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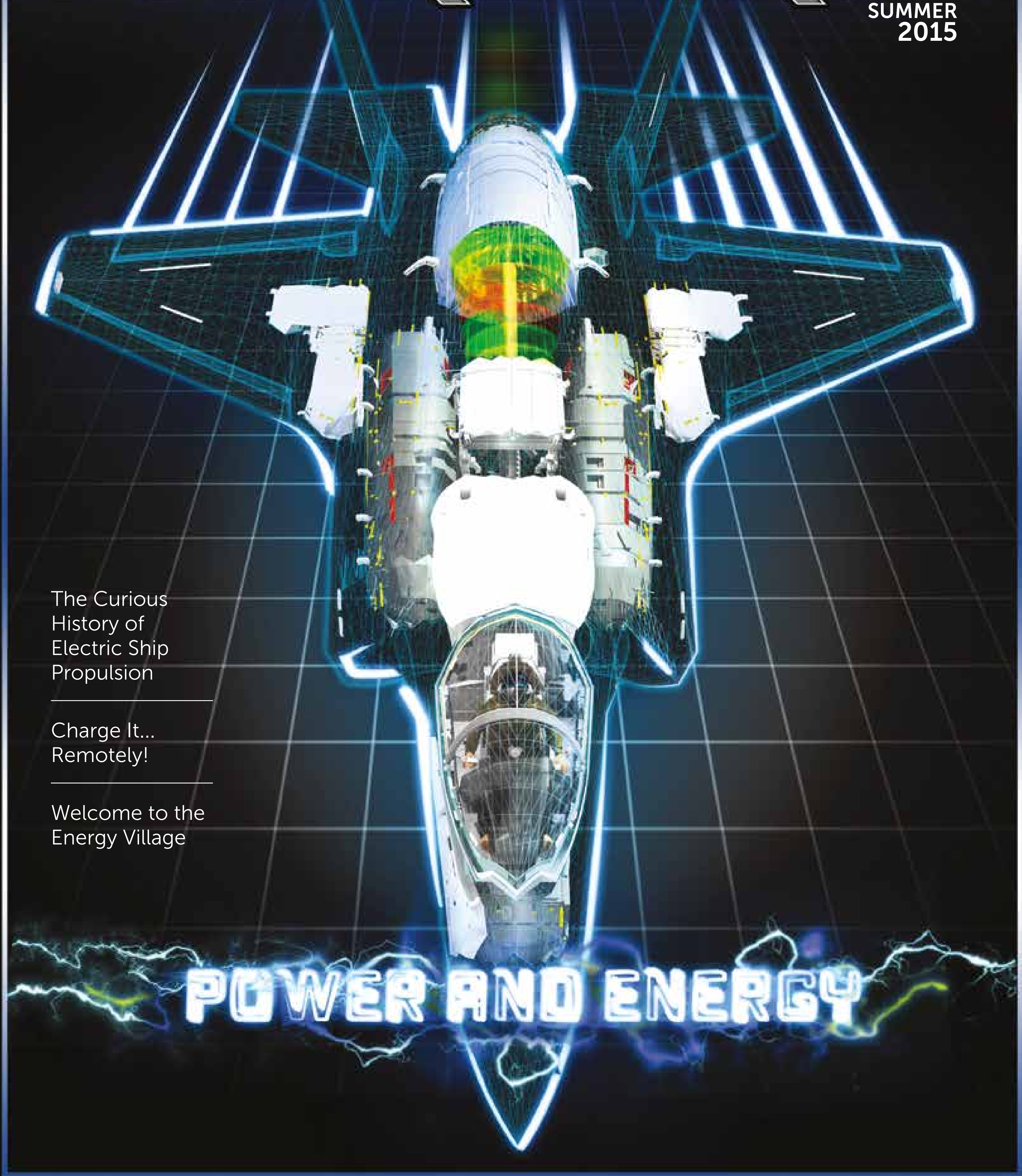

The Curious History of Electric Ship Propulsion

Charge It... Remotely!

Welcome to the Energy Village

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FUTURE FORCE

NAVAL SCIENCE AND TECHNOLOGY MAGAZINE

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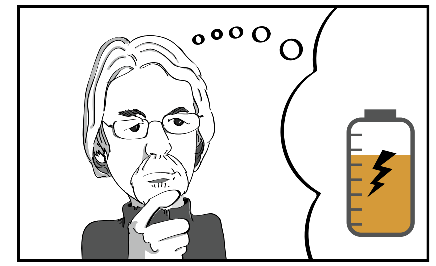

Future Force is a professional magazine of the naval science and technology community. Published quarterly by the Office of Naval Research, its purpose is to inform readers about basic and applied research and advanced technology development efforts funded by the Department of the Navy. The mission of 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: *Power and Energy,* Illustration by Alvin Quiambao

SPEAKING OF S&T ▶▶ Dr. Joseph T. Arcano Jr.

Napoleon is credited with saying "an army marches on its stomach." In much the same vein, our Navy and Marine Corps assets move on their fuel capacity. Endurance, speed, range, and overall warfighting capability are dramatically impacted by the advancement of power and energy technologies, and the associated fuel resources required. The Department of the Navy is committed to reducing dependence on fossil fuels, optimizing endurance on the occasions when such fuels are needed, and finding ways to use alternative fuels. Optimizing our power and energy portfolio and technology advancements in those arenas will lessen the negative impact this challenging logistical tail has on our operational forces.

Across the Naval Research and Development Establishment (NR&DE), scientists and engineers are pursuing many technological breakthroughs focusing on power and energy. As you can see from the diverse stakeholders and their associated power and energy topics represented in the pages of this issue of *Future Force*, these efforts cross a wide swath of domains.

In June the Naval Surface Warfare Center (NSWC) Carderock Division hosted Energy Storage Summit II at our headquarters in West Bethesda, Maryland, building on the summit in October 2014 at NSWC Crane Division. Interested parties from across the Naval Research Enterprise met to engage each other with energy storage as the focal point. This summit brought together some of the best and brightest minds working to reduce the cost of storing energy to support a wide range of future naval capabilities in the air, at sea, and on land.

A highlight was hearing from Mateo Jaramillo, the director of Tesla Energy at Tesla Motors, regarding Tesla's efforts in the energy arena and how we can move to a sustainable energy future. The summit was a success, and there will no doubt be many more—a showcase of the NR&DE's collaborative efforts on future technologies, and an opportunity to continue refining the plans, programs, and concepts that will ultimately help us reach our goal of reducing full lifecycle costs of energy storage to the Navy and Marine Corps.

That's an ambitious goal. But it's just one part of the Navy's commitment to power and energy: to identify, evaluate, and accelerate the transition of solutions to increase our energy efficiency. Collectively and individually we need to come up with the "game changers," the "disruptive technology advancements" that we can use for getting our Navy and Marine Corps customers longer, more affordable endurance with greater mission effectiveness.

This summer issue of *Future Force* features stories on technologies both in development and fielded. It includes highlights of activity at the Naval Surface Warfare Center, the Naval Undersea Warfare Center, the Naval Research Laboratory, the Office of Naval Research, and the Space and Naval Warfare Systems Command. All of us are committed to keeping our Sailors and Marines safe and our Navy the best in the world. These articles highlight just some of the tremendous efforts the Navy science and technology community is working on to meet this goal. I hope you enjoy reading about them.

Dr. Arcano is the technical director of the Naval Surface Warfare Center Carderock Division.

Power and Energy

The systems, materials, fuels, and other technologies that provide motive and labor force to the machines, vehicles, and personnel of the fleet and force.

Photo by PO1 Steven King

Opposite, Dr. Joseph T. Arcano (far right) hosts Chief of Naval Operations Admiral Jonathan Greenert (fourth from right) at the Naval Surface Warfare Center Carderock Division.

Photo by MCC Peter D. Lawlor

By Colin E. Babb

THE CURIOUS HISTORY OF ELECTRIC SHIP PROPULSION

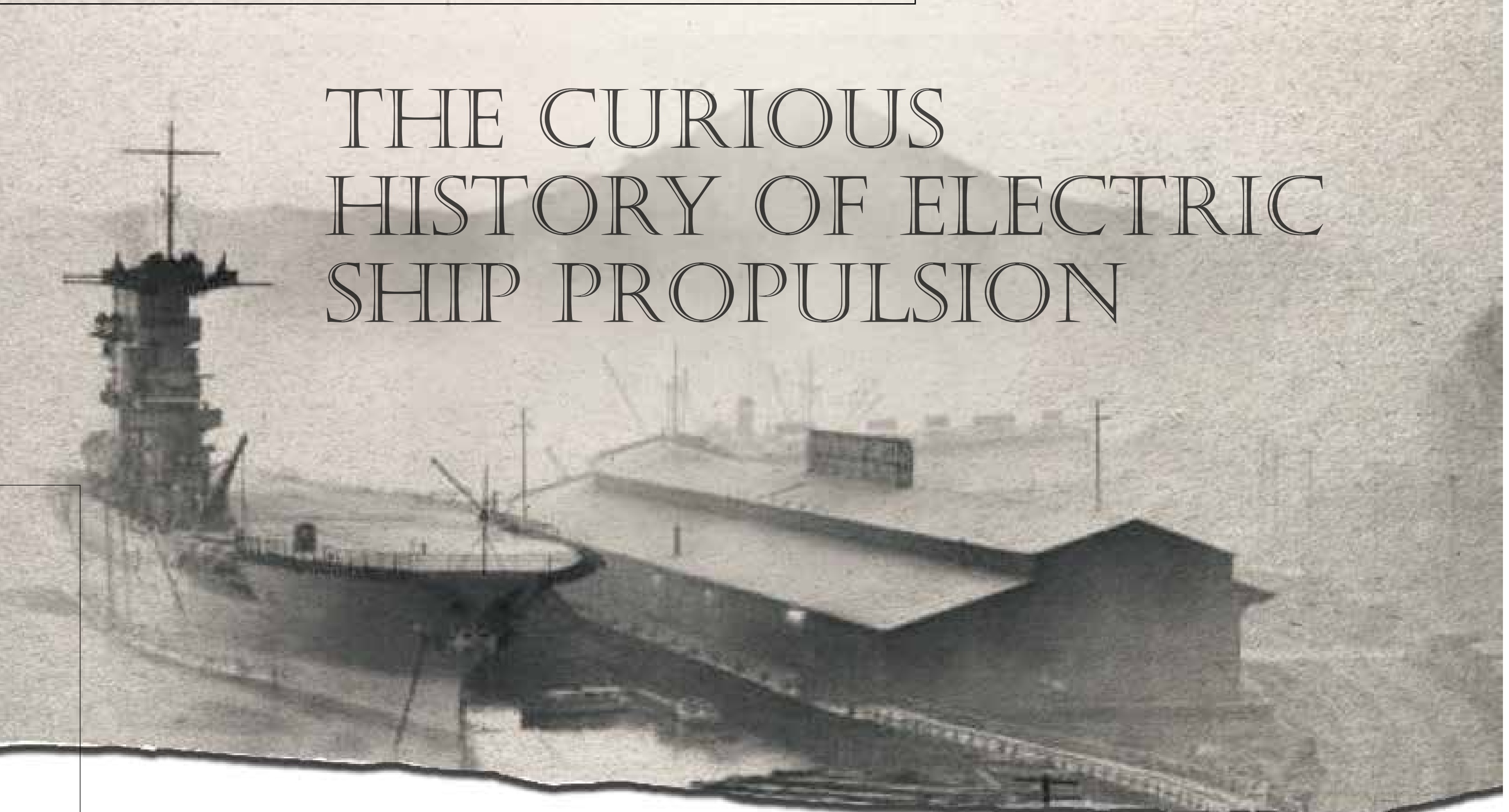


Photo courtesy of Tacoma Public Library

In 1929, USS *Lexington* (CV 2) used its electric propulsion system to power the city of Tacoma, Washington, during an local energy crisis.

For more than a decade, naval engineers and others have been calling for the introduction of the "all-electric" ship in the US Navy. With the increasing electrical needs of communications and radar systems and the rise of entirely new energy-hungry technologies such as lasers and electromagnetic railguns, proponents argue that warships of the near future will demand electric-drive systems that can distribute power among propulsion, communications, weapons, and other ship systems as needed. While the systems needed to power ships are more sophisticated than ever, the idea of the electric ship is, in fact, an old one, and for much of the 20th century the Navy had at least several and sometimes numerous ships powered by electric drive.

What distinguishes electric propulsion and all-electric ships, in the simplest terms, is that the machinery for generating power and the machinery for propelling the ship are not mechanically connected. For the first century of steam propulsion on ships, most engines were joined directly to propellers or paddlewheels through the use of rods and pistons—all falling under the general category of reciprocating engines. Very early in the 20th century, steam-driven turbines began to appear (HMS *Dreadnought*, famous for the novelty of its all-big-gun armament, also happened to be the first major warship to receive this new type of propulsion in 1906). This engine consisted of a high-revolution turbine connected by reduction gears to the more slowly spinning propeller. In an electric drive, the power-generating turbine is connected only electrically to a separate motor or motors, each of which drives a propeller. The most important advantage of such a system is that each component can operate at maximum efficiency—the turbine can spin at consistently high revolutions, and the propeller can be set at the most efficient revolutions for any given speed or situation. In addition, there is no need for a long propeller shaft, freeing room in the ship for other machinery.

A central figure in the history of the Navy's adoption of electric drive is William Le Roy Emmet, a graduate of the Naval Academy Class of 1881 and a longtime engineer at General Electric. Emmet's Navy career was cut short in 1883 after his initial post-academy cruise because of a new law that severely limited the number of officers in the service. Forced to find employment elsewhere, Emmet drifted into electrical engineering and was soon building electric motors for urban rail projects across the Midwest. Working at Edison General Electric and then the General Electric Company after it formed in 1892, Emmet was involved in many of the company's biggest early ventures, including building turbines for the first major hydroelectric power plant near Buffalo, New York. A brief return to naval service during the Spanish War of 1898 reintroduced Emmet to the "New Navy," coinciding with General Electric's turn toward steam turbine projects that eventually would be shopped to the Navy.

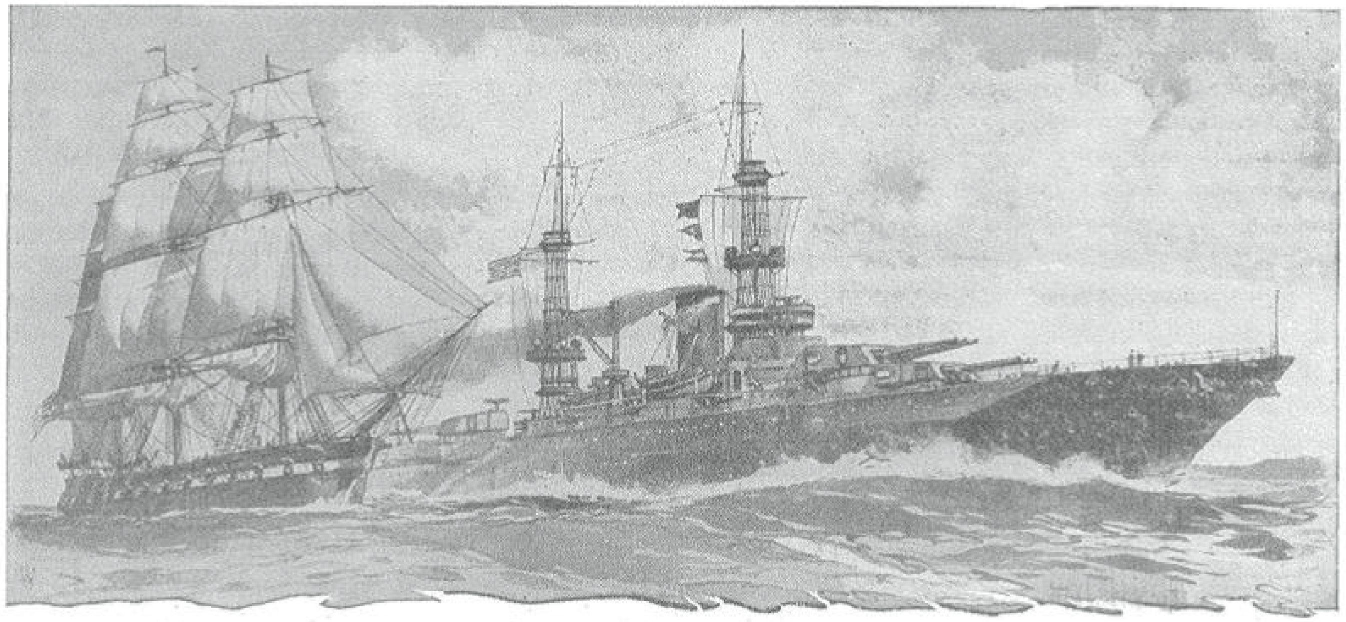
In 1908, according to historian William McBride, Canadian inventor Reginald Fessenden submitted a proposal to the Navy for a turboelectric drive that was rejected. Fessenden, however, was allowed to contact other companies that might be interested in the idea. Emmet at General Electric proved enthusiastic about the possibility of turboelectric drive and formulated detailed drawings from Fessenden's proposal. Emmet outlined his ambitious plans in a lengthy paper in the Transactions of the Society of Naval Architects and Marine Engineers in 1909. Describing two systems—the first being a hybrid electric/steam turbine combination, the other a pure turboelectric drive—Emmet advocated for the installation of electric drives in the Navy's battleships, even though he admitted in practice they had never been tested on anything larger than firefighting boats in Lake Michigan. In Emmet's hands, the electric drive acquired a significant ally in Secretary of the Navy George von Lengerke Meyer. Leveraging an endorsement of turboelectric drive from the Navy's General Board, Meyer authorized the installation of electric propulsion in one of three new coal-hauling colliers that began construction in 1910.

In an attempt to determine the most efficient and effective of the three types of propulsion, the Navy decided that each of the three colliers would have a different engine. In addition, installing new equipment on these noncombatant vessels would avoid the risky step of evaluating them on expensive battleships. The three colliers were: USS *Cyclops* (AC 4), which received reciprocating engines; USS *Neptune* (AC 8), which received steam turbines; and USS *Jupiter* (AC 3), the last of the three to be built in 1912, which was equipped with turboelectric drive. The decision was prudent as well as practical—although they were auxiliaries, the colliers' size (20,000 tons) was comparable to the battleships being laid down at the same time (22–26,000 tons). Once *Jupiter* underwent trials in 1913, the ship proved to be a success and, according to a report by chief engineer S.M. Robinson, exceeded General Electric's economy predictions over the rival engines by 18 percent. Emmet also triumphantly declared in his own report on the trials that, "If my first design for a warship made over four years ago [in 1909] had been accepted by the Navy Department, the vessel produced would have been very greatly superior in respect to economy, reliability, weight, simplicity, and cruising radius to any ship now afloat."

William Le Roy Emmet (1858-1941) designed the Navy's first electric propulsion systems. Image courtesy of Philip Hone Williams.

Meyer's successor, Josephus Daniels, gave Emmet the opportunity he was looking for in 1915 by ensuring that electric drive would go in the battleship USS *New Mexico* (BB 40), the first major warship to be electrically driven. In 1916 and 1917, however, electric drive would be at the center of a major debate between the Navy and the nation's shipbuilders as both groups prepared plans for a host of new battleships proposed under 1916 legislation intended to make the Navy "second to none." One of the interesting features of the controversy was that it pitted the Bureau of Steam Engineering as the proponent of (ostensibly more progressive) turboelectric propulsion for the Navy's latest battleships, against many of the nation's biggest shipbuilders, which lobbied against the new technology as a threat to traditional propulsion (and higher profits). Initially skeptical of electric drive, the bureau was won over by *Jupiter*'s success. Shipbuilders, however, balked at the increased costs of producing the new drives, which were more complex than steam turbines or reciprocating engines.

With the help of vocal bureau spokesmen and, according to McBride, a host of luminaries such as Nicola Tesla who favored electric drive, public opinion swung toward approval of the new system and opposition from industry abated. Five other battleships—USS *Tennessee* (BB 43), USS *California* (BB 44), USS



The "Constitution" of To-day—Electrically Propelled

THE U. S. S. "New Mexico," the first battleship of any nation to be electrically propelled, is one of the most important achievements of the scientific age. She not only develops the maximum power and, with electrical control, has greater flexibility of maneuver, which is a distinct naval advantage, but also gives greater economy. At 10 knots, her normal cruising speed, she will steam on less fuel than the best turbine-driven ship that preceded her.

The electric generating plant, totaling 28,000 horsepower, and the propulsion equipment of the great super-dreadnaught were built by the General Electric Company. Their operation has demonstrated the superiority of electric propulsion over old-time methods and a wider application of this principle in the merchant marine is fast making progress.

Six auxiliary General Electric Turbine-Generators of 400 horsepower each, supply power for nearly 500 motors, driving pumps, fans, shop machinery, and kitchen and laundry appliances, etc.

Figures that tell the Story of Achievement

Length—624 feet
Width—97 feet
Displacement—32,000 tons
Fuel capacity—a million gallons (fuel oil)
Power—28,000 electrical horsepower
Speed—21 knots

Utilizing electricity to propel ships at sea marks the advancement of another phase of the electrical industry in which the General Electric Company is the pioneer. Of equal importance has been its part in perfecting electric transportation on land, transforming the potential energy of waterfalls for use in electric motors, developing the possibilities of electric lighting and many other similar achievements.

As a result, so general are the applications of electricity to the needs of mankind that scarcely a home or individual today need be without the benefits of General Electric products and service.

An illustrated booklet describing the "New Mexico," entitled, "The Electric Ship," will be sent upon request. Address General Electric Company, Desk 44, Schenectady, New York.

General Electric Company

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Colorado (BB 45), USS *Maryland* (BB 46), and USS *West Virginia* (BB 48)—would receive electric drives over the next five years, as would the battlecruisers USS *Lexington* (CC 1) and USS *Saratoga* (CC 3), which would be converted midway through their construction into aircraft carriers. (Consequently, from 1920—when *Jupiter* was converted into the first US aircraft carrier, USS *Langley* [CV 1]—until 1934, all US aircraft carriers had electric drive.)

The first generation of electric drives, however, never proved in practice as radically more efficient than their mechanical rivals as their proponents had theorized, and these were the last major ships to receive electric systems. *Lexington* proved the versatility of electric drive, however, when in late 1929 and early 1930 it provided power for the city of Tacoma, Washington, during a drought that had depleted the town's power-generating reservoir.

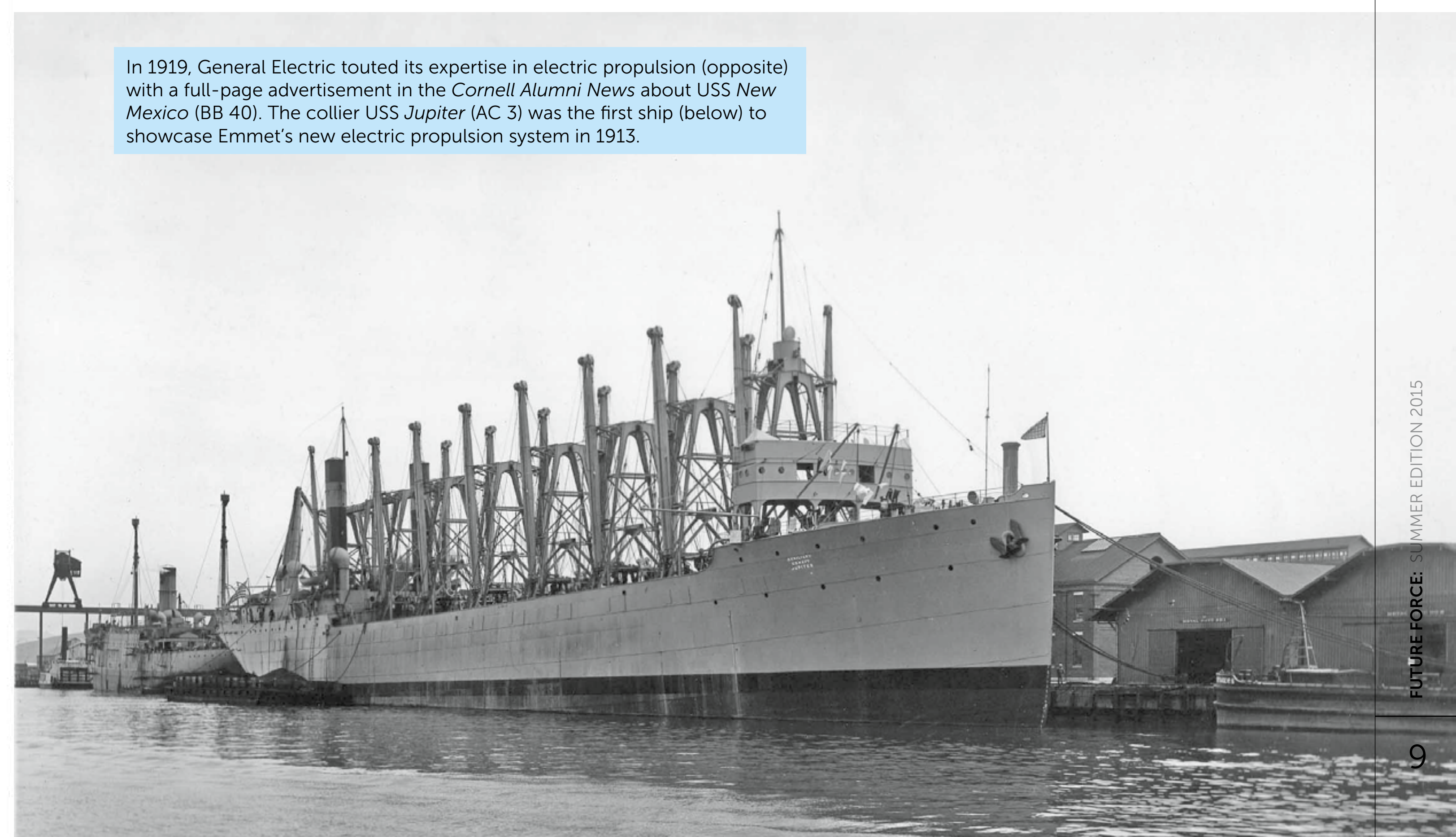
Electric drive would see longer life in smaller vessels, such as the 102 members of the *Buckley* (DE 51) class of destroyer escorts built during World War II, as well as several classes of fast transports. Two submarines—USS *Tullibee* (SSN 597) and USS *Glenard P. Lipscomb* (SSN 685)—also had electric drives (the latter was the last major ship in the US Navy to use electric drive before the modern era). It was in the merchant service, especially cruise ships, where electric drive would continue on to the present day. First appearing in SS *California* (later *Uruguay*) in 1927, electric drive has been a common feature of cruise liners for more than a generation.

The all-electric ships of today are altogether more complex than the ships of a century ago, which had relatively few electrical systems beyond propulsion and rudimentary communications and hotel requirements. The first generation of ships also did not need pulsing—the storing and releasing of high volumes of energy in short timespans. But as the history of electric drive suggests, sometimes good ideas take time to develop fully. In this issue are articles that describe current efforts to make the modern all-electric ship a reality, as well as outline other projects under way in the area of power and energy.

About the author:

Colin Babb is a support contractor serving as the historian for the Office of Naval Research and managing editor of *Future Force*.

In 1919, General Electric touted its expertise in electric propulsion (opposite) with a full-page advertisement in the *Cornell Alumni News* about USS *New Mexico* (BB 40). The collier USS *Jupiter* (AC 3) was the first ship (below) to showcase Emmet's new electric propulsion system in 1913.



"PAY ATTENTION TO THE POWER":
Talking about Power and Energy with Dr. Rich Carlin

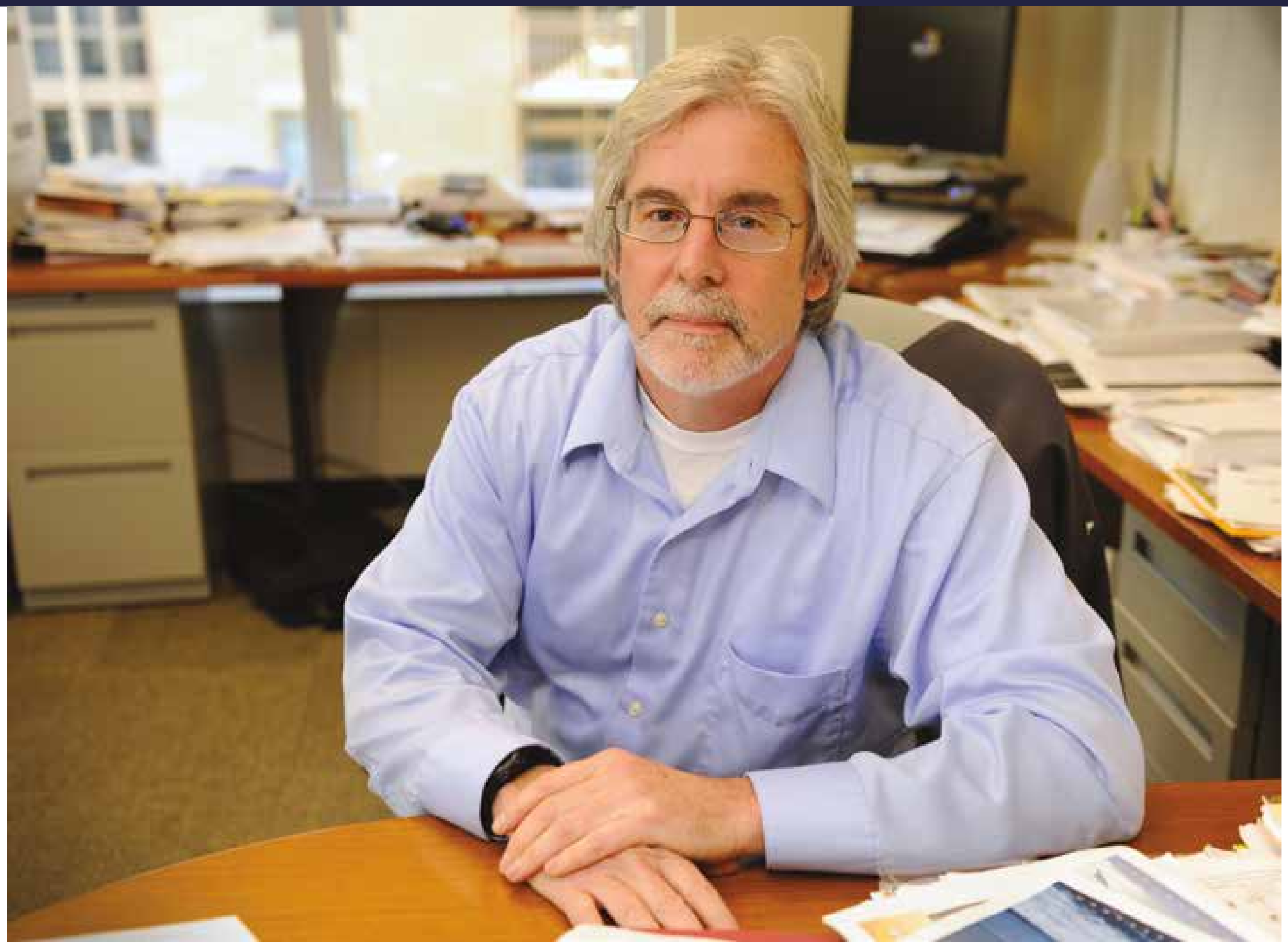


Photo by John F. Williams

***Future Force* sat down to discuss power and energy issues with Dr. Rich Carlin, head of the Office of Naval Research's (ONR) Sea Warfare and Weapons Department.**

Q: I wonder if you could talk briefly about ONR's interests in power and energy. Why is this issue so important for our Sailors and Marines?

A: Energy and power technology is one of the key focus areas here at ONR, so we've had significant investments ongoing and very long term, looking at a broad range of areas—everything from support for our Marine Corps to our ship systems, aircraft systems, and, as of late, a lot of work in the unmanned systems area. So it impacts pretty much everything the warfighter needs, in terms of their capability to go forward.

Also, it's a very high priority within the secretariat, particularly Secretary [of the Navy Ray] Mabus, who has really pushed this forward himself as one of his key areas of interest—with the understanding that it provides critical capability to the warfighter.

Q: As head of the Sea Warfare and Weapons Department, what are some of the power and energy challenges that concern you, and where do you see opportunities?

A: We've had a lot of power and energy investments over the years, and many of those technologies have certainly matured, to the point where we are seeing opportunities now in our ability to start incorporating more advanced technologies into our platforms. That doesn't mean we're going to stop our basic research in power and energy—we're always going to be pushing basic research, technology, and science forward—but when we start looking at the platforms, there's a very strong pull again to move forward and apply the lessons learned, particularly on the electric ship. So many of those capabilities have come along tremendously, and we have some new things that will be coming available very soon.

So now we think that the real challenge at this stage is: How do we start putting all these systems, all this advanced technology, together in a truly working, operating system? We do a lot of work on hardware-in-the-loop, which reduces the costs of development, but now we're looking at it to truly put it into test platforms, integrated—and not just the power system itself. The real challenge here is going to be taking a look at how that power system effectively integrates with the weapon systems now. I think people are very aware of the great work ONR has been doing in directed-energy systems, high-power radar systems, railgun, lasers. All these new technologies that are coming forward, well, they need that power. Now it's time to bring those things together, and I think that's really where our challenge is: to prove out that these things can work together very effectively.

Q: Could you talk a little bit more about your department's efforts as they relate to the electric ship?

A: Sure. With the standard ship design, you have the main propulsion system with a mechanical drive. And there you're talking tens of megawatts of power. When you start looking at the service/auxiliary power capability that ships will have, with all of these high-power systems, the electric power demand is driving to the point now where to provide the electrical power that's necessary, you're either going to have to install a lot more ship service/auxiliary generating capacity, or you're going to have to work it so that the main propulsion plant's power can be directed to the overall electric power system.

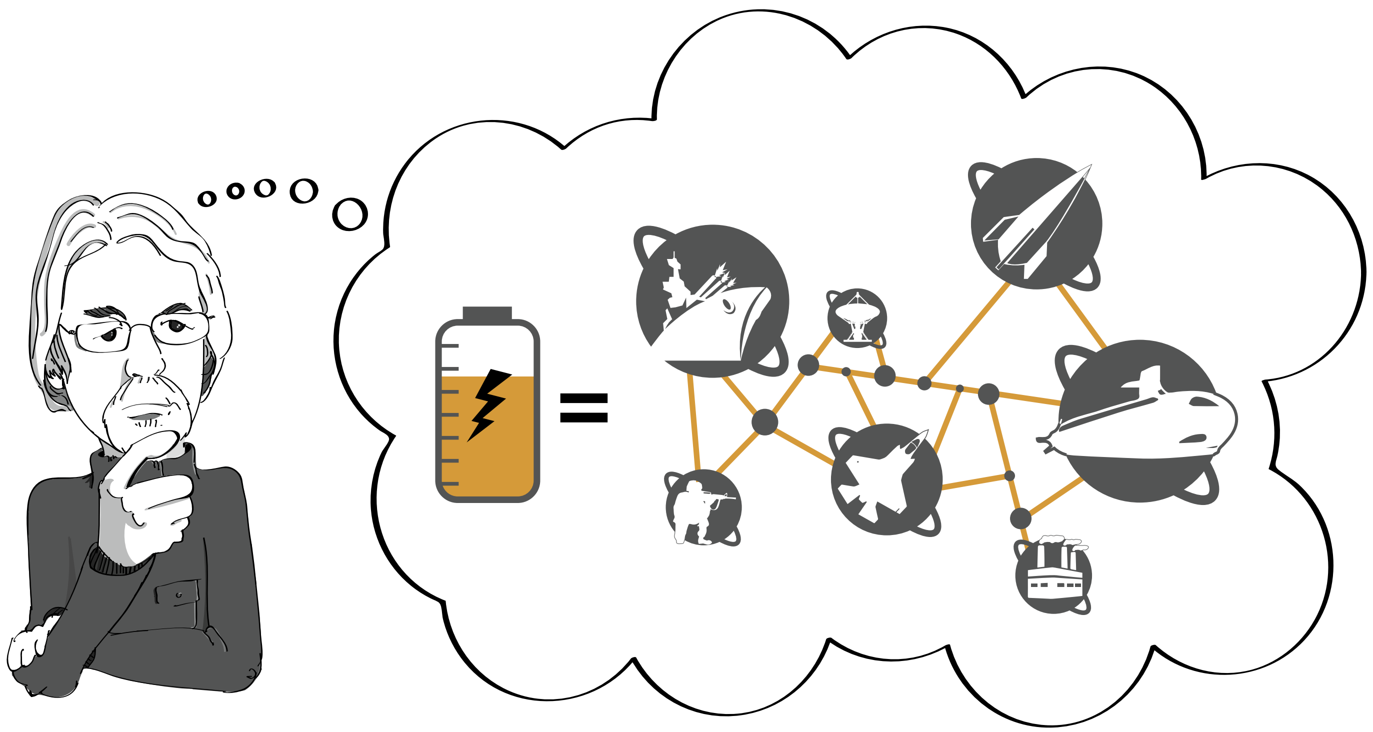
And so that's what leads us, what really drives us to say, "How can we integrate all of our power sources into an electrical system that can provide any power, the high-quality power, and pulse power that are necessary to provide all that full capability to the ship?" That's basically what you're looking at. Think about electric cars. The best example is the hybrid propulsion type systems you see in cars where you have that engine, but think of that as charging the battery, and the car then runs off that battery—you no longer have mechanical drive, you no longer have that transmission. What you have instead is just the flow of electricity throughout the car. Over the years, they've been doing a really good job of developing high-density magnet systems for the electro-mechanical drives that are necessary for cars. That's been a big enabler for them. We'll be doing the same kind of thing. Over the years we have developed very powerful motors for ships.

Q: Orders of magnitude greater than a smart car on I-95.

A: Yeah, just a little bit! You know, with fuel cell cars we talk about 100 kilowatts. So here you're going to go, let's say 100 to 1,000 times more.

Q: Could you talk a little bit about the Sea Warfare and Weapons Department's work and interest in power and energy as it relates to unmanned systems?

A: In terms of my department in particular, we come at unmanned systems power from a couple of directions. One, we've had a long-term program with the undersea platforms—torpedoes but also autonomous underwater vehicles. In that case, we've typically been driven by the platform, and by the constraints the platform is going to provide for us. So, 21 inches is the typical diameter that they talk about with that, and that's really constrained how we can get enough energy and power into the platforms. The Large-Displacement Unmanned Underwater Vehicle opened us up quite a bit and allowed us to continue to really expand on that. So we've been primarily looking at fuel cells because they have the energy density that's necessary and then designing these particular fuel cells to fit into those platforms. We're designing a power system to fit into a platform.



Another approach that we took a number of years ago: We were working fuel cells, and I was talking to one of our performers at the Naval Research Laboratory and asked if they could put a fuel cell into an unmanned aerial vehicle and demonstrate long endurance on that. They took up that challenge, and in a couple of years they were able to demonstrate, over a day, world-record capability in terms of flight. And now they've actually pushed it to two days by changing from gaseous hydrogen to liquid hydrogen. And one of the keys to accomplishing that was rather than designing a fuel cell to fit into the platform, it was designing a platform around that fuel cell. And so when some people talk about this, when you start looking at design space when it comes to electric ship, the Navy's actually taking this viewpoint: We're not going to say, "Here's your space for your power system, now figure out how it fits." It needs to come from an approach of total ship design, to determine what power system you may need to optimize. Then you can arrange that ship in a manner that allows you to have sufficient power from the outset, and you may make some design changes to that ship, accommodations that allow you to provide power to all of the modern and future weapon systems. That is one thing that's nice about the electric systems: It's a break from what they used to call "the tyranny of the shaft." That is, when you look at a mechanical drive, you have to have a shaft that runs through the bottom of the ship to the propulsor. Well, when you go electric, you get rid of that—so now you don't have to worry about accounting for that shaft in the ship when you go with electric drive systems—you just have that large motor, which can open up the design space for that ship.

Q: So instead of fixing something post-design, get it right pre-design.

A: Pay attention to the power. There is a tendency, and a lot of people do this, to design a great platform with all that capability built in, and then they say, "Now don't forget to put the power system in." So it's better if we think in terms of how to include those together. And, in fact, the Navy stood up an organization called Combat Power and Energy Systems, which is bringing together the ship design people, the power architecture people, the weapons people, even the acquisition community, the fiscal people, to work on this electric ship taking a fully integrated, holistic approach.

Q: Speaking of people, on the personnel or people front, you have initiatives and several ground-breaking programs supporting the development of personnel as a key to future advances in power and energy and S&T. Could you talk about some of those efforts?

A: Sure. The first one I'll refer you to is ESTEP, which is the Energy System Technology Evaluation Program. This started actually in fiscal year 2013. It's a program that was focused on doing demonstrations on facilities. It was something the secretary's office wanted to have so that we could lead the way in technologies—renewable energy technologies in particular, but overall energy technologies in general, to improve the energy capabilities at bases. How do you make them more efficient, more secure, more capable on the shore side? And as we were putting this together, we realized there was an opportunity here to approach it differently, instead of doing the normal, "Let's contract this out to one of our standard defense contractors"—who do a great job. But we sometimes miss the opportunity to educate naval personnel or veterans. So we said, "Let's do this differently and require that those doing the project are naval personnel already on the bases." So they get directly involved in the execution of that program and it becomes almost like an in-house facilities demonstration program.

In addition, it turned out there was a local school at that time, San Diego State University, near one of our performers, Space and Naval Warfare Systems Command out in San Diego. They had a veteran internship program. So we were able to say, "Hey, why don't we provide you monies to pay for veteran interns to work on that [ESTEP] project?" And they said, "Absolutely." And so on each of the projects that we've done in our ESTEP program, we've had at least one veteran. They're student veterans, mainly at SDSU, but we are going to look at other schools as well. And those vets have gone through already and in a couple of cases gotten jobs because of this, the establishment of training as an intern.

Q: Would you also please speak about APTEP and Energy Excelerator?

A: We've had this program for a while—it has been congressionally supported—called the Asia-Pacific Technology and Education Partnership. It funds everything from K-12 community outreach to university research and even a program called Energy Excelerator, which is an organization run by a non-profit in Hawaii that funds companies to do demonstrations of their energy technologies in the investment community/entrepreneurship type of world. Instead of just funding the technology, it really focuses on making sure those companies get business training. So it's a professional development type of organization. All of these programs together are working to ensure we foster and support the brightest minds bringing the most innovative technologies to the forefront for our Sailors and Marines in a technological environment that has limitless possibilities.

GENERATING UNDERSEA POWER AT THE GLOBAL ENERGY VILLAGE

By Patric Petrie and Wayne Liu

It's one thing to develop a new sensor or device in your lab. It's another to have it work in the field. But what happens when your lab and field are both underwater and your device must seamlessly integrate diverse technologies that are continuously evolving?

To address such development challenges, Space and Naval Warfare Systems Center Pacific (SSC Pacific) and the Office of Naval Research (ONR) plan to transform San Diego Bay into an undersea test and modeling site for autonomously controlled power sources, sensors, and unmanned vehicles fitted with wireless power and data devices.

Known as ONR Global Energy Village, this project aims to develop undersea power systems and control technologies within a small network of San Diego Bay test sites.

The Global Energy Village

The Navy's need for distributed, persistent undersea surveillance requires a network of power-lean command, control, communications, computers, intelligence, and reconnaissance devices linked to long-lasting energy sources and transfer vehicles or stations. To foster integrated development of these components in a realistic environment, Navy and coalition researchers seek to collaborate through an instrumented test site known as the ONR Global Energy Village—a San Diego Bay science and technology incubator for ONR-supported undersea power, energy, and control technologies.

Led by SSC's Research and Applied Sciences and Intelligence, Surveillance, Reconnaissance, and Information Operations departments, the ONR Global Energy Village represents a field development site for evaluating "tenant" energy nodes, sensors, and vehicles located at SSC Pacific and various Navy waterfronts along San Diego Bay—all in proximity to fleet platforms, commands, and program offices. Initial efforts will include energy mapping, harvesting, and connectivity.

Energy Mapping

To identify San Diego Bay locations for renewably driven energy stations, SSC Pacific intends to model microbial fuel cell power potential as a function of environmental conditions (waves, tidal currents, and seafloor organic matter). This predictive model of in-situ energy potential can help select locations for "dock-in-a-box" vehicle charging stations. The vision is to create a three-part approach to develop this mapping capability, including data mining, modeling, and field verification.

Data mining will compile relevant data sources that provide the best prediction of energy harvesting potential. This would include tidal elevations, current speeds, wave heights, sediment characteristics, and temperature distributions.

This data will be compiled in a geospatial data base and contoured over areas of strategic interest, as well as over designated test areas for subsequent verification.

In the second phase, modeling algorithms will yield a range of energy harvesting strategies.

These algorithms would draw from both theoretical predications and empirical data. The modeling would provide a basis for translating bay sediment conditions into power estimates for various fuel cell methods.

In the final phase, field verification measurements will be conducted at test sites. These would be conducted by placing a limited range of actual fuel cell harvesting devices within the test areas to compare measured power production against the predictions.

Energy Harvesting

Two initial approaches for undersea energy harvesting will be considered for the Global Energy Village: sedimentary microbial fuel cells and nonlinear energy harvesters.

The former typically function by burying anodes inches deep in the sediment to collect electrons released by microbes as they break down and consume trapped organic content. The electrons are then routed through a circuit consisting of the anode collector, a load (sensor or battery), and a seawater-exposed cathode where the electrons are terminally mated with dissolved oxygen molecules.

To develop a non-stationary platform that can charge on and migrate from the sediment surface, scientists have collaborated with mechanical engineers to develop the Mudfish—an SSC Pacific invention that performs microbial fuel cell energy harvesting within a mobile undersea platform. The Mudfish recharges itself by visiting the sediment floor, and it can be scaled up into larger energy payloads for "dock-in-a-box" stations within the Global Energy Village.

The integrated nonlinear energy harvester represents a second harvesting approach that scavenges energy from ambient low-frequency seismic vibrations—eliminating the need for batteries and reducing size, weight, and cost.

Mapping of sediment characteristics in San Diego Bay. Photos courtesy of SSC Pacific.

SSC Pacific is developing a microelectromechanical-system-scale magnetometer using a new class of nonlinear functional materials as the active core material in the sensor. Still in its infancy, this magnetometer's power would be supplied by an integrated nonlinear energy harvester that would scavenge energy from ambient low-frequency seismic vibrations, so no batteries would be needed, reducing size, weight, and cost while simplifying logistics.

The energy harvester is underpinned by a vibrating piezoelectric cantilever with a magnet at the tip; it is opposed by another micromagnet that repels the tip-magnet so that, within a critical separation of the magnets, the cantilever's movement is nonlinear. Experiments have shown that the nonlinear configuration is far better suited to scavenging energy from low-frequency vibrations, which are usually embedded in low-frequency noise, the type frequently encountered in seismic vibrational settings.

ONR Global Energy Village will serve as a science and technology incubator for undersea power systems and control technologies in the evironmentally relevant San Diego Bay, with proximity to fleet commands, vessels, and program officers.

The sensors are expected to have a magnetic field resolution of five to 20 picotesla and last more than five years. The entire package is expected to be silver-dollar size or smaller and cost under $50. The sensors could be deployed anywhere and left unattended for a long time. The sensors would have radio frequency communications and GPS capability, if needed.

This project is the team's most ambitious; it involves an expert in magnetic nanostructures, as well as collaborative partners at the University of California, Berkeley; University of Catania (Italy); University of Perugia (Italy); University of California, Los Angeles; and the Indian Institute of Technology (Mumbai, India). In addition, Albuquerque-based Radiant Technology is tied to this effort through a cooperative research and development agreement.

The work has been funded by SSC Pacific's Naval Innovative Science and Engineering program and ONR. In addition, the energy harvester development was funded by ONR and the Coalition Warfare Program; the latter funding is underpinned by a project agreement between SSC Pacific and the Italian Ministry of Defence.

An interesting side project to the energy harvester work is the development of a macro (centimeter-scale) energy harvester device for scavenging ambient vibrations. This device uses printed electronic technology, specifically a vibrating flexible clamped beam incorporating piezoelectric actuators that are deposited through inkjet printing techniques. At the moment, a laboratory prototype device the size of a cigarette package can generate power to operate a wireless sensor node located approximately 20 yards away.

Energy Connectivity

To replenish the energy stores of nodes throughout the ONR Global Energy Village network, remotely or autonomously driven unmanned vehicles will serve as undersea fuel tankers to inductively (wirelessly) charge each node.

A multidisciplinary SSC Pacific engineering team developed this strategic capability for inductive undersea energy charging. This capability was demonstrated during an SSC Pacific pierside test in July 2014 and will increase the endurance of remote platforms with reduced reliance on manned support missions.

This wireless power capability will drive Energy Village projects in autonomously controlled connectors and wireless power and data devices for vehicles and sensors.

The Way Ahead

Fiscal year 2015 ONR Global Energy Village projects will demonstrate San Diego Bay microbial fuel cell and wireless charging systems. During 2016, the emphasis will shift toward renewable energy-driven remote monitoring and control of Global Energy Village assets (to be proposed to ONR's energy systems and technology evaluation program). Participation in future Rim of the Pacific fleet exercises is planned.

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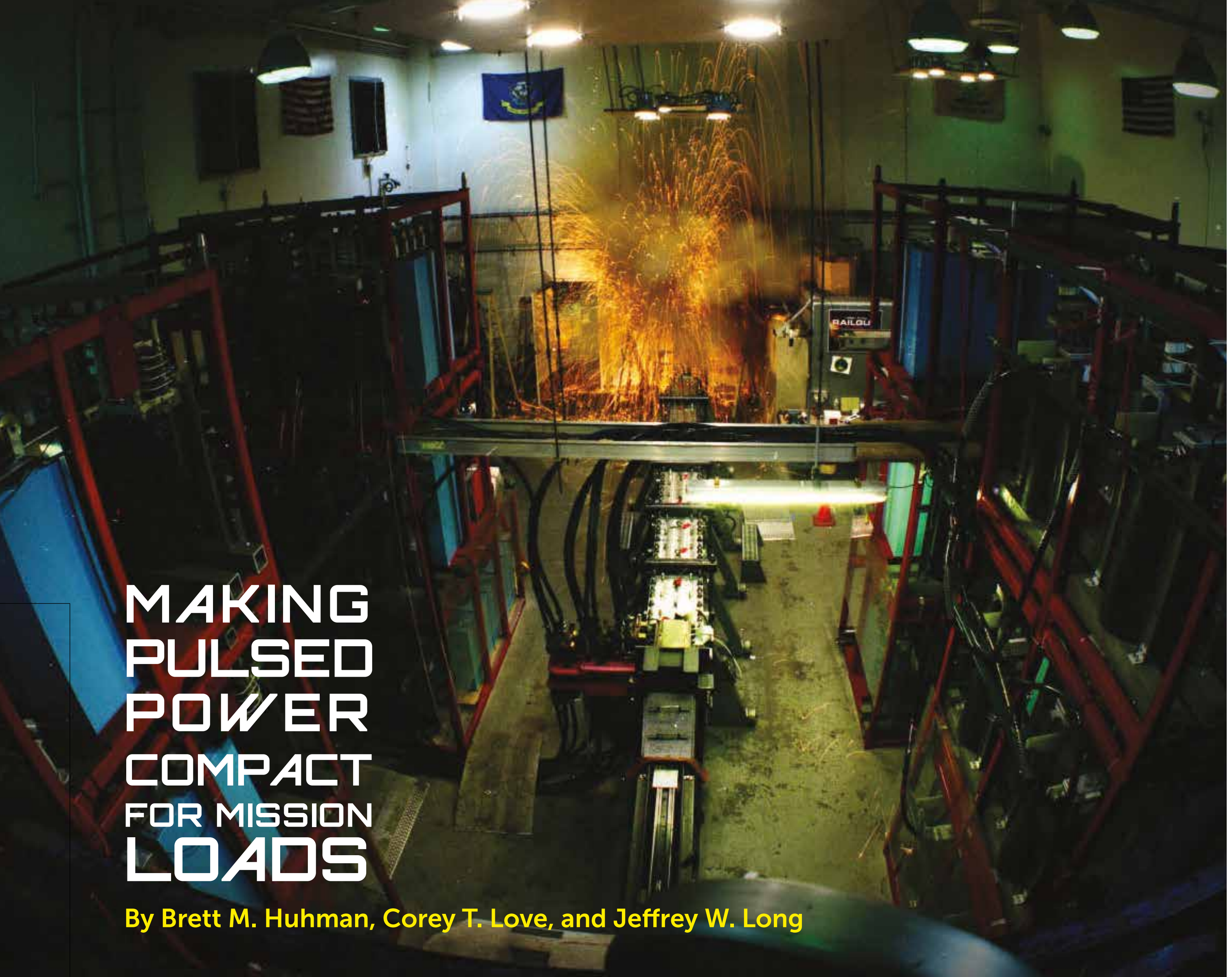

Photos courtesy of the Naval Research Laboratory

MAKING PULSED POWER COMPACT FOR MISSION LOADS

By Brett M. Huhman, Corey T. Love, and Jeffrey W. Long

The Naval Research Laboratory Materials Testing Facility's electromagnetic railgun fires a shot. The pulse forming network can be seen in the foreground, with the mission load (railgun) in the background. Getting pulsed systems smaller and more efficient is a major prerequisite for getting operational railguns aboard ships.

Pulsed power is the science of storing energy over a relatively long period of time and releasing it very quickly, increasing the effective power many times over the original source. This technology has been used for radar since World War II, but the full potential of pulsed power has been limited mostly to laboratory research in directed-energy applications such as lasers, electromagnetic railguns, and high-power microwaves. Starting with USS *Ponce* (AFSB[I] 15), the Navy is on the path to deploy significant pulsed power installations across the fleet to drive the next generation of mission loads, which are defined as electrical loads on ships that draw power from central power plants and are devoted to a specific task. While the basic concept is quite well understood, applying this to a mobile platform at sea under varying environmental conditions is quite challenging. The US Naval Research Laboratory (NRL) has a multidisciplinary effort under way to push the boundaries of science and technology research necessary to support the initial deployment and future incarnations of railgun, laser, and other energy-demanding programs.

With the advent of all-electric ships, especially the *Zumwalt* (DDG 1000)-class destroyer, energy on a ship is suddenly available in large amounts for directed-energy mission loads and ever-more-advanced radars. A *Zumwalt* has a distinct advantage over an *Arleigh Burke* (DDG 51)-class destroyer in its power plant, with a total of 78 megawatts of power at maximum load in the former versus the 7.5 megawatts available from the latter's LM2500 gas-turbine generators. The *Zumwalt*'s $3.8-billion price tag, however, is likely to keep existing ships such as the *Arleigh Burke* class the likely target platform for directed-energy upgrades for some time to come. Energy management, both thermal and electrical, will be the key factors in the application of new technologies.

Intermediate Storage System

A weapon system such as a railgun will need potentially as much as 80 megajoules of energy stored per shot, which is the energy equivalent to nearly 20 kilograms of TNT. When one considers that the mission profile for such a weapon is multishot, more than a billion joules of energy is required to expend the magazine, which is comparable to more than a kiloton of TNT. To put it in more practical terms, every few seconds more than 20 megawatts of electricity needs to be extracted from the ship to fire a railgun. Power generators on a ship do not react well to sudden, significant electrical loads for a few seconds followed by a brief low-load period. Therefore, an intermediate storage system is necessary to both protect the prime mover on the ship and provide instantaneous response to a "call for fire" from a mission load.

The essential concept of an intermediate storage system is that it serves as a buffer between the slow power source that charges in hours, such as the gas-turbine generator on a ship, and the capacitor bank, which charges in seconds and discharges in milliseconds. Gas-turbine generators are excellent at providing large amounts of power when needed but are terrible at fuel efficiency. A generator running at half load consumes nearly as much fuel as a generator at full load. With the Navy studying the feasibility of single generator operations (a projected fuel savings in the excess of $1 million per year per ship), such a system would push the limits of maintaining the power levels of a weapon system in standby. The use of an electrochemical storage system, such as a lithium-ion battery, would be the ideal solution. Batteries prefer to be charged slowly over a long period of time but can release the energy into a capacitor very quickly without compromising any other systems on board a ship.

The Office of Naval Research has awarded a contract to K2 Energy Solutions to develop an energy storage system for just this purpose with delivery of the first modules by the end of 2015. NRL is investigating technologies and methodologies to maintain the safety, efficiency, and lifetime at high performance levels on these new devices. Commercial battery systems are designed to operate at much lower power levels, as it is highly desirable to have a cellular telephone operate for days; in contrast, the Navy needs the energy released over several minutes.

Making Lithium Batteries Safer

While lithium-based chemistries are the most popular secondary battery designs in the world, they can be prone to adverse events such as cell venting (toxic gases), overheating (fire), and dendrite growth (failure, and, if not managed properly, fire). Newer variants, such as the lithium iron phosphate cathode chemistry used by K2 Energy, are able to limit but not eliminate risks. In response to safety concerns surrounding the integration of lithium-ion batteries within the fleet, the Alternative Energy Section in NRL's Chemistry Division is actively researching the three battery failure mechanisms. If the start condition (baseline performance) is properly understood, scientists can develop mitigation procedures to avoid destructive conditions and maintain safe operation for both recharging and discharging these cells. The Navy needs the battery systems to be ready at all times and available for immediate use. In addition, the cells need to maintain peak performance for a sufficient number of recharge/discharge cycles to make them economically viable. Understanding what causes premature cell death is essential to reducing the total cost of ownership of battery-based mission loads.

During recharging, the battery anode is prone to forming lithium metal "dendrites," or spears, which can form a short circuit to the battery cathode, initiating a catastrophic thermal runaway reaction and, ultimately, a fire. NRL has observed that the temperature most conducive to short circuits is at 5 degrees Celsius, where rapid dendrite formation is most likely to take place and cause internal short circuits. This experimental capability now can be used to study the impact of chemical additives in preventing dendrite formation and can guide naval designs to maintain safe operating envelopes for batteries under charge.

Lithium batteries require active management and monitoring. If the battery management system malfunctions and allows the battery to be overcharged or the temperature in the cells to rise beyond a certain point, it can cause the loss of oxygen gas from the metal-oxide battery cathodes. NRL has developed a computational method to screen new battery materials for such instability toward O_2 release.

A third failure mechanism identified in lithium batteries is related to cell overcharge, which is normally avoided by a properly designed battery management system. Forcing a battery to charge rapidly can cause the voltage of individual cells in a pack to "float" higher than their neighbors. If the excess voltage is not drained using a balancing resistor, the cell could be damaged. A newly developed diagnostic tool detects in real time if a cell has suffered damage because of overcharge by using impedance spectroscopy to specifically probe and track a cell's state of health.

Based on this method, a simple electronic device is now being developed to monitor changes within a battery management system that requires minimal analysis. Any irregularities in the impedance behavior can be detected in the early stages of cell damage, so batteries may be taken offline prior to becoming highly damaged, unstable, and dangerous. These useful diagnostics easily can be implemented into new Navy systems or retrofitted into existing installations and will ensure safe and efficient operation of lithium-based battery packs under high-performance conditions.

Moving Beyond Lithium

Because of the significant risk of failure, removing lithium-based batteries from future Navy activities is highly desired. With this in mind, the Surface Chemistry Branch at NRL has developed new materials for zinc-based batteries that promise to meet or exceed the energy density of lithium-ion batteries. Traditionally, zinc has fallen short in battery performance because of the very limited rechargeability and modest capacity (typically less than 60 percent of theoretical maximum) of the zinc electrode. NRL has designed and fabricated 3-D zinc "sponge" anodes that are monolithic and comprise interpenetrating networks of solid and void. The sponge electrode—now wired in 3-D—enables low cell resistances through the discharge process and access to greater than 90 percent of the zinc theoretical capacity. The 3-D structure also ensures electrochemical recharge with more than 99-percent capacity retention. NRL has demonstrated stable cycling to capacities that translate to 100 watt-hours per kilogram in a fully packaged nickel-zinc battery—an energy density far superior to lead-acid—and begins to approach that of lithium-ion batteries but with the safety advantages of using nonflammable aqueous electrolytes.

A complementary energy-storage approach being developed by the NRL's Surface Chemistry Branch is based on a new type of electrochemical capacitor that also uses aqueous electrolytes. This low-cost, safe-to-operate, and environmentally benign replacement for pulsed-power batteries has the potential to exceed the energy density (smaller size) and power density (more energy released at once) of existing supercapacitors. NRL has developed a scalable method of generating conformal coatings of ultrathin (less than 20 nanometers thick) metal oxides on the high-surface-area walls of carbon nanofoam papers. The resulting ultrathin oxides of manganese or iron rapidly take up and release electrons and ions, thereby storing/delivering energy at 300-600 Farads per gram of

A research engineer installs a pulsed power battery pack at NRL. The Pulsed Power Physics Branch is developing a scaled facility to evaluate battery-based pulsed power systems. The battery packs will charge the capacitor over several seconds, which when triggered will release 60 kilojoules of stored energy into the inductor and resistive load in milliseconds.

oxide. In comparison, the typical value for commercial carbon-carbon supercapacitors is less than 150 Farads per gram of oxide. The high surface-to-volume ratio of NRL's electrode designs enables capacitances addressable within a few seconds while retaining the energy for much longer periods of time than a pulsed-power capacitor is currently capable of providing. With this technology, the care and feeding of a complete pulsed power system for a shipboard railgun would be reduced substantially by merging the battery and capacitor arrays into a single system. Successful implementation would reduce operation and maintenance costs, improve reliability, and maintain the Navy's commitment to cleaner seas.

Holistic Thermal Management is Necessary

A pulsed power system is only useful if it can charge and discharge rapidly and repeat many times per minute. Each cycle generates a finite amount of heat energy, which must be removed from the system to enable proper function. Batteries, especially when used under high-power conditions, will generate a substantial amount of heat that must be removed to maintain both safe operating conditions and sufficient lifetime to remain economical for shipboard applications. This is only the beginning, however, of the thermal management challenge. The directed energy and railgun technologies identified as potential new platforms will generate a sizeable amount of waste heat. Existing shipboard cooling systems are not designed for the magnitude of heat load that is likely to result, which will force the Navy either to perform a very expensive refit or use ocean water as a thermal sink. If the heat energy cannot be removed from the system efficiently, however, no amount of cooling water will enable sustained operations of a next-generation weapon system.

NRL is developing solutions to address these thermal challenges. Each component on a pulsed-power system will generate heat, from the direct current (DC)-DC converter (used to charge a capacitor to high voltage), to the capacitor, high-current switches, inductor, and even the cables that transfer power to the mission load itself. NRL's Pulsed Power Physics Branch is building a complete pulsed-power simulator, from the batteries used for the Office of Naval Research railgun program to custom DC-DC converters and a pulse-forming network. A set of four 60-kilojoule capacitor banks will be connected to repetitively charge and dump into a resistive load 10 times a minute to evaluate the heat generated by all of the system components. Each element will need active cooling to maintain proper operation and prevent premature component death, as the amount of current flowing through each later stage is around 100,000 amps.

To cool the battery packs, a four-pass aluminum cold plate is used to move water past all of the cells in each battery set. Without the cold plate, a thermal limit is reached after only 32 shots; with the cold plate installed all 50 shots are fired with a net temperature rise of only 15 degrees Celsius across the battery pack. The next stage in the system, the DC-DC converter, was outfitted with an experimental oscillating heat pipe (OHP) design. The OHP has a working fluid that evaporates, cools, and repeats many hundreds of times per second. This has the effect of a thermal conductivity many times that of pure copper. With this system, NRL has demonstrated a steady-state condition with a 20-kilowatt converter with the OHP installed. For comparison, a commercial cold plate was shown to continuously increase in temperature over the same five-minute test period. The use of the OHP in a DC-DC converter for a pulsed-power system would enable constant energy flow without the need of additional cooling facilities aboard a ship at sea. Future work is needed to apply this technology to the remainder of the system.

Remaining Challenges

NRL has established a number of basic and applied research benchmarks for the deployment of safe, reliable power sources for the Navy at large. The work performed on lithium battery safety is directly applicable to both the current and future Navy, as lithium-based cells will remain in service for some time. Scaling is perhaps the largest challenge, as even the application-based testing by the Pulsed Power Physics Branch at NRL is limited in scope, allowing for maximum understanding of basic principles. While very promising, the successful transfer and commercialization of technologies such as the zinc-air cell and the electrochemical capacitor remains a significant milestone in the future. Further investment into these areas will bear fruit in the long term, ensuring the continuing superiority of the US Navy and fellow services.

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USING HIGH-POWER LASERS TO RECHARGE REMOTELY

By Dr. R.P. Fischer, Dr. A. Ting, and Dr. P. Sprangle

Advances in laser and photovoltaic converter technologies may allow high-power wireless recharging of platforms and sensors at extended ranges. These remote platforms may include flying, land-based, or submerged vehicles, satellites, and sensors at hazardous locations. Commercially available fiber lasers have proven to be an enabling technology in a variety of industrial applications such as cutting, welding, and annealing. These lasers also are having a positive effect in many defense programs—for instance, the Navy's laser weapon system has recently deployed aboard USS *Ponce* (AFSB[I] 15) for at-sea testing. In addition, commercially available photovoltaic converters have advanced to a point where high conversion efficiency from laser energy to electrical energy is now possible.

In the 1890s, Nikola Tesla performed some of the first experiments demonstrating wireless recharging—sometimes called power beaming—using high-frequency electromagnetic radiation. Microwaves have been used since in short-range wireless recharging experiments because of their high power-conversion efficiency. For long-range recharging, however, large transmission and receiving antennae are required because of the longer wavelengths associated with microwave radiation. Practical long-range recharging only can be achieved using the significantly shorter wavelengths associated with laser beams. The use of lasers can significantly reduce the size and weight of the transmitting and receiving platforms.

Research groups at the National Aeronautics and Space Administration, Kinki University in Japan, LaserMotive Inc., and the Naval Research Laboratory have experimented with wireless recharging using a variety of platforms such as rovers, kite planes, helicopters, and climbers using solid-state lasers and photovoltaic converters.

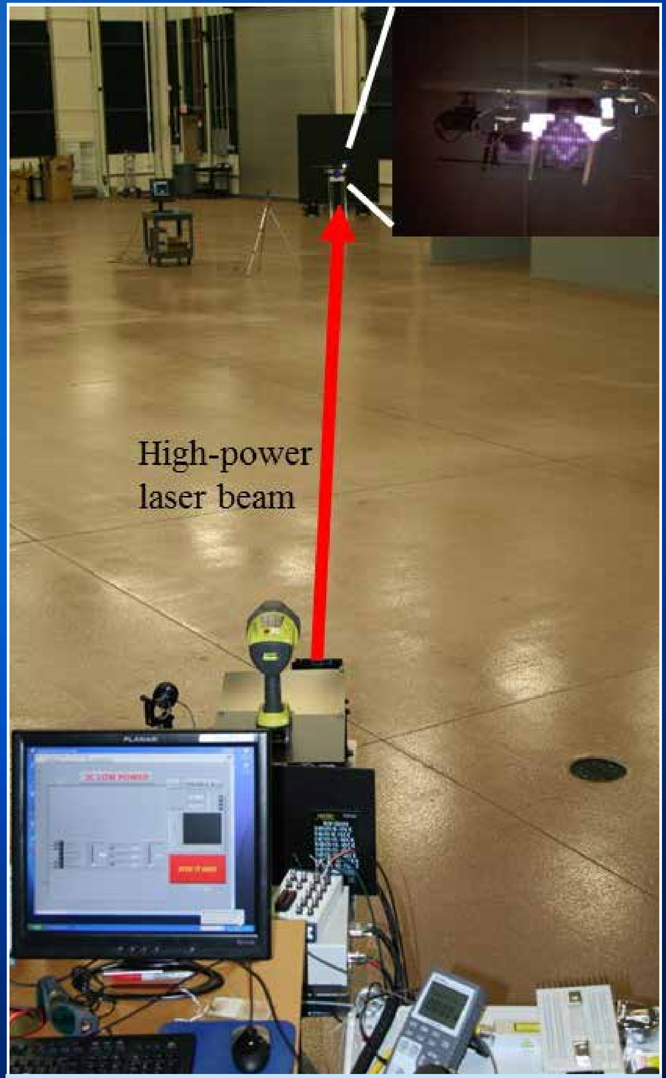
One configuration for remote wireless recharging of an unmanned aerial vehicle (UAV) involves using a high-power, continuous wave fiber laser and beam director. Disturbances in the atmosphere (i.e., turbulence and aerosols) will affect the laser's power propagation and delivery to the platform and may require adaptive optics for correction.

High-Power Laser Wireless Recharging

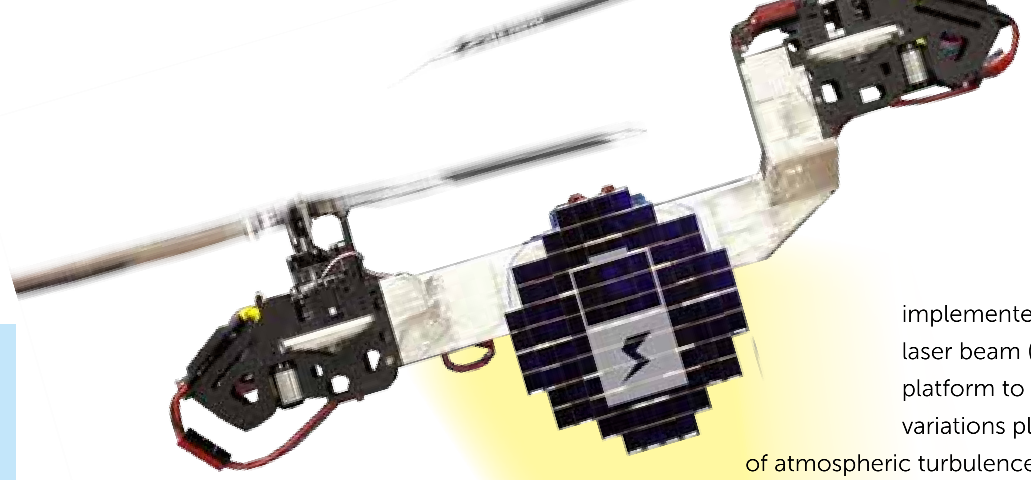
Wireless recharging using high-power lasers has been realized because of the improved output power, efficiency, and reliability of commercially available high-power lasers, power-conversion efficiencies as high as 60 percent in photovoltaic converters, and multikilometer propagation of lasers in the atmosphere. Laser recharging can be used to power UAVs, resulting in increased flight duration, reduced battery weight and manpower requirements, and increased power capabilities of vehicles and payloads. Wireless recharging also can be used to provide electrical power to small UAVs for missions such as persistent surveillance and security, communications relay, off-board decoys, electronic warfare, target acquisition, and reconnaissance of remote or hazardous areas such as forward operating bases.

High-power fiber lasers now are commercially available for directed-energy applications. These lasers are made with active optical fibers and semiconductor diodes, a merger between two of the most innovative and advanced laser technologies. Fiber lasers use single-emitter semiconductor diodes as the light source to pump the active fibers. The beam emitted is contained within optical fibers and delivered through an armored flexible cable. Special optical fibers doped with rare earth ions permit kilowatt levels of high-quality laser power to be generated. These fiber lasers are compact, have long diode lifetimes, low maintenance operation, high wall-plug efficiency, and minimum beam divergence. For example, ytterbium-doped fiber lasers are commercially available with wall-plug efficiencies up to 50 percent. The state-of-the-art power levels for these lasers are 10 kilowatts continuous wave for single-mode operation and 100 kilowatts for multimode operation.

Naval Research Laboratory scientists hold the first patent on the laser-beam-combining architecture used by the Navy ("Apparatus for Incoherent Combining of High-Power Lasers for Long-Range Directed Energy Applications," U.S. Patent No. US 7,970,040 [2011]) and were the first to demonstrate high-power continuous wave (greater than four kilowatts), single-mode, fiber laser beam propagation in the atmosphere over extended distances (greater than three kilometers). These high-



The Naval Research Laboratory demonstrates laser recharging at a range of 40 meters. The laser beam is shown by the red arrow propagating from the lower-right corner to the target, a twin propeller aerial vehicle with a laser converter in front. The vehicle under illumination is shown in the upper right inset where the converter appears violet and white. Photos courtesy of Naval Research Laboratory.



At right is a twin-propeller aerial vehicle with a laser converter mounted in the middle. The photovoltaic cells convert laser power to electrical power at high efficiency to power the two propellers. The laser converter is cooled by the downdraft created by the propellers.

power fiber lasers are particularly well suited for remote wireless recharging.

Most photovoltaic cells are designed and developed for the conversion of the broad spectrum of solar energy into electrical power. The cell delivers the maximum optical-to-electrical conversion efficiency when illuminated by monochromatic (laser) light at a wavelength that closely corresponds to the band-gap energy of the photovoltaic material. Efficient cells based on indium gallium arsenide (InGaAs) are now available commercially for wavelengths near one micron. An optimized photovoltaic converter on a remote platform, such as a UAV, can efficiently convert (about 50—60 percent) laser energy to electrical power. A wireless recharging architecture using fiber lasers and photovoltaic cells can provide a significant weight reduction by removal of batteries, extended flight duration, and increased range.

Wireless Recharging Experiments

The Naval Research Laboratory has successfully demonstrated the recharging of a UAV in flight using a kilowatt-class fiber laser to transmit power and a photovoltaic cell for collection. The photo above shows a panel of highly efficient InGaAs cells on a laser converter panel. When illuminated with a high-power fiber laser, it converts the laser power to the electrical power required to power the twin propellers. The cells are connected in a configuration that matches the current and voltage characteristics required to drive the propellers. The converter has fins on its back to allow cooling by the downdraft of the propellers.

In 2013, a series of flight tests were conducted over a 40-meter laboratory range. A two-kilowatt, single-mode fiber laser (about one micron wavelength) transmitted power to an array fabricated using InGaAs laser-power converter chips from Spectrolab Inc. The individual chips are up to 50 percent efficient at the fiber laser wavelength, and the lightweight array provides 160-190 watts of electricity to the vehicle. Off-the-shelf components were used to develop the optical tracking system, which automatically positioned the laser beam on the center of the laser converter during flight. In the experiment, the remotely controlled vehicle was able to lift off from rest on command. The laser converter lights up (in the inset on page 23) because the laser light, though in the infrared, is visible to the digital camera.

Technological Challenges

There are a number of challenges to address before long-range wireless recharging can be deployed. These include thermally managing the excess heat generated on the photo-voltaic converter and developing higher-efficiency cells capable of more than 60 percent conversion. It is necessary to have a fairly uniform and controlled laser intensity profile on the photo converter. This may require the development of appropriate adaptive optics techniques applied to the outgoing laser beam.

For extended ranges, application of adaptive optics is necessary to control spreading and wandering of the transmitted laser beam as it propagates through atmospheric turbulence. Adapted optics can be implemented by employing a beacon laser beam (low power) on the receiving platform to determine the phase variations placed on the beam because of atmospheric turbulence. Introducing the conjugated phase variation on the high-power outgoing beam will minimize the effects of atmospheric turbulence. Development of efficient, high-power, eye-safer lasers and photovoltaic converters at wavelengths greater than 1.4 microns may be necessary for certain applications. These challenges are of a technological nature, however, and can be overcome in the near term.

Future Directions

Wireless recharging can be an enabling technology that would allow new operational capabilities for the Navy. In addition to UAVs, other unmanned systems stand to benefit from this technology. These include ground vehicles and underwater vehicles. Atmospheric conditions for land-based vehicles, however, are quite different from those for UAV recharging. This is because of the high concentration of scattering particles and increased turbulence affecting laser propagation near the ground. Underwater remote wireless recharging requires laser wavelengths in the blue-green regime.

Wireless recharging of low flying satellites also could be viable to maintain their orbits. Atmospheric turbulence and scattering fall off extremely rapidly as a function of altitude. Hundreds of kilowatts of laser power can be delivered to the satellite at the perigee point (the lowest height position, about 100 kilometers) of the elliptical orbit. The laser intensity on the satellite's photovoltaic cells can be several hundreds of kilowatts per square meter, which is hundreds of times the sun's intensity.

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NEW BIOFUELS ON THE HORIZON FOR THE GREAT GREEN FLEET

By Patric Petrie

The Navy has committed to the deployment of a "Great Green Fleet" by 2016, a carrier strike group fueled by alternative sources of energy such as new-generation biofuels.

Biofuels are drop-in replacements for petroleum-based fuels such as JP-5, used in aircraft, and F-76, used in ships. These biofuels are derived from lipid-rich plants or algae, which are highly renewable energy sources that produce lower greenhouse gas emissions than typical Navy fuel sources and consume carbon dioxide as they grow.

By seeking alternative and renewable fuel sources, the Navy can reduce its dependence on foreign oil while furthering its environmental stewardship, a key element of the Navy's Energy Vision.

Two biofuels currently being tested by Naval Air Systems Command as blends with existing petroleum-based fuels include HRJ-5, a jet fuel made from camelina plants, and HRD-76, a ship diesel made from marine algae. Although these fuels have passed recent fit-for-purpose tests in Navy aircraft and ships, their fate and effects in the marine environment remain unknown.

Prototype energy-efficient technologies have been designed to enhance the combat capability of Navy warships. These include solid-state lighting, which is more efficient and lasts longer than incandescent or fluorescent fixtures; stern flaps designed to help reduce hull resistance when under way; a shipboard energy dashboard that displays energy usage to the operators in real time and informs energy efficient decisions; and gas-turbine online water wash that improves engine efficiency. Similarly, new ship fuels must meet performance specifications, as well as environmental compliance requirements, both of which are essential to operational readiness.

Space and Naval Warfare Systems Command (SPAWAR) scientists are currently assessing the potential ecological risks of these new-generation fuels in the event of fuel spills during storage or transport. Ensuring that the Navy adopts alternative fuels that are no more hazardous in the underwater environment than current petroleum-based fuels will reduce the potential for fines associated with spills and the need for costly assessment and cleanup actions.

Assessing the Ecological Risk

Over the past year, SPAWAR scientists have completed preliminary laboratory studies that investigated the toxicity and chemical characterization of new-generation fuels compared to traditional petroleum-based fuels in marine environments.

Initial range-finding tests evaluated acute toxicity (mortality in short-term exposures of four days) for juvenile mysid shrimp and topsmelt (a small Pacific fish) larvae and chronic/sublethal toxicity (exposures of two to four days) for sea urchins and mussel embryos.

To assess toxic effects, marine organisms were exposed to seawater saturated with water-soluble fuel extracts from alternative renewable or traditional petroleum-based fuels.

Results displayed rapid mortality of mysid shrimp and topsmelt in petroleum-based fuels, while no mortality was observed in alternative fuel samples. Similar responses were observed with embryonic urchins and mussels.

These results suggest that alternative fuels are far less toxic than their petroleum-based counterparts. Differences in toxicity are most likely driven by much higher concentrations of toxic compounds such as volatile organic carbons and polycyclic aromatic hydrocarbons in petroleum-based fuels.

Looking Ahead

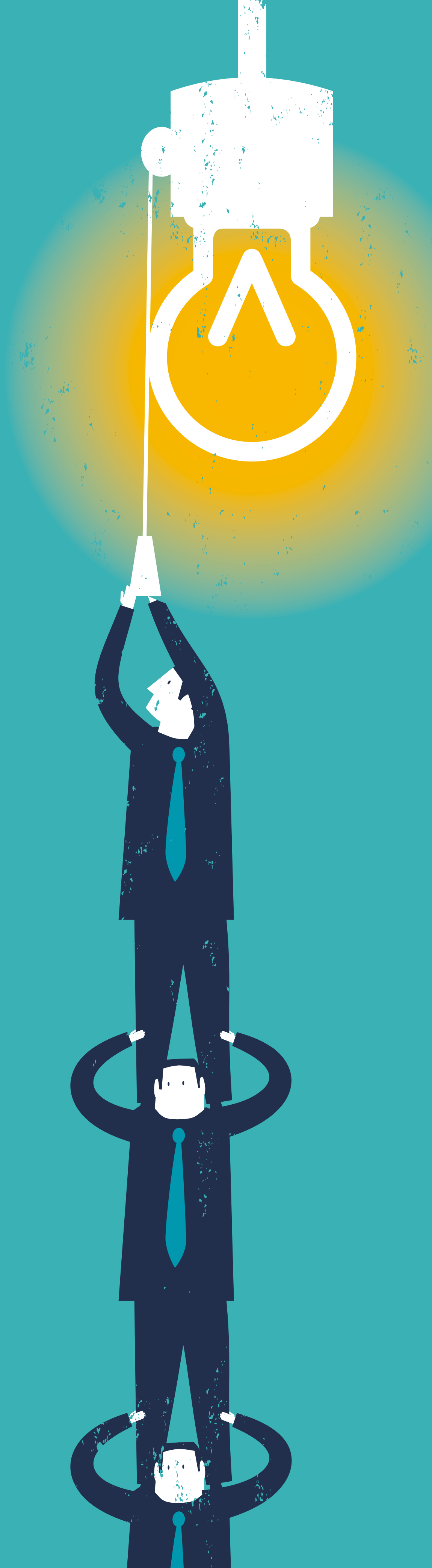
Future studies will more definitively determine toxicity concentrations with complementary chemical analyses. In addition, SPAWAR scientists will be working on identifying and developing of data for key parameters for fate and effects modeling, such as biodegradation, photodegradation, and oceanographic mixing rates of alternative fuels.

Determination of the chemical components of alternative renewable and petroleum-based fuels will provide guidance for forthcoming management and certification decisions in selecting less toxic fuels with similar performance specifications.

USNS *Henry J. Kaiser* (T-AO 187) refuels USS *Princeton* (CG 59) during the Great Green Fleet demonstration in 2012. Photo by MC3 Andrew M. Jandick.

About the author:

Patric Petrie is the lead staff writer for Space and Naval Warfare Systems Center Pacific.



What's the Mission of the Naval Enterprise Energy Team?

By Elisha Gamboa

Space and Naval Warfare Systems Command's (SPAWAR) naval enterprise energy team supports the development of strategic energy planning and project execution for Navy Enterprise Data Center (NEDC) and data center consolidation tasks.

SPAWAR manages and operates the NEDC, located at SPAWAR sites in San Diego, Charleston, New Orleans, and Millington.

The NEDC is conducting a federal data center consolidation effort to combine legacy data centers by virtualizing and hosting them in the NEDC. The consolidation effort will increase data demands at SPAWAR data centers and the incurred need for effective energy solutions to handle demand signals.

The Navy enterprise energy team is a diverse, multidisciplinary workforce with expertise that addresses a range of energy and security challenges within the command, control, communications, computers, and intelligence/information technology domain.

SPAWAR's research is conducted around answering the question: How do you tie in renewable energy and energy efficiency when you have such critical systems that need to be powered?

The team develops near- and long-term data center energy technology solutions using basic and applied research, evaluation, demonstration, smart metering, information technology and virtualization efficiency, and cyber security.

Some of the energy technology solutions currently being developed include:

- Data Center Smart Metering Evaluation: SSC Pacific is currently evaluating technical approaches to smart metering for data centers. A smart meter is an electrical meter that enables two-way communication between the meter and the central system. It records consumption of electrical energy in intervals and communicates that information back to the utility company for monitoring and billing.
- Energy Focused Fused Information System-Integration: SSC Pacific is investing how to develop the methods and expertise required to optimize energy for SPAWAR information technology systems. The goal is to create a capability to monitor, manage, fuse, and optimize energy for enhanced efficiency, security, and performance of C4I/IT systems.
- Data Center Cooling Distribution Efficiency: SSC Pacific is assessing this program and has identified multiple opportunities for energy-efficiency improvements in data centers. Technologies identified either are commercially available or soon will be available to further improve the energy efficiency of cooling infrastructure systems.
- Data Center Consolidation Sustainment and Energy: To address the outstanding costs and extensive use of energy, the NEDC is currently conducting the Federal Data Center Consolidation Initiative. The consolidation effort involves transitioning up to 60 legacy data centers into four NEDCs owned and managed by SPAWAR in San Diego, California; New Orleans, Louisiana; Charleston, South Carolina; and Millington, Tennessee.

"Energy is a critical resource that enables performance, drives total life-cycle cost, is paramount to system reliability, and has far-reaching environmental and national security impacts," said Wotawa-Bergen.

"Energy is a critical resource that enables performance, drives total lifecycle cost, is paramount to system reliability, and has far-reaching environmental and national security impacts," said Wotawa-Bergen.

SPAWAR's naval enterprise energy team will continue to plan, design, and coordinate a strategic energy approach to NEDC and consolidation tasks, ensuring reliability, reducing costs, and promoting Department of Defense energy independence and security objectives.

About the author:

Elisha Gamboa is a Space and Naval Warfare Systems Center Pacific staff writer and technical editor.

Naval Energy Strategy

Signed by Secretary of the Navy Ray Mabus in October 2009, the Naval Energy Strategy focuses on holistic energy values centered on energy security, energy efficiency, and environmental stewardship.

Energy Security: Energy security is critical to success. We will safeguard our energy infrastructure and shield ourselves from a volatile fuel supply.

Energy Efficiency: Energy efficiency increases combat effectiveness. We will expand our tactical reach and minimize operational risks, saving time, money, and lives.

Sustainability: Environmental stewardship is our responsibility. We will reduce the environmental impacts of our energy use, lead in reducing greenhouse gas emissions, and promote sustainability.

By Eric Dow, Maria Medeiros, and Michele Anderson

Unmanned undersea vehicles (UUVs) will transform the Navy's future operations by extending the area and volume that can be sensed, influenced, and affected through power projection. The proliferation of UUVs in quantity throughout the force structure will significantly amplify capacity and enable these vehicles to inherit missions that currently are too dangerous or beyond the capability of manned platforms. UUVs can investigate vast areas of ocean or conduct surveillance of remote undersea locations that are too shallow, difficult, or hostile for traditional platforms to investigate. These craft will be fully autonomous, without a "human in the loop," and they will not have any cables or tethers to provide remote control, navigation, or "power down the wire" from a host ship or platform. Future UUVs will have to carry or harvest all the fuel required to power the vehicle's propulsion, payloads, sensors, and onboard computers while maintaining continuous, unassisted, fully submerged, and very quiet operation.

This is an enormous challenge when you consider that future UUVs will need to operate continuously for more than 60 days without refueling; by comparison, using today's best batteries, such vehicles only would be able to operate for fewer than five days before requiring a recharge. In addition, the engines or motors used to push the vehicles through the water will need to be upward of three times more efficient than today's best automobile engines, all while being much more reliable. Imagine being able to run your car's engine for 1,500 hours of continuous driving, or about 60,000 miles, without ever needing an oil change or routine maintenance.

To solve these difficult problems, the Office of Naval Research (ONR) in 2011 released two broad agency announcements to industry. The first was the Large Displacement Unmanned Underwater Vehicle (LDUUV) Innovative Naval Prototype (INP) Energy program. It addressed the challenge for an LDUUV that will require an energy source capable of upward of 1.8 megawatt hours of electrical energy in a 3.454-liter volume. The second announcement addressed the challenge for a much smaller 21-inch-diameter UUV, the Long Endurance Undersea Vehicle Propulsion (LEUVP) Future Naval Capability (FNC) program, which required an energy source capable of upward of 68 kilowatt hours of energy in a 132-liter volume. Both of these programs will demonstrate a scalable, air-independent power source with improved energy density (three to five times that of silver oxide-zinc batteries), quick recharge or refueling, and operation at an acceptable cost through an integrated, full-scale, land-based test in a UUV energy hull section.

The technology solutions considered to address these challenges focus on fuel cells, including solid oxide fuel cells (SOFC) and polymer electrolyte membrane (PEM) cells. Fuel cells and hybridized approaches with batteries and/or capacitors have the potential to meet both the near-term and far-term UUV energy requirements—which will be in excess of 500 Wh/l (energy density) and 500 Wh/kg (specific energy), including the necessary fuel and oxidizer sources, all while being inherently safe so that they will not impose undue hazards to personnel during handling and storage.

Each of these next-generation UUV power systems will have inherent advantages and disadvantages, making some more or less attractive than others. For example, SOFCs and PEMs are the most efficient power converters. The PEMs operate at relatively low temperatures (80 to 100 Celsius) and require very high purity hydrogen, while SOFCs must operate at very high temperatures (greater than 700 Celsius), allowing them to achieve higher efficiency than PEMs while being more tolerant toward impurities in the hydrogen fuel. For the PEM fuel cell system, sufficient amounts of high-purity hydrogen aboard the UUV requires high-pressure gaseous hydrogen (greater than 5000 psi), very low-temperature liquid hydrogen (-253 Celsius), or other sources of pure hydrogen (such as metal hydrides or chemical hydrides, which typically require cylindrical flasks and result in overall packing inefficiency).

These craft will be fully autonomous, without a "human in the loop," and they will not have any cables or tethers to provide remote control, navigation or "power down the wire" from a host ship or platform.

For SOFCs, in comparison, the hydrogen gas could be derived from common liquid hydrocarbons, such as jet fuel, which can be stored very easily and efficiently at room temperature and pressure. The challenge for SOFCs is extracting the hydrogen from the liquid fuel through a more complex reforming or "cracking" process. Compared to the SOFC and PEM fuel cells, lower-efficiency thermal combustors and Stirling engines can use the liquid hydrocarbons directly without reformation and burn the fuels to generate heat for a turbine or piston-engine thermodynamic cycle. For this approach to be successful, trading off the efficient storage of liquid fuels against the higher combustion temperatures (more than 1,500 Celsius using pure oxygen) and lower system efficiencies are being studied. Regardless of whether the eventual solution is SOFC, PEM, Stirling, liquid fuel, or chemical hydride, the systems likely will use pure oxygen, as air is not an option. This puts a very challenging spin on the UUV energy system development, since the bulk of the US industrial power and energy sector is focused on air-breathing technologies for which their current systems are largely incompatible with a pure oxygen environment.

LDUUV INP Energy System

This INP will demonstrate Technology Readiness Level (TRL) 6 scalable, air-independent technologies for a 48-inch-by-48 inch cross-section UUV. It will use an integrated, full-scale, land-based test in a 120-inch-long UUV energy section that will demonstrate upwards of 37 kilowatts for durations of 70 days, several start/stop cycles, and refuelability without disassembly from the vehicle. The goal is a roughly 1,000-Wh/L energy system ready for transition to the LDUUV for subsequent integration and in-water testing in fiscal year 2018 and as a spiral technology insertion to the future PMS 406 LDUUV program of record acquisition efforts.

LEUVP FNC Energy System

This FNC will demonstrate TRL 6 scalable, air-independent technologies for a 21-inch diameter UUV through an integrated full-scale, land-based test in a UUV energy section to demonstrate 1.5 kilowatts at 7-10 W/l nominal power density, at least 30 hours duration, several start/stop cycles, and refuelability. The goal is a 300- to 500-Wh/L device ready for transition to the PMS 406 UUV Knifefish program of record for subsequent integration into a vehicle for in-water testing in fiscal year 2018.

The UUV air-independent energy technology emerging from both the INP and FNC programs will have the capability to meet the Navy's near-term and far-term objectives to provide a persistent forward presence. Perhaps more important, it will enable manned platforms to operate independently hundreds of miles removed from areas of conflict, resulting in reduced risk to naval personnel and platforms. UUVs with prolonged endurance also will provide force multiplication through the employment of numerous small autonomous vehicles from one host platform. In the future, high-endurance UUVs operating in concert with manned platforms and one another will provide increased search rates and area coverage, improved efficiency, and distributed sensing—all adding significant flexibility and options to future naval operations.

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A POWERFUL LOCATION:
The Naval Ship Systems Engineering Station

By Dr. E. Michael Golda

Photo by Joe Battista

The DDG 1000 land-based test site provides experience with new ship systems going into the *Zumwalt* class.

Since the advent of electronics, US Navy ships have steadily increased their use of energy to provide the additional power required by advances in sensors and weapons. A team composed of experts from the Navy, industry, and academia is working to create and integrate new technologies into shipboard systems that satisfy these constantly increasing requirements. The Naval Ship Systems Engineering Station (NAVSSES) is a key member of this team. NAVSSES, a command within the Naval Surface Warfare Center Carderock Division, is the Navy's center for naval machinery for surface and undersea vehicles. The station's responsibilities span the entire machinery life cycle from concept through development and transition to acquisition, introduction to the fleet, in-service engineering support, and disposal at the end of service life.

A Trend of Increasing Power

To accomplish its mission, a warship's infrastructure of machinery and mission loads (sensors and weapons) must manage both energy (the potential to do work) and power (the rate at which energy is transferred). Since World War II, naval surface forces have exhibited a constant increase in the power requirements for each successive generation of shipboard mission loads as capabilities are improved and new technologies are introduced to meet warfighting requirements. There is nothing to suggest any change in the trend of increasing power requirements for mission loads for the next generation of surface combatants. In addition, providing power when and where needed will become more difficult, as these loads will be larger and nonlinear, stochastic (both random and variable), and pulsed. The capacity of traditional alternating current ship service generation and distribution systems can be increased by using larger generators at a higher voltage to provide additional power. While this approach is being used on the *Arleigh Burke* (DDG 51)-class Flight III, there are limitations caused by increasing power system size and weight.

In January 2000, the secretary of the Navy endorsed an alternative approach to meeting future shipboard power and energy needs—the integrated power system (IPS). By changing from a mechanical to an electrical propulsion system and taking advantage of advances in solid-state power electronics, a ship with IPS can make more effective use of its installed prime movers and use a common distribution system and advanced machinery controls to distribute electric power as required between machinery and mission loads. The *Zumwalt* (DDG 1000)-class destroyer is the first Navy combatant to incorporate IPS. While this system has the flexibility to accommodate the new weapon systems of the last several years, the Navy may need to investigate medium-voltage, direct-current architectures to accommodate the continued increase in the requirement for shipboard power.

The development of shipboard power and energy technologies is a joint effort between the Navy, industry, and academia. Major Navy participants include:

- The Office of Naval Research (ONR) Ship Systems and Engineering Research Division funds the basic and applied research and advanced technology development for shipboard electrical power generation, distribution, storage, and control
- The Electric Ships Office (PMS 320) of Program Executive Office Ships continues the maturation of successful ONR developments to ensure components and systems are available to meet the schedule of future acquisition programs
- Within the Naval Sea Systems Command Naval Systems Engineering Directorate (SEA 05), the technical warrant holder for machinery and electrical systems, is accountable for setting the appropriate technical standards, ensuring safe and reliable operation, conducting effective and efficient systems engineering, and maintaining stewardship of the engineering and technical capabilities that support this technical area.

Developing and Transitioning Technology

NAVSSES's responsibilities are broad in scope and include: mechanical and electrical power and propulsion systems; auxiliary machinery systems; machinery automation, controls, sensors, and networks; comprehensive logistical support; and machinery systems integration. The 1,500 scientists, engineers, and skilled technicians of NAVSSES have the knowledge, skills, experience, facilities, and equipment to conduct science and technology, research and development, test and evaluation, acquisition support, engineering, systems integration, in-service engineering, and fleet support.

NAVSSES centralizes its machinery science and technology and research and development efforts in one division (Machinery Research and Silencing). This enhances efficiency by making it easier to develop and sustain personnel with in-depth technical expertise in naval machinery research by enabling them to focus on monitoring advances in fundamental science and actively participate in developing new technologies. With this expertise, these personnel can also provide technical leadership and respond to emergent Navy needs.

By routinely updating the Electrical Power Systems Life Cycle Master Plan, engineers provide fleet support can identify performance gaps and provide firsthand lessons learned on current components and systems to the scientists and engineers developing new technologies. Researchers and in-service engineers can work together to write clear and concise specifications to ensure the Navy acquires systems with the performance needed to meet warfighting requirements. The input of NAVSSES engineers during the industry design reviews helps identify and resolve technical issues early on, reducing program technical and financial risk. The full-scale testing facilities at NAVSSES provide a cost-effective venue to integrate and characterize a component or system before installation at the shipyard, both during construction and periodic modernizations during a ship's service life.

Exploratory Development

The majority of NAVSSES technology development and transition efforts are funded by ONR, Naval Sea Systems Command, and various program executive offices. However, the Naval Innovation Science and Engineering Section 219 program authorized in 2009 provides the warfare centers with discretionary funding to be used as they direct to foster high-risk basic and applied research, develop programs to transition technologies to the fleet, and support the development of workforce technical expertise. These funds are already making significant contributions to naval energy and power technologies, such as high-temperature superconductivity.

Superconductors are materials that lose all electrical resistance when maintained within an operating region bounded by a critical temperature, a critical current density, and a critical magnetic flux. Metallic superconductors (low-temperature superconductors) became available in long lengths in the 1960s and resulted in the commercial development of magnetic resonance imaging. The absence of electrical resistance enables extremely power-dense machines. The Navy designed, fabricated, and conducted an at-sea demonstration of a prototype superconducting generator and propulsion motor in the early 1980s. The need for liquid helium to cool the superconducting wire was a significant mechanical and logistical issue. The discovery in 1987 of ceramic superconductors that transitioned to the superconducting state at a higher temperature sparked a renewed Navy interest. Liquid helium was no longer required, and compact, commercially available mechanical refrigerators (cryocoolers) could provide the required cooling. ONR funded the development of a full-scale, high-temperature superconducting propulsion motor, which was tested at NAVSSES in 2009.

In 2004, ONR funded NAVSSES to evaluate the feasibility of reducing the weight of shipboard degaussing systems (which make ships less vulnerable to magnetic mines) by replacing the copper cables with superconductors. The study showed that even with the requirement for mechanical refrigerators, significant reductions in the system weight were possible. To accomplish this application, NAVSSES engineers developed and patented a design for a high-temperature superconducting system that used a gaseous cryogen for cooling the cable. Successful laboratory demonstrations validated the concept. ONR SwampWorks funded an at-sea demonstration aboard USS *Higgins* (DDG 76), during which the unit operated for more than 9,000 hours. To speed development in the components required in a cryogenic electrical system, such as cable connectors, circulation fans, temperature sensors, and cryocoolers, NAVSSES engineers developed appropriate interface specifications and took full advantage of the innovative ideas from the Navy Small Business Innovation Research program to fund the design and fabrication. NAVSSES engineers were recognized by both the Naval Sea Systems Command and the Department of the Navy for their accomplishments.

NAVSSES is using Naval Innovation and Science and Engineering 219 funds to develop expertise in areas of high-temperature superconducting medium voltage distribution cables that are unique to naval applications, such as contact resistance and cryogenic dielectric materials. Additional basic research is being conducted to develop both a thermal model of a shipboard superconducting cable and an advanced cryogenic cooling concept.

Test and Evaluation

Electrical rotating machines are key elements of a ship's power systems. Motors transform electrical to rotation mechanical energy to power machinery and propel the ship, while generators convert rotational mechanical energy into electrical energy. The power density of a generator can be increased by raising the rotational speed and voltage. In 2005, PMS 320 contracted with Curtiss-Wright's Electro-Mechanical Division to design and build a 14-megawatt, 7,000-rpm generator with a six-phase, 6,600-volt AC output. By using water-cooling circuits in the rotor field winding, the stator winding, and the stator core, this developmental generator had a power density six times greater than a similarly sized low-speed, conventionally cooled generator.

NAVSSES constructed a test site that would permit full load testing of the generator. The test facility drivetrain uses a 3,600-rpm motor coupled to a speed-increasing gearbox to achieve the 7,000 rpm required by the generator. Following the generator's delivery in 2010, NAVSSES spent the next two years conducting the PMS 320 test plan before the program concluded. Based on lessons learned during this testing, NAVSSES engineers believed there was additional engineering knowledge that could be gained by NAVSSES testing after the PMS 320 program concluded. Using Naval Innovation Science and Engineering 219 funds, NAVSSES engineers investigated and resolved vibration issues in the gearbox foundation. With continued funding in 2013, the test team conducted multiple eight-hour operational tests with outputs up to full load to investigate the performance of the water-cooling circuits at steady state temperatures.

As the Navy's center for electrical power and propulsion machinery, NAVSSES's responsibilities span the full life cycle of electric power technology.

The availability of Naval Innovation Science and Engineering 219 funding resulted in applied engineering knowledge that can be applied directly to the design of both future generators and the associated test sites. In addition, more than 20 junior engineers gained direct, hands-on experience in high-speed machinery analysis and operation.

System Integration

New technologies only enhance Navy capabilities if they are successfully commissioned into service. NAVSSES has pioneered the use of the land-based test site (LBTS) to validate the design, manufacturability, and performance of full-scale machinery components and demonstrate the ability to integrate those components and controls into a system that meets Navy specifications. The LBTS can document full-scale system characteristics with production hardware and identify best practices to lower the risks of shipyard activation and trials. Additional benefits include the ability to provide training for the shipyard, precommissioning crew, and the NAVSSES engineers supporting trials and providing in-service engineering support. Since 1941, the Navy has evaluated 12 full-scale, surface ship propulsion systems at NAVSSES, either to reduce acquisition risk for a new ship class or to develop and demonstrate a new propulsion technology (including IPS).

A single LBTS supported the development and maturation of IPS technology and its transition to the DDG 1000 IPS. The process began in 1995 with the integration of less-costly, smaller components and controls to create a Reduced-Scale Advanced Development IPS to validate the fundamental concept. Full-scale components, such as the main propulsion generator, were then manufactured and integrated as part of the Full-Scale Advanced Development IPS. Testing was completed in 1999 and provided the technical validation needed to select an IPS for DDG 1000. Following the award of the DDG 1000 contract, an engineering development model was installed, which successfully achieved both the design output torque of the propulsion motor and the predicted fuel consumption of the main turbine generator in 2005. Finally, one shaft set of the third production IPS ship-set was installed and tested at the LBTS between 2011 and 2013.

Summary

NAVSSES is a key member in the Navy, industry, and academia team developing technologies to address the power and energy needs of future naval combatants and increase the capabilities of ships already in the fleet. As the Navy's center for electrical power and propulsion machinery, NAVSSES's responsibilities span the full life cycle of electric power technology. The organizational structure of NAVSSES and its extensive facilities and infrastructure provides a locale to integrate advanced machinery components into full-scale systems for test and evaluation, reducing program risk during transition to the fleet.

About the author:

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STORAGE MODULES WILL FUEL THE FUTURE

By Donald J. Hoffman

With an expansion in breadth of capability and mission profiles across the Department of Defense (DoD), current and future naval platforms increasingly require integrated energy storage systems to support the fielding of a multitude of high-power-consumption electrical loads from advanced weapons and sensors. All-electric platform designs, and the cost-driven mandate toward fuel-efficient plant operations, exacerbate the need for hybridized energy storage and transfer solutions. Energy storage systems have long been a compromise between total energy storage, high discharge and charge rates, overall efficiency, and other factors. Hybrid energy storage—which includes combinations of power and energy devices such as batteries, capacitors, flywheels, or a mix of different battery types—is intended to enhance the integration of existing power systems with storage and buffering. This approach maximizes operational safety, reliability, efficiency, and security; optimizes installed storage; and minimizes total weight, overhead, and costs.

Hybrid energy storage modules (HESM) with high-power and-energy densities, high-rate capability, and scalability to all power levels will maximize performance, enhance fuel efficiency, and enable future high-power weapon and sensor systems on current and next-generation vehicles and platforms. This capability will store electrical energy while providing variable charge and discharge rates in high-power-density, dynamic, modularly reconfigurable architectures. The HESM program, cosponsored by the assistant secretaries of defense for research and engineering and operational energy plans and programs, addresses advanced technology development associated with providing the capability to enhance fuel efficiency, maximize performance and reliability, and enable future high-power weapon and sensor systems on current and next-generation Army and Marine Corps battlefield generators and vehicles, Air Force and Navy aircraft, and Navy ships. The Office of Naval Research is leading the overall effort, which has established three overarching track areas associated with Department of Defense (DoD) operations directed by individual services. These include: Tactical (Army lead), a plug-and-play configuration for capability and fuel efficiency in a battlefield environment; Aircraft (Air Force lead), improved generator and power system reliability; Large Power (Navy lead), continuous transient support and fuel-efficient operation.

Each development track is establishing a basis of understanding and benefit of HESM operation in a military environment with planned subscale development and demonstrations. Once demonstrations are complete, the technologies will transition to the individual services.

In partnership, the Advanced Research Projects Agency for Energy (ARPA-E) released a solicitation entitled "Advanced Management and Protection of Energy storage Devices" (AMPED). This effort aims to unlock enormous untapped potential in the performance, safety, and overall cycle lifetime of today's commercial battery chemistries exclusively through system-level innovations, which are distinct from efforts to enhance underlying battery materials and architectures. The AMPED program focuses on novel science and technology advances in sensing, control, and power management technologies to enable entirely new capabilities for battery management and cycle life. The program also provides a toolset of approaches that can be readily leveraged to integrate high-energy battery systems and enable aggressive usage profiles in hybridized energy storage systems.

In November 2014, the Army's tactical track conducted a successful demonstration of HESM capability. The unit, developed by Acumentrics Inc., highlighted the potential to achieve optimal efficient configuration with plug-and-play capability to enhance versatility and reduce fuel use for emerging military microgrids and tactical hybrid power systems. This was accomplished by using a reconfigurable direct current (DC) architecture stabilized by hybrid energy storage. System performance resulted in the ability to power manage multiple dissimilar DC power sources, such as solar photo voltaic cells, fuel cells, etc., working in conjunction with existing generators as needed to achieve higher efficiency total system performance. The HESM tactical track completed its operational demonstration milestone two years ahead of schedule.

The Air Force's aircraft track has two HESM development efforts under way through Eaglepitcher and Pratt & Whitney to improve the capability of the More Electric Aircraft (MEA). The MEA has created opportunities for new subsystem designs and an increase in dynamic electric loads. As a result, more capabilities have been required of the electrical power system, including sourcing more power and reacting to regenerative energy. As more electrically demanding loads are added to aircraft, the electric power system will be required to service higher power peaks at faster rates. The intent is to improve MEA key characteristics: electrical power quality, component lifespan, and overall system performance for all flight conditions, including possible weight and volume savings. A successful program will result in the construction and demonstration of an HESM unit, consisting of an electrical accumulator unit using at least two different types of energy storage devices operating in a coordinated manner to support the overall objective in an optimized manner. The demonstration is planned for fiscal year 2016.

The Navy's large power track is developing three HESM systems through Caterpillar, General Electric, and Raytheon. Each effort examines a different configuration of hybrid energy storage to buffer high-power, stochastic (i.e., random) pulse loads operating in conjunction with existing power generation in large grids such as Navy ships.

Future naval platforms will have demanding and complex electrical loads in shipboard integrated power systems. Emerging loads require a range of power levels over a spectrum of time scales such as milliseconds for advanced weapons, seconds or a fraction of a second for transients, and minutes for single or fewer generator high-efficiency operation and uninterruptible power source functions. These diverse loads are not easily accommodated by a traditional ship's power distribution system supported by only prime mover power generation sources. This shortfall in current designs necessitates hybrid energy storage systems to bridge the energy and power gap in different time scales for seamless and uninterrupted operation. The HESM program objective is to develop and demonstrate scalable and modular HESMs for naval ships' large power applications, supporting continuous pulse loads which can occur in random patterns at multiple time scales, and ensuring the delivery of quality electrical power with safety and reliability, minimal component weight and volume, and maximal component life. Each of these demonstrations will be completed in fiscal year 2015 or 2016.

The first HESM program large power track demonstration was completed by General Electric in May 2015. The proof-of-concept HESM prototype successfully operated under a number of operational modes (e.g., charge optimization, sustainment, and augmentation) with and without prime mover input. Various other load profiles and operating scenarios were tested satisfactorily to validate the HESM capability of supporting continuous stochastic loads with required response time for both alternating current (AC) and DC loads. The modular proof-of-concept HESM can be scaled-up for multimegawatt shipboard distributed and/or centralized installations for low-voltage (less than or equal to 1000 volts) and medium-voltage (1-20 kilovolts) direct current or alternating current integrated ship power systems.

For all HESM efforts, the associated original equipment manufacturer is accounting for AMPED technology integration. The synergy derives from making best use of traditional technology development in each agency. DoD traditionally develops technology driven to meet military mission needs defined by requirements and specifications, depending upon the platform, conops, and environment. To meet mission needs, DoD is willing to accept risk and maturate technology through development and demonstration until the technology readiness level is acceptable. ARPA-E traditionally develops technology for the commercial sector that is driven to generate economic benefits. By nature, the commercial sector is risk averse to adopt new technology unless it is economically viable or can be demonstrated to be ready for implementation. Through partnerships, DoD can benefit by accelerating the development and potential adoption of technology targeted for the commercial sector by the Department of Energy that increases the capabilities of military platforms and reduces costs.

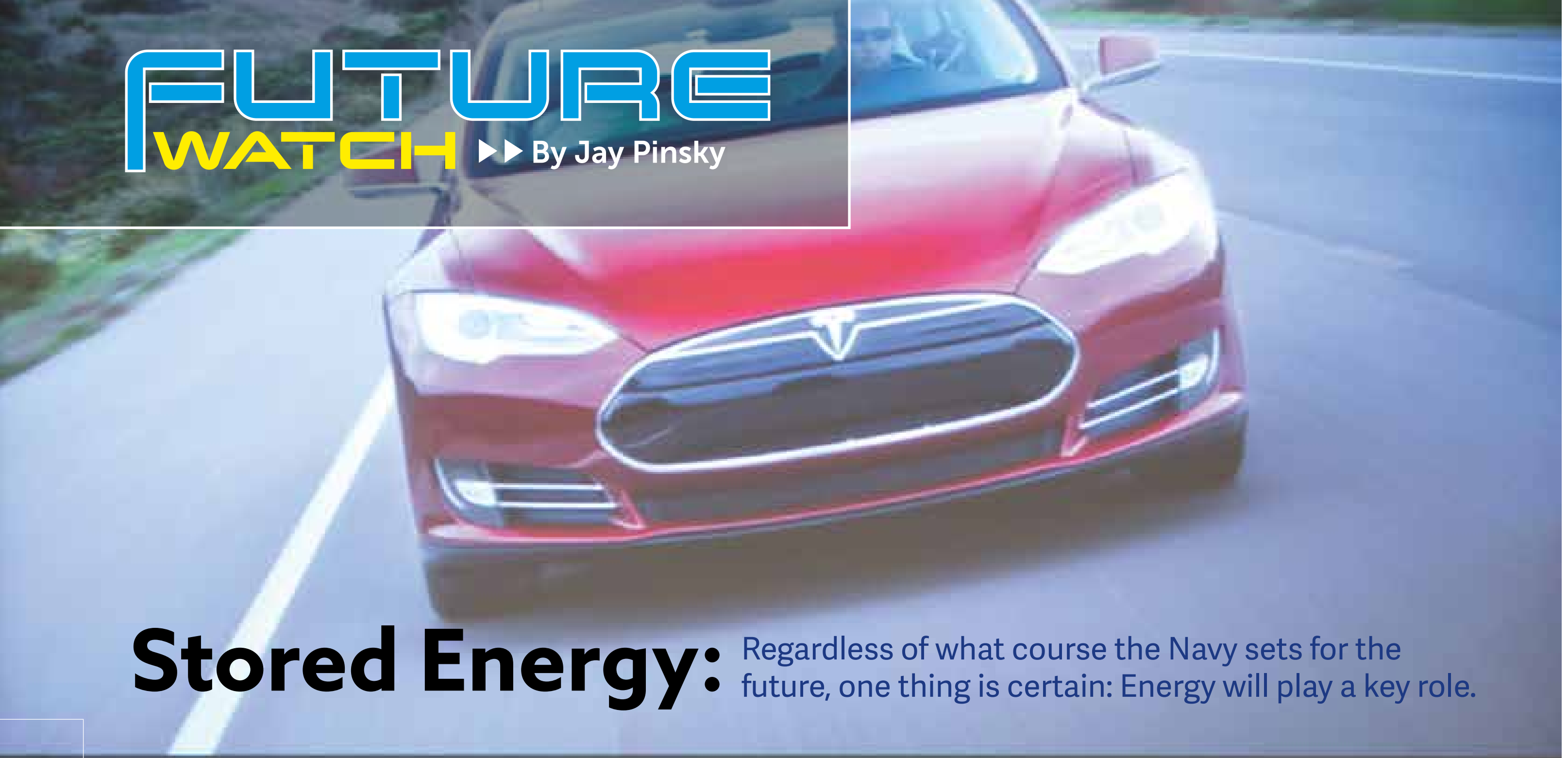
Advancing HESM technology through partnerships of multiple agencies and services provides the vital collaboration for developing, demonstrating, and commercializing advanced technology. HESM will enable modularly scalable solutions for next-generation naval combatants to ensure they will be able to employ the full spectrum of advanced weapons and sensors currently in development. HESM is a vital enabling component required to advance the Navy's power projection and lethality into the future to ensure warfighter dominance in combat.

About the author:

Don Hoffman is the program officer at the Office of Naval Research responsible for the development of power generation and energy storage systems.

FUTURE WATCH ▶▶ By Jay Pinsky

Stored Energy: Regardless of what course the Navy sets for the future, one thing is certain: Energy will play a key role.



Tesla Motors executive Mateo Jaramillo (opposite) talks about lithium ion batteries at the Naval Surface Warfare Center Carderock Division in June 2015. Photo by Devin Pisner.

Where this energy comes from and what it will cost, however, remain unclear. No secret to anyone in the defense industry, the Navy's ongoing quest for clean, safe, sustainable, and affordable energy is the daily motivation of many military and civilian minds. Since great minds think, but not all alike, the leadership at Naval Surface Warfare Center Carderock Division gathered many of the Navy's top energy experts in West Bethesda, Maryland, on 2-3 June for a two-day energy storage summit cohosted by Naval Surface Warfare Center Crane Division to unravel and solve some of the Navy's current and future energy storage requirements.

The summit's findings shed some light on how the Navy plans to mitigate future costs for its energy needs by focusing on the affordability of energy storage solutions for advanced weapon systems; generating energy-efficient power; maintaining undersea dominance; enhancing naval system ranges; lowering individual warfighters' loads on dismounted patrols; and improving intelligence, surveillance, and reconnaissance.

The summit aimed to make significant contributions to the long-term goals of solving the affordability of future stored energy needs; developing better collaboration across the technical communities; and creating a common understanding of the affordability challenges of stored energy—all of which are priorities for the Navy. "The CNO has stated that he wants a comprehensive, system-agnostic, lithium battery certification process to be developed for surface ship, submarine, and other undersea warfare applications now," said Dr. Tim Arcano, Carderock's technical director. "It is a priority of his and has become a funded Speed-to-Fleet program. Success of this program depends on advanced capabilities and safety to maintain military dominance. We need both of these, but we also need to be able to afford them."

One of the most popular topics of the summit was batteries—specifically lithium ion—including how to build them, store them, use them, test and field them safely, and sustain them affordably.

The summit's validation of lithium ion batteries as part of the Navy's stored energy future was highlighted by keynote speaker Mateo Jaramillo, director of Tesla Energy at Tesla Motors, a global leader in battery integration and advancement. Jaramillo shared Tesla's vision for lithium ion battery growth worldwide, highlighting rapid industry advancements in manufacturing, logistics, and sustainability as cornerstones to more affordable fuel storage energy solutions and profitability.

The future of energy storage is especially critical to the unmanned undersea vehicle field, according to Navy Capt. David Honabach, program manager for unmanned maritime systems at Naval Sea Systems Command, who spoke about affordable battery modules during the summit."I see lithium ion [batteries] as a critical steppingstone to support the future integration of advanced energy," he said.

The Navy already has had some success using alternative energy. Arcano cited several well-documented triumphs, including the MK-18 Mod II Kingfish unmanned underwater vehicle mine detection program, the F-35C Lightning II, the Ground Renewable Expeditionary Energy System, and the Experimental Fuel Cell unmanned aerial vehicle demonstration. "They have all shown that advanced energy storage technologies can enable important and disruptive capabilities for the fleet," Arcano said. Ongoing research and development, along with ever-increasing real-world application experience, have created an exponential technology boost globally, with Navy minds eager to capture industry advances for naval applications.

"Energy density of previous battery technologies was limited and insufficient to meet fleet needs," said Arcano. "Nickel-cadmium batteries were overtaken by nickel-metal-hydride in the early 1990s, and lithium ion chemistries have been used over the past 15 years, overtaking automotive, cellular phone, portable device, and military markets. We need to continue to develop and adapt cutting-edge storage technologies and be open to future systems and technologies as they become available."

The visions shared among peers at the summit fell into three basic areas: improving energy storage acquisitions and programmatic tools; improving and standardizing energy storage technologies; and initiating Navy and Defense policies. "The technical community felt we needed to provide better tools to inform and enable the acquisition community," said Eric Shields, group leader for the advanced power and energy group in Carderock's Materials and Power Systems Branch.

One idea was constructing a database of batteries fielded and tested, coupled with a cost-versus-time estimation and reporting tool. According to Shields, there are three primary reasons for maintaining a lithium battery safety database: To identify options and gain a better understanding of scheduling and cost implications of technology selections; to eliminate redundant testing and share knowledge; and to create a centralized database for validation and verification purposes. Shields said the idea's perceived benefits would support commonality among programs, reduce redundant testing, expedite information to program offices, support analyses of alternatives, and act as a risk reducer.

The group first met at Crane last fall and plans to meet again in spring 2016.

About the author:

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TOMORROW'S TECH: Marine Austere Patrolling System

By Phillip Jenkins and Eric South

Marines test out the Marine Austere Patrolling System, which helps to recharge gear in the field, at the Marine Corps Mountain Warfare Training Center north of Yosemite National Park in California.

The modern warfighter's reliance on electronic systems to increase combat effectiveness comes at a cost: a greater pack weight for dismounted Marines that potentially limits mission duration because of limited battery capacity. Expeditionary forces also are hindered from extended mission assignments by requirements to carry all necessary drinking water, which can range from 12.5 to 25 pounds per day, depending on the environment. The Marine Austere Patrolling System (MAPS) has demonstrated a renewable energy capability in the form of solar panels, significantly reducing the need for battery resupply, and tested a prototype portable water filtration system.

MAPS is a collaboration between the Marine Corps Expeditionary Energy Office's Squad Electric Power Network project team and the US Naval Research Laboratory. MAPS is intended to lighten warfighter loads by reducing battery weight and water supplies. MAPS integrates a lightweight, wearable, electrical power management and distribution system, solar energy-harvesting technology, and an on-demand water purification system. The Individual Water Purification System provides a physical barrier from protozoa, bacteria, and viruses, allowing users to collect untreated water directly into the reservoir and purify as they drink. The Army is evaluating other portable systems, and the Marine Corps will look for an opportunity to leverage that technology development.

The MAPS system demonstrates the utility of harvesting energy for dismounted Marines and provides a roadmap for future portable energy-harvesting systems.

Components

The electrical portion of MAPS consists of a central power manager, a conformal wearable rechargeable lithium battery, a high-efficiency solar panel, and distributed charging interconnects for individual components such as radios, GPS, or night vision batteries. All MAPS components operate together while stationary or on the move.

The Protonex Vest Power Manager (VPM-402) serves as the electrical "brain" of MAPS. Its low mass and small size (about the size of a deck of cards) provides an interface between power sources and loads up to 75 watts, between four to 34 volts of direct current. The VPM recognizes connected devices through programmed cables and automatically adjusts each port for the appropriate electrical settings. It provides users with state-of-charge indication, two output load ports, one central power input, and an all-purpose scavenging input port. The VPM can use solar power or be connected to auxiliary vehicle power, scavenging up to 75 watts. It charges standard military batteries commonly carried by dismounted Marines. The VPM-402 is equipped with a data-logging capability and can be used as a USB power and data hub.

While MAPS is capable of scavenging power from different types of power sources, a high-efficiency photovoltaic (HEPV) panel was specially developed for MAPS. The HEPV, developed by MicroLink Devices and the Naval Research Laboratory, uses solar cells similar to those on modern satellites and is four to five times more efficient than those found in first-generation portable power systems. The HEPV solar cells are made from what are known as "III-V" semiconductors (from their location on the periodic table). Using III-V materials allows monolithic integration of a series of three stacked solar cells where each cell converts a portion of the solar spectrum at a higher efficiency than a single solar cell can over the entire solar spectrum. These solar cell stacks are only 10-20 micrometers thick, remain flexible, and are extremely lightweight. HEPV's increased efficiency translates directly to smaller area. The HEPV panel, designed to fit on an assault pack, produces 14-17 watts under real-world conditions and is small enough to remain on an assault pack deployed. The panel can be worn for solar charging on the move and easily detached for rapid deployment in stationary operation. Multiple HEPVs can be "daisy chained" and used by a single VPM.

Configurations

An important element of MAPS integration is form factor, or size. An individual system needs to be modular and configurable to fit different mission profiles and human factors:

Wearable: Individuals may choose to wear MAPS gear by Modular Lightweight Load-carrying Equipment (MOLLE) weaving onto the vest. Placement of the components varies significantly according to individual size and billet within a squad. Squad leaders may find that wearable configurations (adjusted to their own preferences) provide access to power management, electronic control, and state of charge while on the move.

Packable: MAPS gear can be packaged in a backpack-style kit. The kit resembles a day pack in size. Members of the squad without a large electronic load may find a packable solution allows a high degree of modularity or flexibility in carried MAPS components. The system can be removed and replaced most easily in the packable configuration.

During development, it was always recognized that end-user feedback was the only way to properly design MAPS's form, fit, and function. Conducting early field trials established the best ergonomic fit and attachment system even before the optimal electrical functionality was available. The initial MAPS field demonstrations took place in summer and winter conditions at the Army National Guard Maneuver Training Center at Virginia's Fort Pickett during two Marine Corps training exercises. These demonstrations monitored solar conditions to establish performance expectations and set up experiment and control groups with and without the MAPS. During these exercises individual warfighters used the gear, giving valuable insights into what would become the ultimate embodiment of MAPS.

The final effort from the MAPS program was tested with much success at the Marine Corps Mountain Warfare Training Center located in the Humboldt-Toiyabe National Forest in California. The final product was demonstrated as versatile, small, and lightweight. These trials helped to tune the capability, improve essential features, and discard little-used or redundant features and has provided quantified, real-world experience.

About the authors:

Phillip Jenkins is an electrical engineer and head of the Naval Research Laboratory's Photovoltaic Section. He has more than 25 years of experience in advance photovoltaic research serving both the Defense Department and NASA missions.

Eric South is an electrical engineer at the Naval Surface Warfare Center Dahlgren Division. He is the lead engineer for MAPS and its follow-on efforts with the Marine Corps and Army, and serves as a subject matter expert for dismounted infantry energy sustainment.

A LOOK AHEAD
ADVANCED MATERIALS

By Dr. Julie Christodoulou

The next edition of *Future Force* will focus on advanced materials, which enable each of the emerging capabilities being developed to support our Sailors, Soldiers, Airmen, and Marines.

Materials science and engineering is the practice of harnessing chemistry and physics to discover and develop new materials for improved performance or extended service. These also may involve the development of new processing schemes for existing materials for higher performance in new applications, or reduced cost-of-system or platform production.

Advances in materials and materials systems, including thermal and environmental barrier coatings, have enabled military and commercial aircraft turbine engines to operate at temperatures in excess of the melting temperature of the metal alloys used in the critical components. Higher operating temperatures allow for higher fuel efficiencies. Current efforts to expand these systems' resilience to the harsh environment faced by shipboard turbine engines will bring these efficiencies to naval ships, while reducing required maintenance operations. New systems based on ceramic matrix composites will allow the next generation of turbine engines to operate at temperatures 200-400 degrees Fahrenheit higher.

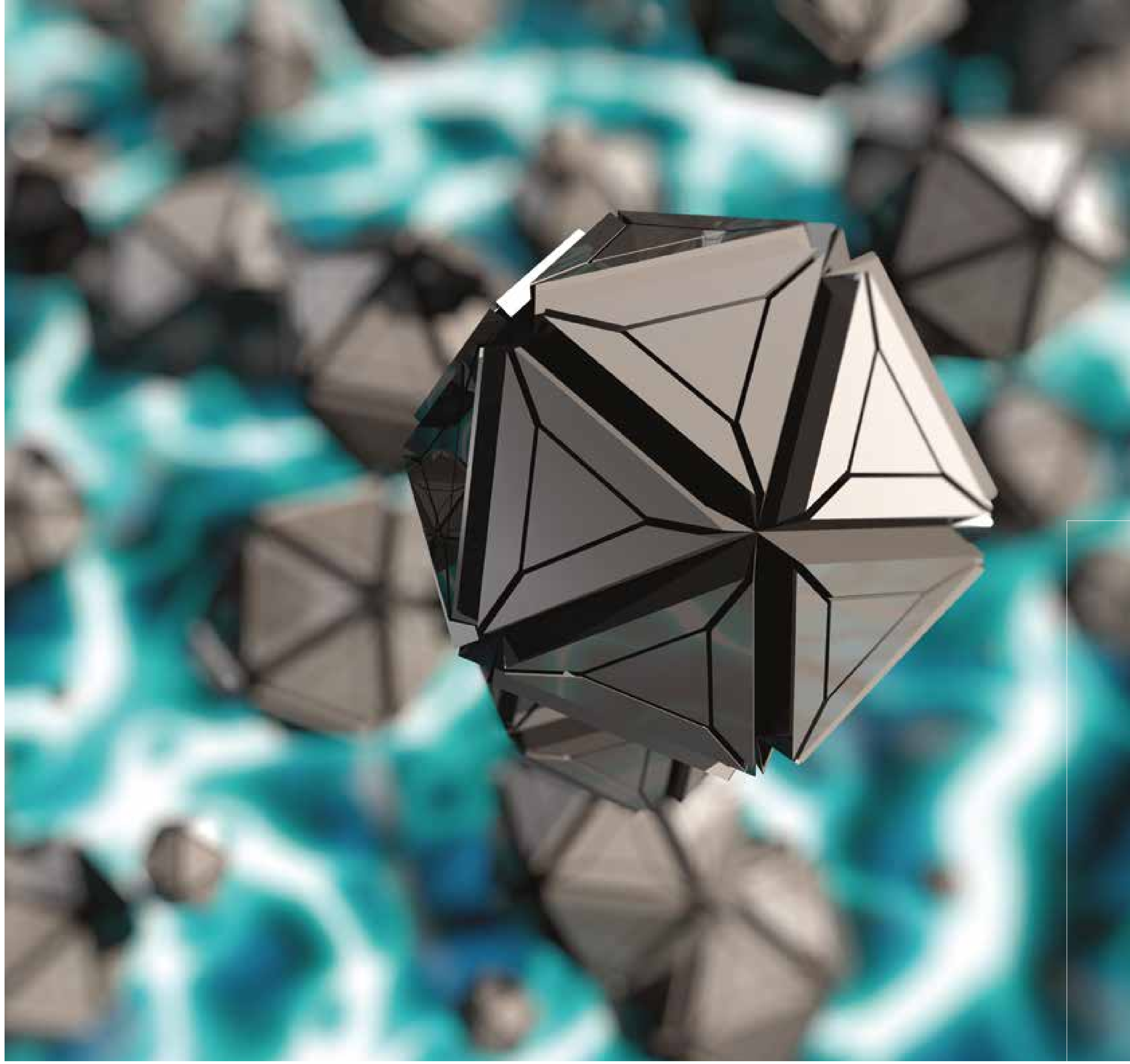
Understanding the complex biochemistry of biofoulants and the adhesives they use to establish themselves and their families on ship hulls is leading to new nontoxic and effective surface coatings that prevent the transport of nonnative species. Some of these coatings are modelled after very efficient biological systems, including shark skin, which have surface features at the scale of nanometers that make biofouling impossible. These materials technologies allow the Navy to operate anywhere in the world while complying with environmental regulations. They also reduce maintenance costs, as well as drag, improving fuel efficiencies for transit by as much as 4 percent.

New electroactive materials—and the deep understanding of how they perform as a function of composition and processing and how they degrade in service—are leading to new high-energy-density capacitors to provide reliable and more compact power capabilities. New compositions and structures are enabling more efficient and more stable batteries for large systems onboard ships and Marine Corps vehicles, as well as the portable communications gear that Marines carry into missions. New active materials systems for solar cells are bringing ever-renewable and affordable power to expeditionary bases.

Survivability is imparted at acceptable weights and volumes through the development of new systems of materials and deeper understanding of how these materials and systems respond to high-energy, dynamic loading events. Ultra-high-temperature materials are enabling forward projection by providing the stability and control needed for advanced missiles and projectiles. New optical windows that can withstand hypersonic flight are enabled by new compositions and processing capabilities. Affordable manufacturing and production is enabled by emerging processing capabilities, including solid-state joining and surface modification through friction stir welding and processing, advanced composite processing, and agile manufacturing technologies including powder processing and additive manufacturing.

Underlying all of these advances is the foundational understanding that allows for performance prediction and accelerated certification of materials and processes. Because the number of materials of interest to the Navy and Marine Corps is nearly infinite, the coming issue of *Future Force* will provide just a few snapshots of current efforts sponsored by the Office of Naval Research and being conducted in the Naval Science and Technology Enterprise—our laboratory system, universities here and abroad, and defense industry laboratories.

Dr. Christodoulou is the director of the Naval Materials science and technology division at the Office of Naval Research.



Advanced Materials

The science and systems that harness chemistry and physics to discover new materials or innovative ways of using existing materials for naval applications.

The Large Displacement Unmanned Undersea Vehicle-Innovative Naval Prototype was on display publicly for the first time at the Office of Naval Research exhibit during the Navy League's 50th annual Sea-Air-Space Exposition. The power demands of undersea and other unmanned vehicles such as this are spurring new and important areas of research.

Photo by John F. Williams

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