NAVAL SCIENCE AND TECHNOLOGY

FUTURE FORCE™

VOL. 9, NO. 1, 2023

GROWING ENERGY RESILIENCE

LET'S GET SMART ABOUT LITHIUM-ION BATTERIES

PLANNING FOR A 500-SHIP FLEET

VOLUME 9
#01
2023

FUTURE FORCE

NAVAL SCIENCE AND TECHNOLOGY MAGAZINE




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Future Force is a professional magazine of the naval science and technology community. Published quarterly by the Office of Naval Research, its purpose is to inform readers about basic and applied research and advanced technology development efforts funded by the Department of the Navy. The mission of this publication is to enhance awareness of the decisive naval capabilities that are being discovered, developed, and demonstrated by scientists and engineers for the Navy, Marine Corps, and nation.

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Front Cover: Illustration by Jeff Wright.

SPEAKING OF S&T

By Rear Adm. Lorin C. Selby, USN

Photo by MC2 Nadia Lund

Welcome to a new edition of the Navy's premiere science and technology magazine, *Future Force.* Across the Naval Research Enterprise (NRE)—comprised of the Office of Naval Research, the Naval Research Lab, the Office of Naval Research Global, NavalX, and PMR-51—we are charged with looking into the future and creating capabilities for our Sailors and Marines to continue to be the dominant naval force in the world, able to deter adversaries from aggressive actions, and if required, winning the fight and coming home safe.

A key to that continued dominance is advancing our unmanned systems—in agility, in mission capabilities, and in quantity and scale. There is a very real and decisive shift in today's Navy and Marine Corps toward smaller, more agile, more numerous—and mostly unmanned—systems. Fortunately, the NRE has been a leader in this research for decades, and our emphasis today on what we call "the Small, the Agile and the Many" unmanned systems to provide a complement to our larger manned platforms, is critical. The NRE is leading the way in new capabilities for swarming drones, long-endurance air, surface and subsurface unmanned systems, and more. The sometimes hard but always rewarding work of S&T will provide our fleet and force the tools they need for the future fight.

A primary challenge to all of these systems, as with manned systems, has always been power and energy. How do we ensure our systems have the endurance to execute their missions, especially when they may be hundreds or thousands of miles from any ability to be refueled or recharged? We're seeing similar challenges in modern society today as electric vehicles advance, but power and energy are forever of vital interest to modern militaries. *Future Force* first featured these topics in its Summer 2015 issue; eight years later, we return with new focus and insightful articles on the same themes. The current edition you are reading focuses primarily on the science and technology of batteries and mobile power. Whether it's power for the latest unmanned undersea vehicle or an ocean-going vessel such as Sea Hunter in a hybrid fleet, the needs of the sea services are very real. We need to ensure these systems can support the mission without interruption.

In the Office of Naval Research, we are working on these problems across the command, including in our Sea Warfare and Weapons Department. Around the world, ONR Global is partnering with brilliant researchers and leading institutions to solve different power and energy challenges. Amazing work is advancing at the Naval Research Laboratory. Our partners across the Naval Research and Development Establishment are likewise supporting outstanding programs across the system commands and warfare centers on these critical topics. It is an all-hands-on-deck effort as we move into the future.

This issue of *Future Force* seeks to illuminate some of the power and energy projects under way that are making possible this larger shift into the manned-unmanned hybrid Future Force.

Rear Adm. Selby is the Chief of Naval Research.

POWER AND ENERGY

Power and energy are forever of vital interest to modern militaries. Now more than ever, today's Navy and Marine Corps are moving toward smaller, more agile, more numerous—and mostly unmanned—systems. This issue of *Future Force* seeks to illuminate some of the power and energy projects, systems, and ideas under way that are making this shift possible.

GROWING ENERGY RESILIENCE THROUGH RESEARCH

By William Anderson, Arie Kaufman, Amir Rahmati, Yoonsang Kim, Sanket Goutam, Michael Gouzman, Yacov Shamash, Alex Shevchenko, Claran J. Marti, Nicolaos Maltas, Peng Zhang, Yifan Zhou, Benjamin Hsiao, Vyacheslav Solovyov, Juan Pablo Trelles, Fanglin Che, Hsi-Wu Wong, Alessandro Sabato, Christopher Niezrecki, Douglas Van Bossuyt, Dan Nussbaum, and H. Scott Coombe

GREEN AND RENEWABLE ENERGY SOURCES ARE JUST THE START OF RESILIENCY: SMART MANAGEMENT OF MICROGRIDS WILL HELP PROTECT NAVAL AND EXPEDITIONARY POWER SOURCES FROM ENEMIES BOTH NATURAL AND MAN-MADE.

Our naval forces are increasingly enabled by, and dependent on, energy availability. Interruptions to the supply of energy equate to interruptions to the mission. To maximize warfighting effectiveness, naval forces require that we always understand energy supply and have strategies to repair and reinstate energy supply quickly after disruptions.

The Department of Defense's definition for energy resilience is "the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements" (10 US Code §101).

There are typical interruptions to energy supply that are more commonly understood, such as component failures, weather-related issues, etc. There are also other categories that we must understand, anticipate, and respond to—these can be categorized as high-impact, low-probability events. These include cyber intrusions, deliberate attacks, and climate effects. Understanding how to achieve energy resilience is an ongoing challenge that is common across both the military and civilian sectors. There are challenges in both military and civilian power grids, microgrids, and stand-alone systems. Figure 1 provides a means of visually understanding the concept of energy resilience. Reduction of the area above the curve represents improved energy resilience. Essentially, we want to limit any performance degradation (y-axis) and limit the duration of the disruption (x-axis).

Because there are common aspects of energy resilience across military and commercial sectors, the Office of Naval Research's energy resilience applied research efforts employ a team approach that includes both commercial

Photo by UT2 Maruyama Austin

and military electrical grid partners, naval platform developers, industry, and academia. The team includes the Naval Facilities Command, Naval Surface Warfare Center Philadelphia Division, the Naval Postgraduate School, and the State University of New York Stony Brook and the University of Massachusetts at Lowell. The following is a description of a few examples of the ongoing projects.

Intelligent Microgrid Management

An intelligent microgrid monitoring system built at Stony Brook provides excellent situational awareness, the first step toward taking corrective action within the microgrid. Easily deployable self-configured sensors automatically generate a digital twin of the microgrid. This versatile monitoring system identifies the instantaneous topology of the grid when its structure spontaneously changes or if prior documentation of the grid is not available.

A novel single fiber bidirectional communication link using a single wavelength provides the radio silent communication infrastructure for the system. Since a regular single fiber link uses a different wavelength to carry data in each direction, the transmitter and receiver pairs must be matched. Therefore, two similar devices cannot be linked together without a switch/router. The system developed in this work allows for universal modular devices that can connect to each other and create a network of homogeneous devices. This facilitates installation of the system quickly and easily.

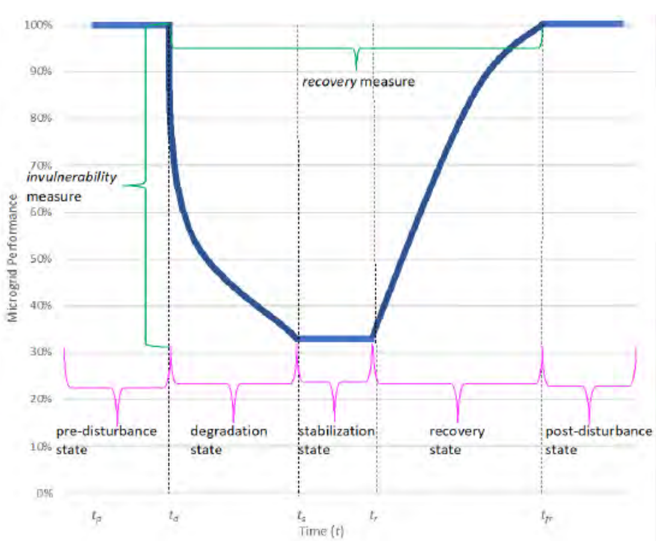
A self-healing network using smart switches provides extended stability for critical loads in the microgrid. The system automatically routes power from different distributed energy resources to the loads in the most efficient manner. Under extreme conditions, when power availability is less than demand, the critical loads are prioritized in the routing of the available power. The capacity of the power source, runtime, startup time, etc., is considered when choosing the sources to route power to critical loads. This ability to share power in the grid enables the critical loads to be powered for much longer periods of time than any local storage-based backup system. A laboratory-scale grid that demonstrates these novel technologies has been built to test the feasibility of real-world deployment.

Microgrid Fault Resistance and Cyber/Physical Security

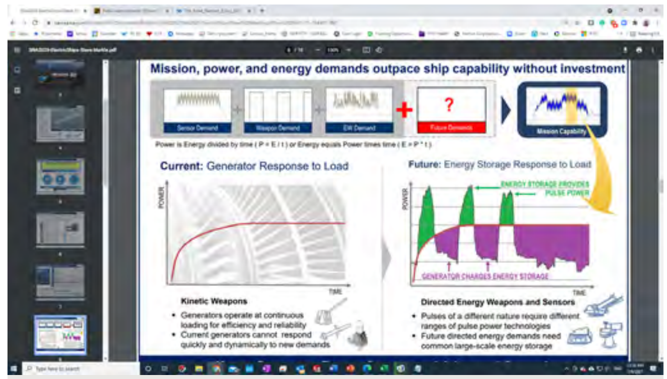
The Power Systems Lab at Stony Brook University is developing two critical solutions to ensure cyber and physical resilience in microgrids: a distributed and asynchronous active fault management (DA-AFM) technology and a deployable "three lines of defense" model.

DA-AFM is a powerful real-time tool that manages fault currents by controlling the power electronic interfaces (e.g., microgrid inverters) and eliminates those barriers against microgrid resilience and ultra-reliable operations of distributed energy resources/microgrids in Navy sites and systems. When faults occur because of an accident, Mother Nature, or hostile attack, DA-AFM aims to: maintain the total fault current unchanged to avoid detrimental impacts on the naval power grid, eliminate the damaging power ripples for inverters in distributed energy resources/microgrids, and ensure that the quality of the power flow of each individual microgrid after the fault is identical to its quality before the fault to avoid loss of loads and maintain microgrid stability. DA-AFM has been virtualized in a distributed computing platform, executed through microgrid inverters, and fully tested on Stony Brook's cyber-physical microgrid testbed where its resilience benefits have been validated.

The Power Systems Lab is delivering a deployable three lines of defense model that integrates the lab's unique techniques—programmable active security scanning (PASS) and crypto-control and software-defined microgrid controls (SDC)—to enable unprecedentedly self-protecting, cyber-resilient microgrids. The model will significantly boost microgrid resilience in that: PASS enables fast detection, localization, and mitigation of various cyberattacks and certain physical attacks; SDC provides ultra-fast recovery of controller functions upon attacks; and cryptocontrol prevents adversaries from intruding into microgrids. Together, these features will minimize the scope and timescale of adverse events and enable speedy recovery of microgrid operations.



The microgrid resilience curve.



The traditional (solid line) load curve of a grid and pulse load of a modern Navy microgrid.

Currently, the Power Systems Lab and partners plan to integrate DA-AFM and the three lines of defense model with advanced controls, high speed, and artificial intelligence into a programmable platform that can transform naval power infrastructures into autonomic microgrids capable of surviving cyberattacks, faults, and disasters. The demonstration will be performed in two stages. First, Stony Brook will integrate a functioning programmable microgrid platform through their newly established microgrid testbeds. Later, this programmable platform will be tested on Naval Facilities Command's microgrid testbed and, if possible, a real naval microgrid. Stony Brook will quantitatively examine how this platform improves cybersecurity, electricity resilience, stability, and reliability using both deterministic and randomized tests and validate how this platform can help achieve the Navy's resilience goals for zero-trust infrastructures. Our team will leverage the Navy's resilience metrics and follow the Department of Defense's Tactical Microgrid standard and Secure Tactical Advanced Mobile Power code while validating these technologies.

Stored Energy Integration for Microgrid Resilience

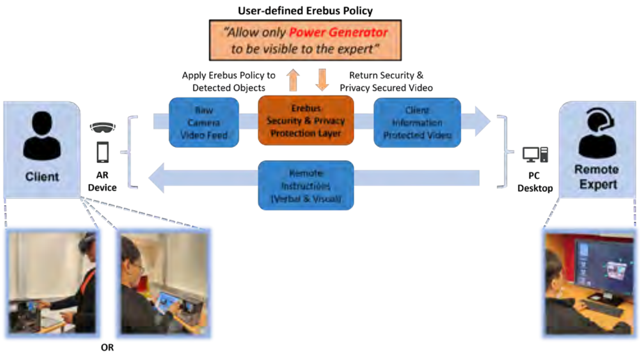
This project addresses the effective management of high-voltage supercapacitive energy storage to significantly improve resilience in high-voltage microgrids subjected to pulsed loads and disruptions, as part of the fully integrated power and energy systems we foresee in near-future Navy microgrids. Providing an instant high-power response to a voltage disturbance is critical for maintaining microgrid stability in either land-based or on-board microgrids.

Reliable high-power density supercapacitor storage can be tied directly into the microgrid through an inexpensive transformerless inverter, also working in tandem with longer-term battery storage. The Stony Brook team is working with two New York-based companies, IOXUS Inc. and Unique Electrical Systems, to develop and test the operation of kilovolt-class supercapacitor units in conjunction with lithium-ion battery storage in a testbed microgrid located at the New York State Advanced Energy Research and Technology Center of Excellence in Stony Brook's research and development park. The system features separate capacitor and battery units integrated through a high-speed broadband datalink.

The team has designed a 500-volt energy storage unit using six IOXUS 93V/83F modules, totaling 1.6 megajoules stored energy. The units are being integrated into an existing DC/AC test microgrid that is already supplied with Brenergy 480 lithium-ion battery storage units. The team is developing an energy dispatch algorithm that optimizes energy storage discharge based on the learned state of both lithium-ion and supercapacitor energy storage units.

Smart Microgrid Security

Through recent smart grid initiatives, the electrical grid has been transformed into a connected, distributed system, where many semiautonomous microgrids, including Navy bases and ships, produce their own power and share resources, load, and information to achieve better efficiency, reliability, and availability. Achieving the smart grid vision, however, brings about unique security and privacy challenges. Maintaining the correct functionality of an interconnected infrastructure requires trustworthy real-time distribution of information across the various players



The Erebus design concept. The on-site client is communicating with a remote expert using an augmented reality device to receive instructions for microgrid maintenance (in this case, a mock power generator).

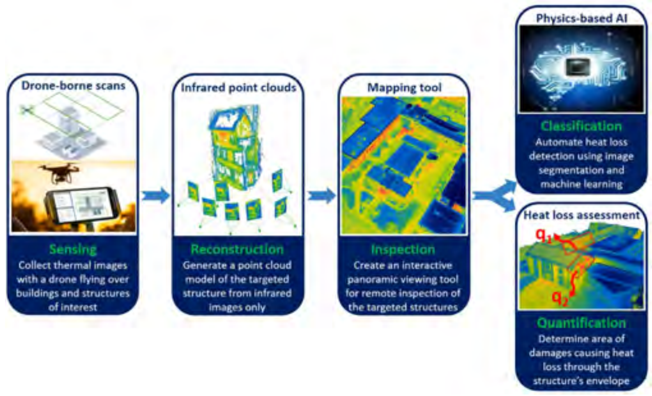
while preserving the security and privacy of information for entities at each level. In this research, Stony Brook has tackled the problems of access control and information leakage in microgrid environments, and they have focused on three challenges:

1. Identity management: The use of certificates and public key infrastructure for electrical cyber-physical systems
2. Allowing for remote shared maintenance: Selectively sharing information of the microgrid facility among on-site maintenance workers using augmented reality technology and remote experts through network communication
3. Side-channel information leakage: The use of side-channel aware power management in microgrids.

For identity management, Stony Brook has developed a public key infrastructure for the complex ecosystem of the microgrid that may include many heterogeneous sensors, generators, transformers, actuators, and the like. The new infrastructure is built on top of the existing infrastructure used for the web and provides a unique identity for each device. This identity is tied to the manufacturer of the device and can provide equivalent security guarantees for cyber-physical devices as for communications over the web. For remote shared maintenance, Stony Brook has implemented a framework called Erebus to prevent any security-sensitive visual information from being shared with unauthorized remote maintenance personnel. The client-defined Erebus policy is applied to the visual feeds acquired from the augmented reality device of the client. It can filter out all detected objects/information except the target objects/information that the client allows to be shared with the remote expert.

Erebus eradicates the potential security and privacy threats that may reside in the video feed of the client during the process of collaborative telecommunication while providing intact visuals of the target object to the remote expert. Furthermore, Erebus connects the remotely located maintenance expert to collaborate with the client on a maintenance task through video and audio network channels. This removes the need for an expert to be physically present at the site, enabling prompt, responsive, and secured maintenance. In addition, Stony Brook has developed a permission control framework for augmented reality applications. This provides the client fine-grained control over the permissions of augmented reality applications and heightens the safeguarding of clients' security and privacy sensitive information. For side-channel information leakage, a side-channel-aware power management system has been developed for microgrids. This system allows the microgrid infrastructure to reduce information leakage by selectively using stored energy (to flatten an energy spike) and storing generated energy (to create a spike) as needed.

This research provides a more reliable, resilient, efficient, and secured use of microgrids. Achieving trustworthy identity management across cyber-physical energy systems in a microgrid ensures the integrity and trustworthiness of the data and operations across these devices, increasing their reliability and resiliency against adversaries. Allowing remote shared maintenance enables microgrids to operate with increased efficiency and reliability while ensuring



Approach workflow to generate photorealistic models from droneborne infrared images to create 3D maps of targeted areas and detect defects causing heat loss. Graphic provided University of Massachusetts at Lowell

resilience against adversaries who wish to exfiltrate data. Preventing side-channel information leakage in microgrids also ensures the resiliency of the microgrid against attackers who wish to discern information about the operation of the unit based on its activities.

Tunable Plasma Catalytic Reactor

The on-demand production of ammonia as a carbon-free energy storage medium from nitrogen (from air) and hydrogen (water electrolysis) has potential for increasing the autonomy and resiliency of future naval operations in some scenarios. Plasma provides alternative energy channels to thermo-chemical activation that can lead to compact and rapid-response systems suitable for modular and scalable deployment. A tunable plasma catalytic-membrane reactor is being investigated by the University of Massachusetts at Lowell team for the synthesis of ammonia at atmospheric pressure and low-temperature conditions.

Assessment of Energy Infrastructure Systems

This University of Massachusetts at Lowell project uses drone-borne infrared scans combined with a point cloud technique to reconstruct photorealistic three-dimensional thermal models of buildings to identify heat loss, subsurface damages, and water infiltrations. The automated classification of defects causing heat loss also is implemented using customized convolutional neural network algorithms. This research develops a cost-effective monitoring tool for assessing energy loss on naval bases and platforms to reduce energy consumption and to facilitate periodic inspection of critical energy infrastructure to reduce their risk of failure.

At Naval Facilities Engineering Command, researchers are assessing a microgrid's climate resilience and corresponding costs by adapting resilience and cost models employed by the command's Engineering and Expeditionary Warfare Center. These models are being adapted by first creating an optimized renewable energy microgrid architecture and changing the objective function from minimizing lifecycle costs (or lifetime costs of energy for the demand) to minimizing carbon dioxide emissions.

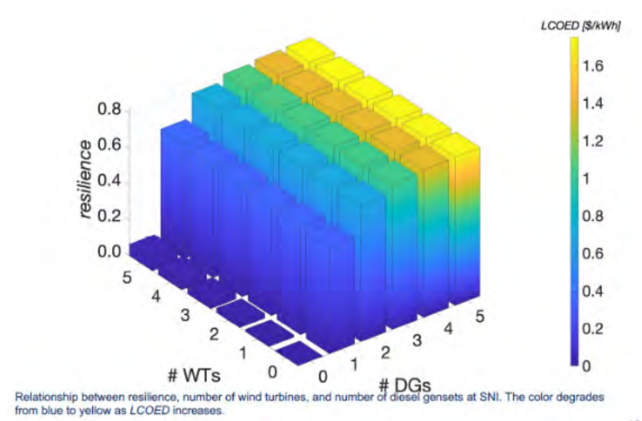
Variations on this optimized microgrid are then created by altering type, capacity, and number of distributed energy resources. Each of these architectures is subjected to a climate-driven extreme disturbance, such as wildfires, tsunamis, or hurricanes. The resilience score is then calculated by running the model through time steps until full recovery is attained.

Each of the data points (climate resilience, and costs) are plotted with as many as two distributed energy resources to create the climate resilience and costs trade space. This trade space is then used to enable more meaningful decisions on how much climate resilience is desired, for a corresponding cost. Once this decision is made, the corresponding microgrid architecture can be designed, installed, and operated.

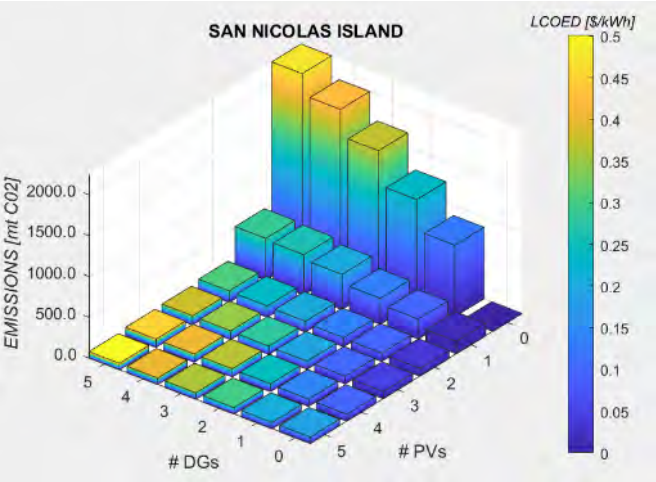
Finally, the two trade spaces ((below and opposite) can be compared to determine the optimal architecture that best meets both objectives. Ultimately, it is expected that a multiobjective optimization will generate this solution. The initial research into this was conducted by Jennifer Chavez and the University of Texas at El Paso.

Training and Education

It is important to educate naval officers, enlisted personnel, and civilians on energy resilience to ensure the fleet understands the relevancy of resilient energy and can rapidly implement resilience improvements. Energy resilience touches all parts of the Navy, from shore facilities and bases to operational activities and tactical activities. The



The relationship between resilience, number of wind turbines, and number of distributed energy resources (diesel generators). The color degrades from blue to yellow as lifetime costs of energy for the demand increases. Image provided Naval Facilities Engineering and Expeditionary Warfare Center



The relationship between climate (emissions), number of distributed energy resources (diesel generators), and amount of photovoltaics available. Again, the color degrades from blue to yellow as lifetime costs of energy for the demand increases. Image provided Naval Facilities Engineering and Expeditionary Warfare Center

complex relationship of energy systems with every aspect of naval operations demonstrates the need for multidomain education to address the challenge. The Navy has tasked the Naval Postgraduate School to lead efforts to develop educational curricula that address naval energy resilience across multiple domains.

The Naval Postgraduate School's Energy Academic Group has a purpose to educate warfighters on the critical importance of operational energy to the Navy-Marine Corps mission. This group's Curricula Development Team is making progress under the Naval Enterprise Energy Education and Training program, an effort sponsored by Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation and Director, Innovation, Technology Requirements, and Test and Evaluation (N94). Three graduate-level certificates have been created: directed energy logistics, refuel (contested) logistics, and unmanned systems persistence. All three certificates focus on energy resilience in contested environments. The unmanned systems persistence certificate will be Energy Academic Group's first offering and will commence in spring 2023 through asynchronous distance learning. All three certificates focus on energy resilience in contested environments.

The curricula development team is developing introductory courses in operational energy. The preliminary course, Operational Energy I, will be in-residence and is designed for forward-deployed Sailors and Marines. This course will address the four primary operational energy competencies of fuel, power development and distribution, energy storage, and energy management.

The Navy Shore Energy Technology Transition and Integration and Energy System Technology Evaluation program funded by the Office of Naval Research has supported a multidisciplinary team of faculty, students, engineers, and installation energy managers led by the Naval Postgraduate School in partnership with the University of Wisconsin Milwaukee, Naval Facilities Engineering and Expeditionary Warfare Center, Naval Station Rota, and Naval Air Station Sigonella to develop analysis tools that assess existing and proposed installation and operational microgrids for resilience. The tools span the systems engineering, electrical engineering, and power engineering domains to provide a more holistic interpretation of microgrid resilience, and they provide potential paths forward to improve resilience.

The energy resilience research and training activities described above are just a few of the ongoing initiatives. There are many other efforts in progress that aim to improve our collective understanding of how best to affect the energy resilience of systems, whether they be commercial power grids, naval installation grids, or ship microgrids. The multidisciplinary team assembled here is making contributions applicable to naval installation as well as operational energy resilience. As we move forward with this energy resilience work, the emphasis will lean more toward lab and field demonstrations of the emerging technology, training, and advancement of concepts in formal transition projects such as Office of Naval Research Technology Candidate projects, Future Naval Capabilities, and Innovative Naval Prototypes.

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Photo by Ens. James French

LET'S GET SMART ABOUT LITHIUM-ION BATTERIES

By Todd Hurley

TODAY'S VEHICLES AND SYSTEMS—AND THEIR BATTERIES—DEMAND A HIGH LEVEL OF ENGINEERING TO BRING EFFECTIVE, AND SAFE, CAPABILITY INTO THE FIELD FOR WARFIGHTERS.

The US Navy, as well as the entirety of the armed services, has long had prodigious energy needs; with the rise of critical new technologies, that demand for power and energy is growing exponentially. Lithium-I on batteries have become the enabling technology to address these power and energy demands to support surface, undersea, air, and ground requirements. Because of the inherent risks of lithium batteries—they can be both a fire and explosion hazard if handled improperly—containment strategies are critical to their successful deployment. Container solutions supply both a transportation and storage functionality, as well as provide risk reduction in the event of a battery casualty. For the last several years, Naval Surface Warfare Center Carderock Division has tested commercial- and government-designed container solutions and developed different container storage methods to reduce platform risk associated with the transportation of lithium-ion batteries.

"A safe means to transport, store, and charge lithium-ion batteries is critical for preventing catastrophic failure, and to enhance operational readiness for the warfighter," said Jessica Schwartz, a chemical engineer in Carderock's Battery Certification and Integration Branch.

While becoming increasingly more popular, battery containment methods are not a new concept. More than a decade ago, battery testing evaluated the heat and gas released from high energy dense lithium batteries intended to be transported on amphibious assault ships. These data were used in the development of the Lithium Battery Facility, which was designed with specially designed lockers and ventilation and fire suppression systems for the compartment. The work done in support of the facility's development has informed later container designs.

The MK-18 Mod 2 unmanned underwater vehicle MILVAN (a modified shipping container, similar to the one above) is the Navy's first large container system, designed by the Army's Prototype Integration Facility. It weighs 13,000 pounds and has a dual purpose as a mitigation containment unit and general workspace. It holds two MK-18s, sitting on top of two workbenches. It has been deployed since 2013 with no issues reported. The MILVAN was designed with a fire detection and actuation system with dual-trigger smoke and heat detectors, gas extraction systems, and water suppression, including fire suppression and ventilation.

The Prototype Integration Facility also designed the Knifefish Support Container, which holds 42 Knifefish unmanned underwater vehicle batteries inside 42 lockers and is an environmentally controlled workspace for charging and discharging. The container also is equipped with dual-trigger smoke and heat detectors, gas extraction systems, and water suppression. Testing demonstrated that a battery casualty could be contained to a single locker.

Currently, Carderock Division has evaluated more than 10 government designed container options and three commercial options. The division's Battery Certification and Integration Branch has designed two container solutions. One is the Charging-capable Lithium-ion Autonomous Safe Storage Interservice Container (CLASSIC).

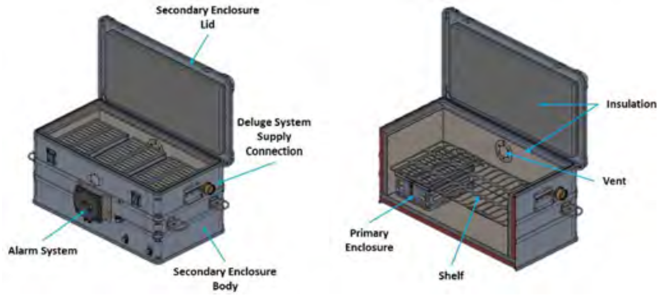
A large part in Carderock's container approach was not getting too complicated with the design, but instead focusing more on predicting when a battery will fail.

The CLASSIC is a 2,000-pound container that was created in response to an Army request to transport aggregated small lithium-ion battery safely by air. CLASSIC incorporates the Army's Universal Battery Charger, sensors capable of detecting a battery casualty, active fire mitigation agent, and passive mitigation measures to prevent propagation of failure to other batteries stored within. Dr. Thomas Hays, a materials scientist in Carderock's Expeditionary and Developmental Power and Energy Branch, led a battery burn demonstration using the CLASSIC at the Aberdeen Proving Ground in Maryland in November 2021, which showed the severity of a potential fire when batteries are not stored properly.

"In addition to being good at containing fire, the CLASSIC is robust, so it can help protect the batteries from damage," said Hays. "The CLASSIC is good at what it does, but it is very large, so we also need some of these other containers for certain situations. The overall hope is for decision makers to see our product and decide to fund or support us in the technology transition process. Some funding agencies are more aimed towards getting products that have proven to work, so it is nice that we have been able to move into that territory with the CLASSIC."

Another container method is the Vehicle-Transportable Aggregate Storage Container (VTAS), which is identical in mechanical architecture to the CLASSIC, with the only differences being the types of batteries that are serviced: VTAS is designed for Lithium 6Ts—the rechargeable Li-ion battery replacement of lead-acid batteries in military ground vehicleand the onboarding charging configuration.

Naval Surface Warfare Center Carderock Division's Charging-capable Li-ion Autonomous Safe Storage Interservice Container (CLASSIC) before being testing during a battery burn demonstration at the Aberdeen Proving Ground in Maryland. Photo by Thomas Hays



The Coacting High Integrity Material Energetic Release Attenuation (CHIMERA) system, with a side-by-side view to demonstrate the system's interior design, with two rows of three, one on top of the other. The CHIMERA system is designed with six primary compartments for battery storage, which are placed in a secondary enclosure container that is lined with the proprietary insulating and abrasion-resistance material. Graphic by Jessica Schwartz

Both containers were designed specifically for shipboard or shore use, but are not suitable for submarine deployment. One such container that has been designed, but not tested, by the Navy is the Coacting High Integrity Material Energetic Release Attenuation (CHIMERA) system, which was designed with six compartments for battery storage.

"The CHIMERA is a container within a container; the primary enclosures are placed in a secondary enclosure container," said Schwartz. "It is small enough to be hand carried, and the company has demonstrated through limited testing some propagation resistance between the battery storage compartments. Our review of the company's testing and evaluation proved that it could be a viable option for submarines."

Currently, Carderock is starting a new project, the Department of Navy (DoN) Family of Containers.

"This is a multiphase effort that intends to develop a common standardized DoN Family of Containers systems that could be utilized at forward operating bases and aboard ships, submarines, or military aircraft," said Schwartz. "This will reduce the reoccurring engineering costs and get critical system to the fleet faster and bring commonality to containers."

This effort will look to address container strategies in a modular way to introduce a common set of solutions. The intention of the container design is to cover a large range of lithium batteries and capabilities. While this will not be the final lithium battery container effort in the Navy, it will provide a suite of solutions for program offices to leverage, without having to invest more money in container development than is necessary.

About the author:

Todd Hurley is a writer with Naval Surface Warfare Center Carderock Division public affairs.

CRANE-PURDUE COLLABORATION MANAGES BATTERY TEST LAB

By Sarah K. Miller

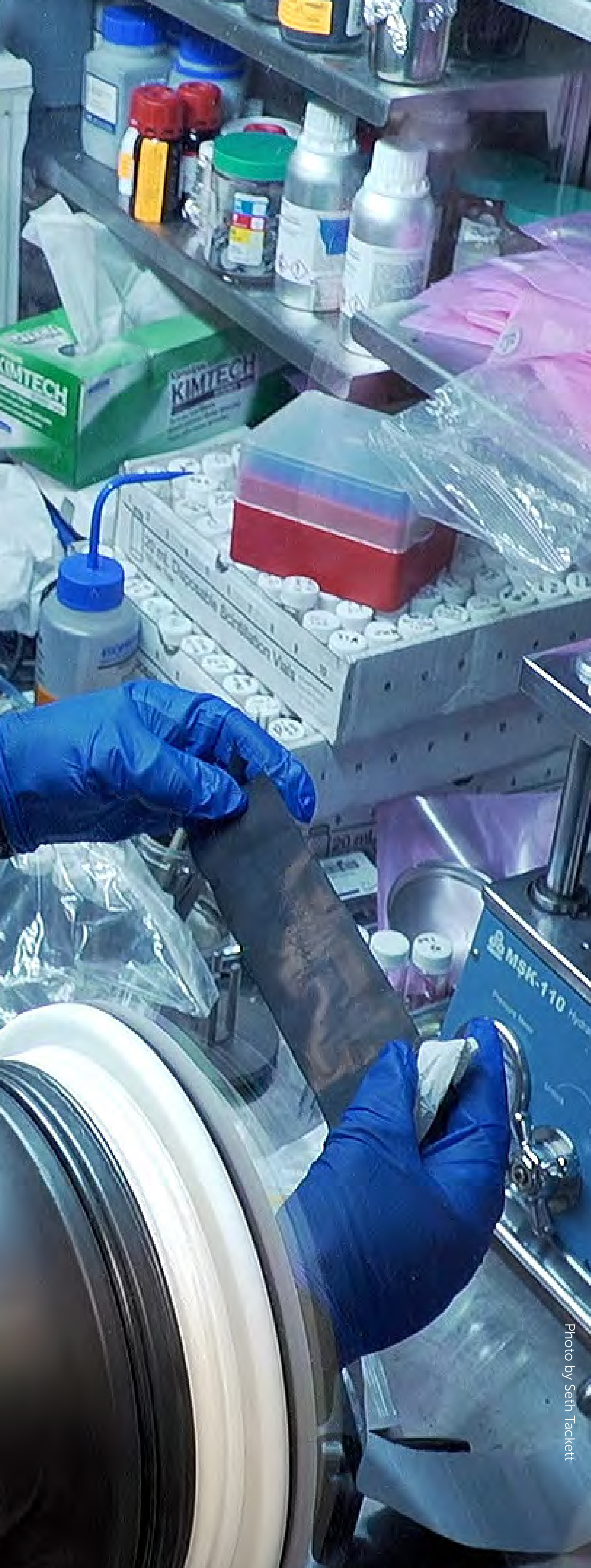


Photo by Seth Tackett

A COOPERATIVE ARRANGEMENT LED BY THE NAVAL SURFACE WARFARE CENTER CRANE DIVISION HAS CREATED A LABORATORY FOR RESEARCH AND TESTING RELATING TO LITHIUM-ION BATTERIES.

Naval Surface Warfare Center Crane Division continues its collaboration with Purdue University researchers to establish laboratory testing capability, enhance performance, and improve safety of lithium-ion batteries. Since a cooperative research and development agreement with Purdue was signed in 2018, the Navy and academic teams have launched a lab for testing, conducted unique research, developed modeling and simulation techniques, and published nine academic papers on their efforts.

Since 2017, Dr. Kyle Crompton, a chief engineer at Crane, has led this effort to build a lithium-ion experimental cell fabrication and testing lab and collaborated with Purdue for research. Crompton was a Department of Defense Science, Mathematics, and Research for Transformation (SMART) scholar who used internal Naval Innovative Science and Engineering funding for several years to form this capability.

"It has been exciting setting up the lab and establishing the relationship with Purdue," said Crompton. "We've had to take some risks, focus on the long-term vision, and pursue the science. The ultimate goal is to produce new knowledge and new information, where people can grab it and grow from it whether they are in the military, academia, or industry. Not only have we published research, but we have data sets that can be leveraged in a public repository."

Lithium-ion batteries power everyday technologies, from personal electronic devices such as cell phones and electric toothbrushes, to larger technologies such as electric vehicles, large power grid sources, and backup batteries for buildings and facilities. Lithium-ion batteries are popular mobile energy resources because of their lightweight, high-energy density, and rechargeability.

Crane Division has supported energy storage systems for more than 60 years. For instance, the Airborne and Space Energy Systems Branch, where Crompton was previously the manager, has capabilities such as system engineering and test and evaluation for aircraft, satellite, and spacecraft energy storage. This includes battery engineering for military systems such as fighter jets and missiles.

The Navy requires rigorous testing of these batteries before their use on the fleet's systems to ensure full functionality and safety. This rigorous testing process for high-powered lithium-ion batteries can be costly and hazardous.

"Lithium-ion batteries have higher energy density, can store more energy per mass of the battery with up to five times storage capability than legacy batteries—it's lighter and smaller which is a big advantage," said Crompton. "However, with more energy comes a safety challenge."

Thermal runaway, Crompton emphasized, is the main safety concern of lithium-ion batteries.

"It can happen when lithium-ion batteries are abused, and cause a rapid fire or explosion," said Crompton. "Mitigation of this safety concern is currently based on extensive testing and containment engineering. Our idea has been to develop and validate a model that can take the place of some testing and therefore, save time and cost. Through the [agreement] with Purdue, we've made substantial progress building a detailed 3D model that can simulate thermal runaway of lithium-ion batteries. This has been a lofty goal, with a lot more research and development still needed. In about 4 years' time though, we have made a lot of progress."

Purdue and NSWC Crane have complementary capabilities for this experimentation and simulation-based research.

"The collaboration has been mutually beneficial; Purdue has modeling and theory expertise and NSWC Crane has unique laboratory testing capability," said Crompton.

Dr. Jason Ostanek, an assistant professor at Purdue University and temporary faculty member at Crane, leads the collaborative research from Purdue's perspective. He works in the Applied Thermo-Fluids Laboratory with students on a wide variety of projects. Prior to his work at Purdue, Ostanek was an employee at Naval Surface Warfare Center Philadelphia Division for several years. He says individual battery cells, when operated within their specified parameters, are not likely to catch fire.

"The reputation of the lithium-ion battery is that they catch fire," said Ostanek. "In reality, the failure rate of individual cells is one in tens of millions. Batteries for Navy platforms, like ships, are much larger, consist of thousands of individual cells connected to one another. In these larger systems, the chances of failure increase, first because there are more points of failure, but second because it is more difficult to maintain every individual battery cell within its specified operating parameters. It is standard process that these large battery systems have to go through a certification process before they are fielded. Only after a battery passes this process can it be used in the fleet; that process is extremely costly, and is time consuming. For instance, if you were to certify a cell phone battery—testing would be quick, easy, and if the battery was destroyed in testing it's not a big deal. That's where this project comes into play."

Ostanek's team at Purdue is modeling the physics of battery failures.

"There's a lot of research and data available on single cell batteries that we can check our modeling against—but there's far less data available when you have multiple battery cells similar to what the Navy uses," said Ostanek. "There are many variables and it is much more complicated. The computer simulation needs a lot of inputs: battery geometry, dimensions, arrangement of different materials, and amount of heat the battery creates in a failure."

There are several challenges to this effort that provides valuable research output.

"Battery failures come with messy thermophysical processes that result in a lot of variability in the outcome of a failure—you could experiment ten times and get a spectrum of answers," said Ostanek. "It takes time to develop theory, models, interpret results, program and make it run quickly. We're modeling gas generation, venting, and combustion of those gases, which nobody has done before with battery modules. With these advances, we're closer to capturing the variability observed in experimental testing. If we continue to build capability, capture the key physical process, then our models will have greater predictive capability and may someday help supplement the certification process."

These research efforts feed into the knowledge base for lithium-ion battery performance and safety.

"Our basic and applied research can help get future batteries safely and reliably to DoD platforms safely," said Crompton. "It feeds into providing general capability, reliability, and improved workforce knowledge level. Going forward we want to continue developing the general modeling capability, but also are beginning to pull value from the models developed so far by using them to solve problems from narrower, more specific aspects of lithium-ion battery safety."

CRANE BUILDS NEW SUB BATTERY FACILITY

The team that supports the Submarine Battery Evaluation Center test facility at Naval Surface Warfare Center Crane Division. Photo by Victoria Baker

Naval Surface Warfare Center Crane Division held a ribbon cutting ceremony for a unique submarine testing facility for the U.S. Navy in July 2022. The Submarine Battery Evaluation Center (SUBBEC) test facility was built to better test and evaluate submarine batteries. The first test and evaluation of cells using SUBBEC is anticipated to take place in early 2023.

Crane has served as the in-service engineering agent for underwater vehicle batteries dating back to the 1980s and includes engineering support such as battery design, manufacturing, and testing. In 1996, the Submarine Main Storage Battery in-service engineering agent moved to Crane.

The Program Office for In-Service Submarines (PMS 392) supported the establishment of SUBBEC. Captain Garrett Burkholder, the program manager for PMS 392, says SUBBEC provides crucial capability to the fleet.

"Simply put, our nation's submarines cannot operate without a main storage battery that provides adequate, predictable performance," said Burkholder. "The work done by [Naval Surface Warfare Center] Crane as the battery [in-service engineering agent] is critically important to our ability to sustain submarine operations. Completion of the SUBBEC facility illustrates [Naval Sea Systems Command] ongoing commitment to operating world class laboratory facilities and represents a quantum leap in our submarine battery test facilities by providing a unique capability to operate a complete submarine main storage battery in a lab environment."

The Navy has a need for dependable power systems, which require testing and evaluation of batteries. SUBBEC will provide full-scale submarine battery and energy storage testing and modeling capabilities unique to the Navy. SUBBEC evaluates design or profile changes prior to implementation of profile changes to the fleet. SUBBEC testing will improve the Navy's ability to predict, control, and mitigate low-capacity batteries.

Bryan Parker, the submarine battery engineering manager at Crane supporting the battery technical warrant holder at Naval Sea Systems Command headquarters, said SUBBEC provides significant cost savings to the Navy.

"Before, testing required it to be manned, which is costly," said Parker. "With SUBBEC, we can test submarine batteries and operate the testing 24/7 without constant management. We can run years of testing without huge cost to the program."

Trent Frady, the supervisor for the Undersea Power and Energy Systems Branch at Crane, said SUBBEC provides technically rigorous battery testing.

"Not only can it be testing 24/7, 365, but also, the test facility provides the capability to test a full battery string," said Frady. "Usually, testing facilities test six to twelve battery cells, but with SUBBEC, we can test up to 256 cells at the same time. This means we no longer have to extrapolate from the results of six to twelve cells what a full battery is doing capability-wise. This provides a technical rigor capability increase that was missing before and ensures we have the best battery profiles going to the fleet."

SUBBEC supports both of Crane's mission areas of expeditionary warfare and strategic missions.

EMN1(SS) Jonathan Galusky, a process supervisor at Crane, is an active-duty Sailor serving as an engineering technician in the battery laboratory.

"SUBBEC provides a new capability for our group here at Power and Energy Systems Division at NSWC Crane to evaluate a full-scale submarine storage battery," said Galusky. "Our team works hard to ensure that the testing that will take place here directly benefits sailors as well as improve the operational capability of our submarine platforms."

Parker said being part of establishing this capability is meaningful to him.

"For me it's significant to provide the Fleet the best battery possible—we get to impact the Fleet directly," said Parker. "The submarines are there providing strategic defense. We take great pride in testing these batteries and providing this capability to the fleet."

Frady said the implementation of SUBBEC provides warfighters with added capability.

"The ultimate impact is to support the warfighter—that's the first thing on everyone's mind," said Frady. "Nowhere else in the United States does the Navy have a next generation test system used to evaluate next generation submarines—with SUBBEC we'll be supporting the warfighter today and tomorrow."

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SETTING SAFETY STANDARDS FOR ENERGY STORAGE

By Nick Jennings, David Wetz, Rick Langley, and John Heinzel

ARC FLASHING CAN BE HAZARDOUS EVEN WITH COMMON EVERYDAY ELECTRICAL DEVICES—IT IS FAR MORE DANGEROUS AND DEADLIER WITH HIGH-POWERED MILITARY SYSTEMS. EFFORTS ARE UNDER WAY TO SET BETTER SAFETY STANDARDS FOR THE NEWEST GENERATION OF BATTERY SYSTEMS.

The Army, Navy, and other services are pursuing higher-power capabilities leveraging high-voltage, high-capacity energy storage systems and power conversion. The Navy is studying the employment of energy storage and direct current (DC) architectures to support next generation pulsed and dynamic loads. These systems operate at voltages as high as 1,000 volts DC, which results in inherent risks to those who perform installation, operation, and maintenance on these systems. Arc flash is an extremely dangerous example, as this potentially lethal phenomenon is not yet able to be assessed with consistency because of the complexity of arc behaviors, as well as the unknowns associated with source behaviors. Each year more than 2,000 people are admitted into hospitals because of injuries sustained from arcing events.

DC systems to be employed in Department of Defense applications need to be understood and characterized so risks and mitigations can be appropriately assessed and implemented. The installation, operations, maintenance, and dismantling of these advanced DC energy systems increases the risk for arc flash hazards to warfighters, civilians, and electrical infrastructure. This has created a need to address personal protective equipment requirements for working in and maintaining these systems. Unlike most alternating current (AC) power systems, DC power and energy storage systems that use batteries, photovoltaic modules, and capacitors cannot be switched off or isolated at some points in the electrical system to eliminate an arc flash hazard. The electrochemical reactions in batteries are difficult, if not impossible, to control during faulted conditions. These types of power sources therefore present unique electrical safety challenges. With funding provided by the Office of Naval Research and under the technical guidance provided by the Navy team, the University of Texas at Arlington's Pulsed Power and Energy Laboratory (PPEL) and the Electric Power Research Institute (EPRI) in Knoxville, Tennessee, have collaborated to study DC arc flash phenomena. The team has evaluated sources that include valve-regulated lead acid and lithium-ion batteries at potentials consistent with future DC interfaces.

The safety concerns are based on the electric shock and arc flash hazards at the cell, module, and full battery levels. These concerns arise from the energy released from an electric arc that forms when a short circuit fault occurs between two energized parts of the power system. Under certain conditions, the arc may produce, or release, dangerous and destructive levels of energy. This type of event is known as an arc flash, and it releases energy in the form of sound waves, concussive-forces due to pressure, and extreme temperatures. The arc also produces radiant heat, known as incident energy, that can engulf workers and leave them with fatal or life-altering burns.

The National Fire Protection Association's (NFPA) 70E, Standard for Electrical Safety in the Workplace, is the primary electrical industry resource for helping companies and employees assess the risks and severity of occupational injuries and fatalities.[1] The NFPA 70E was created to provide guidance for complying with the rules and regulations for worker safety defined by Occupational Safety and Health Administration. NFPA 70E outlines a risk assessment method when workers are exposed to arc flash hazards. When substitution, elimination, and engineering controls are found to be insufficient methods of risk controls for arc flash, then additional protective measures, such the use of personal protective equipment, may be required. According to NFPA 70E, when additional protective measures include the use of this type of equipment the arc flash boundary must be determined.

Under certain conditions, the radiant energy released by an electric arc is capable of permanently injuring or killing a human being several feet away. Skin-burn injury studies have shown that the onset of a second degree burn on unprotected skin is likely to occur at an exposure of 1.2 calories/centimeter2 (5 Joules/centimeter^2) for one second. NFPA 70E allows for two methods for determining the arc flash boundary. One is called the Personal Protective Equipment Category Method and the other is called the Incident Energy Analysis Method. The former is limited in application. The NFPA 70E provides tables that list arc flash personal protective equipment categories and arc flash boundaries for a limited set of equipment and electrical conditions. This method should be used only when strict adherence to the equipment and electrical conditions found in the tables exist. This method also is suitable only for use where open-air arc flash hazards exist, such as those found in DC power and energy storage systems located in open areas or rooms. The problem is that many applications under consideration by the Navy, electric power utilities, and others will result in DC power and energy storage system designs where the limitations of this method may be insufficient (e.g., when an arc flash hazard exists within an electrical enclosure, such as power distribution panelboard). In these situations, the Incident Energy Analysis Method is the recommended approach.

The thrust of research and standards work concerning arc flash to date has been geared toward three-phase AC power systems producing standards such as IEEE 1584 and NFPA 70E.[2] IEEE 1584 provides models and an analytical process to calculate the incident energy and arc flash boundary of a three-phase AC power system. The process covers the collection of field data if applicable, consideration of power system operating scenarios, and calculation parameters. Applications include electrical equipment and conductors for three-phase AC voltages from 208 volts to 15 kilovolts. Unfortunately, the scope of IEEE 1584 specifically says that single-phase AC and DC power systems are covered by the modeling or analytical process provided in the document. NFPA 70E lists two methods for analyzing arc flash incident energy for DC power systems, but these methods have not been as extensively researched. Currently, there is no arc flash incident energy calculation method for DC power systems that has been widely accepted, adopted, or recognized by industry or industry standards-making bodies. Multiple methods, including the two methods briefly described in NFPA 70E, exist that often differ significantly in their results.

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Without a consistent and proven method, those who apply arc flash hazard analysis may grossly over or underestimate DC arc incident energies. In some cases, the arc incident energy levels have been shown to be incorrect by as much as an order-of-magnitude. This is problematic because personnel whose job it will be to install, operate, maintain, and dismantle DC power and energy storage systems may be required to wear unnecessary or overly restrictive personal protective equipment. Of course, the opposite situation could also exist where estimates grossly underestimate the incident energy level, potentially leading to inadequate mitigation choices.

Arc flash at single energy storage cell voltages will not produce a harmful impact to personnel and equipment but the study at the cell level allows for future scaling and model development. The PPEL has worked with EPRI to study a valve regulated lead acid and two lithium-ion battery chemistries. The lead acid modules studied have a rated capacity of 97 amp hours and nominal voltage of roughly 12 volts. As many as 72 modules have been assembled in series at EPRI to study arcs induced by batteries with open circuit potentials as high as 930 volts DC. The lithium-ion chemistries studied are lithium iron phosphate and lithium titanate oxide. The former batteries are made up of multiple 20S/4P modules connected in series and parallel; as many as 16 modules have been assembled in series at PPEL to study arc events induced by batteries with open circuit potentials as high as 540 volts DC. The latter batteries are made up of multiple 16S/1P modules connected in series; as many as 20 modules have been assembled in series at EPRI to study arc flash events induced by batteries with open circuit potentials as high as 910 volts DC. Lower voltages of each battery type and chemistry have been studied with higher parallel module counts at both the University of Texas and EPRI. Together both institutions have fabricated and implemented sensing technologies to measure incident energy, light intensity, and sound pressure.

When an arc is formed and burns, the conductivity of the arc increases up to a point, causing the current to reach a maximum that is sustained until it decreases depending on the source's stiffness and energy. As the short circuit current supplied by a battery increases, the individual cells' conduction voltage decreases, reducing the battery's ability to ionize the gap and sustain the arc. The arc will extinguish when the conduction voltage can no longer sustain the arc, when the source is out of energy, when something in the circuit fails open, or when some protection device engages to open the circuit. Incident energy calculations make use of the bolted fault current or short circuit current of the system. To develop an arc flash prediction tool, a short circuit model of the batteries must be employed. The batteries studied here have undergone an "enhanced characterization procedure" defined by EPRI and PPEL. The valve-regulated lead acid batteries identified have been studied at continuous discharge currents of 39 amps (4x), 194 amps (20x), 970 amps (100x), and 1940 amps (200x) using DC programmable loads. A series of experiments was also performed using the same batteries in which two modules were connected in parallel and studied at scaled rates to study how the modules share the load under controlled short circuit events. The 10-amp-hour, lithium-ion phosphate battery has been subjected to continuous discharge currents of 4 amps (4x), 20 amps (20x), 100 amps (100x), and 200 amps (200x). The lithium titanate oxide battery has been subjected to continuous discharge currents of 40 amps (8x), 200 amps (40x), 1,000 amps (200x), and 2,000 amps (400x). The short circuit current prediction models generated from the enhanced procedure for each respective module type are shown in Figure 1.

The development of a predictive model to address worker personal protective equipment requirements means that measurements of incident energy, voltage, current, light intensity, sound, and pressure all are of importance. Incident energy measurements and their correlation to the arc's voltage and current is the foundation of the model. The measurement of voltage and current of the arc and battery at a high temporal resolution allow for greater precision in determining the arc's duration. Measurement of light intensity, sound, and pressure follow those used in IEEE 1584's experiments are a primary focus in PPELs efforts.[3] The light and pressure are measured at a working distance of 45.72 centimeters (18 inches) and sound is measured 61 centimeters (24 inches) from the arc fault. High-speed

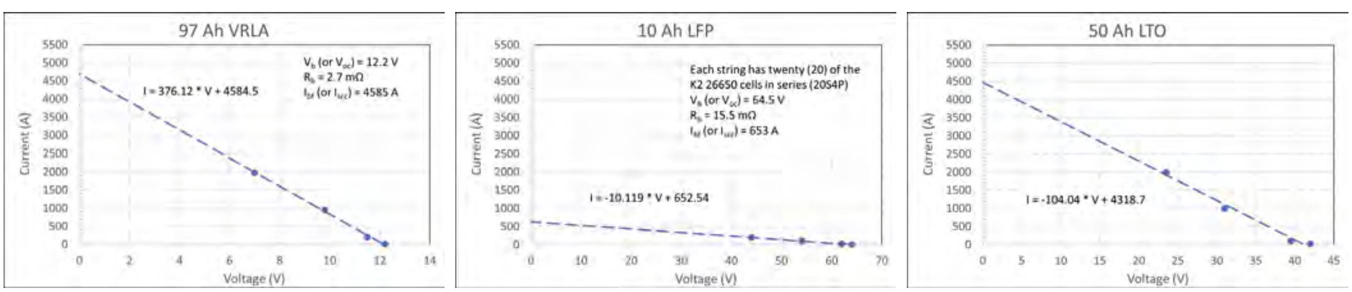

Figure 1: Battery models of the 97-amp-hour valve-regulated lead acid (left), 10-amp-hour lithium iron phosphate (middle), and 50-amp-hour lithium titanate oxide (right), created using the University of Texas' and Electric Power Research Institute's enhanced high current testing procedure. All figures courtesy of authors

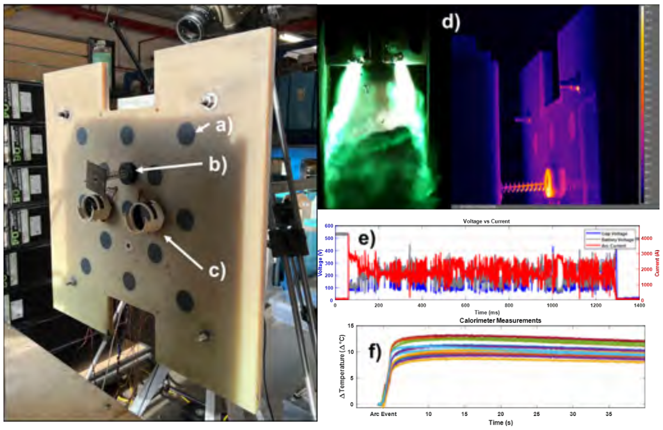

Figure 2: Measurement suite at the Pulsed Power and Energy Laboratory with: a) 13 calorimeters painted black, b) pressure measurement, c) two light intensity sensors, d) high-speed video, e) voltage and current measurements, and f) calorimeter temperature measurements.

video and thermal imaging are used to understand the arc dynamics better and to validate the temperatures measured by the calorimeters. A sensor board used by the University of Texas to make all these measurements is shown in Figure 2, along with some sample high-speed images and oscilloscope voltage and current data. Photographs of the experimental setup at EPRI along with some oscilloscope data and high-speed images are shown in Figure 3.

Many prior arc flash research efforts have studied the enhancement induced when arcs are initiated inside an electrical equipment enclosure. This is important since personnel working on battery systems are likely to be working in and around power distribution enclosures. Aligning with recommendations found in IEEE 1584 low voltage systems, copper electrodes in a vertical configuration are used in an enclosure of 20 inches3.

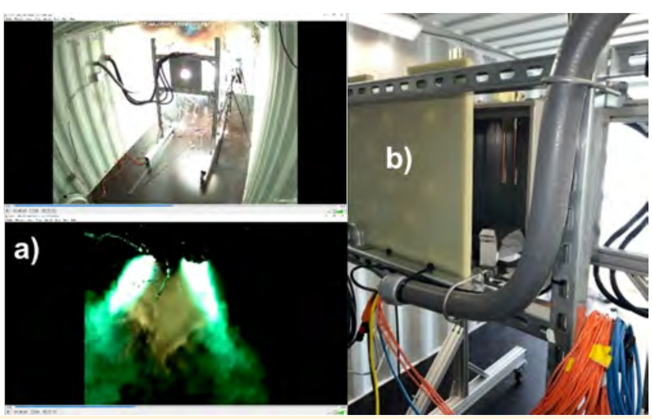

Figure 3: Measurement suite at the Electric Power Research Institute with: a) high-speed video, b) arc-in-a-box design that can be locked in place and positioned at various distances, and voltage, current, and calorimeter temperature measurements.

The spacing of the copper electrodes, where the arc will be created, is modified to study the effects of electrode gap distance on the incident energy of the arc.

Though quite a bit of data have already been collected, arc flash experiments are still ongoing at both PPEL and EPRI. Throughout these tests, the destructive evidence of arc flash and potential harm has been well recognized. in one experiment, a 930 volts DC lead acid battery was arc faulted. Much of the 1.25 centimeter (0.5 inch)-diameter copper electrodes were vaporized and melted during the arc duration of 900 milliseconds. The lithium iron phosphate modules used also have produced similar results. An experiment performed with four parallel strings of modules assembled with an open circuit potential of 540 volts DC produced significant damage to the PPEL test fixture. This experiment resulted in incident energy levels of greater than 1.2 cal/cm2.

The experiments performed by the University of Texas and EPRI have highlighted the potential danger that electrical workers face when they are working on energized DC energy storage systems. The full suite of planned experiments is being actively performed, and the University of Texas and EPRI hope to be able to provide data-backed evidence to begin defining the personal protective equipment requirements for Navy electrical workers. These results will support transition efforts by Naval Sea Systems Command to ensure that assessments and recommendations for protection are updated to protect personnel working around such sources. This work is aimed at ensuring the Navy maintains its superiority while keeping its Sailors safe.

References

[1] NFPA 70E®, *Standard for Electrical Safety in the Workplace*, National Fire Protection Association, 2021.

[2] IEEE 1584-2018, IEEE *Guide for Performing Arc-Flash Hazard Calculations*, 2018.

[3] Wei-Jen Lee, Zhenyuan Zhang, Shiuan-Hau Rau, T. Gammon, B. Johnson and J. Beyreis, "Arc flash light intensity measurement system design," 2015 IEEE IAS Electrical Safety Workshop (2015): 1-7, doi: 10.1109/ESW.2015.7094872; Z. Zhang, S.H. Rau, W.J. Lee, T. Gammon, and B. Johnson, "ARC flash pressure measurement system design," 2016 IEEE IAS Electrical Safety Workshop (2016): 1-7, doi: 10.1109/ESW.2016.7499707.

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Photos courtesy of NIWC Pacific

BRINGING THE POWER OF INFORMATION TO THE FIGHT

By Arthur Rubio, John deGrassie, and Patric Petrie

THIS FIRST-OF-ITS-KIND SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEM AT MARINE CORPS BASE PENDLETON IS THE LATEST ENERGY RESILIENCY TECHNOLOGY BUILT BY THE ENERGY INNOVATION LABORATORY AT NAVAL INFORMATION WARFARE CENTER PACIFIC.

That an army marches on its stomach, and not just its feet, is a well-known expression dating to the 19th century or even earlier. Without food and other resources, an army is unable to march or fight. This observation can be extended and rephrased, in the case of modern armies and militaries, to the matter of fuel. The military services require not only fuel, but also information, connectivity, and uninterrupted power to position its platforms around the globe, to project peace, to supply humanitarian relief, and, potentially, to fight in armed conflict.

Ensuring that each platform, anywhere in the world, has enough fuel to complete its mission is a complex logistical issue. A successful mission commander must know whether needed platforms have sufficient fuel and trust that all critical infrastructure will remain online. Every day, civilians take for granted the fuel gauge in their cars, ubiquitous fueling stations, and continuous wall plug power that make their personal fuel logistics problems relatively easy to mitigate—save for those unfortunate moments when we push the gauge well past "E," too busy to stop for gas.

These fuel and infrastructure logistics stand to grow in kind and number for Navy operations. Unpiloted platforms, coordinated control of distributed platforms, and operations in contested environments push the limits of logistics and demand new types of information and battlefield awareness. How can a mission commander view, monitor, and manage fuel levels or battery life of far-forward forces? How does the garrison keep its infrastructure fully connected and ready to give support to any mission? Near-real-time data on fuel levels from distributed platforms and information-driven infrastructure monitoring is required. Bringing fuel and energy information to the fight will make it possible to optimize resources before, during, and after missions. By integrating this information directly into systems, future commanders will be able to focus on mission outcome, trusting that systems are optimizing fuel and power to realize commander's intent.

Building the Future

The Naval Information Warfare Center Pacific has more than 80 years of experience innovating data solutions to enhance and revolutionize command, control, communications, computers, intelligence, surveillance, reconnaissance, and targeting capabilities and methods for naval forces. The warfare center's Energy Innovation Laboratory (EIL) focuses on researching and engineering solutions for current and future Navy and Marine Corps fuel and energy needs. EIL solutions span the entire logistics chain from base installations on native soil to expeditionary forces at the edge. In all cases, EIL creates access to new, critical information to optimize mission support and execution.

In 2021, the team installed and commissioned a fully functional Supervisory Control and Data Acquisition (SCADA) system for the Marine Corps Base Pendleton electrical infrastructure. This first-of-a-kind system for Pendleton brought real-time data monitoring and control for critical and time-sensitive equipment, dramatically reducing infrastructure downtime. Currently, the EIL is working to enable operational energy awareness for command and control by coordinating multiple efforts: for the growing fuel information needs, the team is currently developing a system of systems solution to bring near-real-time fuel data to commanders to test and prove the concept, build requirements for a future program of record, and for potential integration of these data into other operational systems.

Near-Real-Time Fuel Information

The EIL systems-of-systems solution to the fuel data need is the Fuel Automated Reporting System (FARS). The FARS project team identified warfighter end-user communities with a need and desire to build and test prototypes, to prove the concept and scale the solution. Warfighters need informational awareness of fuel data today. To build a resilient solution quickly, the EIL team identified high technical readiness level technologies for each link of the end user's fuel data chain, engineering them into a complete system. Making use of its advanced manufacturing capabilities, the EIL designed specific mounting and power solutions for commercial fuel sensors for installation on warfighter platforms. The fuel data is transmitted wirelessly using conventional communication methods to a portable metering unit. All the information is pushed to a web-enabled, customizable data dashboard that brings the near-real-time fuel data to mission logistics planners and mission operators.

The EIL has a longstanding practice of working directly with warfighter end-users in its research and engineering efforts. In fact, many EIL team members are themselves former active-duty military members, starting their civilian service by joining Naval Information Warfare Center Pacific through the Veterans to Energy Careers program (which provides internships and hiring pathways into the private and public sector for former military earning engineering degrees). Throughout the SCADA installation and within the FARS engineering development, warfighters remain part of the EIL team. These end-users provided instant feedback on the developing solution, making it something they want to use and creating a warfighter-centered solution, tough enough for field use and agile enough to scale for the next big innovation. Feedback from warfighters on the new FARS-enabled, near-real-time data source and informational display for fuel levels is extremely favorable.

The Energy Innovation Laboratory's full-scale power grid simulator testbed supporting development of advanced sub-metering to optimize energy, water, and wastewater with data.

Bringing the Power of Information to the Fight

The initial FARS capability is only the starting point for the EIL work in fuel and power information. Upcoming tests of FARS in Marine Corps operational exercises will provide the pertinent data for building requirements for a future program of record to roll out the FARS capability to other operational groups in need of this valuable information. Engineered for scale, FARS will grow to add more types of platforms and types of fuel information to the dashboard (such as battery life). The FARS is one part of the growing EIL vision to build a complete capability for operational energy awareness for command and control, a concept meant to enable global logistics awareness, diversify distribution, improve sustainment, and optimize installation to support sustained operations. Enabling global logistics awareness leverages energy awareness in a distributed, contested, and austere environment for the purposes of achieving an energy and resource-resilient posture—delivering the right resources, to the right place, at the right time, for the right reasons.

In delivering the first SCADA system to Marine Corp Base Pendleton and developing the capability of automatically monitoring fuel levels, the EIL ushers in a new era for naval fuel and energy information. These new data provide immediate benefit through situational awareness, but moreover can integrate into the warfare center's suite of solutions, to take full advantage of the ongoing developments in data science, machine learning, and artificial intelligence for naval operations. Real-time monitoring and control of base installation power and near-real-time fuel data will train machine learning algorithms that will optimize power distribution and fuel consumption. Fuel level information can integrate directly into mission planning tools and battle management aids, further automating commander's intent. Scaling this power and energy information with the increasing capacity to compute at the edge will enable future platforms to manage resources directly, through artificial intelligence with minimal reach back for mission success. Naval Information Warfare Center Pacific is bringing the power of energy information to the fight for the warfighters of today and tomorrow.

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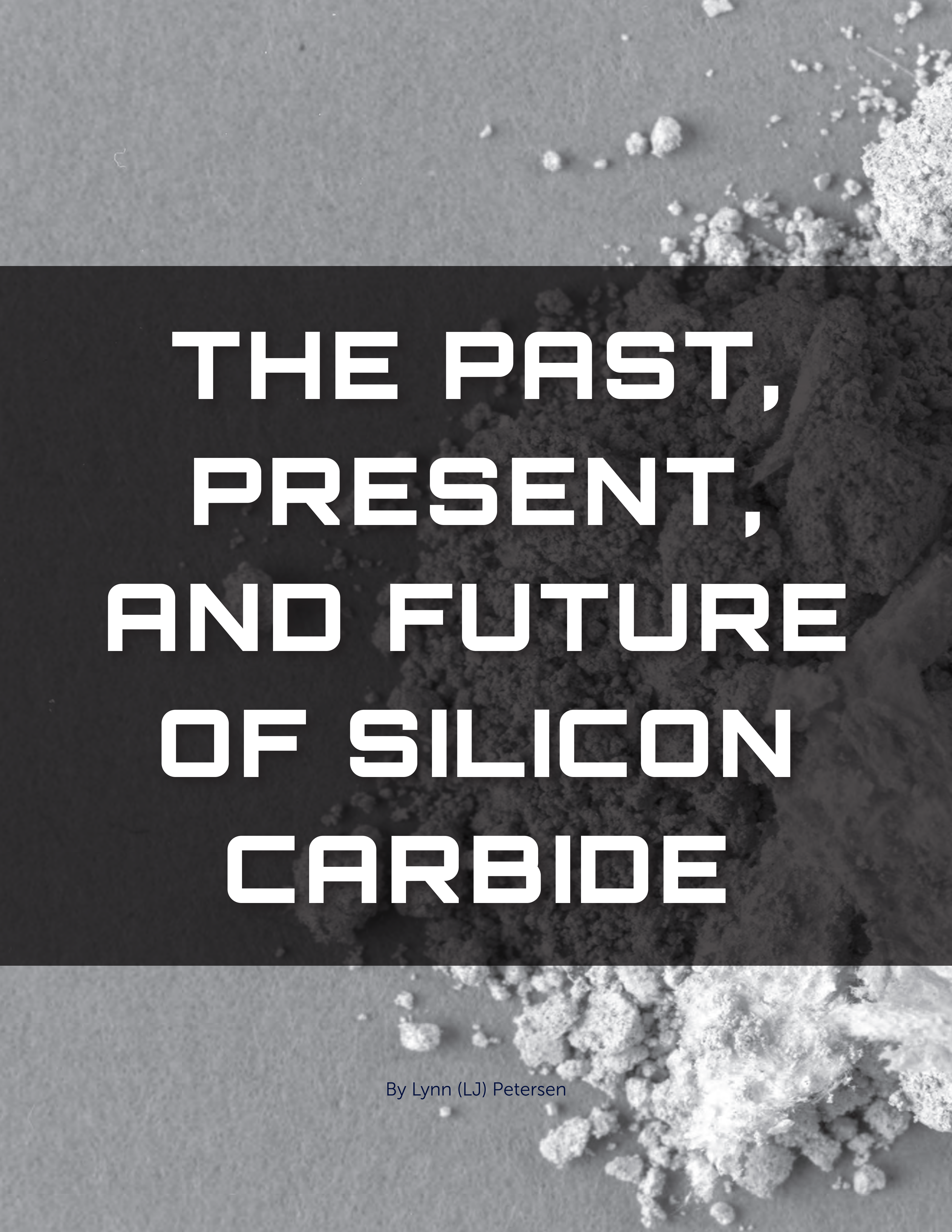
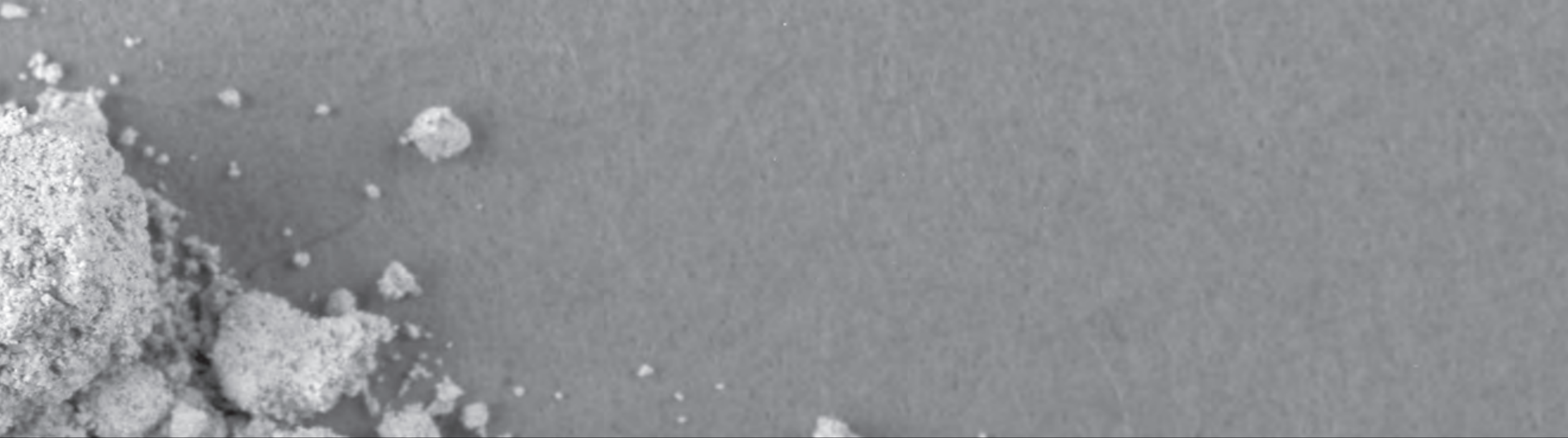


THE PAST, PRESENT, AND FUTURE OF SILICON CARBIDE

By Lynn (LJ) Petersen

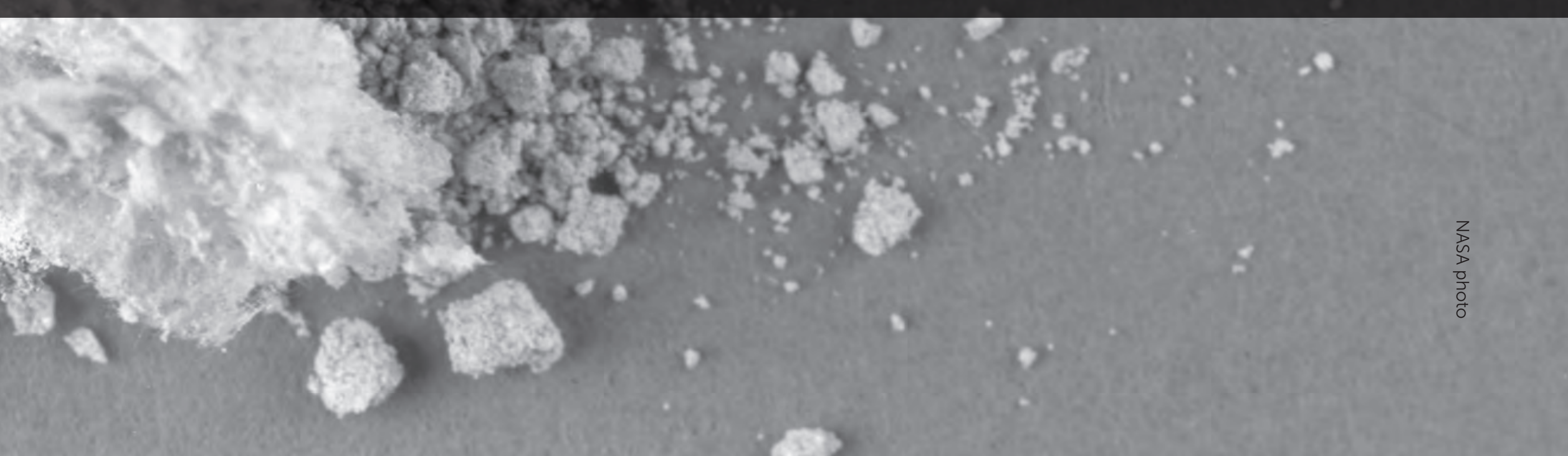


SILICON CARBIDE, NATURALLY RARE ON EARTH BUT ABUNDANT IN THE UNIVERSE, HAS SERVED A WIDE VARIETY OF INDUSTRIAL USES FOR MORE THAN A CENTURY. FOR THREE DECADES, THE MATERIAL HAS BEEN THE FOCUS OF THE OFFICE OF NAVAL RESEARCH'S POWER ELECTRONIC BUILDING BLOCK PROGRAM.

In 1994, the Office of Naval Research (ONR) established the Power Electronic Building Block (PEBB) program. PEBB is an integrated program of material, device, circuit, and system science and technology development the core objective of which was to reduce the size, weight, and cost of power electronics to enable future affordable and powerful electric warships.[1] ONR had been developing wide-bandgap (WBG) material, device, and circuit technologies for sensor systems, and has been doing so since the 1960s. The PEBB program office was formed to focus these efforts for shipboard power systems.

Understanding that WBG technology would drive future electrical power and energy systems, fundamental research was initiated on WBG materials and devices. Early on, it was noted that silicon carbide (SiC) was the most likely WBG technology to mature in a reasonable time frame.[2] A multi-university research initiative was competitively approved to complement the Naval Research Laboratory and ONR basic research programs. SiC had many material defect and crystal growth challenges, but it would enable the higher voltages needed to power future shipboard systems. The Army and Air Force needed the higher temperature systems enabled by SiC. The Army, Air Force, NASA, and DARPA joined with the Navy and coordinated their programs to meet these challenges.

The cooperation between the different research organizations began to bear fruit. During this same time, progress was made in SiC manufacturing and device development. DARPA, in conjunction with ONR, developed three-inch SiC wafer manufacturing and defect diagnostic processes and demonstrated a four-inch capability. The Army concentrated on wafer epitaxy technologies and low-voltage/high-temperature devices. The Air Force also concentrated on low-voltage/high-temperature devices for aircraft power. The Navy focused on high-voltage 10 kilovolt epitaxy and high-voltage devices. ONR, with industry, developed 10-kilovolt/120-amp SiC modules based on four-inch production and used them to demonstrate a 13.8-kilovolt alternating current (AC) solid state power substation at 20-kilohertz switching frequency.



NASA photo

In 2012, ONR demonstrated a 4,160-volts AC to 1,000-volts direct current (DC) converter switching at 40 kilohertz for shipboard applications using the 10-kilovolt/120-amp SiC modules. Starting in 2013, a Defense-Wide Manufacturing Science and Technology (ManTech) program was started, cost sharing the Army, Air Force, and Navy programs. The objective was to improve manufacturing techniques and increase wafer production to six inches to reduce SiC costs and increase manufacturing yield.

In 2017, ONR in conjunction with the Department of Energy completed the development of a 10-kilovolt/240-amp SiC metal-oxide-semiconductor field-effect transistor (MOSFET) module. Also, ONR demonstrated the General Electric PEBB1000—a 160-kilowatt, 1-kilovolt-to-1-kilovolt, solid-state, DC-to-DC transformer with switching at greater than 100 kilohertz. A six-kilovolt-to-one-kilovolt, DC-to-DC converter employing the PEBB 1000 technology was developed under ONR's Hybrid Energy Storage Module under the fiscal year 2015 Future Naval Capability program and transitioned to the General Electric Wind product line (which includes commercial wind turbines). In July 2022, under a follow-on ONR project, a 4,160-volts AC to 1-kilovolt DC, liquid-cooled PEBB was developed and demonstrated. Further in 2017, Virginia Tech developed and tested their version of PEBB 1000. Unlike the General Electric PEBB, the Virginia Tech PEBB did not include the high-frequency transformer that provides galvanic isolation, but it did explore technologies to enable the least replaceable unit (LRU) concept, human/machine, thermal, and control interfaces. Testing performance validated the 26-pound unit's 70-kilowatt, 100-kilohertz, 98-percent efficiency. The LRU is a fully functional building block, that when stacked together like building blocks, can provide the full voltage and or current needed for a specific application. One of many benefits include easier replacement of a failed LRU without having to perform a hull cut, potentially entailing a dry-docking period.

During this period, ONR found that increasing switching frequency dramatically reduces converter size and weight, promising a possible two-to-four-fold increase in power density while reducing conversion losses by 50 percent. In addition, six-inch wafer production promises to reduce SiC cost to that of silicon alone or below for equivalent power capability.

The PEBB 6000 concept was established by Virginia Tech, employing the Wolfspeed 10-kilovolt/240-amp MOSFET module (i.e., the XHV-6). PEBB 6000 is a 6-kilovolt-to-1-kilovolt, DC-to-DC converter, rated at 1-megawatt power, 40-kilohertz switching frequency, and weighing 23 pounds. PEBB 6000 was completed in the spring of 2022, displayed at the Advanced Research Project Agency-Energy (ARPA-E) summit in Denver in May 2022, and was lab demonstrated in July 2022 to rated capability: 99.4 percent efficiency, 15 megawatt/m3, and 30 kilovolt partial discharge inception voltage. It is interesting to note that while the PEBB 6000 was being constructed, a collaborative program funded by ARPA-E leveraged the early design considerations and resulted in a 24-kilovolt grid concept demonstrator and demonstrated reconfigurability from either an AC or DC input to a DC or AC output. PEBB 6000 is now slated for component hardware-in-the-loop characterization at the Florida State University Center for Advanced Power Systems funded under the Electric Ship Research and Development Center (a consortium of colleges and universities focused on research, development, and de-risking electric-ship technologies) grant managed by ONR. Multiple PEBB 6000s will be developed and integrated to support the Power Electronics Power Distribution System program.

One final project benefiting from the technological advancements in SiC is the Navy integrated power electronic building block (NiPEBB). Resulting from knowledge gained in both the Virginia Tech PEBB 1000 and General Electric PEBB 1000, NiPEBB is a 250-kilowatt, 500-kilohertz, 1-kilovolt, DC-to-DC converter, employing a high-frequency transformer. NiPEBB is pushing the state of the art for passive magnetic components needed for inductors and transformers.

Recent Breakthroughs

Two characteristics of semiconductors include: on-resistance, which is used to determine conduction losses (while the semiconductor switch is in the "on" mode) and is used to determine efficiency; and breakdown voltage, the voltage that the semiconductor can conduct before it breaks down and can no longer conduct electricity. The objective is to minimize on-resistance while maximizing breakdown voltage. While it is clear that SiC has much lower theoretical on-resistance and much higher breakdown voltage than Si, there are still significant improvements to be made with both characteristics. There are other characteristics by which semiconductors are evaluated and compared (such as thermal conductivity) and together inform power electronics engineers of the trade-offs between each of the semiconductors.

ONR has been investing for more than two decades in gallium nitride (GaN) and making significant progress under Dr. Paul Maki's leadership for radio frequency applications. ONR been investing in GaN for power applications, however, only since 2014. Other services, such as the Air Force, have been investing in gallium oxide (Ga^2O^3). GaN is attractive for high-voltage, high-switching-frequency, and high-efficiency power and energy applications. Progress is being made toward the Power Electronics and Electromagnetism Science and Technology long-term goal of 20 kilovolts and 200 amps through grants with Stanford University and the University of Illinois Urbana Champaign as well as

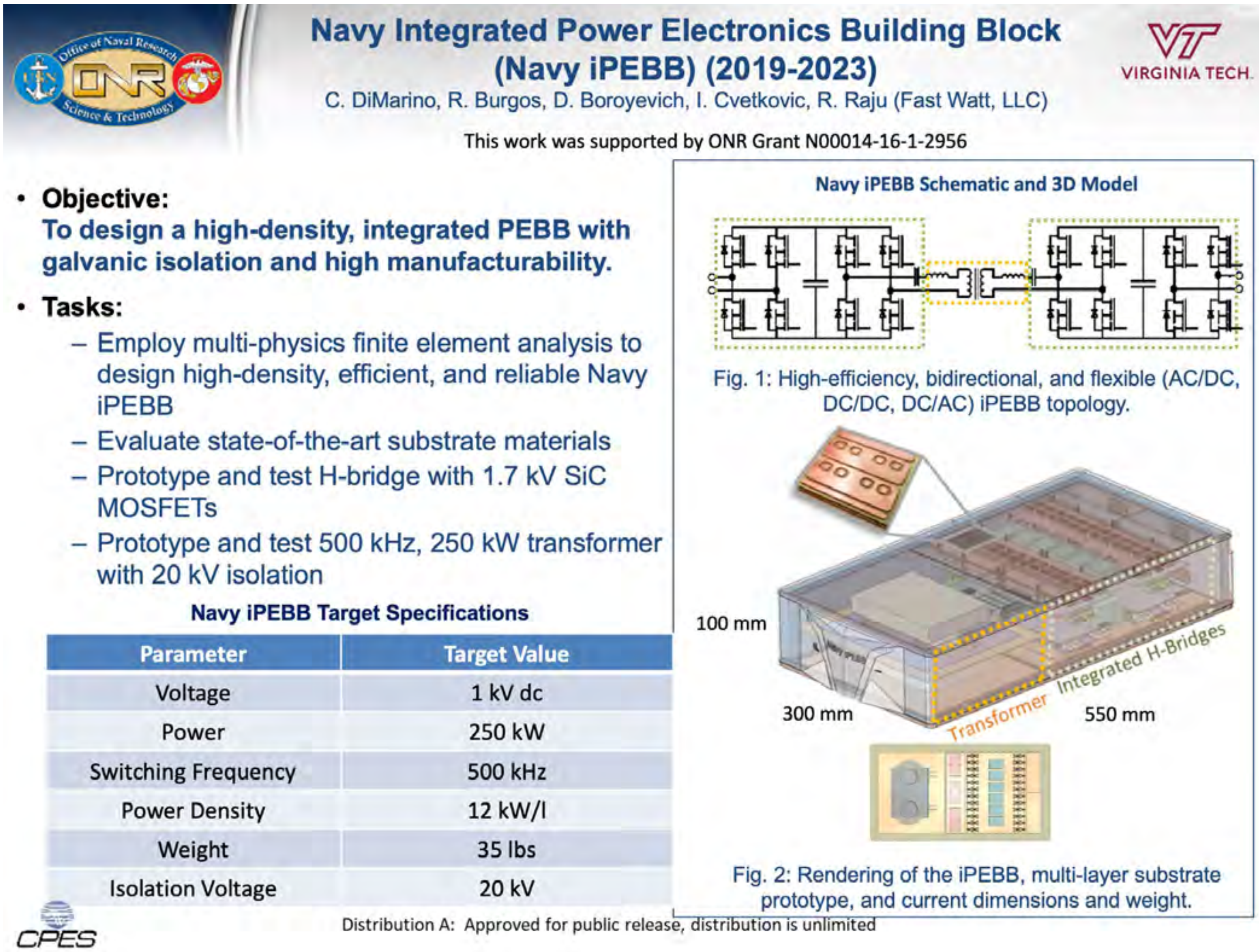


Figure 1: Virginia Tech's Navy Integrated Power Electronics Building Block (iPEBB). All graphics courtesy of authors

the nearer term research goal of a 10-kilovolt super junction device through a collaborative effort between Penn State University and Virginia Tech led by the Naval Research Laboratory (NRL). In addition, in 2018, a professional and technical development internship was established between the Naval Academy and NRL, the Naval Postgraduate School, and Penn State University, giving Bowman and Trident Scholars the opportunity to develop skills associated with WBG semiconductors.

Given the potential capability of emerging ultra and extreme WBG semiconductors, it will be feasible to achieve both 1 megawatt and 1 megahertz for a power electronics converter within the next five years. A converter, however, is much more than just the semiconductor switches. Passive components such as inductors and capacitors are needed for filtering, transformers are needed for protection and voltage step up/down, and thermal management is needed to spread and remove wasted heat, among other considerations. To reach the goal for a 1 megawatt and 1 megahertz power converter, basic research is needed now for the development of advanced magnetic materials for inductors and high-frequency transformers. Under the ONR Power Electronics and Electromagnetism basic research program, investigation is under way in soft magnetic materials with funded grants with the University of Pittsburgh, Northeastern University, Sandia National Laboratories, and the Naval Academy.[3]

Thermal issues pose significant challenges to the reliability of power electronics systems. In 2018, ONR competitively awarded a multidisciplinary university research initiative to address thermal barrier resistance of WBG and ultra WBG semiconductors. The team was led by Georgia Tech and included the Massachusetts Institute of Technology (MIT), Notre Dame University, University of South Carolina, University of Virginia, and University of California Los Angeles. In November 2021, this initiative under the leadership of Dr. Alan Doolittle of Georgia Tech University made a major breakthrough in P-Type doping of aluminum nitride (AlN) in partnership with a similar initiative under the Air Force Office of Scientific Research.[4] This discovery could be a game-changing find, given that the critical electric field of AlN is one and a half times more than Ga^2O^3, three times that of GaN, and five times more than SiC, with lower on-resistance and higher breakdown voltage.[5] The discovery and invention of low-resistance ohmic contacts are needed now to make a medium-voltage AlN PEBB a reality, and three grants were initiated in fiscal year 2022 with Georgia Tech, the University of South Carolina, and Penn State University with that goal in mind.

Another recent potential game changing semiconductor breakthrough, cubic boron arsenide (BA), was discovered through an ONR-supported (Dr. Mark Spector, ONR 331) collaborative effort by MIT, the University of Houston, the University of Texas at Austin, and Boston College. Cubic BA exhibits a ten-fold improvement in thermal conductivity over Si and a relatively high bandgap and high mobility for holes and electrons (i.e., holes and electrons travel with less resistance). More investigation is needed, however, to determine a practical way to manufacture cubic BA in usable quantities.[6]

Implications for the Future

Much has been done for WBG semiconductor materials and power-conversion components over the past 30 years at ONR, but a document published in 2020, "Power Electronic Power Distribution Systems (PEPDS)," envisions the future employment of not only the family of PEBB converters, but also the controls, energy storage, thermal management, and protection of an innovative, integrated power and energy system. PEPDS will marry the more than five decades of SiC development with the necessary control systems to move the right power and energy from the specified source to the right mission load at the right time.

PEPDS has two assumptions associated with it: medium voltage DC is rectified from a medium voltage AC generator (or medium voltage AC is distributed); and no load or source is directly connected to the medium voltage DC bus, but rather the sources and loads are connected to the bus via a WBG SiC PEBB converter. This arrangement forms a system of systems of converters that communicate among themselves and facilitates the flow of power and energy when and where needed.

The all-electric ship is essentially a microgrid.[7] PEPDS is a form of a microgrid, whereby a shipboard application is decoupled from the grid and will rely on advanced controls to effectively manage power and energy.[8] The Electric Ship Research and Development Consortium—consisting ofFlorida State University, University of South Carolina, MIT, University of Texas Austin, Mississippi State University, Purdue University, the United States Naval

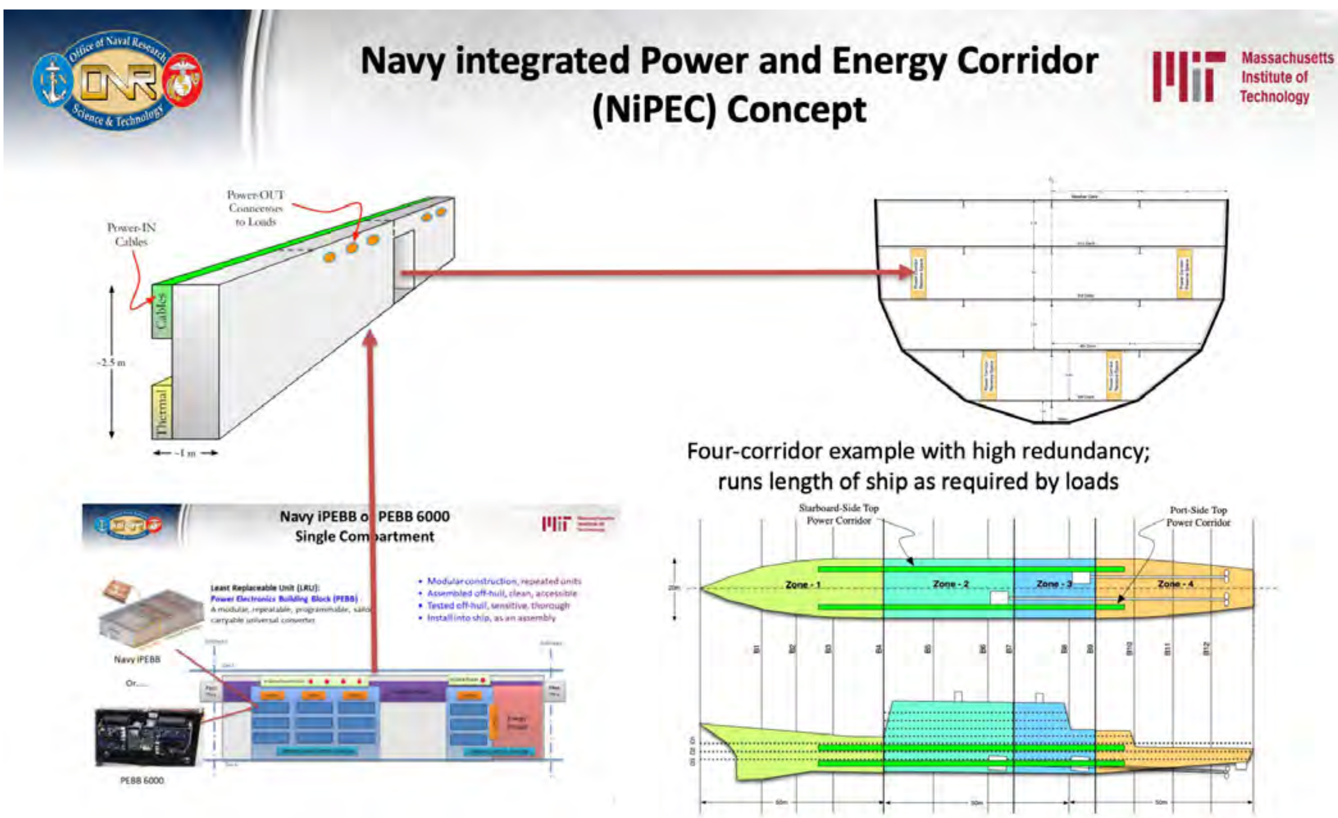


Figure 2: Navy integrated Power and Energy Corridor (NiPEC) concept.

Academy, and the Naval Postgraduate School—has been investigating PEPDS-enabling technologies including controls. The University of South Carolina, has assembled a system of systems of computers emulating a mini-PEPDS structure and has demonstrated extremely fast communication rates between the converters. An IEEE working group, which focused on control layers and the associated speed at which communication decisions needed to be made, was employed in developing the PEPDS communication network.[9]

Cyber security for PEPDS is being addressed through grants to Florida International University and Clarkson University collaboratively with the University of South Carolina and Florida State University's Center for Advanced Power Systems through the development of a PEPDS smart grid and subjecting the smart grid to malware intrusions to de-risk cyber related challenges and concerns.

A transformational and innovative concept to house or contain PEPDS has been devised by MIT, known as the Navy-integrated Power and Energy Corridor. In essence, the corridor solves the long-standing issue of multiple long cables running throughout the ship, and the many power and energy cabinets, also installed throughout the ship This concept offers many potential advantages:

- **Cost:** Modules are constructed off-hull and assembled onboard, common LRU increases number of identical components in supply chain with logistics, training, and repair advantages and modularity enables access for maintenance and facilitates alterations/upgrades
- **Arrangement:** Defines the space for the corridor in the earliest stages of design and enables full customization at the bulkhead level, and co-location of vital distributed systems such as personnel corridor, data, etc.
- **Survivability:** Co-location of supporting (serial) electrical components and geographical separation of redundant (parallel) electrical components in multiple corridors—failure of one component does not take down entire load
- **Safety:** All electric connections, protection, and power conditioning equipment are in a highly defined, enclosed space away from any chance for unintended exposures
- **"Green":** Energy storage tied directly to the distribution bus can be sized for in-port battery operations, single generator operations, and energy-efficient management.

Figure 2 depicts a single-compartment power and energy corridor concept with consideration for a Navy-integrated PEBB, PEBB 6000 population, or both. What is transformational is that with the installation of these corridors comes significant space that can now be allocated to mission space and significant payload fraction increase needed for the ship to perform its mission(s.)

In conclusion, over the past half century, ONR along with other the other services, academia, and industry has been advancing the material development of WBG technologies. This effort most recently has harvested the fruit of the material advances of SiC into applications that will benefit both the Department of Defense and industry—enabling higher efficiency, reliability, and availability.[10] SiC cost continues to approach the cost of Si. The future is bright not only for SiC WBG based technology, but also other emerging ultra and extreme WBG semiconductor technologies.

References

[1] T. Ericsen and A. Tucker, "Power Electronics Building Blocks and Potential Power Modulator Application," *Proc. 23rd Int. Power Modulator Symposium* (June 1998): 12-15.
[2] T. Ericsen, "Future Navy Application of Wide Bandgap Power Semiconductor Devices," *Proceedings of the IEEE* 90, no. 6 (June 2002):1077-82, doi: 10.1109/JPROC.2002.1021572.
[3] L. Petersen, "Advanced Magnetics Needs for High Frequency/Power Power Electronic Building Blocks Applications," Government Microcircuit Applications and Critical Technology Conference, March 2022; L. Petersen, "Power Electronics Power Distribution System (PEPDS) enabled by Navy Integrated Power Electronics Building Block (NiPEBB) and through Navy Integrated Power and Energy Corridor (NIPEC): Revolutionary changes to Power and Energy System Design, Integration and Implementation, Providing Highly Efficient and Effective Technology to the Warfighter," Advanced Magnetics for Power and Energy Development Annual Meeting, October 2021.
[4] H. Ahmad, J. Lindemuth, Z. Engel, C. Matthews, T. McCrone, and W. Doolittle, "Substantial P-Type Conductivity of AlN Achieved via Beryllium Doping," *Advanced Materials* 33, no. 42 (September 2, 2021).
H. Ahmad, J. Lindemuth, C. Matthews, and W. Doolittle, "Realization of Homojunction PN AlN Diodes," J. *Appl. Phys.* 131, 175701 (2022): https://doi.org/10.1063/5.0086314.
[5] W. Doolittle and S. Graham, "AlN: A New Pathway to High Voltage, Power and Temperature Ultra-Wide Bandgap Power Electronics," presentation given at fourth-year ONR MURI program review, Columbia, South Carolina, June 2022.
[6] D. Chandler, "The Best Semiconductor of Them All?" *MIT News on Campus and Around the World*, July 2022, https://news.mit.edu/2022/best-semiconductor-them-all-0721.
[7] L. Petersen, "Navy Application of Silicon Carbide (SiC) Wide Bandgap (WBG) Semiconductors Enabling Future Power and Energy Systems," plenary presentation at IEEE International Electric Machines and Drives Conference, Miami, Florida, May 2017; L. Petersen, "The Electric Ship as a Microgrid," plenary presentation at IEEE Second International Conference on Direct Current Microgrids, Nuremburg, Germany, July 2017.
[8] T. Ericsen, "The Second Electronic Revolution (It's All About Control)," *IEEE Transactions on Industry Applications* 46, no. 5 (2010): 1778-86, doi: 10.1109/TIA.2010.2057400.
[9] "Power Electronics Building Block (PEBB) Concepts," IEEE publication 04TP170 prepared by the Task Force 2 of Working Group i8, 2004.
[10] L. Petersen and T. Ericsen, "A History of Silicon Carbide (SiC) Advancement: Basic Research to Product Applications," IEEE Transportation Electrification Community Newsletter, June 2017.

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US Navy photo

BETTER PLANNING LEADS TO BETTER DECISIONS

By Christian X. Szatkowski, Dr. Karl F. Van Orden, Dr. Jason H. Wong, and Patric Petrie

THE TRAGIC LOSS OF 290 LIVES IN 1988 WITH THE DOWNING OF IRAN AIR FLIGHT 655 BY A US NAVY AEGIS CRUISER WAS A WAKE-UP CALL TO MANY ABOUT THE CHALLENGES OF MODERN MILITARY DECISION-MAKING. THE ADVANCED MULTI-ECHELON PLANNING TOOL IS THE LATEST RESULT OF DECADES OF SUPPORT FOR DECISION-MAKING RESEARCH BY THE NAVY.

Over the past 50 years, research in human decision-making under conditions of uncertainty has revealed many biases that can explain sometimes questionable decision outcomes. As naval warfare becomes ever more complex, and various analytics and tactical aids are being introduced to the fleet at a rapid pace, human decision-makers will face greater information and time-pressure challenges. This could exacerbate the propensity for biased decision-making. Consequently, there is a need both to train individuals about the pitfalls of biases as well as to build systems that are designed to mitigate those biases.

Operational decision-making can create a lot of stress by itself, but the Navy and Marine Corps planning processes are subject to their own stresses as well. Each step of the planning process requires the collection of information, generation and analysis of multiple courses of action, and then choosing a single course of action to develop plans and orders for implementation.

This article will describe how several cognitive biases can affect decision-making, and then delve into how the Office of Naval Research (ONR)-funded Advanced Multi-echelon Planning Tool (AMPT) seeks to mitigate these biases. ONR is funding the Naval Information Warfare Center Pacific to develop AMPT as part of the Minerva Innovative Naval Prototype to modernize naval planning by integrating artificial intelligence and machine learning tools.

Cognitive Biases in Decision-Making

Table 1 provides a list of some of the more common decision biases, and there is evidence of many of these biases in naval history. For example, anchoring bias can lead to putting outsize importance on the earliest information received, which results in misunderstanding the problem space. From there, confirmation bias can cause subsequent information to support the suspected hypothesis. This can have disastrous outcomes, as was the case in the shooting down of an Iranian airliner in 1988 by USS *Vincennes* (CG 49), a state-of-the-art, Aegis-equipped missile cruiser. The crew detected radio signals from an airfield indicating a potentially hostile aircraft. When the airliner took off and ascended, on a course directly toward the ship, it was suspected as being the detected military aircraft. Simultaneously, *Vincennes* was actively evading Iranian gunboats, heightened the stress level amongst the crew. Eventually, a rapidly changing character readout display was misread to indicate a descending aircraft—an attack posture. Surface-to-air missiles were fired, and the airliner was destroyed and its 290 passengers and crew members were killed.

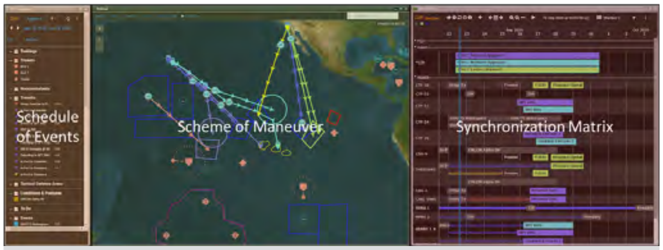
The *Vincennes* incident generated significant interest in several areas. The Office of Naval Research initiated the Tactical Decision Making under Stress program, which found that the distortion of time perception under stress could be ameliorated with displays showing how much time actually remained before decisions had to be made. Findings also led to the use of altitude-by-time graphical plots instead of changing numerical readouts to reflect current altitude change trends and history. Other research indicated a compromised ability to switch attention efficiently, resulting in cases where individuals would perseverate on particular issues at the expense of maintaining situation awareness in general.

Other biases have implications with decision-making in national defense. The sunk cost fallacy may cause decision-makers to stay in a fight for longer than may be otherwise desirable. Information pooling bias is less common, but highly relevant to naval operations. In this bias, team members are reluctant to sharing information that is only known to them, and instead focus on information more broadly known to other team members. Rajivan and Cooke (2018) studied this bias in the context of three-person cyber defense teams. They found that the most effective bias-reduction strategy was information mapping, where all information known to team members was critical compared to a Wiki-based information sharing capability or no mitigation strategy at all.

Decision biases are not easily overcome; general findings in this area have led some to conclude that decision biases are "hard-wired" in the brain. Korteling, Brouwer, and Toet (2018) argue for a neurobiological source of biases, where perceptual systems are biased to discriminate differences in what we see, hear, touch, etc. Motor systems are biased toward reacting rapidly and sometimes unconsciously. Together, these two systems are evolutionarily oriented toward rapid action, so the brain naturally defaults to using these decision-making heuristics that are prone to biased decision making.

Bias Type	Definition
Anchoring Bias	*Tendency to overweight the first information considered for an eventual decision. (Tversky and Kahneman, 1974)*
Confirmation Bias	*Selecting and interpreting information that supports a preconceived hypothesis. (Nickerson, 1998)*
Framing Effect	*Riskier decisions when outcomes are presented as potential loses instead of potential gains. (Tversky and Kahneman, 1981)*
Sunk Cost Fallacy	*The tendency to continue an activity if you have already invested time, effort or money into it. (Arkes and Blumer, 1985)*
Information Pooling Bias	*Tendency not to share information only known to oneself and instead focus on information more broadly known to others (Rajivan and Cooke, 2018).*

Table 1. Some common decision biases.



The sections of AMPT dynamically create the schedule of events, scheme of maneuver, and synchronization matrix, saving planners hours of labor-intensive processes. Graphics courtesy of author

Military operational planning represents a new area where artificial intelligence and analytics are increasingly being used to increase both speed and quality of decisions. AMPT is designed with the goal of mitigating bias in decision-making.

The Advanced Multi-Echelon Planning Tool

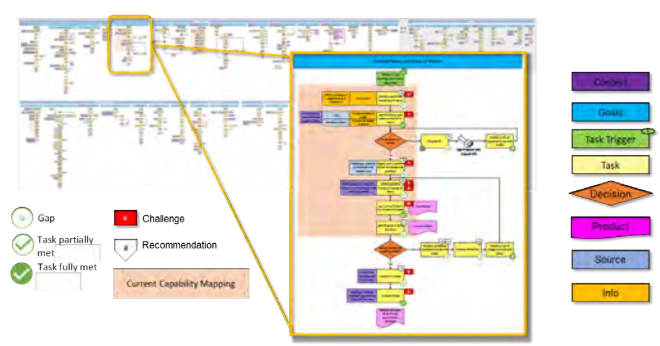
AMPT supports Maritime Operations Center and force-level planning, which focus on power projection and sustainability in a given region of the world. This tool provides a web-based framework to capture tasking and plans digitally in the form of common planning elements data structures. Business process models then call applicable machine learning services to provide planning recommendations. Planners are able to adjust mission priorities, acceptable risk levels, and constraints/restraints to guide the automated planning services. Planners then can select and modify individual elements to generate a final plan for subsequent machine evolution. Once a plan is generated, planners will be able to war game these recommended plans and explore manual adjustments via automated assessments from the same services used to generate initial alternate courses of action. The key to AMPT's success is that it facilitates rapid production of common planning products that the staff use as shown in Figure 1.

AMPT supports the planning workflow, starting from doctrine (such as NWP 5-01, Naval Operational Planning) and then validating with warfighters from the numbered fleets and the Maritime Operations Center training team. AMPT addresses the biggest challenges of current-day planning by building knowledge products automatically as information is entered into the system. Mapping AMPT capabilities onto the workflow in a gap analysis directly enables insight into how well the tool supports the tasks, decisions, and products of the planning team. The gap analysis then becomes extremely valuable as a means for communication with warfighters, as the AMPT team can highlight how problem areas are being supported or discuss plans for future development to address major gaps.

By moving toward a digital plan, planning data is available for artificial intelligence and machine learning services. AMPT's understanding of operational planning processes will automatically call these planning services as they are required and present the results from each on a unified planning experience (Figure 3). AMPT is developing novel visualizations to combine the information of multiple decision aids together to reduce the cognitive load on warfighters having to process all the available information. One example of this is with the "Gumball" design (Figure 4), which enables warfighters to quickly evaluate the feasibility of routes or areas across time without having to step through multiple time points to get individual answers. Two artificial intelligence services AMPT is currently utilizing are Smart Force Composition (SFC) and Specialized Plan Recommendation through Intelligent Template Extraction (SPRITE), a mission-plan template learning algorithm.

SFC seeks to optimize forces for military tasking, which is a nontrivial problem when accounting for variables such as situational awareness, unit weapon/sensor capabilities, tasking priorities, and enemy combatants. Four services (suitability, survivability, supportability, and selectability) are designed to indicate if a set of units assigned to a task contains the capabilities required to complete the task, how likely they are to survive it, if they have the required logistical support, and if they have the current ability to communicate without impeding task completion. These feed into the Composability Service that then calculates the minimum required force needed to meet a set task success probability threshold while maximizing the remaining force available for tasking. By applying techniques from operations research and machine learning, algorithms can recognize important aspects of different scenarios such as friendly and hostile unit capabilities (weapons, sensors, movement, etc.), environmental conditions (terrain), and task/objective priorities.

The SPRITE service can learn reusable templates from sample plans, recommend templates in context, and adapt templates to current mission needs. Generalization is accomplished through a combination of heuristic rules and relationship discovery methods that identify important connections among plan elements by



Detailed workflow of naval operational planning (NWP 5-01) from mission analysis to orders development and dissemination. The analysis also identified major challenges, gaps in capability, and mapping of artificial intelligence and machine learning services to specific sections of the workflow.

considering background knowledge related to force structures and capabilities. By embedding discovered relationships and constraints, templates can quickly be adapted to new missions. A visualization of the template enables a user to drill down to see the tasks as well as what types of resources are to be used, where, and when. After specifying required parameters, the template is automatically instantiated into the current AMPT plan. Users can make any necessary adjustments to finalize the task for the mission at hand.

Mitigating Decision-Making Bias

AMPT's user-centered design process, ranging from doctrinal analysis to working closely with warfighters, has led to a user interface that integrates advanced optimization algorithms and machine learning technologies that aid in all stages of planning. AMPT's design also supports bias reduction in warfighter decision-making.

Information pooling bias is reduced because of the collaborative nature of AMPT. The system allows the staff to enter and access all the information from a common plan. This results in the team working together to build up all aspects of the plan with AMPT providing the ability to layer that information onto the plan. This is a change from today where the team member information is commonly built separately and presented piece by piece instead of cohesively. Everyone on the team having all the information readily available is likely to make a big difference.

AMPT helps to reduce overconfidence bias because it allows for visualization of blue force capabilities relative to red force adversaries. This information is available at any point during a mission plan and considers multiple data sources. One example of this is the weather effect on missions, which can drastically change the capabilities on both sides of the fight. AMPT can pull in meteorological data and provide that to the battle management aids. These aids are then able to take in the current planned situation with meteorological data and provide clear visualizations of our capabilities versus the adversaries' enabling warfighters to make better informed decisions about the current state of capabilities.

The naval planning process requires the development and analysis of multiple courses of action. Traditionally, planners only explore one to two ideas because of the amount of time and difficulty in changing the products required by leadership. This reduces the interest to explore novel options and encourages the sunk cost fallacy because scrapping a course of action that has taken a lot of time and effort to develop is undesirable. AMPT automates aspects of the planning process and integrates with more information sources, allowing warfighters to develop and explore more actions and their associated products. Planners are then freed to explore more possibilities and make more drastic changes to actions under consideration, reducing the possibility of sunk cost fallacy.

Finally, AMPT's connections to more sources of data and the ability to integrate into the planning process automatically should reduce anchoring and confirmation biases by making more information available. Of course, information overload is a possibility with AMPT. The SFC and SPRITE services help warfighters synthesize this information, generate insight, and highlight information that may be otherwise overlooked.

Conclusion

Biases in decision making are common, difficult to detect by the person making the decision, and are challenging to mitigate through training. In naval contexts, biased decision making can have disastrous effects. Tools such as AMPT enable planners to use artificial intelligence and machine learning services collaboratively to maximize force projection while balancing acceptable multidomain constraints. This allows warfighters to spend more time on problems and less time on building the products; it also reduces potential sources of bias in multiple ways, including pooling all available information and reducing the feeling of sunk costs in a limited number of options. By taking a user-centered design philosophy to development, AMPT will provide an invaluable tool to the fleet to enable rapid and effective planning for the fights to come.

References

Arkes, H.R., and Blumer, C., "The Psychology of Sunk Cost," Organ. Behav. Hum. Decis. Process 35 (1985): 124–40, doi: 10.1016/0749-5978(85)90049-4.

Korteling J.E., Brouwer, A.M., and Toet A., "A Neural Network Framework for Cognitive Bias," Front. Psychol. 9 (2018):1561, doi: 10.3389/fpsyg.2018.01561.

Nickerson, R.S., "Confirmation Bias: A Ubiquitous Phenomenon in Many Guises," Rev. Gen. Psychol. 2 (1998): 175–220, doi: 10.1037/1089-2680.2.2.175.

Rajivan, P., and Cooke, N.J., "Information-Pooling Bias in Collaborative Security Incident Correlation Analysis," Human Factors 60, no. 5 (2018): 629-35, doi: 10.1177/0018720818769249.

Tversky, A., and Kahneman, D., "Judgment under Uncertainty: Heuristics and Biases," Science 185 (1974): 1124–31, doi: 10.1126/science.185.4157.1124.

Tversky, A., and Kahneman, D., "The Framing of Decisions and the Psychology of Choice," Science 211 (1981): 453–8, doi: 10.1126/science.7455683.

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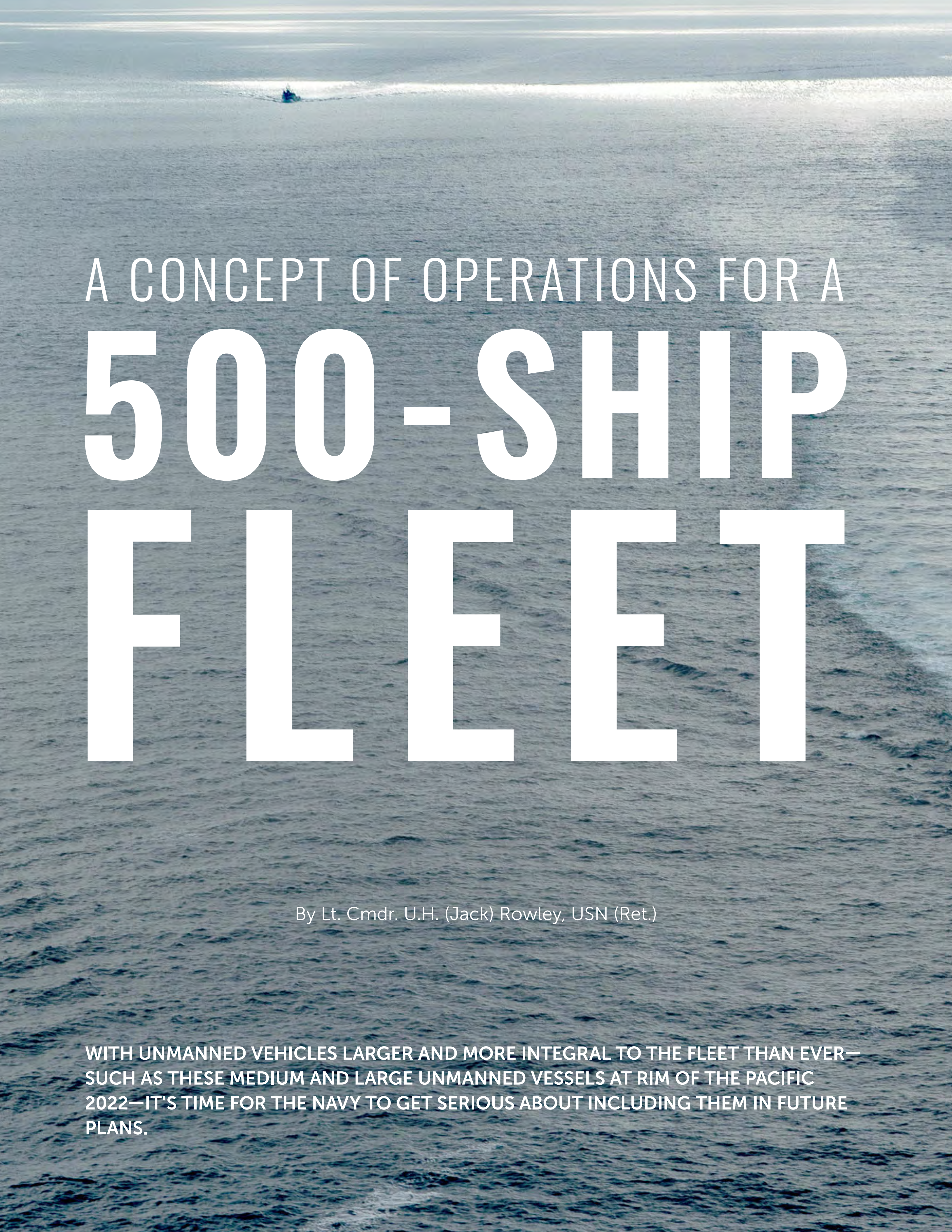

A CONCEPT OF OPERATIONS FOR A 500-SHIP FLEET

By Lt. Cmdr. U.H. (Jack) Rowley, USN (Ret.)

WITH UNMANNED VEHICLES LARGER AND MORE INTEGRAL TO THE FLEET THAN EVER—SUCH AS THESE MEDIUM AND LARGE UNMANNED VESSELS AT RIM OF THE PACIFIC 2022—IT'S TIME FOR THE NAVY TO GET SERIOUS ABOUT INCLUDING THEM IN FUTURE PLANS.

Photo by MC3 Terrin Hartman

In an address at the 2022 AFCEA/US Naval Institute "West" conference, Chief of Naval Operations Admiral Michael Gilday revealed the Navy's goal to reach 500 ships by adding approximately 150 unmanned maritime vehicles to the Navy's inventory. This plan added additional detail to the Navy's Unmanned Campaign Framework.

Most recently, previous speeches and interviews alluding to the number of unmanned surface vehicles the Navy intends to field culminated in the issuance of the Chief of Naval Operations NAVPLAN 2022 and Force Design 2045, both of which call for 350 manned ships and 150 large unmanned maritime vehicles. These official Navy documents provide the clearest indication yet of the Navy's plans for a future fleet populated by large numbers of unmanned surface vehicles (USVs).

However, Congress has been increasingly reluctant to authorize the Navy's planned investment of billions of dollars on USVs until the service can come up with a concept of operations for using them. In fairness, Congress has a point. The Navy has announced plans to procure large numbers of unmanned systems—especially large and medium unmanned surface vehicles—but a concept of operations, one in even the most basic form, has yet to emerge.

While the Navy appears to be committed to buying large numbers of unmanned surface vehicles, it must come up with a convincing concept of operations for how they will be used during a conflict against a determined adversary. Unless or until the Navy can evolve such a concept, it is unlikely that a 500-ship fleet populated by 150 unmanned surface vehicles will ever reach fruition.

A Bridge to the Navy After Next

During the height of what has become known as the Reagan defense buildup in the mid-1980s, the Navy evolved a strategy to build a "600-ship Navy." That effort resulted in a total number of Navy ships that reached 594 in 1987. That number has declined steadily during the past 35 years, and today the Navy has less than half the number of active, commissioned ships it had then.

The increasing cost to build ships, and especially the cost to man these vessels (70 percent of the total ownership costs of surface ships is the cost of the personnel who operate these vessels over their lifecycle), and the fact that the Navy is literally wearing these ships out more rapidly than anticipated, and it is easy to see why the Navy has great difficulty growing the number of manned surface vessels.[1]

The rapid growth of the technologies that make unmanned surface vehicles increasingly capable and affordable has provided the Navy with a potential way to put more hulls in the water. This has led to the Navy's commitment to field a force comprising 150 large and medium unmanned surface vehicles.[2]

Some have noted that the Navy's Unmanned Campaign Framework is high on aspiration but low on specifics.[3] Said another way, this vision is good as far as it goes, but the Navy has endured withering criticism from a skeptical Congress that is not warm to the service spending billions of dollars on USVs until the Navy can come up with a concept of operations for using them.

As the Navy looks to allay congressional concerns and accelerate the fielding of unmanned maritime systems, the emphasis should be on no longer thinking of each unmanned maritime system as a "one-off," but rather to package these together as multiple-sized and multifunction vehicles designed for specific missions.[4] The emphasis must remain on USV ship design that is modular to accommodate sensors, weapons, and payloads for specific missions, where the platform remains constant and the modularity within the platform allows for the "modular shift" to support multiple missions.[5]

A Concept of Operations

The concept of operations proposed is to marry various size unmanned surface, subsurface, and aerial vehicles to perform Navy missions—current and future—as the Navy After Next evolves. Simply put, the Navy can use the emerging large unmanned surface vehicle as a "truck" to move smaller unmanned vehicles into the battle space in the increasingly contested littoral and expeditionary environment.

There are numerous important Navy missions this integrated unmanned solution could accomplish, but this article will focus on two: intelligence, surveillance, and reconnaissance; (ISR) and mine countermeasures (MCM). There are many large, medium, small, and ultra-small unmanned systems that can be adopted for these missions. The technical challenge remains that they must be designed to ensure that the "multiple sized" unmanned systems associated with these missions can be adapted to work together in a common mission goal.

This article will offer concrete examples using commercial unmanned systems that have been employed in recent Navy and Marine Corps events. In each case, these systems not only demonstrated

The medium-displacement unmanned vessel Sea Hunter transits the Pacific Ocean during the Rim of the Pacific exercise in 2022. Photo by MC1 Tyler R. Fraser

An early variant of the Common Unmanned Surface Vehicle (CUSV) autonomously conducts maneuvers on the Elizabeth River during its demonstration during Citadel Shield-Solid Curtain 2020 at Naval Station Norfolk. Photo by MC3 Rebekah M. Rinckey

mission accomplishment, but also the hull, mechanical, and electrical attributes and maturity that Congress is demanding before proceeding ahead with robust acquisition of Navy unmanned systems.

While there are a wide range of medium unmanned surface vehicles (MUSVs) that can potentially meet the Navy's needs, there are three unmanned surface vehicles that appear to be furthest along in the development cycle. These vehicles cover a wide range of sizes, hull types, and capabilities.

The Vigor Industrial Sea Hunter and the follow-on Sea Hawk are the largest of the three. The Sea Hunter was launched in 2016 and was built at a cost of $20 million.

- A 132-foot-long trimaran with twin screws, powered by two diesel engines
- Weighs 135 tons, which includes 40 tons of fuel; the craft can carry a payload up to an additional 10 tons
- Cruise speed of 12 knots and a burst speed of 27 knots
- Designed to be under way unmanned for 70 days; at cruise speed, it will have a range of 10,000 nautical miles
- Can operate in sea state 5 and be survivable in sea state 7.

The Textron monohull Common Unmanned Surface Vessel, now referred to as the MCM-USV, features a modular, open architecture design.

- A length of 39 feet, a beam of 11 feet, and a draft of 26 inches
- Propulsion is provided by a twin-screw diesel
- Weighs 17,000 pounds and can carry a payload of up to 3,500 pounds
- A cruise speed of 12 knots with burst capability up to 35 knots
- An endurance range at cruise speed of 1,200 nautical miles
- Designed to operate in sea state 4 and be survivable in sea state 5.

The Maritime Tactical Systems catamaran hull unmanned surface vehicles include the Devil Ray T24, T38, and T50 craft. All three of these USVs feature a modular and open architecture design. The composite carbon fiber hull is designed to minimize the hydrodynamic drag by moving the laminar-to-turbulent flow breakpoint further aft.

- The T24, T38, and T50 range in size from 24-50 feet long, in beam from 10-12 feet wide, and in draft from 14-28 inches depth
- Weight varies from 7,300-13,000 pounds, with payloads ranging from 1,800-10,000 pounds
- Cruise speeds vary from 15-40 knots, with burst speeds from 60-80 knots
- At cruise speed, the vehicles' endurance range varies between 600-2,000 nautical miles
- The vehicles can operate in sea state 4/5 with survivability in sea state 7.

Each of these MUSVs is a viable candidate to be part of an integrated unmanned solution concept of operations. Part of evolving an operational concept for employing unmanned surface vehicles involves placing them in the environment where they can perform their missions of ISR and MCM. This is not a trivial task, especially since the United States must be prepared to deal with peer and near-peer adversaries with robust anti-access and area denial capabilities.

If the Navy wants to keep its capital ships out of harm's way, it will need to surge unmanned maritime vehicles into the contested battlespace while its manned ships stay out of range of adversary systems, sensors, and weapons. Small and medium USVs, unmanned aerial vehicles, and unmanned undersea vehicles need a larger vehicle (LUSV) to deliver them to an area near the battlespace. The Navy envisions LUSVs as being 200 feet to 300 feet in length and having full-load displacements of 1,000-2,000 tons.[6]

Depending on the size that is ultimately procured, the LUSV could carry several MUSVs and deliver them, largely covertly, to a point near the intended area of operations. MUSVs would then be sent independently to perform the ISR mission, or alternatively, could launch one or more smaller vehicles. Building on work conducted by the Navy laboratory community and sponsored by the Office of Naval Research, the T38, for instance, will have the ability to launch unmanned aerial vehicles to conduct overhead ISR.

For the MCM mission, the LUSV can deliver several MUSVs equipped with mine-hunting and mine-clearing systems. These vessels can then undertake the "dull, dirty, and dangerous" work previously conducted by Sailors who had to operate in the minefield. Given the large mine inventory of peer and near-peer adversaries, this methodology may well be the only way to clear mines safely in the future.

This scenario and concept of operations is built around an expeditionary strike group that is underway in the western Pacific. This strike group includes three LUSVs under supervisory control from a large amphibious ship. The Chief of Naval Operations suggested this concept of operations in early 2022 when he noted that he "wants to begin to deploy large and medium-sized unmanned vessels as part of carrier strike groups and amphibious ready groups in 2027 or 2028, and earlier if I can."[7]

Supervisory control of these three LUSVs is provided from a control station on a single ship. The supervisory control station includes seating for a single operator who controls multiple USVs, in addition to an adjoining sensor/payload operator monitoring and controlling the mission sensors/payloads onboard each of the craft. A single supervisory operator station will be required for each LUSV. The LUSV will then be further configured with multiple smaller unmanned vehicles.

Operational Scenario

The expeditionary strike group in the western Pacific is on routine patrol about 500 nautical miles from the nearest landfall. An incident occurs in their operating area and the strike group is requested to obtain reconnaissance of a near-shore littoral area, associated bays, and river accesses and determine if the entrance to a specific bay has been mined to prevent ingress. The littoral coastline covers 200 nautical miles. This area must be reconnoitered within 24 hours without the use of air assets.

Command staff decides to dispatch the three LUSVs for the mission: two are configured with four MUSV-ISR craft each and the third is configured with four MUSV-MCM vessels. The single supervisory control station for the three LUSVs remains manned in the mothership for the initial transit to the MUSV departure point, at which time two other control stations will be manned to provide further supervisory control.

The three LUSV depart the strike group together in a preset autonomous pattern for 250 nautical miles to a waypoint that is central to the 200-nautical-mile ISR scan area, 250 nautical miles from shore. At this waypoint, each LUSV will stop and dispatch the smaller craft and then wait at this location for their return. Steaming at a cruise speed of 25 knots, the waypoint is reached in about ten hours. At the dispatch waypoint,

The Devil Ray T38 is one of a family of medium-sized craft built by Maritime Tactical Systems. Photo courtesy of author the two additional supervisory control stations are manned (now one per LUSV) and command is given by the supervisory controllers to launch the smaller USVs.

Two MUSV-ISR craft are launched from each of the two ISR LUSVs. The autonomous mission previously downloaded specifies a waypoint location along the coast for each of the four craft. These waypoints are 50 nautical miles apart from each other, indicating that each of the four MUSVs will have an ISR mission of 50 nautical miles to cover.

Two MUSV-MCM craft are launched from the third LUSV. The autonomous mission previously downloaded has them transit independently along different routes to two independent waypoints just offshore of the suspected mine presence area, where they will commence mine-like-object detection operations.

In this manner, each of the six craft will be transiting independently and autonomously to their next waypoint which will be the mission execution start point. The transit from the LUSV launch point, depending on the route, will be about 250-300 nautical miles to their near-shore waypoints. Transit will be at 70-80 knots to their mission start waypoint near the coast. Transit time is between four and five hours.

The plan is for each of the MUSV-ISR craft to complete their scan in four to five hours each, and for the two MUSV-MCM craft to scan the sea bottom and the water column for the presence of mine-like objects in four to five hours at a scan speed of six to eight knots.

The MUSVs transit to the objective area and conduct their missions. The timeline for the entire mission is as follows:

- LUSV detach strike group to launch point and deploy six MUSVs: 10-12 hours
- MUSVs transit from launch point to ISR/MCM mission start waypoints: 4-5 hours
- ISR/MCM mission time from start to completion: 4-5 hours
- MUSVs transit from mission completion point back to LUSV for recovery: 4-5 hours
- LUSV recover MUSVs and return to strike group: 10-12 hours

Even with the expeditionary strike group 500 nautical miles from shore, the strike group commander had the results of the ISR and MCM scan of the shoreline littoral area within 20-24 after the departure of the LUSVs from the strike group. The LUSVs were back on station in the strike group in less than 40 hours, ready for the next mission scenario.

Moving Forward with Effective Deployment

The Chief of Naval Operations envisions large and medium unmanned vessels as part of carrier strike groups and amphibious ready groups later this decade. His goal is to take an evolutionary approach and to scale up unmanned surface vessels in order to have large numbers of USVs available to commanders.[8] This nested dolls approach can accelerate this effort.

I am certain that readers of Future Force can think of additional concepts of operation for ways that unmanned vehicles can perform missions that are important—and vital—for the Navy. I offer this one as a starting point for further dialogue in the community.

This is not a platform-specific solution, but a concept. When fleet operators see a capability with different-sized, commercial unmanned platforms in the water working together and performing the missions presented in this article, they will likely press industry to produce even more-capable platforms to perform these missions.

While evolutionary in nature, this disruptive capability delivered using emerging technologies can provide the Navy with near-term solutions to vexing operational challenges, while demonstrating to a skeptical Congress that the Navy does have a concept-of-operations to employ the unmanned systems it wants to procure.

References

[1] Megan Eckstein, “Navy Adds ‘Wholeness Balance Reviews’ to Budget Process to Consider Total Ownership Costs,” USNI News, January 18, 2018.
[2] Sam Lagrone and Mallory Shelbourne, “CNO Gilday: ‘We Need a Naval Force of Over 500 Ships’” USNI News, February 18, 2022; Sam Lagrone, “Navy’s Force Design 2045 Plans for 373 Ship Fleet, 150 Unmanned Vessels,” USNI News, July 26, 2022.
[3] David Larter, “U.S. Navy’s New Unmanned Plan Has ‘Buzzwords and Platitudes’ but Few Answers,” Defense News, March 17, 2021.
[4] Tim Gallaudet, “Three Ways the Navy Can Surge Its Unmanned Surface Force,” Real Clear Defense, February 26, 2022.
[5] Justin Katz, “Navy Needs to Prep for Unmanned Integration, Says SWO Boss,” Breaking Defense, July 26, 2021.
[6] Ronald O’Rourke, Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress, CRS Report 45757.
[7] Bradley Peniston, “Navy Chief Sees Robot Ships Alongside Aircraft Carriers Within Five Years,” Defense One, February 16, 2022; Sam LaGrone, “CNO Gilday Taking a More ‘Realistic’ Approach to Unmanned Systems in the Fleet,” USNI News, February 16, 2022.
[8] Justin Katz, “From 7 Classified ‘Spirals’ to Coming Robotic Ships: Gilday on Navy’s Unmanned Task Force,” Breaking Defense, February 17, 2022; Megan Eckstein, “Unmanned or Minimally Manned Vessels Could Deploy Alongside Strike Groups as Soon As 2027,” Defense News, February 17, 2022.

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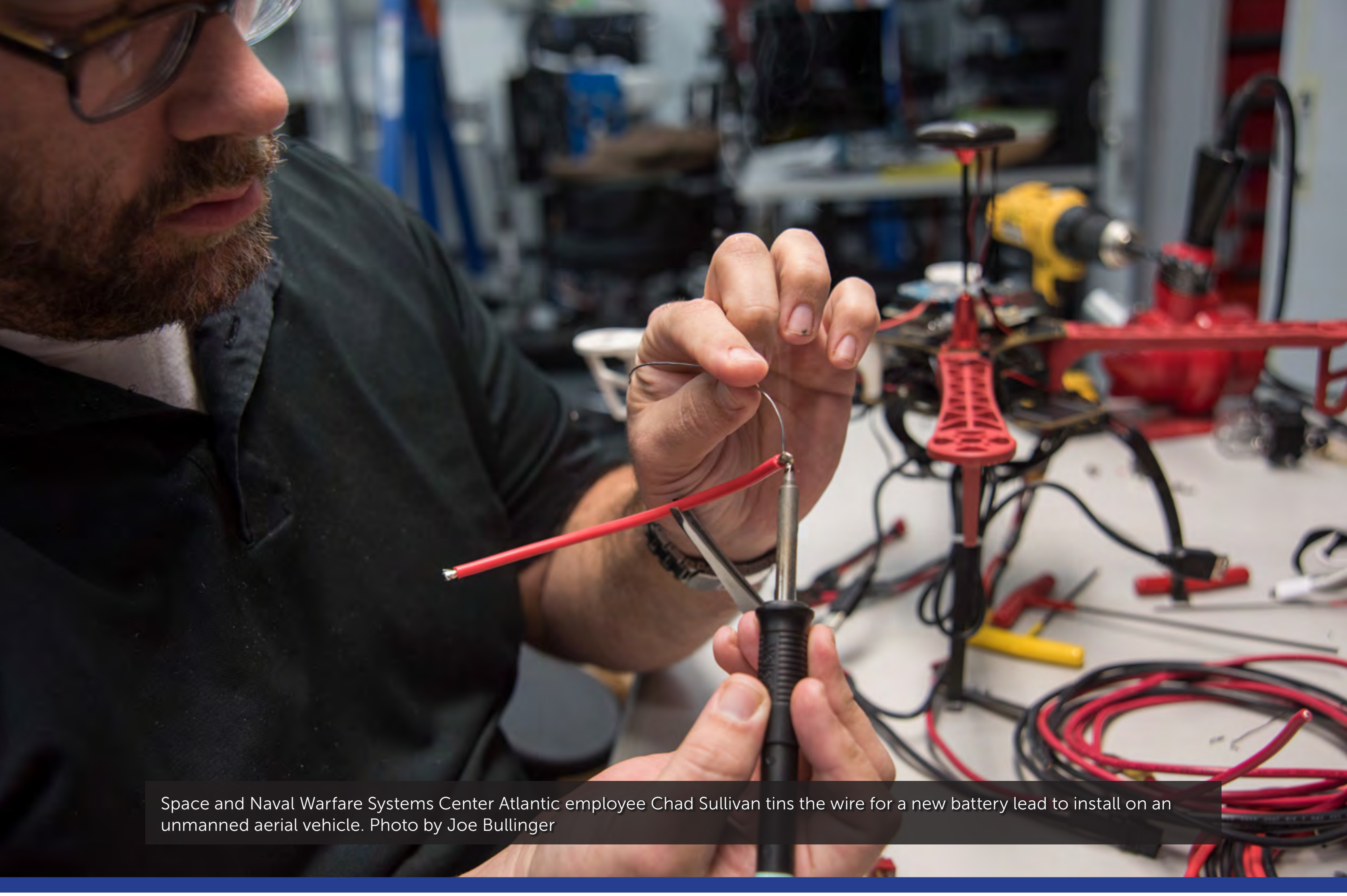

Space and Naval Warfare Systems Center Atlantic employee Chad Sullivan tins the wire for a new battery lead to install on an unmanned aerial vehicle. Photo by Joe Bullinger

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