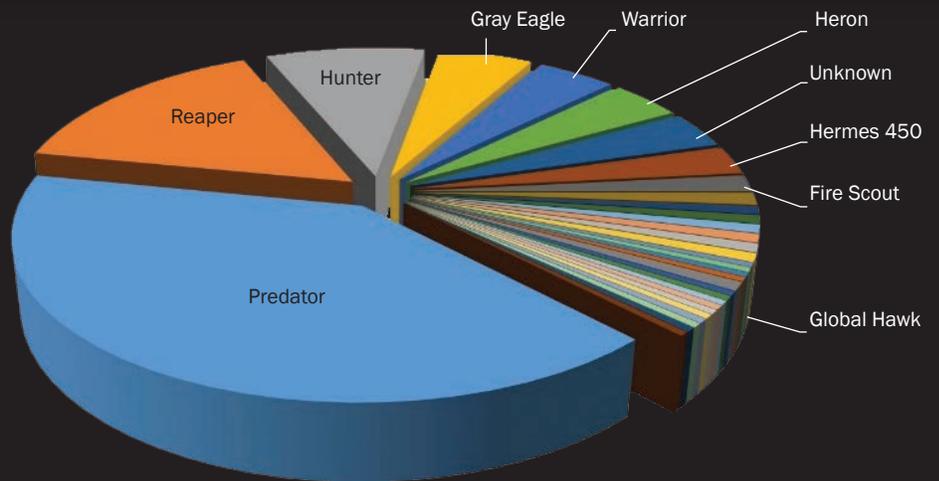


Figure 4: Washington Post Crash Records Distributed Over a Range of UAV Models.

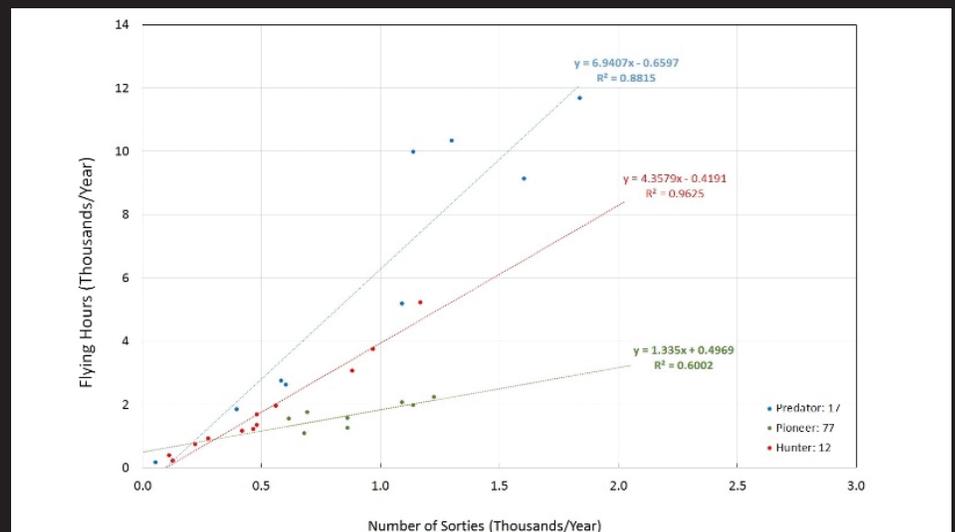
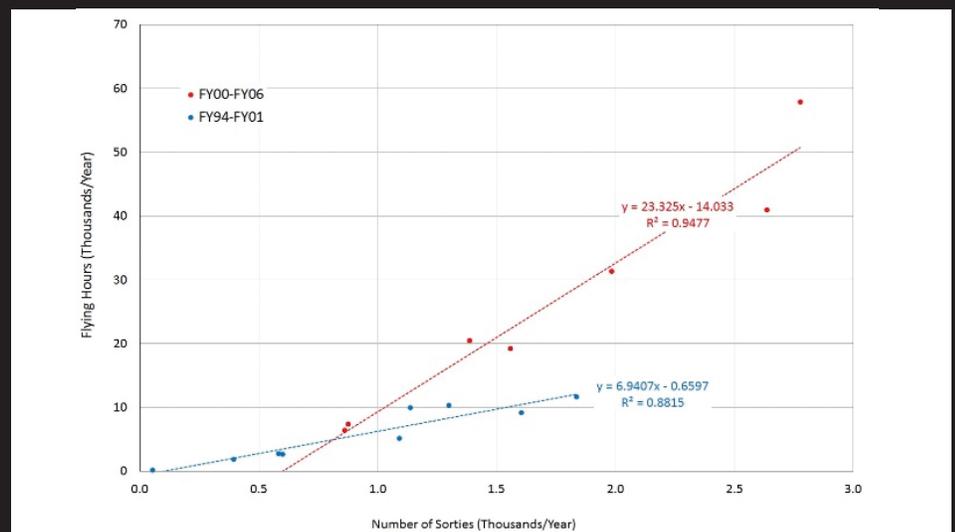


Figure 5: Operational Tempo of Predator UAV During Development and Then Deployment (Top) and Operational Tempos of Predator, Hunter, and Pioneer Between 1994 and 2001.

## Compartmentalizing aircraft reliability is a useful way to organize and conduct initial reliability assessments and modeling.

axis correspond to increasing numbers of sorties per year.

The bottom graphic in Figure 5 shows similar operational tempo data from the mid-1990s through 2001 for Predator, Pioneer, and Hunter. The legend of this later graphic gives the cumulative mishaps that occurred over this timeframe. Without further additional information from investigations following each of the mishaps represented here, the wide scatter in the data makes trend analysis risky at this point, though the plots do indicate Predator often undertakes much longer sorties than the other two models. Background factors such as environmental and battle conditions, failure mode, and prior history are all relevant to appropriately grouping data into sets for comparisons of failure rates. For instance, it would be unfair to group aircraft that were shot down by enemy fire with those that failed due to an engine malfunction.

Returning to the OSD report from 2003, those investigators were able to access records to isolate and group failure modes into categories involving the power plant (power and propulsion), flight control systems, communications, human factors, and a miscellaneous bin. Data (reproduced as pie charts in Figure 6) were provided in the report for

two versions of Predator and Pioneer and one version of Hunter. Note that a word of caution about interpreting these graphics is warranted. In both Predator and Pioneer, it would appear that design modifications between RQ-1A and RQ-1B and between RQ-2A and RQ-2B caused reliability issues with the power plants in these two aircraft. However, this appearance/presumption is incorrect, given that these charts are limited to percentage scales. Focus on other system reliability issues, such as flight control and human factors, would reduce failures in these later subsystems and improve overall system performance while shifting upward the relative contribution of power and propulsion to system unreliability, even though the overall performance of aircraft reliability has improved. Compartmentalizing aircraft reliability, as shown in Figure 6, is a useful way to organize and conduct initial reliability assessments and modeling, and it should continue into further subcategories within each of these subsystems as the design gains field experience.

At least two of these UAV platforms were transitioned and acquired by the DoD by way of accelerated development pathways, and continued design and reliability improvements were sustained through much of the lives of the program. The investigation of Long et al. (some of whose data have been reproduced in Figure 7) provides considerable insight regarding potential impacts this approach can have on system reliability. For the Predator and Global Hawk (Block 10) platforms, they assessed increases in mean time between failures (MTBF) over time as a metric for reliability growth and improvement.

Increasing MTBF is generally associated with increasing reliability, if failures

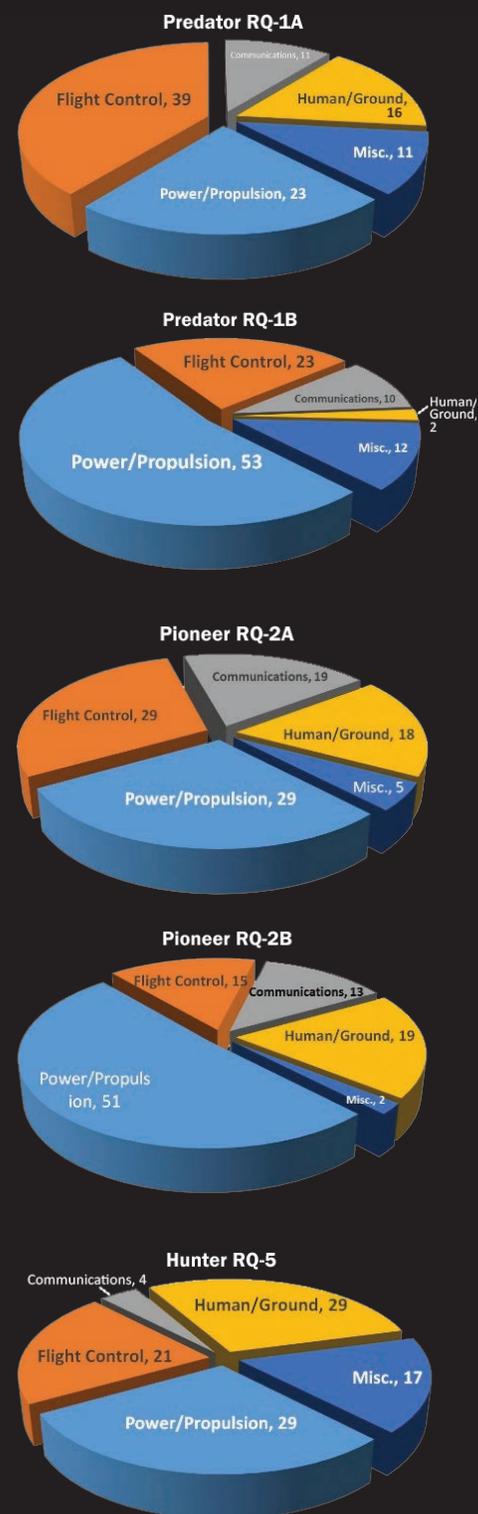


Figure 6: Distributions of Failure Categories in Predator, Pioneer, and Hunter UAVs.

are exponentially distributed—that is, if failures are random and do not impact one another. The plots in Figure 7 show increasing MTBF for both Predator

and Global Hawk (Block 10) over substantial portions of the program lives. Interestingly, Long et al. also carefully untangled all of the program costs and were able to determine the dollars devoted just to improvements in reliability over the time represented by the plots. They found that for Global Hawk, system failure rate was reduced by 42% from 2001 to 2006 and life cycle support costs were reduced by 23%. This finding allowed them to calculate a return on reliability dollar investment (RORI) of 5:1. For Predator, the figures were even more impressive. Between 1998 and 2006, improvements in platform reliability reduced failure rates by more than 48% and reduced life cycle support costs by 61%. The RORI in this case was 23:1.

The lesson to be learned here is that when reliability becomes a focus of management, it improves markedly, even for systems developed and transitioned under accelerated circumstances when quality and reliability have to take second place behind other priorities. As summarized in Figure 8, reliability also improves over time as knowledge and experience with the technology are gained both in the production plant and in the field by users. This fact has long been a part of the general body of knowledge [12]. Preliminary models of reliability today often provide optimistic predictions because many nuances associated with field use conditions are missing or are not practically considered in early models. Initial prototypes show demonstrably lower measured reliabilities because they capture unanticipated interactions between components and use conditions, but these are culled with continued development and design optimization. Reliability increases accordingly. Mass production then introduces additional variances associated with scale and

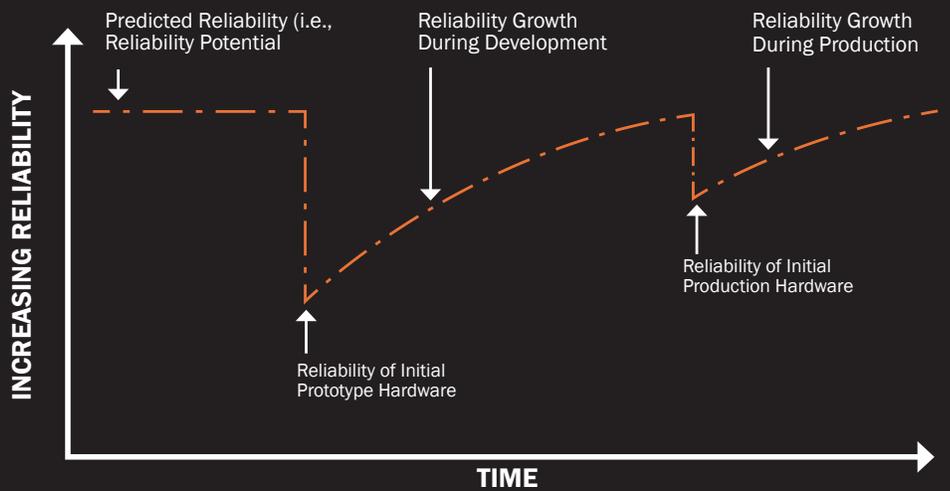
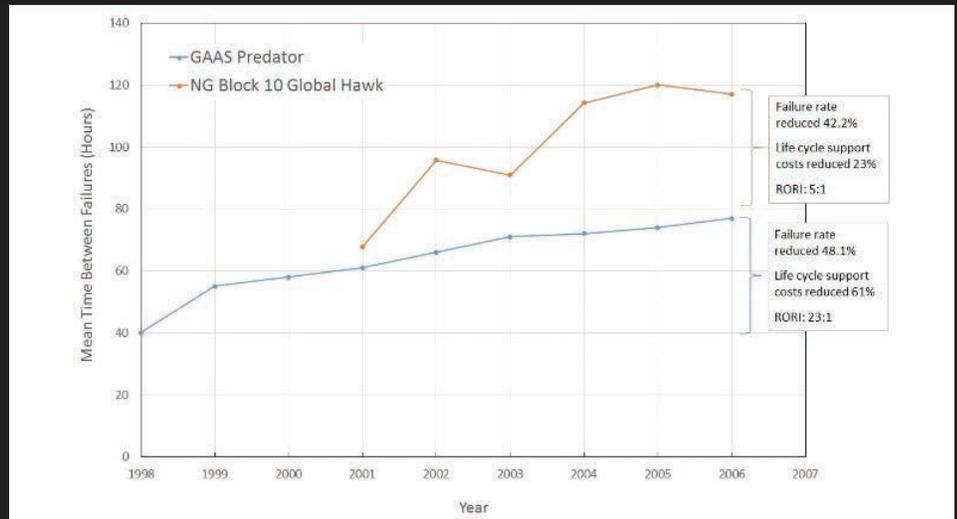


Figure 7 (top): Plots of MTBF for Predator and Global Hawk, Based on the Investigation of Long et al. [11].  
 Figure 8 (bottom): Reliability Growth Through Development and Production as Knowledge and Experience Are Gained and Evolve.

materials used in fabrication, but with time, these variances are reduced as quality assurance improves, production experience evolves, and reliability grows.

Also understood only in general terms is how reliability is affected by end-use conditions, which can include mission creep and accelerating operational tempo. These factors are summarized in the graphic of the “bathtub” curve of failure rates over time when the design is subjected to different combinations and intensities of environmental stress factors known to accelerate senescence of material systems (Figure 9). Heat,

cold, ultraviolet radiation, rapid thermal cycling, thermal shock, low-frequency and acoustic vibrations, mechanical impacts, environmental pollutants, and other conditions commonly associated with high-performance aircraft and airborne defense systems are known to increase antecedent failure rates and reduce product life accordingly.

These environmental factors, collectively accounted for in models by overly simple factors representing “harsh conditions,” operate individually, tandemly, and synergistically to drive airborne electromechanical systems

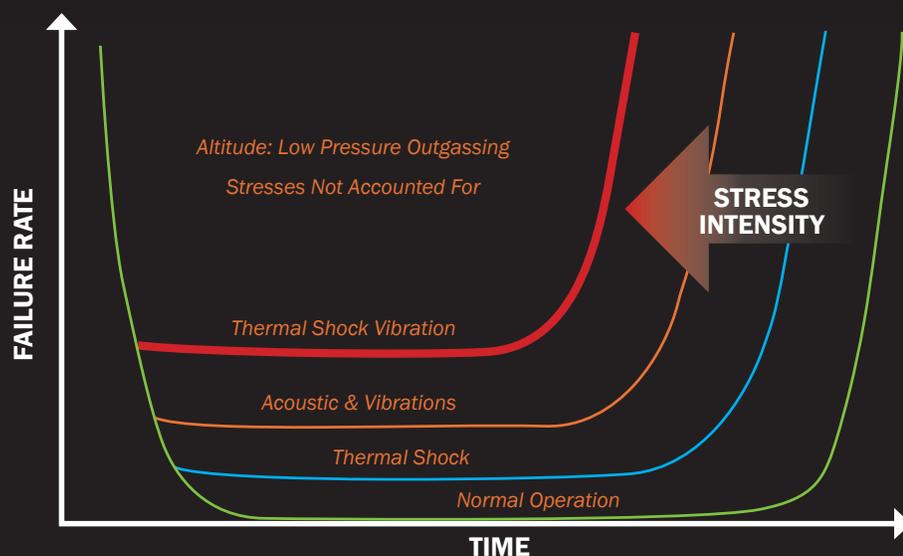


Figure 9: Increased Failure Rate and Decreased Product Life as a Result of Sustained/Repeated Exposure to Environmental Stress Factors, Mission Creep, and Operational Tempo.

to fail prematurely. These failures continue to emerge despite industry's best efforts to eliminate inherent flaws, design vulnerabilities, and defects during design, parts selection, and manufacturing processes. Synergetic effects of these conditions are leading factors affecting failure rates of aerospace components and assemblies.

## CONCLUSIONS

A perception persists in industry that quality manufacturing is all that is required to assure the reliability of complex electromechanical systems and assemblies. While a consistent high-quality manufacturing is no doubt a necessary prerequisite to product reliability, only a "design for reliability" (DFR) approach can assure that well-manufactured designs maintain high reliability in intended applications. Until this approach becomes part of the fabric of our industrial culture, disparities will continue to be commonly observed between operational reliability and specified reliability requirements that do not adequately account for all potential causes of operational mission failure.

To cost efficiently prioritize, organize, and implement ALT strategies in support of high inherent system reliability objectives, reliability and test engineers need to habitually employ systematic experimental design, as well as analysis tools such as finite element modeling. In addition, these engineers need to include a variety of tandem or mixed accelerated life techniques to stress components and assemblies in conditions that more closely mimic the wide range of field conditions where military equipment is being used. Only failure analyses based on physics of failure and materials science will provide effective diagnoses of failure modes and mechanisms, will identify points of design vulnerability, and will support development of efficient failure mitigation strategies.

Military system developers have become more receptive to strategies using advanced environmental screening methods, such as highly accelerated life testing (HALT) and highly accelerated stress screening (HASS) [13]. Testing systems to withstand preproduction thermal ramping and random vibration,

When reliability becomes a focus of management, it improves markedly, even for systems developed and transitioned under accelerated circumstances.

collectively referred to as HALT, is becoming considered critical to the development process, as is testing the ability to withstand post-production (HASS). Two principal technology standards available for the performance of these frequently required procedures include 6-degree of freedom (6DoF) and NAVMAT. Significant differences in the basic characteristics of these two approaches can result in different accumulated fatigue damage, and hence different abilities to precipitate failures originated from design and manufacturing defects.

Emerging new electromechanical technologies provide increasing challenges with respect to assuring the quality and reliability of components and assemblies, particularly associated with component and assembly miniaturization, and with increasing demands in these products and materials for higher performance, lower cost, less space and weight, and more compactness. Perhaps the most efficient path to rapid realization of new or emerging technologies will take advantage of new capabilities in integrated computational engineering design (that incorporate finely

tuned but generic stress and aging functions) together with novel material combinations (having properties and established failure modes suitable for military applications derived from an integrated database that comprises our body of knowledge augmented search and learning algorithms).

In addition, investment and development in ICME need to be performed. The value of using (ICME) design tools will reduce the program development costs of new UAVs by improving the inherent reliability when the vehicle is subjected to new manufacturing processes, advanced material systems, and extreme environment use conditions. The principal reason for investing in an ICME approach is to capitalize on the continuing integration of verified and validated computational tools and methodologies into contemporary design and manufacturing processes that address common causes of failures by facilitating the design and manufacturing of UAVs with greater durability and reliability. By coupling advanced characterization and experimental techniques with a data exchange system and computational modeling, lengthy and expensive research and development cycles can be replaced by mathematical models with the requisite computational and predictive performance capabilities. ■

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## BIOGRAPHIES

**GEORGE HANSEN** is a materials reliability engineer and the sole proprietor of Advanced Material Designs and Reliability (AMDR), which develops high-reliability products and materials for niche applications and extreme conditions and environments. With nearly 30 years of experience developing products and materials for defense and medical device applications, Dr. Hansen has specialized experience and expertise in ceramics, metals and alloys, natural and synthetic polymers and composites, and high-strength fibers, as well as diverse physical and chemical property measurement tools, accelerated life testing, systematic failure analysis, computer modeling, reliability prediction and assessment of electronics, electromechanical systems, electronic materials, polymers, and composites. He has a Ph.D. in chemical physics and high-temperature chemistry from Rice University and is certified in reliability engineering by the American Society for Quality.

**FRANK ZELLER** has 27 years of experience in engineering design, analysis, system reliability testing, and product development at Texas Research Institute/Austin. More than 20 years of this experience has been in manufacturing process engineering, product and hardware development, software development, finite element analysis, and failure mode and effects analysis. He has conducted reliability evaluations of air launch cruise missiles, Kevlar overwrapped pressure vessels, and lead-free solder for use in DoD environments. He has also developed physics-of-failure based accelerated life testing regimens and associated chambers and processes for lifetime performance assessments and reliability estimates of hardware and electronic systems. Mr. Zeller has a B.S. in industrial technology from Texas State University.

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



# UAS THREATS,

## SOLUTIONS, AND THE COLLABORATION IMPERATIVE

By Joseph Schuman and Edward Hall

### BACKGROUND

**D**epartment of Defense (DoD) leadership, academic experts, and industry professionals agree that the threat that unmanned aerial systems (UASs) pose to U.S. military forces is growing and will continue to do so for the foreseeable future. The Pentagon, recognizing this problem, requested that Congress shift \$20 million to provide seed money to develop counter-UAS solutions [1, 2]. While some promising

Photo Credit: DroneShield

technological solutions are emerging [3, 4, 5, 6], the DoD still does not have sufficient deployable counter-UAS solutions, particularly a man-portable system to protect dismounted troops. Although devoting resources toward traditional methods of product development is important, the DoD will continually be playing catch-up until it changes its methods of problem-solving. Investing in programs that promote the collaboration of diverse and nontraditional stakeholders relevant to DoD problems has been, and will continue to be, critical in producing counter-UAS solutions. The DoD must continue to support collaborative efforts if it wishes to get ahead of the next emerging threat.

## THE DRONE PROBLEM

Through the use of UASs, which includes rotary- and fixed-wing drones, nonstate adversaries are now able to threaten U.S. forces with airborne capabilities [7]. According to the Combating Terrorism Center at West Point, drones can be used by adversaries in five ways: (1) for surveillance, (2) for strategic communications, (3) for smuggling or transporting materiel, (4) for disrupting events or complementing other activities, and (5) for use as a weapon [8]. The use of drones for the purposes of surveillance by nonstate actors is well documented [1, 9]. However, the emerging threat of commercial drone weaponization seriously concerns military personnel and government officials.

In recent months, the Islamic State (ISIS) has attempted using various tactics to use drones (such as the one shown in Figure 1) to launch attacks against coalition forces [1], including grenade-dropping drones near Mosul, reportedly deploying 10 explosives during an

hour of fighting [10]. Hezbollah has used similar tactics to drop explosives on Syrian rebels [9]. Another tactic, reportedly being used by ISIS in Syria [10], is to strap explosives to a drone and use it as a kamikaze bomber. Lastly, ISIS has used a drone as a decoy improvised explosive device (IED) in what has been dubbed as a Trojan-horse-style attack by embedding explosives inside a drone, which detonated when the downed drone was recovered by coalition forces [11]. Two Kurds were killed, and two French Special Forces operatives were seriously injured in the attack [11]. These instances of UAS weaponization, although still relatively rare, have become serious enough that American commanders in Iraq have warned troops to “treat any type of small flying aircraft as a potential explosive device” [1].

Experts predict that the threat from weaponized UASs by nonstate actors will increase “dramatically” in the future [12, 13]. The Combating Terrorism Center at West Point identifies three drivers that will likely increase the frequency and effectiveness of weaponized drone use in the future: (1) the expected proliferation of drones and enhancement of capabilities, including increased payload capacity, flight time, and communications security; (2) the increased connectivity between actors, resulting in derivative weaponization attempts; and (3) the accessibility and distance provided by UASs that allow for actors with marginal interests and motivation to engage in kinetic attacks from afar [8]. Given these drivers, U.S. forces can expect an increase in weaponized UAS attacks in the future. The question remains, however, as



Figure 1: Iraqi Counter Terrorism Forces Examine an ISIS Drone Modified to Drop Small Explosives (Photo Courtesy of Mitch Utterback).

to whether U.S. forces will be able to defend against this rapidly evolving threat.

## TECHNICAL SOLUTIONS

Given the attention and resources being devoted to the UAS threat by the DoD, it is not surprising that some promising technologies have emerged. DroneShield, for example, produces a sensor network with “acoustic detection technology” that can sense a drone invisible to radar and lacking radio frequency links by analyzing its acoustic signature and comparing the sample to a database. If the observed acoustic signature matches a signature in the database, the system issues an alert to the user. Then, using DroneShield’s DroneGun (pictured in Figure 2), a user is able to “jam” drones, purportedly within a 2-km range and in a variety of environmental conditions [4].

Another promising technology, MESMER, developed by Department 13, also detects and identifies drones. However, MESMER does not kinetically attack or jam drones. Rather, it employs a low-power and low-interference strategy called “protocol manipulation,” whereby MESMER sends signals to a drone that persuade it to listen to a new control system other than the pilot (as illustrated in Figure 3). After the drone is “mesmerized” by the new signal, the threat can be mitigated by forcing the drone to land in place or in a predesignated area [5].

Many other potential technical solutions exist, as evidenced by the 50 counter-UAS systems tested at the DoD’s Black Dart event [9]. However, counter-UAS systems continue to face a variety of problems. For example, “jamming,” as is done by DroneGun, can be highly problematic. If a UAS is carrying an

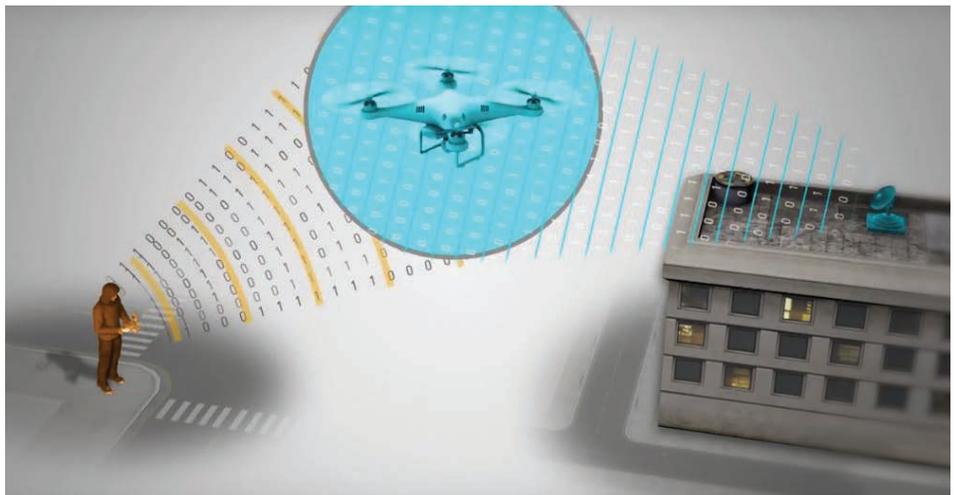


Figure 2 (top): DroneGun (Image Courtesy of DroneShield).

Figure 3 (bottom): Representation of MESMER Sending Signals to Manipulate Drone Protocol (Image Courtesy of Department 13).

explosive payload over a populated environment, disabling the drone might prevent it from reaching its intended target, but at the risk of potentially injuring civilians beneath the drone. Another problem with DroneGun is that it consists of a large rifle attachment and a backpack. While DroneShield touts its product as “portable,” it requires troops to add a significant amount of weight to the modern-day soldier’s already heavy load, which can limit maneuverability and increase risk of injury [14]. In addition, both DroneShield and MESMER require large, stationary sensing hardware, eliminating the possibility that either solution could be employed by dismounted troops in forward operating environments.

According to the Asymmetric Warfare Group (AWG), given the number of issues identified with the promising technologies previously identified, it is understandable that the UAS threat to DoD personnel and equipment is still considered “absolutely pressing,” despite the prevalence of potential counter-UAS solutions.

## THE COLLABORATION IMPERATIVE

The DoD has recognized that success in its counter-UAS mission will require successful integration of numerous capabilities across several domains [15]. While it is clear that investing time and resources in developing counter-UAS capabilities needs to continue, what

may be less clear (but arguably more important) is that the DoD needs new *methods* of developing solutions. When facing a threat that is evolving as rapidly as the UAS threat, the DoD needs to engage with nontraditional stakeholders in ways outside of the normal development and acquisition process. This necessity is the *Collaboration Imperative*.

The DoD has made efforts to this end, especially when it comes to intragovernmental collaboration. In the fall of 2016, the DoD held a counter-drone exercise called Black Dart, which tested technologies for detecting, identifying, tracking, and defeating UASs. Black Dart featured more than 20 variants of UASs, more than 50 counter-UASs, and some 25 government entities, including the Department of Homeland Security and the Federal Aviation Administration, and numerous organizations from academia and industry [9].

While an interagency approach can be a productive problem-solving method, the Combating Terrorism Center at West Point justly questions whether internal efforts such as Black Dart are “forward-leaning enough” [8]. The West Point report concludes by prescribing that the government remain open minded and equally creative about the government and nongovernment structures it creates to facilitate the meaningful exchange of ideas and the people it brings in to serve as advisers [8]. The structures and methods identified by the West Point report have been formalized into a concept called the Defense Innovation Base, developed by Adam Jay Harrison, Director of the MD5 National Security Technology Accelerator.

The Defense Innovation Base would include, “a more diverse, independent,

and unencumbered set of participants,” including commercial firms, academic institutions, and private citizens, to improve the capacity of the DoD to adapt to disruption [16]. Thus, the base would not only bring new and diverse individuals into the problem-framing and -solving process, but it would also improve the speed at which the DoD reacts to “an uncertain, rapidly evolving world subject to disruptions that cannot be predicted or planned for with a high level of certainty” [16].

Investing in programs that promote the collaboration of diverse and nontraditional stakeholders relevant to DoD problems has been, and will continue to be, critical in producing counter-UAS solutions.

The creation of a Defense Innovation Base can be accomplished through a variety of rapid, iterative development events, ranging from “hackathons” (collaborative problem-solving sprint events involving participants with diverse backgrounds) and challenges to educational classes. While the particular details of these events are not necessarily important, the critical variable is that any such programming must leverage the diversity of stakeholders, inside and outside of government, that come together to participate in any given event. To its credit, the DoD has begun to engage in some collaborative programming, albeit

at a limited scale. Nonetheless, the successes of two programs relevant to the UAS threat, outlined in following text, deserve mention.

### **#HackTheSky**

In the summer of 2016, the Naval Postgraduate School (NPS) held a hackathon called #HackTheSky to better understand how to hack into the code controlling autonomous swarming drones. The event brought together cyber experts, data scientists, Silicon Valley tech representatives, and other hackers, representing more than 70 organizations, most of which had never before worked with the government. At the end of the event, Cmdr. Zachary Staples, Director of the NPS Center for Cyber Warfare, stated, “The event proved to achieve all we had hoped it would—improved control software and several steps forward on some innovative technology developed on a shoestring budget” [17]. Hackathons such as #HackTheSky and others hosted by the MD5 National Security Technology Accelerator in New York, NY, and Austin, TX, are promising examples of efforts to address the Collaboration Imperative [18].

### **Hacking for Defense (H4D)**

H4D, a university-sponsored class that pairs real DoD problems with student teams who, through stakeholder interviews, conceive and discuss potential solutions, is another promising example of the DoD leveraging nontraditional innovators. Piloted at Stanford University in the spring of 2016, H4D has since expanded to four universities, including Georgetown. At Georgetown, the AWG has charged one team of students with creating a man-portable solution to detect, identify, and neutralize UASs [19]. As

described in the next section, this team, called H4Drone, is already discovering information through stakeholder interviews relevant to the UAS problem that would not have been discovered by internal innovation processes. At the end of the class, this team, along with the other teams, will present their solutions to representatives of the corresponding governmental agency. And (as was the case with the inaugural Stanford class) a number of these solutions will likely either be implemented internally or receive funding for further development [20].

## WHY COLLABORATION WORKS

Collaborative programming and efforts such as #HackTheSky and H4D work for three reasons: (1) the diversity of participants involved, (2) the ability of diverse participants to identify the specific needs of individuals and agencies, and (3) the speed at which the participants can make progress toward deploying solutions.

### **Diversity of Participants**

The benefits of diversity of thought as a result of diversity of participation is built into events such as hackathons and classes such as H4D. For example, Cmdr. Staples noted that the NPS Hackathon was designed to increase the diversity of the Navy's technological base because the Navy recognizes that, "diverse teams address and solve problems with greater flexibility and creativity" [17]. Similarly, H4D leverages the diverse perspective of university students compared to internal DoD personnel. The AWG, which sponsored H4Drone's counter-UAS problem, noted that AWG submits real government problems to the course because it appreciates fresh perspective and

values student input. According to Mr. Alex Kravets, a master's degree candidate at the Georgetown School of Foreign Service and a team member of H4Drone, "military folks are really good at certain things, but creative thinking and thinking about commercial solutions is a little foreign to them." Thus, by enlisting the perspective of stakeholders outside of government, collaborative programming leverages diverse expertise toward internal DoD problems that would otherwise not be used.

While it is clear that investing time and resources in developing counter-UAS capabilities needs to continue, what may be less clear (but arguably more important) is that the DoD needs new methods of developing solutions.

### **Product Fit**

Given the diversity of needs across DoD organizations, it is no surprise that one solution does not fit all applications, for the UAS threat and beyond. For example, MESMER might be appropriate for defending military infrastructure but would not satisfy the man-portable requirement specified by AWG's problem statement. Collaborative programming, however, allows participants to get a better understanding of the problem space, including agency constraints and requirements, and potential solutions. Mr. Michael McGruddy, another master's degree candidate at the Georgetown

School of Foreign Service and H4Drone team member, found through the H4D customer discovery process that "each agency and service sees the problem differently according to their own needs." He also noted that the process enables participants to get a perspective that few others are able to achieve, even experts in the field." Similarly, hackathons, when properly designed, bring together the DoD and military personnel who experience a given threat on a daily basis with nontraditional problem-solvers, who can gain an in-depth understanding of the problem through a similar interview process. Therefore, collaborative programs not only bring more ideas and perspectives to the table, but they also allow for the synthesizing of ideas and perspectives to create a better understanding of the problem space and potential solutions relevant to specific end users or beneficiaries.

### **Speed**

The speed of product development and deployment of new technology is critical to its effectiveness in modern military operations. Experts predict a series of "action-reaction-counter-reactions" between coalition forces and adversaries in the UAS fight, as occurred with the roadside IED threat in Iraq and Afghanistan [7]. Traditional development and acquisition processes are too slow to adapt to the pace of change in the modern battlefield environment. In the context of the UAS threat, Mr. Kravets notes, "The technology is advancing incredibly rapidly. A solution that might work for countering drones 6 months out most likely won't be effective 12-18 months out." Collaborative problem-solving, however, allows for solutions to be solved at speed. Although no complete solution can likely be developed at a

hackathon or H4D course, hackathon participants work long hours over multiple days to produce partial solutions and often make significant progress, as was the case at the NPS Hackathon [17]. H4D is also conducted at an incredibly fast pace. As such, collaborative problem-framing and -solving produce a concentration of focus and effort that can significantly contribute toward progress on a given problem in ways that are not always possible through traditional methods of product development.

## CONCLUSION

Technology is the battlefield of today and tomorrow. And to “own the high ground” on that battleground, the U.S. military must master the tactics of innovation [16]. Given the pace of technological innovation and the increasing number of adversaries able to innovate at low cost, traditional DoD development and acquisition are insufficient, as evidenced by the UAS threat and response. As the Combating Terrorism Center at West Point argues, our ability to prevent weaponized drone attacks is only as good as our ability to think in creative ways [8]. And creative thinking, produced by the collaboration of diverse stakeholders in nontraditional environments, must be a priority if the DoD wants to mitigate emerging threats. Such is the Collaboration Imperative. ■

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**JOSEPH SCHUMAN** is a research assistant for the MD5 National Security Technology Accelerator at the West Virginia University Innovation Corporation. Previously, he served as a research assistant for the Massachusetts Institute of Technology (MIT) Security Studies Program and a research intern at the Brookings Institution’s Center for Technology Innovation. Mr. Schuman holds a B.S. in mechanical engineering and political science from MIT.

**EDWARD HALL** is a program manager at the West Virginia University Innovation Corporation. He has more than 20 years of experience in the areas of defense and energy sector business incubation and technology transfer. Previously, he served as the Chief Operations Officer at Resilient Technologies LLC. Dr. Hall earned a B.A. in economics from Dartmouth College and a J.D. from the University of Virginia School of Law.

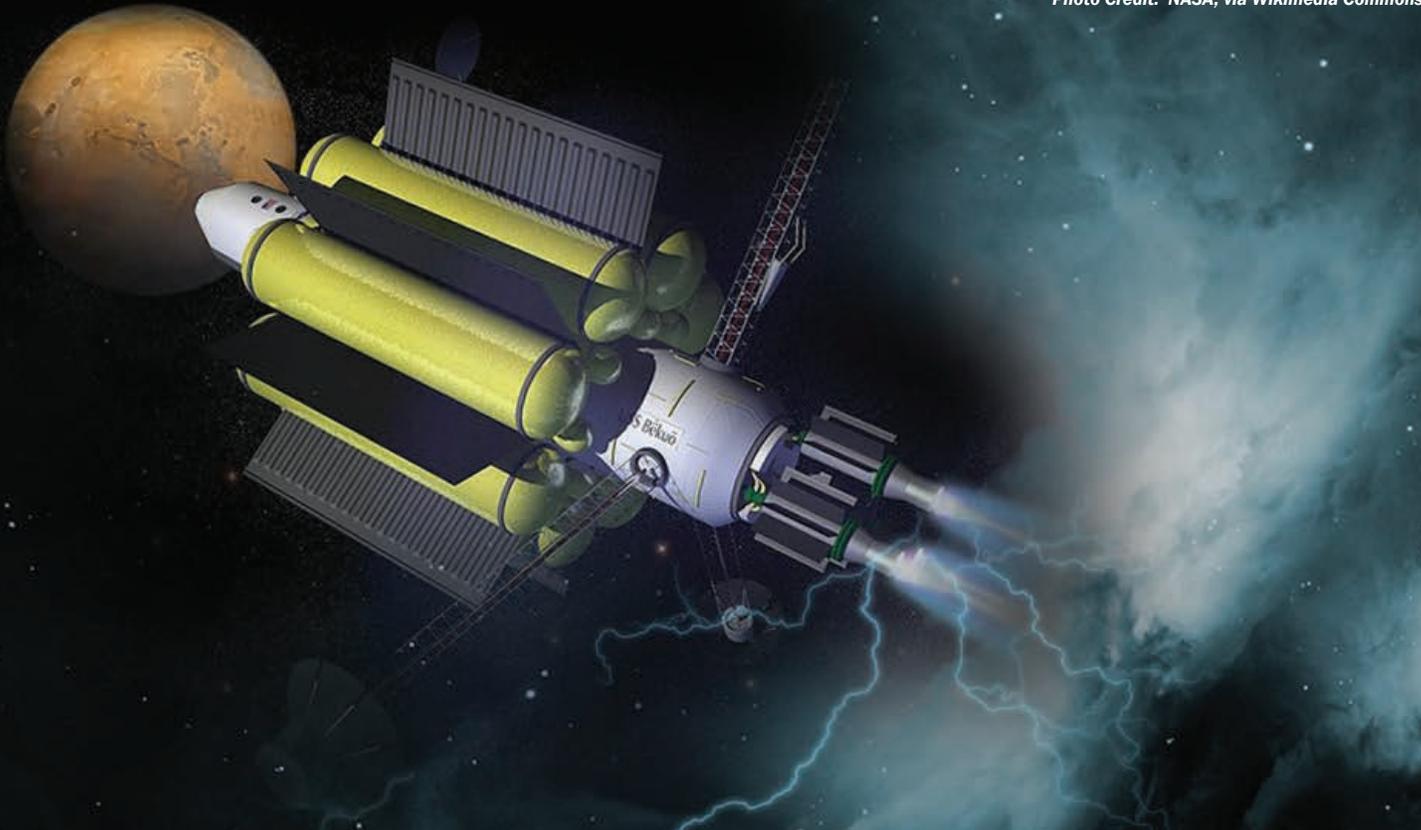


Photo Credit: NASA, via Wikimedia Commons

# SPACE TRAVEL AIDED BY PLASMA THRUSTERS

## PAST, PRESENT, AND FUTURE

By Albert DeFusco, Christopher Craddock, and Wesley Faler

### INTRODUCTION

**L**ike other contemporary energetic and propulsion technologies, electric propulsion—of which plasma thrusters are a subset—has been around for nearly a century. As Goebel and Katz, from the California Institute of Technology's Jet Propulsion Laboratory, point out in their book *Fundamentals of Electric Propulsion: Ion and Hall Thrusters* [1]:

*“Electric propulsion was first envisioned 100 years ago, and throughout most of the 20<sup>th</sup> century was considered the technology of the future for spacecraft propulsion. With literally hundreds of electric thrusters now operating in orbit on communications satellites, and ion and Hall thrusters both having been successfully used for primary propulsion in deep-space scientific missions, the future for electric propulsion has arrived.”*

Although the basic concept of operation for plasma thrusters has not changed since their first demonstration, much advancement has been made over the years due to extensive research, design, testing, and engineering. Goebel and Katz consider ion and Hall thrusters “more modern electric engines that are finding increasingly more applications.” Further understanding the principles of operation and seeking ways to improve the technology for future

advanced applications continue to be the challenges facing many private companies, government institutions, and universities across the world.

## A BITE FROM U.S. HISTORY

Although much of the news about space travel in the 1960s was dedicated to Earth-based heavy rocket launches and landing a man on the moon, electric propulsion similarly enjoyed a flurry of activity and amazing successes (though much less celebrated) at the time.

The first in-space demonstration of an electric ion thruster developed by the United States was achieved by NASA in early 1964 aboard the Space Electric Propulsion Test I (SERT I) spacecraft. One of two ion engines, carried into space by a Scout rocket, performed as expected and operated for a full 31 minutes, delivering high-velocity mercury ions from its thruster.

Later in 1970, to prove long-duration operation, SERT II demonstrated two ion thrusters, which performed for 3 and 5 months, respectively. In fact, the SERT

II engines were operated intermittently from 1970 to 1981, with up to 300 engine restarts, while in-flight data were collected while in Earth orbit. The 1960s and 1970s showed considerable progress in electric propulsion by NASA, followed by a hiatus during the 1980s.

Work was revitalized in the 1990s with the NASA Solar Technology Application Readiness (NSTAR) ion thruster used aboard the Deep Space-1 (DS-1) spacecraft. Although size has grown over time for these thrusters with the SERT I mercury engine at a 10-cm diameter (and a 1.4-kW power demand and a 4,900-s specific impulse [ $I_{sp}$ ]), thrust and power demands for NSTAR at a 30-cm diameter have remained relatively unchanged (at a 2.3-kW power demand and a 3,100-s  $I_{sp}$ ). Furthermore, xenon gas, as opposed to toxic mercury, has now become a common fuel. Thrust-time (a measure of total impulse [ $I_T$ ]) has also increased considerably, as measured by 10,000 hours of working time and fuel consumption of 30 kg of xenon for NSTAR in the DS-1 spacecraft. Sovey et al. provide an excellent summary of NASA developments in their article

“Ion Propulsion Development Projects in U.S.: Space Electric Rocket Test 1 to Deep Space 1” [2].

## ELECTRIC PROPULSION VS. CHEMICAL PROPULSION PERFORMANCE

During the last 5–6 decades, many different types of electric propulsion designs have been developed, tested, and deployed for space flight. Table 1 compares the properties of a small number of these devices along with chemical propulsion for reference. Electric propulsion reigns supreme in terms of  $I_{sp}$  but provides low thrust levels compared to chemical propulsion. While chemical propulsion derives its energy from consumption of combustible organic and inorganic materials in a vented, pressurized chamber to accelerate a complex mixture of gas particles through a nozzle, electric propulsion relies on electrical or electromagnetic energy input to generate electrically charged fundamental particles with extremely high velocities (Figure 1).

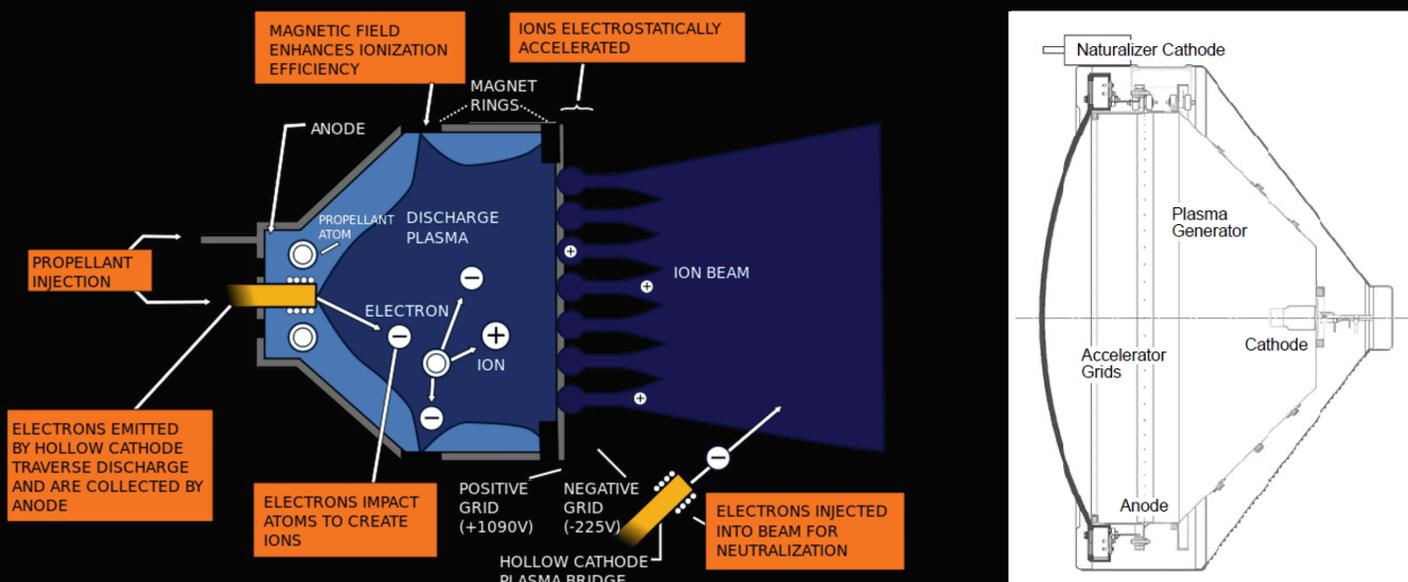


Figure 1: Conceptual Representation (A) and Design Cross Section With Electrified Grids (B) of an Ion Thruster [1, 2].

With its comparatively high thrust, solid rocket propulsion is suited for earth-restricted launch, usually for heavy vehicles, such as missiles and space rockets. Energy is generated nearly instantaneously to create high thrust and acceleration, which quickly dissipate as the propellant is consumed. On the other hand, electric propulsion is desirable for vehicles already in Earth orbit or outer space, where low thrust and high particle velocity are used to constantly accelerate spacecraft and provide high fuel efficiency with exceptionally long operational times.

Chemical propulsion typically expends its stored energy on the order of seconds to minutes, while electric propulsion

Although the basic concept of operation for plasma thrusters has not changed since their first demonstration, much advancement has been made over the years.

can last from months to years, eventually achieving and surpassing vehicle velocities achieved by chemical propulsion. Electric propulsion also offers restart and pulsing features,

making it suitable for controlled and long-range space missions. Since the late 1900s, electric propulsion has been used, for example, to keep satellites in Earth orbit or to move them to higher orbits (i.e., station keeping and orbit adjustment) and conduct deep-space probe missions. Samples of the variety of electric thruster designs are shown in Table 1 and are further described in Table 2 [1].

## CATEGORIES OF ELECTRIC PROPULSION

As shown in Table 2, electric propulsion can be divided into three categories: electrothermal, electrostatic, and electromagnetic. Electrothermal

Table 1: Electric vs. Chemical Propulsion

	Technology	$I_{sp}$ (s)	Thrust (lbf)	Input Power (kW)	Efficiency (%)	Propellant
CHEMICAL	Solid Chemical Propellant	150–270	Up to $\sim 2 \times 10^6$	-	90–98	Binder-oxidizer-fuel compositions
	Solid Air-Breather Propellant	400		-	80–90	Air and fuel-rich compositions
	Liquid Bipropellant	300–450		-	90–98	Liquid oxygen (LOX)/liquid hydrogen (LH) and various others
ELECTRIC	Resistojet	300	$\sim 0.02$ –2	0.5–1	65–90	Hydrazine
	Arcjet	500–600		0.9–2.2	25–45	Hydrazine
	Pulsed Plasma Thruster (PPT)	850–1,200		<0.2	7–13	Teflon
	Hall Thruster	1,500–2,000		1.5–4.5	35–60	Xenon
	Ion Thruster	2,500–3,600		0.4–4.3	40–80	Xenon
ADVANCED ELECTRIC	Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	3,000–12,000	$\sim 0.02$ –1.3 [4, 5, 10, 11]	28–200	Up to $\sim 70$	Argon
	Dual-Stage Four-Grid (DS4G) Ion Thruster	$\sim 15,000$	$\sim 0.5$ [6]	250	$\sim 60$	Xenon
FUSION-	Proton-Boron (p-B) Plasma Thruster	$\sim 3,500^a$	$0.0011^a$ ( $\sim 5$ at 100 kW <sup>b</sup> )	$0.022^a$ (base module)	$\sim 70^a$	Hydrogen and boron

<sup>a</sup>Theoretical values based on initial experiments.

Table 2: Description of Different Electric Propulsion Concepts

	Thruster Type	Description	Characteristics
ELECTRO-THERMAL	Resistojet	Electrothermal, fuel passes over resistively heated element, thrust is produced from exhaust velocity of heated fuel	Low $I_{sp}$
	Arcjet	Electrothermal, fuel passes through electrically generated arc	Weak ionization, low $I_{sp}$
ELECTRO-MAGNETIC	Pulsed Plasma Thruster (PPT)	Electromagnetic thruster, fuel partially ionized through arc, ions accelerate past magnetic field	Pulse rate determines thrust level, moderate $I_{sp}$
	Hall Thruster	Electromagnetic thruster, ions accelerate past magnetic field	Moderate $I_{sp}$ , simple design
ELECTRO-STATIC	Ion Thruster	Plasma thruster, ions accelerate through electrostatic grid	High efficiency, high $I_{sp}$
ELECTRO-MAGNETIC	Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	Radio frequency (RF) magnetic thruster, ions generated by dual RF fields then accelerated through a magnetic nozzle	High and variable $I_{sp}$ and thrust, predicted long life
ELECTRO-STATIC	Dual-Stage Four-Grid (DS4G) Ion Thruster	RF-generated ion thruster, dual-stage accelerating screens	High and variable $I_{sp}$ , low sputtering damage for extended component life
FUSION-	Proton-Boron (p-B) Plasma Thruster	p-B fusion assisted plasma	Compact, low power, low mass, moderate $I_{sp}$

propulsion relies on heating a propellant gas stream to produce thrust, with little ionization of the gas (plasma formation). Operation of electrostatic and electromagnetic thrusters relies on the generation of a plasma stream, which is accelerated through electrified porous screens (grids, typically three) or a magnetic field (Hall effect), as shown in Figures 1 and 2, respectively.

Plasma streams of ions are created from a gas such as xenon (fuel, propellant), which is introduced through a hollow cathode (spark generator). In an electrostatic thruster, plasma ions collect in a chamber and are then accelerated past electrified grids,

thereby increasing particle velocity to produce thrust. In a Hall thruster, or similar magnetic-assisted thruster, ions are accelerated past a magnetic field, eliminating the need for grids. Particle acceleration can be varied by the strength of the magnetic field, which is typically generated from electromagnets.

An exciting new enhancement to these designs is a concept recently proposed by Rocketstar LLC and developed by Fluid & Reason LLC, which uses proton-boron (p-B) fusion to enhance its ConstantQ thruster [3]. This fusion-enhanced plasma thruster, which is currently under development and testing, can be incorporated into

electrostatic and electromagnetic designs, as discussed further in succeeding text.

### TRENDING TOWARD HIGHER SPECIFIC IMPULSE

Recent examples of advanced thrusters under development and testing by NASA, universities, and foreign institutions are the VASIMR [4, 5] and Dual-Stage Four-Grid (DS4G) [6, 7] engines, which provide high  $I_{sp}$  and predicted long life. VASIMR is an open design and uses radio frequency (RF) energy to ionize gaseous fuel along with

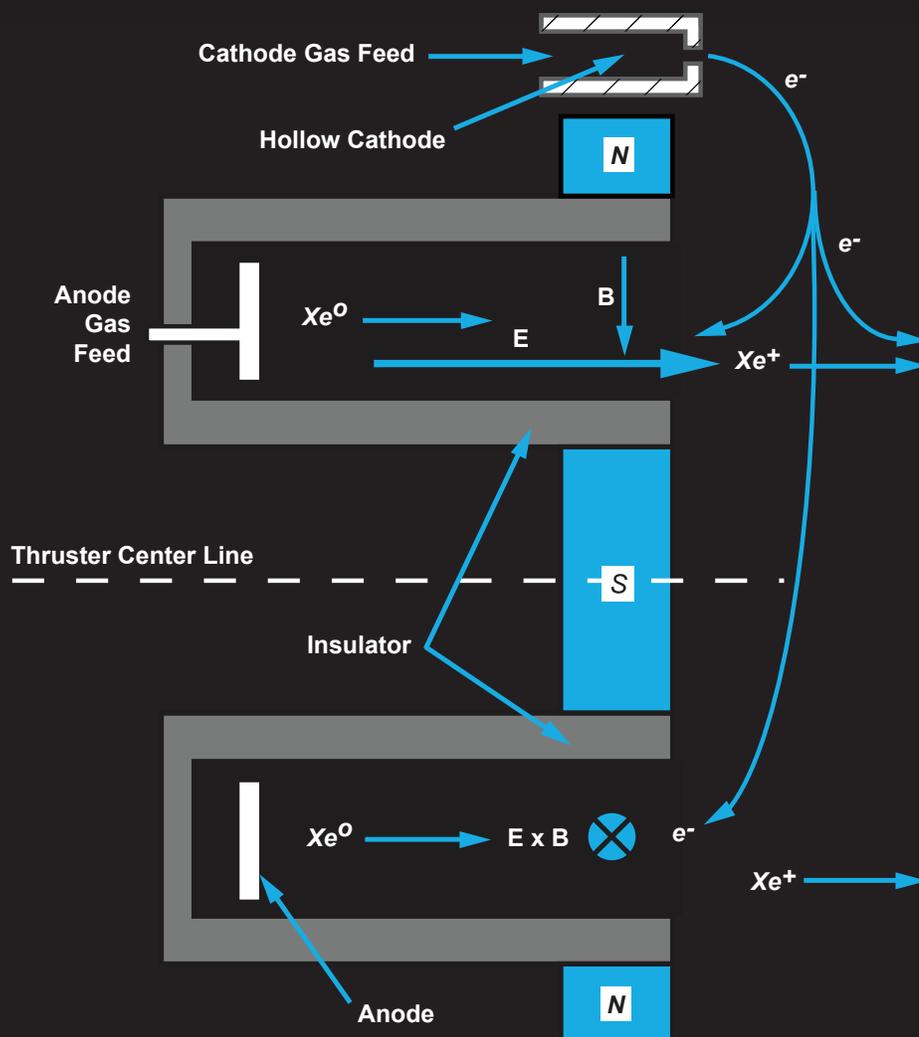


Figure 2: Concept Design for a Hall Thruster With Magnetic Fields for Accelerating Particles [1].

superconducting magnets to accelerate ions through the nozzle, as shown in Figure 3. The variable impulse feature, which can allow vehicle acceleration or deceleration by changing the electrical current in the magnets, is expected to be most useful for deep-space applications. And because weight savings and fuel efficiency are critical to all space flights, NASA believes that the VASIMR engine could be powered by a limited supply of hydrogen fuel for travel to Mars, where it could then refuel for the journey back to Earth [8]. Deployment of VASIMR is still many years away, but development is progressing.

The DS4G ion thruster concept was inspired by controlled thermonuclear reactor (CTR) experiments that use multiple grids to direct high-energy particles. As illustrated in Figure 4, the concept employs four grids (A, B, C, and D), grouped in pairs. The spacing distance (hence, electrical potential) between the second (B) and third (C) grids provides acceleration of the ions. A typical three-grid system in electrostatic ion thrusters extracts ions from the source and simultaneously accelerates them. In these designs, particle accelerations are limited by beam acceleration electrical potentials

of about 5 kV due to ensuing beam divergence, as well as impingement and erosion of grid material (sputtering, widening of grid holes), which ultimately limits  $I_{sp}$  values to much less than 10,000 s (see Table 1).

Inspired by CTR designs and experiments with high-energy particles, DS4G decouples ion extraction and acceleration in two stages. As a result, reduced sputtering is realized on the first (A) and second (B) grids. Higher acceleration potentials ( $>>5$  kV) can also be achieved for increased particle velocities between the second (B) and third (C) grids. Overall low beam divergence (6–12° compared to 12–15° in typical ion thrusters and 40° in Hall thrusters) is also realized. Together, the European Space Agency (ESA) and the Australian National University's Plasma Research Laboratory have conducted laboratory-based experiments on the DS4G thruster and have seen excellent results. Values for  $I_{sp}$  as high as 15,000 s were measured, along with a thrust of 0.64  $lbf$  using beam acceleration potentials in the range of 10–30 kV.

## CHALLENGES FOR FUTURE ELECTRIC PROPULSION

Because plasma streams are highly energetic, one can envision the need for materials that are potentially rare, exotic, and expensive to impart useful life to the components of these designs. Electrical and thermal insulating materials, particularly ceramics, are a necessity since issues such as grid erosion (sputtering), chamber erosion, cathode life, overheating of external components, and electrical effects on the vehicle can be limiting factors for overall performance and working life.

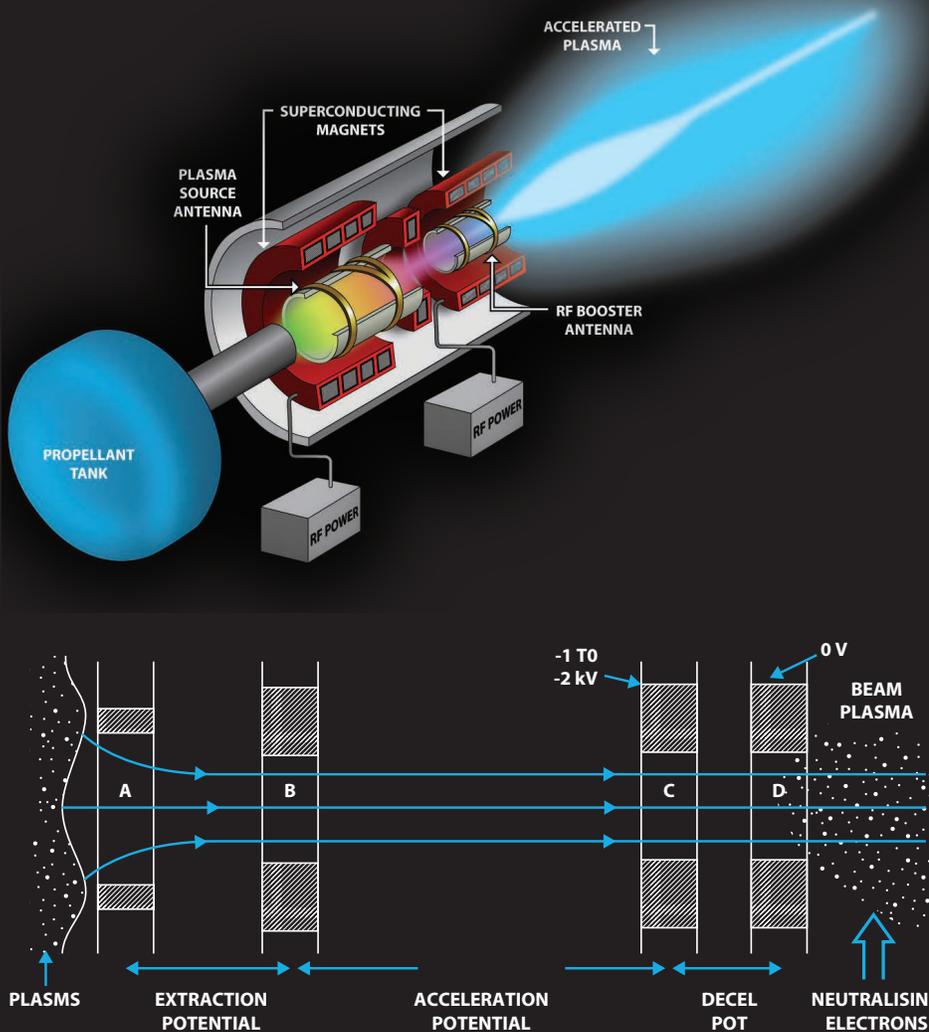


Figure 3 (top): VASIMR Concept Design.  
 Figure 4 (bottom): Depiction of DS4G Concept [6].

Energy supply and demands, component weight, and external hardware (such as gas fuel tanks) are concerns for extended-life and extremely-long-distance missions, such as manned space flight (MSF) to Mars or solar system exploration.

As with many other technologies, miniaturization of plasma thrusters with high impulse and efficiency is also needed. Much like chemical propulsion, electrical propulsion seeks more advanced concepts and designs

that can reduce size, mass, stress on components, and overall cost, as well as eliminate the need for external auxiliary components, increasing performance ( $I_{sp}$  and thrust) and using less power. To address some of these needs, for example, NASA is currently promoting competition among universities and nonprofit institutions to support its CubeSat mission, which is directed toward demonstrating deployment of multiple small (10 cm x 10 cm x 10 cm) satellites into Earth orbit [9].

A proton gun can be as small as a nickel, while the boron used could be the size of a quarter for small satellites.

### NEW CONCEPT COUPLED WITH FUSION

One concept being developed to address these challenges is the previously mentioned p-B fusion-assisted ConstantQ plasma thruster, which is a joint project between Fluid & Reason LLC and Rocketstar LLC [3]. In general, the concept fires a proton gun at solid B to create plasma ions that then accelerate through a thruster, as depicted in Figure 5. Like throwing a softball down a hallway with a turbine fan at one's back, a boosting effect is created by the fusion reaction to increase acceleration of ions through the thruster chamber. Theoretically, the fusion reaction will also clear the exit nozzle of any recombining particles, as well as give exit thrust even after ions have left the apparatus. Fusion will continue to occur outside the system not only to free the exit area of any interference but also to increase particle velocity, and hence the delta-velocity of the vehicle.

Fusion is the key to addressing higher velocity particle ejection (i.e.,  $I_{sp}$ ) in the p-B-enhanced ConstantQ geometry thruster. It clears the way for the particles to move at an accelerated pace and gives a boost both behind and in front of the plasma thruster. Particles

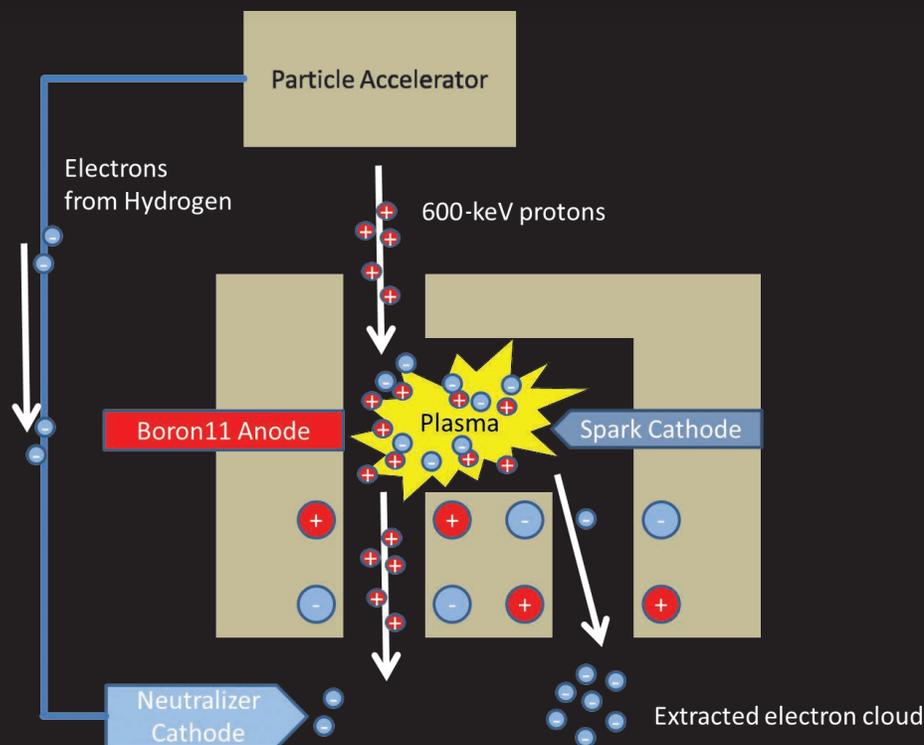


Figure 5: p-B-Enhanced Plasma Thruster Concept (Photo Courtesy of Rocketstar LLC and Fluid & Reason LLC).

are rapidly flushed through the system. Because more power is generated compared to that at the start, due to the fusion reaction, the advantage on particle acceleration occurs on two fronts—the initial acceleration from the thruster and p-B fusion plasma and then the continued fusion outside the vehicle as particles exit the thruster.

## THE p-B FUSION AFTER-BURNING EFFECT

In a way, fusion acts as an after-burner for plasma engines. Typically, as ions exit a plasma thruster, they collect and obstruct the acceleration of new ions, thereby diminishing performance. This repulsive (clogging) effect is essentially eliminated with the presence of fusion. Fusion breaks the plasma ions into several smaller, extremely high velocity particles, which exit the thruster faster than the heavier plasma ions. The path

is essentially cleared for subsequent ions to accelerate through the thruster. It is this after-burning clearance of space-charge build-up that is unique to the fusion-enhanced thruster, giving it the potential for higher performance in an overall smaller package.

In fact, most ion thrusters would benefit from a fusion after-burner since they face the challenge of releasing new ions into a repulsing exhaust cloud. All can benefit from clearing the waste exhaust sooner. However, some thrusters, such as the ConstantQ, get an extra benefit as the exploding ions from the fusion reaction create fast-moving positive fragments. As they race outward, they attract the negatively charged plasma components. The p-B-enhanced concept in the ConstantQ geometry retains a small number of extra electrons in its exhaust (a virtual cathode), adding to the pull experienced by the ions and reducing the repulsion. With the aid

of fusion, ions (electrons) are dragged far from the craft, increasing the acceleration of additional ions leaving the engine.

## THE p-B-ENHANCED ConstantQ THRUSTER

Beyond higher performance and vehicle delta-velocity, the p-B-enhanced ConstantQ concept potentially addresses other issues, such as size and fuel storage. There is no gaseous fuel to carry since protons can be generated from hydrogen molecules collected on the spacecraft (Brussard ramjet), from decaying radioactive material, or from other proton guns. A proton gun can be as small as a nickel, while the boron used could be the size of a quarter for small satellites. As shown in Figure 6, the plasma thruster that is married to the fusion apparatus is extremely small. And power requirements are low, as large magnetic fields are not needed in this design. Boron can be transported in stick or brick form since it is nonreactive in normal and man-rated environments.

The ConstantQ thruster also addresses the lower cost concern. It uses a simple design for manufacturing and maintenance. Because the United States is the largest producer of boron in the world, feedstock is inexpensive and little threat to limited supply. Boron is also not a safety concern and is even less hazardous than a compressed gas cylinder. The use of boron also eliminates the necessity of scouring off-shore countries, especially those involved in military conflicts (such as Afghanistan), for exotic fuels. Additionally, the thruster design lends itself to advanced manufacturing techniques, such as additive manufacturing (i.e., three-dimensional [3-D] printing) for easy prototyping of complex geometries, if needed, and repair. Theoretically, if

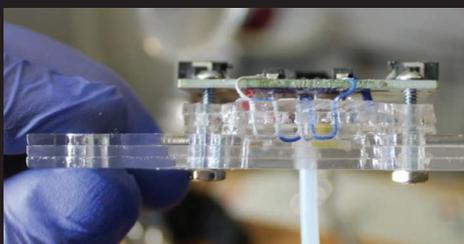
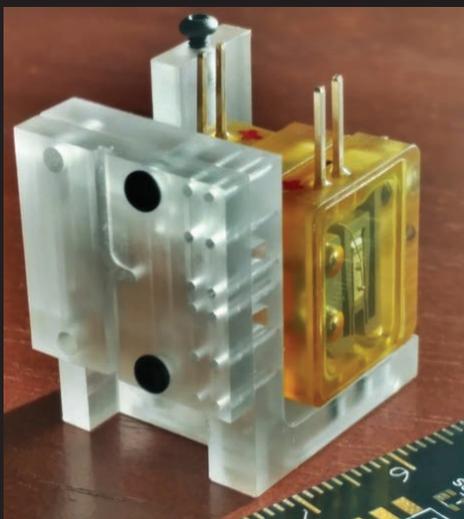


Figure 6: The Extremely Small ConstantQ Thruster (Photos Courtesy of Rocketstar LLC and Fluid & Reason LLC).

the spacecraft carried the necessary materials on board, or collected them along its journey, it could 3-D print parts necessary to fix any problems with the fusion thruster. Simple designs, such as the ConstantQ thruster, along with advanced manufacturing technologies, may someday eliminate the need for Earth-based repair solutions followed by resupply and repair missions to spacecraft. Lastly, since the feedstock is nonreactive, it is easy to transport, pack, and clear before flight.

Because the ConstantQ thruster design is so simple, it can be scaled easily to almost any size. It can be compacted to almost a two-dimensional (2-D) structure for use in space-limited applications, such as attitude adjusters on small satellites, or designed as a main power plant on an aircraft carrier. Conceivably, a fusion-enhanced thruster could be turned inward and placed on board

a submarine for use as an efficient reactor, allowing submersion for extended periods. Due to the nature of the fusion reaction, and the fact that the system can be suspended in a magnetic field, the particles that are generated could be passed over an electron trap to create a current that provides power to electrical devices, siphoning power directly from the fusion reactor. In addition to being used as a power plant, the fusion-enhanced thruster could be used as a fusion torch to break up incredibly tough regolith on asteroids or planetoids and extract volatile materials, such as oxygen and nitrogen, supporting deep-space colonization or deep-sea mining.

With the enhancement of fusion to a plasma thruster, space transit times can also be drastically reduced. Conceivably, with a sufficiently large power plant, a Mars Transportation Orbiter could travel from the Earth to Mars in 10 days or fewer, where most of that time would be spent on acceleration and deceleration. If the craft were automated, the reactor optimized, and significant solutions to inertia implemented, a Mars cyler could leave earth and reach Mars in a few days. In short, other than general

The ConstantQ thruster design lends itself to advanced manufacturing techniques, such as additive manufacturing for easy prototyping of complex geometries, if needed, and repair.

relativity and size constraints, there is potentially no limit to the speed and distance of the spacecraft with this fusion-enhanced thruster.

## CONCLUSION

Electrical propulsion has certainly gained a lot of momentum since its conception nearly 100 years ago. Unlike chemical propulsion, which may have reached its practical energetic limit, electrical propulsion may continue to enjoy advances in increased performance, lower cost, smaller size, longer working life, improved safety, and reduced energy demands (and perhaps with no end in sight just yet). Accordingly, the upcoming century should prove interesting and fruitful as electrical propulsion continues to aid and expand the possibilities of future space travel. ■

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## BIOGRAPHIES

**ALBERT DEFUSCO** is currently a senior scientist at the SURVICE Engineering Company and a DSIAC subject-matter expert in energetic materials. He recently retired from Orbital ATK, where he spent 30 years in various capacities, including propellant and warhead formulating and energetic material synthesis. He also held various management positions in Orbital ATK's Program Office and Engineering departments. He started his career as a National Research Council post-doctoral fellow at the Naval Weapons Center (NWC) in China Lake, CA, and also worked in NWC's Polymer Science Branch of the Research Department. Dr. DeFusco has a Ph.D. in organic chemistry from the University of Vermont and a B.S. in chemistry from the Worcester Polytechnic Institute.

**CHRISTOPHER CRADDOCK** is the founder and CEO of Rocketstar LLC, a launch service provider dedicated to launching small satellites into low Earth orbit and beyond. Previously, he founded CC Trading Company, a registered commodities broker, which he headed for 10 years; and he has more than 16 years of Wall Street experience, from selling stocks and bonds at Salomon Smith Barney to trading futures and debt obligations at private wealth firms. Mr. Craddock has a B.S. in physics from the State University of New York at Stony Brook.

**WESLEY FALER** is the founder and CEO of Miles Space Inc., bringing to market the ConstantQ thruster, satellite designs, radio aperture arrays, and other technologies. Previously, Mr. Faler founded Fluid & Reason LLC, where he invented the ConstantQ thruster over a 15-year period of investigating plasma propulsion. He is also a founder of Team Miles and is a three-time NASA-award-winning CubeQuest Challenge competitor. Mr. Faler has a B.S. in manufacturing systems engineering from Kettering University, with emphasis on automation and artificial intelligence.

## APPLY TO BECOME A DSIAC SME

DSIAC's Subject-Matter Expert (SME) Network is one of the most valuable resources to the user community. SMEs provide a wealth of knowledge and information through a variety of means. For example, SMEs are prime contributors to journal articles and webinar presentations. In addition, they are routinely used to respond to technical inquiries, assist with State-of-the-Art Reports (SOARs), and perform research and analysis to support Core Analysis Tasks (CATs). To join DSIAC's SME Network, please email us at [contact@dsiac.org](mailto:contact@dsiac.org). A DSIAC administrator will then contact you with further instructions on how to become an SME and how to complete the online survey.

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  - **Work Experience** (years in the field, positions held, past programs, etc.)
  - **Publications** (refereed and nonrefereed reports, journal articles, conference papers, etc.).

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- Authoring/reviewing journal articles
- Responding to technical inquiries
- Presenting webinars
- Authoring State-of-the-Art Reports (SOARs) and Critical Review/Technology Assessments (CR/TAs)
- Performing research/analysis to support CATs



Figure 1: A Casualty of an IED  
(Photo Courtesy of Defense.gov).

# The JLTV Applies Lessons Learned in UNDERBODY BLAST PROTECTION

By Brian Benesch

## INTRODUCTION

**T**he prolific use of the improvised explosive device (IED) in recent years by enemy combatants has forced U.S. combat vehicle designers, testers, and analysts to focus on protecting military vehicles and their occupants as never before. The IED threat, assembled from readily available ingredients, is relatively cheap to construct and employ. It thus poses a significant threat to troop mobility and military personnel safety.

Consider the violent chain of reaction resulting from an IED detonated when driven over by a military vehicle (such as shown in Figure 1). The explosion produces a supersonic pressure wave that propagates through the soil, sending a combination of high-velocity dirt, rock, and air smashing into the truck's underbody. The vehicle's mobility is often an assumed casualty of this event. Shock waves quickly ripple through the vehicle before military personnel inside are even able to react.

The ultimate effect on these personnel, of course, is dependent on numerous factors, including the size of the

explosion and the design of the truck. However, the range of possible personnel injuries can vary from complete protection (i.e., no injury) all the way to severe injury and loss of life for some or all of the occupants. While it is true that not even the best military vehicle on today's market can protect occupants against large, overwhelming explosions, it is equally true that the way a vehicle is designed to protect against such attacks can literally save lives.

This article briefly describes the recent history and theory of protecting occupants within armored ground vehicles against underbody blast (UBB)



Figure 2: The JLTV (Oshkosh, CC BY-SA 4.0 via Wikimedia Commons).

attacks while using the upcoming Joint Light Tactical Vehicle (JLTV) (such as the one pictured in Figure 2) as a case study of a recent application of a truck designed to offer both high mobility and high occupant protection from UBB.

## THE RISE OF THE MRAP

UBB attacks quickly became a significant problem to U.S. troops entering Iraq and Afghanistan in the early 2000s [1, 2]. Enemies fashioned IEDs using homemade materials, allowing the explosives to be large in size and widespread in usage. The traditional High-Mobility Multipurpose Wheeled Vehicle (HMMWV)—commonly referred to as the Humvee—that was used for ground transport was clearly not suited to protect against these sorts of attacks [3]. Thus, the U.S. military rapidly issued the production and delivery of new Mine Resistant Ambush

The military identified the need for a vehicle that affords the protection level of an MRAP but with the mobility of the HMMWV. Enter the JLTV.

Protected (MRAP) trucks (such as those shown in Figure 3). These trucks quickly proved to be highly successful in providing the much-needed UBB protection [4].

Key features that have led to the success of the MRAPs include their high ground clearance, V-hull design, strong crew capsule, and energy-attenuating

seats and floors. However, MRAPs weigh in at approximately 30,000 lbs, and thus they are less agile than 8,000-lb HMMWVs. So the military identified the need for a vehicle that affords the protection level of an MRAP but with the mobility of the HMMWV. Enter the JLTV.

## THE GENESIS OF THE JLTV

The JLTV program was officially approved in November 2006, and a request for proposals (RFP) was put out to vehicle developers in 2008 [5]. Numerous developers competed for the work, but eventually the Oshkosh Corporation was awarded the contract in 2015 to design and fabricate JLTVs for the U.S. military [6].

Oshkosh's JLTV will soon undergo official live fire test and evaluation. The testing will, in part, consist of a buried explosive being detonated beneath the vehicle. Inside the JLTV will be



Figure 3: The MRAP Solution for the UBB Problem (U.S. Navy Petty Officer 2nd Class Molly Burgess).

the approximately 2- to 3-ft ground clearance for MRAPs. By contrast, the HMMWV has a clearance of only about 14 inches from the ground to the bottom of its hull.

MRAPs have also benefitted in standoff by way of their noteworthy V-shaped hull. The ground clearance is, of course, lowest for UBB detonations beneath the center of the V-hull, but for off-center detonations, the effective ground clearance increases as a function of the angle of the V-hull. Although the specific hull shape of the Oshkosh JLTV cannot be discussed at this point, it is expected to incorporate the same sort of benefits as the MRAP's V-hull (even if it does not perfectly replicate it).

anthropomorphic test devices (ATDs) (like those shown in Figure 4), which are designed to measure responses that a human occupant would sustain. The JLTV will be evaluated by how it protects occupants (or, in this case, ATDs) against UBB in these tests.

Due to the sensitive and proprietary nature of the JLTV's specific designs, a detailed dissection of its underbody protection cannot be provided here; however, the following sections highlight the top-level characteristics of the JLTV and describe the general means by which these characteristics protect occupants against UBB.

### HIGH GROUND CLEARANCE

In terms of UBB protection, air is a cheap and potent help. As illustrated in Figure 5, the distance between the source of an explosion and the truck is critical, as pressure decreases rapidly as a function of distance [7]. So every inch that can be afforded to increase the distance of a truck's underbody from a buried explosive yields a major protection benefit.

The JLTV features large tires and a suspension that gives its hull a high ground clearance, comparable to

### STRONG CREW CAPSULES

In addition to offering increased ground clearance for off-center detonations, the V-hull design used in MRAPs also provides occupant protection from UBB due to the V-hull's structural rigidity. Just as pitched roofs on houses provide more support against collapse than flat roofs, so the V-shape strengthens the truck's hull better than flat-bottom hulls. The loading to the V-hull from the



Figure 4: ATDs in a Vehicle to Simulate/Measure Human Occupant Responses (University of Virginia, National Highway Traffic Safety Administration).

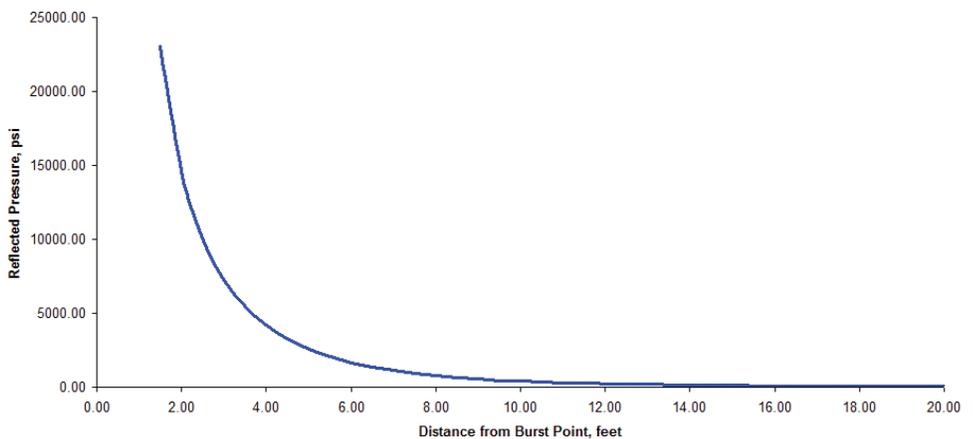


Figure 5: Reflected Pressure vs. Distance From Burst Point for 20 lbs of TNT.

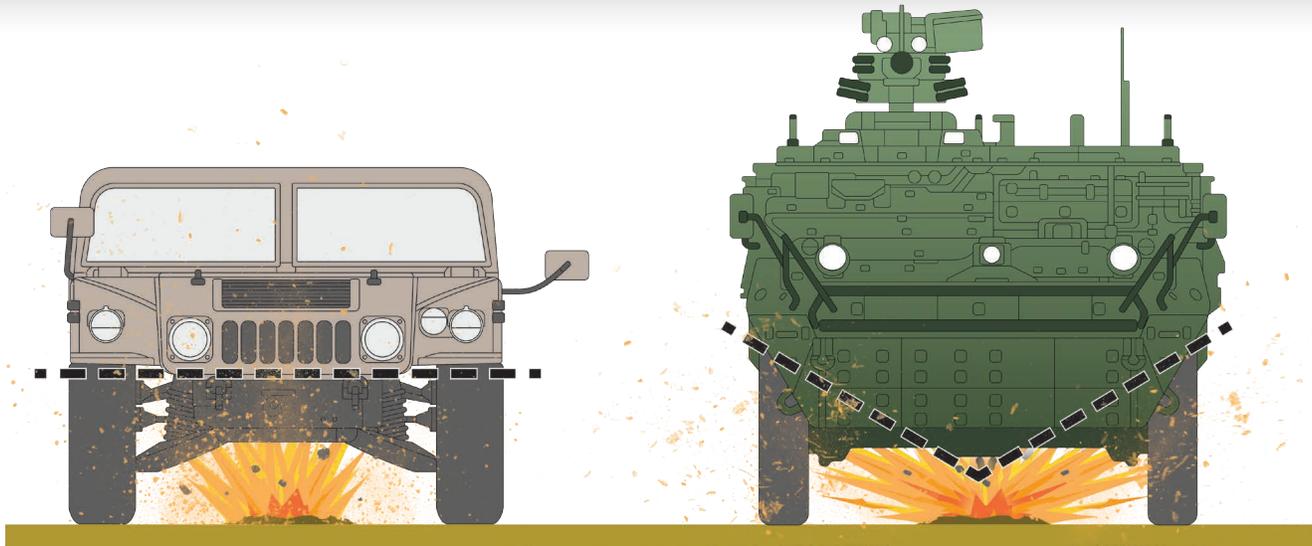


Figure 6: Notional illustration of loading on a Flat Structure vs. a V-Hull.

UBB is distributed to the vehicle side walls, whereas on a flat-bottom vehicle, the loading primarily forces the flat hull to bend, inducing seam failure or hull rupture (see Figure 6).

A common myth about the V-hull is that its main beneficial effects for UBB protection are in deflecting the blast. In reality, however, the blast's pressure wave is imparted to the vehicle hull regardless of its shape. The primary benefits of the V-hull shape come from the previously mentioned increased ground clearance and increased structural rigidity that the V-hull offers.

Nonetheless, the hull is typically the truck's first component to be impacted by the fast-moving pressure wave. Thus, it must be strong enough to resist deformation or rupture. The hull of a basic HMMWV is relatively thin and prone to rupture even against a small charge, while the MRAPs and JLTV have much thicker, stronger hulls.

It is also important to ensure that the rest of the crew capsule is robust enough to handle the loading being sustained by the hull. This requirement

A common myth about the V-hull is that its main beneficial effects for UBB protection are in deflecting the blast.

means that the side walls and roof must be securely attached. Attachment methods may consist of bolted or welded connections; some MRAPs even use a seamless monocoque hull. For the JLTV, Oshkosh primarily uses thick bolts to hold the crew capsule together.

Another key principle in this regard can be related to a popular school physics experiment, wherein students are tasked to design a capsule to protect an enclosed egg from a high drop. Good egg-drop designs follow the simple principle of having a strong outer layer and then soft inside components to absorb the shock. Similarly, a good truck design should have both a strong outer shell and absorbent components

inside (as discussed further in following sections) to protect the occupants. And the JLTV design has just that.

## ENERGY-ABSORBING FLOORS AND BLAST MATS

Given a sufficiently resilient crew capsule, the occupants inside are then protected by mitigating the shock wave from producing severe loads to the floor that the occupants' feet are placed on and to the seats in which the occupants are seated.

The foot/lower-leg is the main impact point to an occupant in UBB attacks (see Figure 7), and elevated loads to the floor can induce serious injuries to the foot and lower leg. To protect against these injuries, the forces passed to the floor and then the occupants' feet must be mitigated. Methods to disconnect or "float" a floor from the rest of the crew capsule or hull have been effectively used in MRAPs [8]. Additionally, it is helpful to move the point where the floor is connected to the crew capsule as far upward and away from the source of the UBB as possible.



Figure 7: The Highly Vulnerable Leg in UBB Events (Photo Courtesy of the U.S. Army and Diversified Technical Systems Inc.).

Ultimately, the key to good floor designs is in breaking up the load path so there is not a direct means of transmitting the full shock wave encountered by the hull to the walking floor. By contrast, the floor that occupants place their feet on in HMMWVs is the same as, or directly attached to, the hull exposed to the UBB. The JLTV's particular methods of mitigating forces to the floor are proprietary, but it is reasonable to assume that designers have learned from MRAP design and testing the importance of ensuring that the floor receives as little of the shock wave as possible to protect the occupants' lower legs.

Blast mats have also proven themselves to be an easy and effective add-on to further reduce forces to the occupants' feet and lower legs. These mats, which are simply placed on the floor between the occupants' feet and the walking floor, are designed to further absorb the injurious loading that makes its way to the walking floor. The mats function by compressing under high loading. To this

end, the thickness of the mat is a key characteristic of its utility. The amount and rate of compression is dictated by the mat's internal structure. For example, SKYDEX mats, which have been included in thousands of MRAPs [9], absorb energy via compression of their hemispherical cells [10] (see Figure 8). Once again, the specific mat used in the JLTV is proprietary, but it is expected to feature a specially designed blast mat



Figure 8: Energy-Absorbing Blast Mats (Photo Courtesy of Viconic Defense).

that further protects occupants from injurious loading to the feet and lower legs.

An alternative and highly effective method of protecting lower legs is to keep feet off the floor completely, such as via a foot rest. Some methods of incorporating foot rests integrate them into seats [11, 12] (see Figure 9). However, foot rests built into seats have been found to create a ride comfort issue, forcing occupants to tuck their feet up onto their foot rests or outstretch them onto foot rests on opposing occupants' seats. In both cases, the posture can be difficult to endure for long trips. In addition, even with foot rests, attention must first be paid to designing a quality floor for the inevitable cases in which foot rests may not always be used and feet are placed on the floor during an UBB attack.

## ENERGY-ABSORBING SEATS

In addition to the floor, the other main point of contact between a seated occupant and the vehicle is the seat itself. The primary principle to protect occupants from forces to the floor also applies to the seat: mitigate the shock wave running through the crew capsule



Figure 9: Protective Measures for Occupant Legs in UBB Events.

using energy-attenuating devices in the load path to the occupant. This mitigation can often be accomplished by mounting the seats to the side walls or roof, as far from the UBB as possible.

Furthermore, whether floor- or wall-mounted, seats are generally designed as standalone systems with their own energy absorption mechanisms. Like blast mats, energy-absorbing seats (such as those shown in Figure 10) generally function by compression of some component. Examples of components designed in seats to absorb energy include a crushable link built into the frame, a wire or rope holding the seat designed to stretch, and a flared tube designed to narrow by the stroke of a movable collar.

Additionally, the aid of a compressible seat cushion should never be overlooked, as a thick foam can dissipate much energy before that

The aid of a compressible seat cushion should never be overlooked, as a thick foam can dissipate much energy before that energy reaches an occupant.

energy reaches an occupant. Finally, more exotic energy absorption methods, such as using magnetorheological fluid (a fluid that can provide dynamic damping as a function of a magnetic field applied onto it) for seat protection measures, have also been the topic of some research [13, 14, 15, 16].

HMMWV seats were not designed with blast attenuation in mind, and so they typically consist of generic automotive seats mounted to the floor. The JLTV, however, is expected to incorporate seating systems specially designed to absorb shock loads from UBB.

## MULTI-POINT SEAT RESTRAINTS

Seating restraints are also an important element to occupant protection from UBB. The primary shock loading from a UBB will often induce gross motion of the vehicle and occupants such that, without seating restraints, occupants may be tossed around the vehicle and thus be susceptible to head or limb injuries from impacting the surrounding structure. Seat restraints do not need to have a special blast-attenuating design; they serve the occupant best by simply keeping the occupant in the seat while a vehicle is launched into free flight from a UBB. That said, most seats in military trucks such as MRAPs, HMMWVs, and (likely) the JLTV, use four- or five-point seat harnesses to more securely restrain occupants than typical automotive seat belts/restraints.

## ACTIVE PROTECTION SYSTEMS

As discussed previously, a UBB rapidly imparts an initial force/velocity to a vehicle, often sending it up into the air and then back to the ground. The velocity of the vehicle when it returns to the ground is, of course, controlled by the rate of gravity and thus is a function of the max jump height. Accordingly, active countermeasure systems (such as shown in Figure 11) have been proposed to reduce the vehicle's max jump height and its return-to-ground velocity to soften the impact and protect occupants from sustaining additional

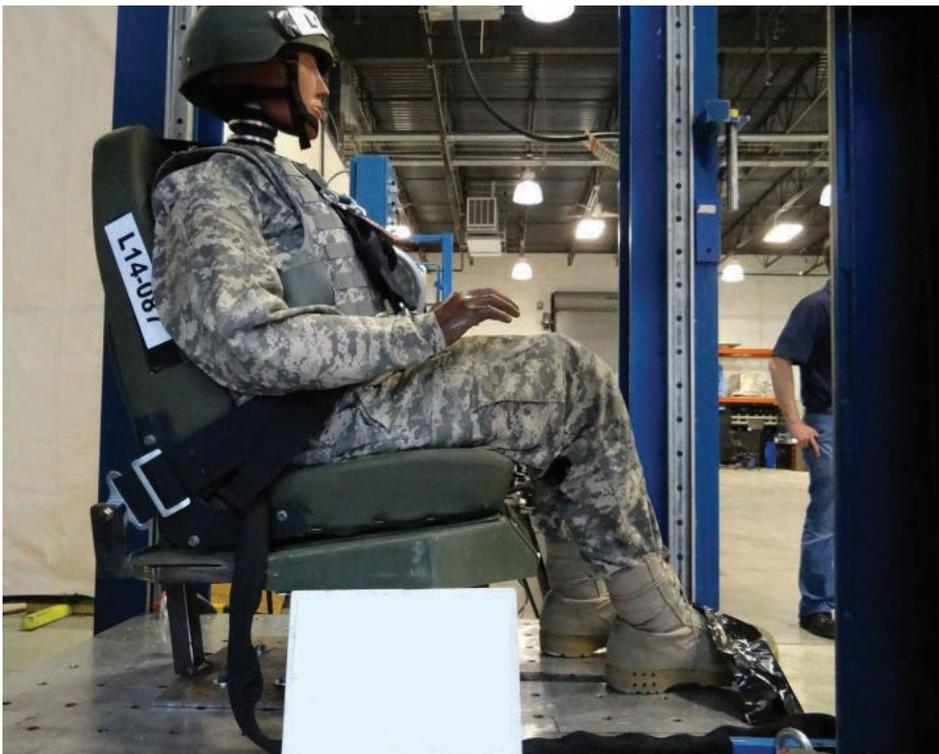


Figure 10: Current Blast-Attenuating Seats (Photo Courtesy of Viconic Defense).

injuries (beyond what may have already been incurred during the initial launch of the vehicle). The systems reportedly can sense and rapidly activate externally mounted thrusters to limit the max motion and control the rotation to prevent rollover [17]. Unfortunately, although these systems may prove to limit rigid-body response, the act of “pushing back” against the UBB may actually increase localized loading to the vehicle. Thus, before these active countermeasure systems are fielded, ongoing research and development will need to test and analyze the positive-negative tradeoffs that come with them. Currently, there is no reason to expect the JLTV to don such active countermeasure systems, but they remain a promising technology that is being researched for future concepts.

## CONCLUSION

The U.S. military has learned much about protecting occupants from injuries against UBB. The combat-tested MRAPs have proven that ground vehicles with a high ground clearance, strong crew capsule, and energy-absorbing mechanisms (such as floors, mats, and seats) can successfully save lives against UBB. The JLTV is expected to take all of these survivability-enhancing characteristics and apply them to a faster, more agile vehicle. As a result, U.S. troops are expected to be both better protected and more mobile as they complete their missions. ■

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Figure 11: An Active Protection System (Photo Courtesy of ©TenCate Advanced Armor).

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## BIOGRAPHY

**BRIAN BENESCH** is currently an employee of the SURVICE Engineering Company and the Technical Project Lead with DSIAC, where he assists in all aspects of the technical and managerial oversight of the center. Prior to this position, he spent more than 8 years supporting various teams and efforts at the U.S. Army Research Laboratory. There, he gained significant experience assessing live-fire UBB tests, innovating accelerometer data reduction and analysis methods, and developing survivability and injury analyses used to expand and enhance the Army's UBB modeling methodology. Mr. Benesch holds a B.S. in engineering science from Loyola University of Maryland as well as an M.S. in engineering of energetic concepts from the University of Maryland.

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Fredericksburg, VA

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Hurlburt Field and Eglin AFB  
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8-11 May 2017  
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<http://www.xponential.org/xponential2017/public/Enter.aspx> ▶

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9-11 May 2017  
Fort Worth Convention Center  
Fort Worth, TX

<https://vtol.org/annual-forum/forum-73> ▶

#### 60<sup>th</sup> Annual NDIA Fuze Conference

9-11 May 2017  
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<http://www.ndia.org/events/2017/5/9/fuze> ▶

#### OpenWERX Hackathon

12-13 May 2017  
SOFWERX,  
Tampa FL  
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#### 2017 Tactical Wheeled Vehicles Conference

15-17 May 2017  
Hyatt Regency Reston  
Reston, VA  
<http://www.ndia.org/events/2017/5/15/tactical-wheeled-vehicles-conference> ▶

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15-19 May 2017  
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<http://www.crows.org/event/192-aoc-conferences/2017/05/15/79-fms-2017.html#Agenda> ▶

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1 June 2017  
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10-12 July 2017  
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Surburban Collection Showplace  
Novi, MI

<https://www.army.mil/tardec> ▶

#### 2017 Strike Challenge - Domestic Capabilities and Specialized Response Equipment Demonstration

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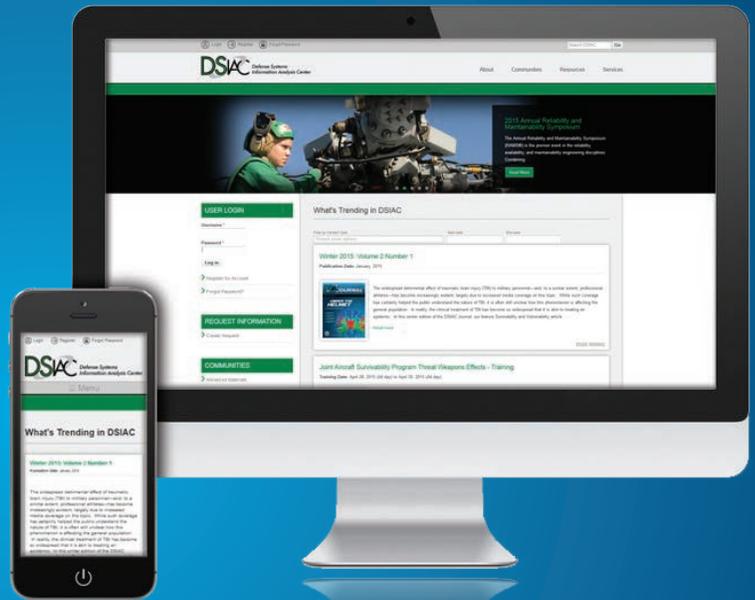
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