



INNOVATION

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BREAK THROUGH TECHNOLOGIES

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\ BRĀK-,THRÜ \

TECHNOLOGIES

Larry Schuette, Ph.D., Acting Director of Research, Office of Naval Research

There are three different definitions for the word breakthrough found in the Merriam-Webster online dictionary.

The first definition states that a breakthrough is, “an offensive thrust that penetrates and carries beyond a defensive line in warfare.” Our mission at the Office of Naval Research (ONR) is to invest in the next generation of science and technology to ensure that our Sailors and Marines have the future capabilities that they need to protect and serve our country. As our Chief of Naval Operations, Admiral Jonathan Greenert puts it in his three tenets, “warfighting first, operate forward and be ready.” It’s our job at ONR to make sure we provide our warfighters with technologies that ensure that they are ready and can breakthrough any situation that puts our national security at risk.

The meaning of the next definition is, “an act or instance of breaking through an obstacle.” There are teams of stakeholders and partners involved in the development of new technologies. From the team of scientists who dream up these new concepts, to the engineer who builds and delivers the technology, to the program officer who diligently manages the development and keeps the program on time and budget, it takes a team to champion

innovative new technologies and eventually deliver them to the fleet. This type of disciplined work is not for the faint of heart. It takes a team of dedicated and persistent individuals to breakthrough the maze of requirements and the lengthy acquisition process to ensure that the new technology is delivered into the hands of our warfighters.

The last definition for breakthrough is, “a sudden advance especially in knowledge or technique, e.g., a medical breakthrough.” Since the Naval Research Laboratory (NRL) first opened its doors in 1923, naval scientists and engineers across the country have been making breakthroughs in research that transform our warfighting capabilities. Beginning in 1934, when researchers from NRL received the first U.S. radar patents. With radar capabilities, all of a sudden we were able to detect aircraft, ships, spacecraft, missiles, and even weather formations, using radio waves. The ability to know where your enemy is located—even in low visibility situations—was a huge game changer in its day. Not only did it make a difference in our warfighting capabilities, but it also changed the way meteorologists study the weather and the way shipping companies do business by using radar to detect and avoid nearby ships.

When we first considered an issue focused on Breakthrough Technologies, we were originally a little intimidated by what we set out to accomplish. How do you even begin to scope and define what is and isn’t “breakthrough?” Breakthroughs, sometimes big—like the deployment of a new detection system like radar, or sometimes smaller, but still a significant milestone for a particular research program, are hard to quantify and compare. We decided to go straight to the folks across the naval research community and ask for their expertise. With their input, we were able to pull together a robust newsletter that features a small sample of some of our most recent and noteworthy breakthroughs. Like the different meanings of breakthrough suggest, our Navy breakthroughs take on many different forms. Whether it’s the deployment of a laser system for the first time or the persistent improvement of an old technology like spray dried plasma, we continue to improve technologies to better serve our Sailors and Marines. They deserve the best. Ultimately, we think that ten years from now we will look back at this work and be grateful for where it led us.

Enjoy this issue of the newsletter and please let us know if you have ideas for future topics—we love to hear back from you! ■



FROM SCIENCE FICTION TO THE U.S. NAVY

The Laser Weapon System (LaWS) temporarily installed aboard the guided-missile destroyer USS Dewey (DDG 105) in San Diego, Calif., is a technology demonstrator built by the Naval Sea Systems Command from commercial fiber solid state lasers, utilizing combination methods developed at the Naval Research Laboratory. LaWS can be directed onto targets from the radar track obtained from a MK 15 Phalanx Close-In Weapon system or other targeting source. (U.S. Navy photo by John F. Williams/Released)

Mr. Dave Smalley, Corporate Strategic Communications, Office of Naval Research

In the 1960s, the “Star Trek” television series showed the starship Enterprise firing powerful laser beams at adversaries in outer space. The crew, led by the daring Capt. Kirk, also used handheld “phasers”—essentially, directed-energy pistols—on missions. Less than a decade later, “Star Wars” took the idea one step further; in the movie’s opening scene, spaceships fired laser weapons at each other, with distinct sounds and colors for each ship’s rays. The personal weapon of choice (for the non-Jedi, at any rate) in that galaxy far, far away, was a “blaster” pistol or rifle using colored beams of directed energy.

In those days, the vision appeared fantastical, futuristic by even the most passionate scientist’s most optimistic vision. It seemed like science fiction’s outer reach.

Yet the laser itself was actually already in existence—it was invented in the late 1950s (debate raged over patent rights and actual date of discovery for the next 30 years). And the Navy, particularly the Office of Naval Research (ONR) and the Naval Research Laboratory (NRL), was a leading player from the start.

Early technical hurdles to weapons-level capabilities were significant, but the research never faltered.

But while scientists were working away in the technology’s infancy, it was Hollywood mixed with moon landings that fired the imagination of kids like Peter Morrison, who went on to become a Navy scientist, and one of the world’s foremost authorities of laser power.

Morrison, now with ONR, recalls: “Science fiction was part of every kid’s education in the ‘60s. Nearly every sci-fi book or movie after the 1957 invention of the laser had one form or another of a laser included in it. The bright flash of light that cut through anything, like a knife through warm butter—that could be used for peace, or for war. But my attention really focused when the first landings on the moon occurred, and I recall the discussion by Walter Cronkite that the astronauts left mirror reflectors on the moon. The mirrors would allow for very precise scientific measurements of the distance from Earth to the moon, using an Earth-based high energy laser, in real time.”

THE FUTURE IS NOW

Fast forward to 2013. Lasers have crossed into the everyday, the technology no longer the stuff of dreams or science fiction. And the Navy, so long a catalyst in their study, continues to lead. Scientists at ONR are working on a free electron laser (FEL), using magnetic fields and a stream of supercharged electrons to create a powerful laser beam that can take out the toughest targets, like incoming enemy fighter jets. And though a megawatt-class airborne laser program recently fell victim to budget constraints, the technology remains promising. (Officials are now looking into the possibilities of fielding smaller airborne lasers to take out smaller missiles.)

Today, a ship-based laser weapon is drawing the world's attention. It's the advanced weapon of the future, and the future arrived early. At this year's Sea-Air-Space Symposium—an annual gathering of top defense officials, academics, industry representatives and journalists—Chief of Naval Operations Adm. Jonathan Greenert unveiled a video where a laser gun, aboard a Navy ship, targets and takes out an unmanned aerial vehicle (UAV) in flight. That solid state laser, or SSL, will be deployed on USS Ponce in the Persian Gulf in 2014 for further tests—a huge step forward in the application of the technology.

We're not at a "Star Wars" level. Not yet. SSL lasers don't have the anticipated power levels of the FEL; drones can be shot down, but fighter planes or hardened targets cannot. But the story has turned, even in the popular culture, from sci-fi to how-to. The current Laser Weapons System (LaWS) is truly lethal, designed to counter asymmetric threats including swarming small boats, UAVs and other low-cost weapons. And it has the ability to vary its options, from simply "dazzling" or disrupting an incoming attack, to full lethality. (Morrison calls this "The Five D's" of capability: deter, disable, damage, defeat and destroy.)

The media and the public are fascinated, understandable when one considers the iconic images associated with laser weapons in pop culture. Within 48 hours after the SSL video was released, media stories, both print and

broadcast, numbered in the hundreds around the world—including, tellingly, the Iranian news agency. YouTube hits of the video were in the millions. (In fact, Navy officials said the video reached over 3 million views on their site in record time.) But beyond the impressive numbers was the strategic impact of the announcement, particularly given geopolitical developments and the deployment of Ponce to a relevant operational location in the Persian Gulf. To any potential adversaries, the message was clear: We have the edge.

There seems little question directed energy will revolutionize warfare, perhaps even in our lifetime. Shipboard lasers could be to conventional ordnance what the invention of gunpowder was to the bow and arrow, says Morrison. But as important as it is for the world to understand the significance of laser weapons, the back story—the "how"—is equally important. There are lessons in the technology's evolution that can and should be routinely applied to DoN research efforts.



Chief of Naval Operations (CNO) Adm. Jonathan Greenert announces the deployment of a solid-state laser aboard the Afloat Forward Staging Base (Interim) USS Ponce (AFSB(I) 15) in 2014 during the sea services luncheon at the Navy League's Sea-Air-Space Exposition. (U.S. Navy photo by John F. Williams/Released)



CONDITIONED FOR SUCCESS

First and foremost: SSL is a “breakthrough” technology that took years—decades, really—to develop. It’s proof positive of the importance and potential of long-term, methodical 6.1 and 6.2 research, something ONR officials well understand. While LaWS itself is a fantastic success story, no one would deny it was made possible by research underway since the 1950s.

In short: It takes hard work and overcoming setbacks to get from fantasy to laser-sharp reality.

“The development of this technology has been long and not always easy, but clearly worth it,” said Morrison. “And with technology advances across the board in related core research areas, our success rate has improved exponentially in recent years; especially within the last three years, we have seen significant improvements in high power fiber lasers used to form the laser beam.”

The primary improvement, experts say, was in the amount of power that could be generated in a single fiber while maintaining a good beam quality. The latest fiber lasers permit a 10-fold improvement in beam quality, and have more than double the range of previous efforts.

“It does show the advantage of not giving up,” Morrison added. “In the early days, chemical or gas-based laser systems were not easy to put onboard a ship. But recent advances with solid state lasers eliminate many of the old constraints, while still using the valuable lessons learned from them.”

So lesson one in the SSL story: *Perseverance*. Breakthrough technologies need more than great ideas to make it from the original “what if” inspiration to actual use. They require long-term vision, and requisite consistent funding. To put it a different way: Great weapons aren’t born; they are made.

Lesson two of the LaWS story: *Partnership*. ONR has long recognized the importance of shared research, not only to tap different expertise of scientists in other commands, but to pool scarce resources, and avoid duplication of research efforts. LaWS itself is a government prototype system, developed at Naval Surface Warfare Center–Dahlgren Division with the Directed Energy and Electric Weapon Systems Program Office (NAVSEA PMS 405), based on research from the NRL and shepherded through ONR.

“The recent advances in laser technologies have been the result of many partners,” said Morrison. “A real key was the test of the Joint High Power Solid State Laser in 2009.” That test produced 100 kilowatts of power in a lab, with nothing more than electrical power and cooling water; the goal is to have an operational prototype laser weapon of that caliber on a ship and tested at sea by 2016. ONR partners in the laser effort include Naval Sea System Command; the Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology; the Office of the Secretary of Defense-High Energy Laser Joint Technology Office; the Air Force Research Laboratory; and the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command. And NRL’s advanced laser lab continues to push the envelope in capability.



Video stills show the Laser Weapon System (LaWS) striking a remote-controlled target aircraft. These still images show an exercise conducted by a technical team from the NSWC Dahlgren Division, managed and funded by ONR, Naval Sea Systems Command, OSD's High Energy Laser Joint Technology Office and supported by U.S. Fleet Forces Command. (U.S. Navy photos/Released)

(1) A split-screen view of LaWS sensing a target. (2) A view from the drone of the LaWS system sending up a laser. (3) The flash of the laser. (4) A split-screen view of the LaWS system hitting the target drone. (5) The drone has been disabled by the laser.

Partnership with industry has also been pivotal. LaWS utilizes commercial lasers, a commercial tracking mount and commercial optics with customized software controls capable of identifying, illuminating, tracking and lasing enemy surface and air threats.

"A number of major advances in all of this came about due to investments that we and other partner services have made," said Morrison. "The laser story is a model for intellectual and financial collaboration."

And that leads to lesson three: *Affordability*. In an era when words like "sequestration" and "furloughs" are heard in everyday conversations, a new era in fiscal awareness has arrived. Chief of Naval Research Rear Adm. Matthew Klunder has said he doesn't want the old days where a multi-million dollar system takes out a thousand-dollar incoming missile—instead, he wants the reverse: to make the enemy spend big, and to get the strategic advantage by prudent spending on our side.

The SSL does just that. At an outside cost of a dollar per shot, and with a potentially never-ending magazine (as long as there's electricity and water on hand for cooling), the weapon aboard the USS Ponce is the new definition of fiscal restraint, all while increasing effectiveness/lethality. Against specific threats, the cost per engagement is orders of magnitude less expensive than comparable missile engagements. Lasers offer precision engagements without the associated collateral damage of an exploding warhead.

Even the development costs for LaWS have been modest: Approximately \$40 million was spent over the last six years developing technologies, assembling hardware and conducting relevant demonstrations. The total cost for system upgrades, installation, deployment and removal is expected to cost less than \$45 million over three years.

The timeline for LaWS going to sea was shortened from four years to two, itself an enormous cost-saving feat. This was accomplished through careful planning and lessons learned in two at-sea demonstrations over the past two years (LaWS and the Maritime Laser Demonstration), as well as leveraging investments made through other defense departments and services and agencies.

BREAKING THROUGH

"Breakthrough technologies" sound exciting, and they are. But they don't happen in a vacuum. It takes hard work, commitment, prudent investment and partnership—the sparks that light the fuse of innovative reality—to get from light-bulb moment to the satisfaction of seeing a drone shot down from a ship at sea.

For the moment, blasters and phasers are still the stuff of sci-fi writers and movie directors' imaginations. But soon, perhaps sooner than we think, they may be less science fiction and more science fact. ■

ONE + ONE IS NOT TWO

Keye Martin, Ph.D.
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Innovation is sometimes the result of re-examining certain fundamental beliefs about the way the world works. To illustrate, consider a few of the simple questions one can ask about information:

- (a.) Can information always be copied?
- (b.) Given two identical pieces of information, can we read each one and get different results?
- (c.) Is it possible to have complete information about the whole, but no information about any of the parts?

Conventional thought would have us believe that the answers to these questions are (a) yes, (b) no and (c) no. In Quantum Information Science (QIS), though, the answers are just the opposite: (a) no, (b) yes and (c) yes. While each of these properties stands in contrast to our everyday experience, perhaps the most counterintuitive aspect of quantum information is that collectively they have the potential to radically improve the way we transfer, process and acquire information, including but not limited to the way we communicate, compute and perform sensing.

Currently though, the most developed technology offered by QIS is quantum key distribution, which provides a way to generate

In Quantum Information Science, as in the work above, the whole can be more than the sum of its parts. (Used with permission of the artist, specially commissioned for this article)

shared private keys that appears immune to eavesdropping. It has been commercially available for several years now. In the Informatic Phenomena Group at Naval Research Laboratory (NRL), our view on QIS is that technologies like quantum key distribution represent a small fraction of the area's true potential. Our position is not merely intended to help safeguard against overinvestment. It is also grounded in the belief that within the realm of Information Technology, changing the basic unit of information from classical to quantum could be a 21st century version of splitting the atom. Only when the central idea in QIS is taken seriously, that it is an entirely new paradigm of information, and only when we learn how to naturally apply its laws, do we expect to see it have a revolutionary and lasting impact on Information Technology.

At the center of this new paradigm lies the qubit: a revolutionary challenge to the classical bit. A classical bit can assume either the value 0 or 1. A quantum bit, or qubit, is capable of being 0, 1 or "anything in between 0 and 1." Unlike classical bits, qubits cannot necessarily

be copied, and while this poses a definite challenge when trying to perform certain tasks, it can also help prevent an eavesdropper from listening in on quantum communication. To read a qubit, one performs a “measurement” on it which yields a classical bit. The result of a measurement is in general nondeterministic, so more often than not we can read two identical qubits and obtain different results. This might seem to be completely problematic—however, if we use a qubit to store information and an attacker manages to steal it, the chances are good that they will not be able to read the information we want kept secure.

One of the most fascinating properties of quantum information is entanglement. When two qubits are entangled, measuring one changes the other, no matter how far apart the qubits are from each other. In the case of maximal entanglement (*Figure 1*), it is possible to “teleport” a qubit from one place to another: the qubit is transferred from point A to point B without ever travelling through space. With maximal entanglement, we have complete information about the whole without having any information about the parts i.e. the whole (2) is more than the sum of its parts (1+1).

A major problem in QIS is dealing with the environment that a qubit evolves in. This might be fiber, freespace or even water. The environment is not merely a canvas on to which

a qubit is painted—the two interact with each other, often resulting in noise. Or they may be entangled, which can cause information to be unwillingly leaked into the environment. Though usually in smaller doses, even the curvature of spacetime itself (gravity) can cause noise, which requires taking relativistic effects into account—imagine a qubit on a satellite orbiting Earth for instance. A major thrust of our group’s research at NRL is to investigate mathematical models for all of these situations and use them to develop methods for optimizing performance in a noisy environment. This research in turn suggests the possibility of a number of new Naval technologies. Let us now consider one such example: using entanglement to enable stealthy vehicle navigation under the arctic shelf.

This is a difficult problem because (1) compasses and gyrocompasses are less reliable in higher latitudes, (2) GPS signals cannot penetrate water and ice, and (3) the shape and thickness of the ice shelf is variable. To avoid a potentially catastrophic collision, an underwater arctic vehicle might use an active sonar array to detect its proximity to the ice. In a combat environment, however, the use of navigation sonar could give away the position of the vehicle. Our research on QIS has shown that the operational requirements of stealthy underwater arctic navigation are tailor-made for entangled qubits. Here’s how it works.

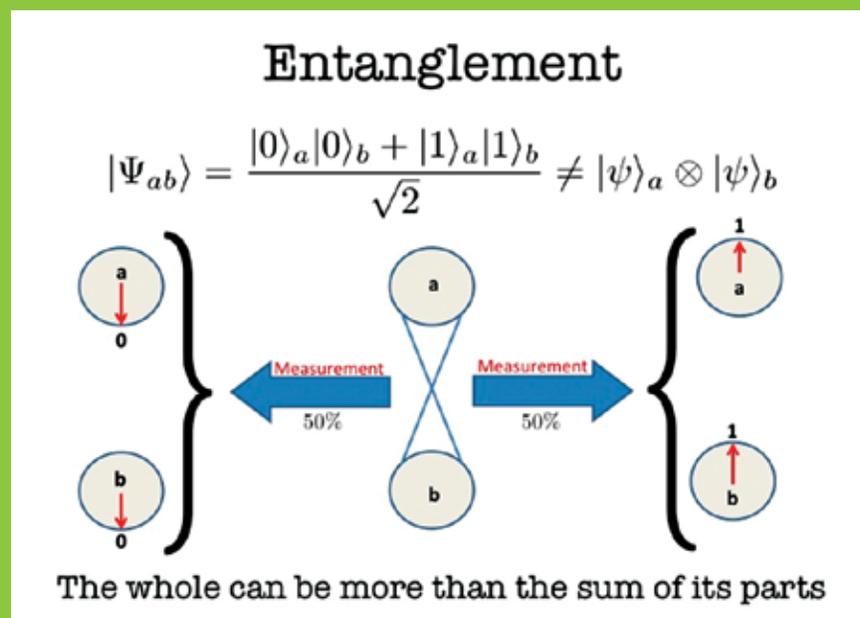


Figure 1. With a maximally entangled state, we have complete information about the combined system without having any information about the individual subsystems.

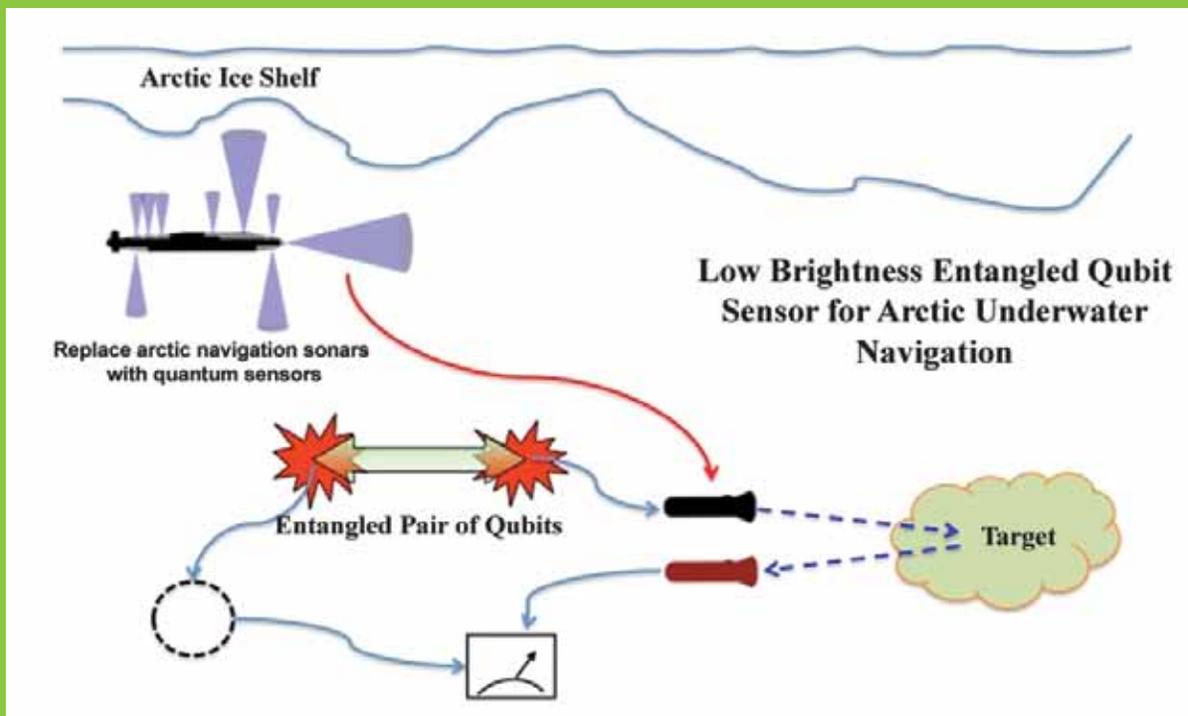


Figure 2. By using entangled qubits in place of sonar, it is possible to perform stealthy underwater arctic navigation.

First, we replace the navigation sonar array with a collection of low brightness quantum sensors. Then an entangled pair of qubits is produced; one qubit is kept within the sensor while the other is emitted towards a region of space. Afterward, entanglement correlations are used to distinguish between noise qubits and those signal qubits that are bounced back to the detector due to the presence of a target (e.g., the ice shelf, the bottom, or another vehicle) (Figure 2). Calculations performed at NRL suggest that if this system were built, it would be capable of operating in low brightness levels using a small number of qubits and in an extremely noisy environment, making the existence of the sensor practically invisible to those without access to the entanglement correlations: our quantum sensor hides the signal qubits in environmental noise, and entanglement is the key to detect them. Specifically, assuming a signal-to-noise ratio of $2 \cdot 10^{-6}$, a quantum sensor can detect a

target 437 meters away in clear oceanic waters (Jerlov Type I). For the same signal-to-noise ratio, the detection probability of a quantum sensor is 6 times better than a laser and 8 times better than sonar. Two of the major challenges in making this system a reality are building better photodetectors and faster sources of entanglement than presently exist. In a similar way, we have used entanglement to design various approaches to radar, lidar, magnetometry and gravimetry.

The revolutionary potential of QIS stems from scientifically re-examining the nature of information itself. But we should not stop with QIS. There may be other, as of yet undiscovered, paradigms of information. By abstracting the essential properties of classical and quantum information, it may be possible to use common mathematical structure as a guide in discovering some of these. ■

Titanium mid-ship section.

INNOVATION AT THE DECK PLATES



TITANIUM HULLS FOR NAVY SHIPS

Ms. Kelly Cooper, Program Officer,
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T-CRAFT PROVIDES AN OPPORTUNITY

Several years ago, I had the opportunity to visit a small shipyard in Fukuoka, Japan. While I was there I saw a three ton fishing vessel called 'Akimaru' that was made entirely—keel to deckhouse—of titanium. To train their shipyard welders, the shipyard owners had built a small titanium rowboat, which had floated in saltwater for more than 15 years without rusting. This “no maintenance” hull tweaked my interest in the silver-gray metal and its long-term potential for Navy ships. If this small Japanese shipyard could build a titanium fishing boat without the need for an anaerobic chamber, I thought, perhaps the Navy can build a larger vessel in titanium. But, knowing a few things about titanium, I ruminated; it will have to be carefully done.

At that time, I was managing a promising ONR program called the Transformable Craft

(T-Craft) that sought advanced designs for a fast, long range, truly amphibious vessel that could transport materiel from the future Navy Sea Base through the surf zone onto dry land. Critical to the T-Craft concept was the ability to carry more payload, at higher speeds, over longer ranges, than had ever been previously accomplished. Lighter hull forms would translate directly into more payload or less fuel, and therefore aluminum, composite materials, and even titanium had to be considered.

One proposal for the T-Craft came from Textron Marine and Land Systems (TM&LS). TM&LS had built the Landing Craft Air Cushion (LCAC) fleet for the Navy, and it had recent experience working with titanium on the Army light weight howitzer, so they felt that it would indeed be possible, but clearly, they had reservations. I could sense their skepticism about the whole idea. Building a full-scale hull section in titanium verged on the radical. Reluctance to use titanium in ship hulls was grounded in two solid facts: aircraft grade titanium was outrageously expensive and converting to titanium in a historically steel and aluminum shipyard would potentially slow welding speeds by an order of magnitude.

Raw material as received, waterjet cut into shape.



Weld process development.



I decided to find out if a shipyard could use lower cost, marine grades of titanium to fabricate a full-size mid-body T-Craft hull section. My experience told me that if any company could build it, TM&LS had a great chance. Treading carefully, I accepted a proposal from Dr. Pingsha Dong at the University of New Orleans (UNO) to conduct basic research into titanium welding. Their team consisted of MiNO Marine, a local naval architecture firm to design the titanium hull section, and TM&LS to construct it. Keystone Synergistic Enterprises provided welding expertise.

Dr. Dong is an expert in fatigue and fracture assessment of metals. The construction of this mid-ship section would provide supporting data for his work. While he conducted basic research into the welding process, Booty Cancienne, TM&LS's Production Superintendent, took the lead in organizing his team of welders to work out how to construct a large titanium structure in their yard facility in Bayou Sauvage, just east of New Orleans. The titanium mid-ship hull section experiment was underway.

T-CRAFT MID-SHIP SECTION IN TITANIUM

In "The Nature of Technology," author W. Brian Arthur points out that it takes a team of dedicated people to innovatively solve a problem. However, each step they take toward the ultimate solution requires solving sets of subsidiary problems along the way. Welding titanium on a shipyard production basis is like

that. Along the way, the team struggled with residual curvature of the metal as it is uncoiled from the roll, diligently separating the metal by grade, stocking and managing weld wire for each type, precision cutting, dressing of joints, special jigs or fixture modifications, pre-heating, bending limits for curves, training and organization of welders, gas shielding and many lesser problems. Most importantly, the Textron team needed to stay in constant touch with MiNO designers who were laying out T-joints, stiffeners, ribs, and sheet dimensions, to take full advantage of the benefits of titanium while also considering the realities of what does work, and what cannot work in production practice.

A major part of the mid-ship structure was the main deck. It is a broad, flat, continuous piece forming the "top" of the section. In the process of welding together the 20 ft long main deck from six individual plates, the UNO/MiNO/TM&LS team created the world's longest production welds in titanium using a relatively new process known as Friction Stir Welding (FSW).

WHAT IS FSW?

Friction Stir Welding joins metals using the heat of friction produced when a spinning metallic tool (called a pin) is forced down onto the pieces to be welded at a common joint. The friction of the high speed rotating pin causes the two adjoining pieces to heat up to a "plastic" condition near the joint line, but not to melt. As the tool passes down the joint line,

Pin tool.



the hot, plasticized metal from both pieces is stirred together by the pin's rotation forming the weld in its wake. The essential element of this technique is pin design and material that can withstand the pressure and high temperature of the process, minimizes the use of expensive tungsten-based alloys, and reduces weld contamination from the erosion of the pin during welding.

Basic and applied research in FSW led by ONR over the last eleven years became a palpable reality in this titanium main deck plate. Most FSW joins aluminum pieces together using pins made of hardened tool steel, essentially the same material used for drill bits. ONR's Drs. Julie Christodoulou and William Mullins were interested in developing FSW to weld the High Strength, Low Alloy (HSLA) steels used in ship hulls. For these tougher, stronger steels (and titanium) hardened tool steel pins simply are not satisfactory. ONR began extended research developing the tools, efficient process design, and the associated metallurgy, to reduce the use of materials such as tungsten-rhenium¹. Their basic research investigated the performance of polycrystalline cubic boron nitride (PCBN) a material originally developed for machining of tool steels. In addition to being strong at elevated temperatures, PCBN is chemically inert and minimizes contamination

¹ Rhenium is the most expensive metal on Earth.

Final assembly of titanium mid-section.



from the pin in the resulting weld. Keystone Synergistic Enterprises, Inc., developed pin designs and processes for Ti-alloys using FSW equipment at the NASA's Michoud Assembly Facility in New Orleans. The early, foundational basic and applied research conducted by ONR which was matured through ONR and Air Force Research Laboratory, Small Business Innovation Research (AFRL SBIR) programs, were the vital precursors to the practical FSW of the titanium plates for the main deck.

TITANIUM AND S-N CURVES

Bending a paper clip back and forth until it breaks is a perfect example of fatigue fracture induced by cyclic loading and unloading. As you bend it back and forth, microscopic cracks appear in the metal structure and continue to grow as the cyclic loading continues. Eventually, the metal clip fractures catastrophically. A ship's structure must withstand similar cyclic force loading from constant waves, rolling and pitching, equipment-generated vibration, antenna rotation, gun recoil, missile launch, and other forces. Dr. Dong had previously developed a more accurate way to predict metal fatigue for Navy ships. His method, called the Master S-N Curve², accounts for more kinds of stressed joints in the ship's design and more completely calculates the actual forces experienced at

² S refers to the level of stress induced in each cycle, and N to the number of loading and unloading cycles experienced before fracture.

those joints.³ His method produces a more accurate and comprehensive understanding of fatigue life for ships. The mid-ship section construction provided data that helps validate his master S-N curve method.

TITANIUM SUMMIT

Late in 2011, I wanted to get a broader, more comprehensive estimate of the industrial capability to produce an entire ship hull made of titanium. Many of the challenges associated with using such a radical material are organizational, economic, even cultural rather than technical. The mid-ship section was progressing nicely as I organized a summit meeting for experts in titanium production, economics, manufacturing, design, and joining to discuss and assess the broadest potential for a future titanium hull.

After thoughtful deliberation about ore sources, processing methods, subsidiary supply chains, and market forces, the summit experts concluded that US titanium production capacity does not constrain the Navy from building a high-performance titanium ship hull. They estimated that for a nominal 1,000 ton ship, a suitable design would need 150 tons of Commercially Pure (CP) titanium, and 50 tons of titanium alloys. They expressed moderate concern about several aspects of manufacturability and they stressed vigorously the necessity of thorough training and organization for production. However, they believed that existing and newly developed

³ Navy has been using a traditional rule-based fatigue design method by classifying ship connection details into seven geometrically distinct joints on which historical fatigue test data are available under simple test loading conditions. These data are represented as seven stress vs. cycle to failure curves, or S-N curves. Two major uncertainties exist in practice. One is that actual ship structures may contain many joint types that cannot be related to any of the seven existing categories or S-N curves. The other is that even for those joints that may be related to the existing categories, the actual loading conditions on those joints can be much more complicated than test conditions. The master S-N curve method adopted by the 2007 ASME Div 2 Code and since has solved these two major problems. A computer based mesh-insensitive stress calculation method is used to characterize complex stress state at a joint in the form of a single fatigue-related parameter. This parameter allows the consolidation of all existing S-N curves, e.g., the seven used by Navy, into a single master S-N curve. Therefore, uncertainties associated with the joint category determination process can be eliminated.



joining methods were adequate to the task. Overall, they confidently supported the idea that it is possible to design, build, and manufacture in a shipyard, a full titanium ship hull.

In 2012, sitting on the quay in Bayou Sauvage, was a complete titanium mid-ship hull section, the strong, straight, gleaming evidence supporting their conclusion.

INNOVATION RESULTS

Primarily, that full-scale, ship-size structures can be produced in metal-working shipyards from marine grade titanium. Hull production in titanium requires attention to material grades, shipyard organization, shop practice, training, welding materials and procedure, and a custom design that takes advantage of all titanium's strengths and minimizes its few shortcomings.

Secondarily, data from this titanium section supports Dr. Dong's groundbreaking work on predicting fatigue in weld joints, and will substantially improve the accuracy of predicating fatigue life for Navy ships.

Finally, that friction stir welding is a shipbuilding improvement because it can be done at a higher linear speed (shorter manufacturing time), has excellent weld penetration (a secure weld), and produces little or no heat distortion of the titanium near the weld (better fits and reduced manufacturing tolerances are needed in design).

WHAT'S THE FUTURE?

Hulls do not drive ship acquisition cost (combat systems do) but, current hulls are now expected to last longer, in some cases 40 years

Side hull construction.



or more. The hull of the ex-USS Enterprise decommissioned last November was in service for more than 50 years. And, in all new ship designs, manning is declining.

As crew size decreases, and cross-training of each crew member inevitably results, time and priority for hull maintenance will decline. Perversely, as hull maintenance declines and hulls continue to age, corrosion increases. The cost to cope with corrosion goes up with age and approaches an estimated \$10K per ton late in service life. Compared with an initial cost of ~\$800 per ton (for HY 100 steel), the cost of corrosion control throughout an extended service life is significant. In 2008, Navy spent more than \$3B on corrosion for ships and across DoD, about a hundred million dollars annually is invested in corrosion-related research. Using marine grade titanium for ship hulls, Navy could “buy back” the initial cost of titanium in about half the ship’s service life with just the money not spent on future hull maintenance. The service life cost of corrosion maintenance for fuel storage tanks is even more expensive than costs for the hull. Over a service life

of 50 years, a titanium hull is a good total ownership investment.

CONCLUSION

Titanium can virtually obviate routine hull maintenance, decrease dry dock time, decrease fuel costs, substantially reduce corrosion maintenance for fuel tanks, and increase ballistic and fire protection. The nagging problem is that its initial cost is higher than HY-100 grade steel. If extended service life is expected, titanium’s higher initial cost can be amortized over that extended service life, but careful design, well trained people, and use of lower cost marine grades of titanium are vital. Titanium hulls will deliver great benefits at lower total ownership cost over the ship’s service life, with fewer Sailors needed to chip and paint them. And inevitably, when the ship is decommissioned, the titanium hull will yield considerable salvage value further mitigating its ownership cost. ■

The author acknowledges Mr. Dave Edwards for his support and contributions to this article.



(Courtesy of Sciaky)

THE FUTURE OF MANUFACTURING IS AS SIMPLE AS ADDITION AND A LITTLE SUBTRACTION

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Imagine being able to build any object of any shape, of any complexity, of any material, at any time, anywhere. Imagine being able to print whatever you can think or whatever you can draw. Imagine being able to design a part at one location and have it produced at another. Imagine being able to scan a broken part and have its replacement made at the push of a button. The first glimpses of this future of manufacturing are evident today in part because of early investments by the Office of Naval Research (ONR). That is the excitement of Additive Manufacturing.

Additive Manufacturing (AM) is the ability to create a solid object from a digital model. Starting with a computer-aided design (CAD) file, a machine builds its physical replica by incremental addition or fusing of small volumes (voxels) of material. The CAD model is decomposed into slices, optimal tool paths to form each slice are determined, and a machine is instructed to create and stack the slices while building the 3D

object. *Figure 1* illustrates the AM concept.

AM opens up the window for making objects never before possible. Thanks to AM, objects can be built of multiple materials and have complex internal and external geometries. If you take a look at *Figure 2*, you'll see a few examples of objects constructed by AM: components with conformal cooling channels (2a), components with moving parts (2b), customized parts (2c), and any imagined decorative artwork (2d). Other materials and structures possible are metamaterials (e.g., auxetic, cloaking), and variable-porosity structures (e.g., bone- or wood-type). These complex shapes and composite structures cannot be produced by traditional means such as machining, casting, or powder consolidation. Conventional processes require fixturing, tooling, and mostly produce simple geometries.

The benefits of AM to the Navy are plenty. The Navy and DoD are dealing with aging systems. Legacy systems are increasing in number and facing obsolescence. If a part breaks, we are faced with non-existent suppliers, unreliable foreign sources, and unavailable drawings. In such a scenario, it is possible to *reverse engineer* the damaged part and have

a replacement produced by AM. Another concern is storage and stockpiling. Spare parts occupy precious space and are prone to damage, deterioration or obsolescence. The parts *on-demand* capability of AM should mitigate stockpiling problems. As illustrated in *Figure 3*, instead of a stockpile of parts, we'll have a stockpile of CAD files. For the Navy it would be useful to have a point-of-use manufacturing capability such as at a maintenance depot, an intermediate base or a sea base. AM can make *remote manufacturing* happen.

ONR has been at the forefront of AM research and development since AM's early days in the late '80s. ONR's core Manufacturing Science Program sponsored the early development of most AM processes, many of which have reached commercialization with machines available for research, production, and/or repair. Our basic research efforts are developing the fundamental principles for the design, control and manipulation of AM processes at appropriate length scales to produce components with specified properties that can be integrated into useful engineering systems. We have developed an understanding of melt-pool dynamics, thermal gradients, temperature histories, structural properties, residual stress, sintering behavior, binder chemistry, photopolymerization, and other phenomena. The program has driven research

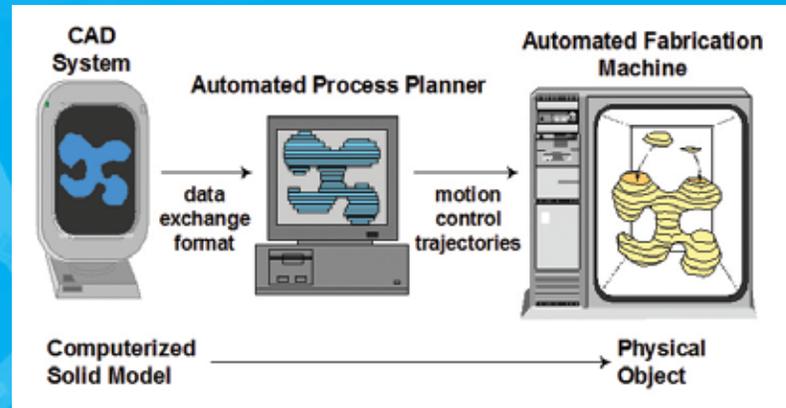


Figure 1. Schematic of Additive Manufacturing (AM).



Figure 2. Examples of objects made by Additive Manufacturing. (a) Internally cooled nozzle. (Courtesy of ExOne.) (b) Planetary gears. (Courtesy of University of Texas-Austin.) (c) Cellphone cover. (Courtesy of MIT.) (d) Artwork. (Courtesy of University of Texas-Austin.)



Figure 3. Stockpile of CAD files ready for additive manufacturing on-demand.

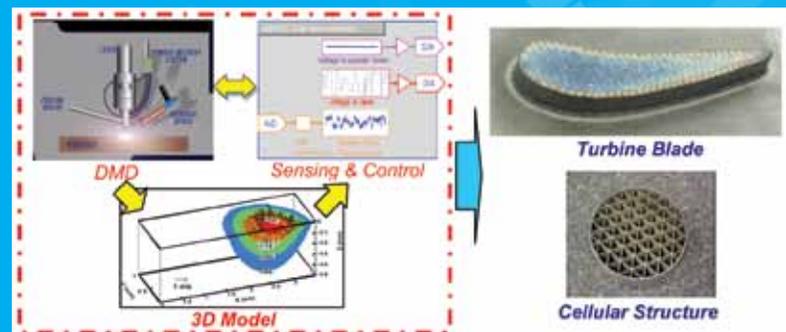


Figure 4. Close coupling of 3D model, and sensing and control for direct metal deposition of quality parts. (Courtesy of Professor Jyoti Mazumder, University of Michigan.)

in geometric representations, visualization, and standards. These studies were essential to the development of reliable fabrication workstations, the spread of the technology, and contribution to our manufacturing economy.

AM addresses a critical military need for small lot production of replacement parts, and repair and refurbishment of worn or broken components as military equipment is often used beyond its original useful life. In many cases, the manufacture or repair technology is awaiting lengthy and costly qualification and certification process. Once these steps are accomplished, then AM will have achieved universal recognition. To facilitate qualification and certification, we initiated the cyber-enabled manufacturing systems program, which is designed to apply cyber-physical systems concepts of computation, communication and control to AM systems. We are addressing qualification concerns at the fundamental level by encouraging the development of close-loop sensing, manipulation and control of additive processes using physics-based materials and process models. An example of the basic research is shown in *Figure 4*. It describes the direct metal deposition (DMD) process for part production using 3D physics-based models and process sensing and control to ensure production of quality components.

The challenge with AM is because of the layer-by-layer build process, the part surface is inevitably scalloped or stair-stepped. The implication of the ‘rough’ surface finish is a possible loss of mechanical properties such as fatigue and fracture toughness. The surface roughness can be ameliorated with a little finishing or machining, i.e., a “little subtraction”. Surface finish issues suggest a hybrid additive/subtractive manufacturing solution, which is currently being experimented with, but may present speed and accuracy challenges. Some components will require other post-processing such as heat-treatment to obtain the desired mechanical properties. Ideally, the maximum benefit of AM can be had when all post-processing is eliminated. AM research is heading in that direction.

We believe the future of AM is to go truly digital, i.e., design and build objects voxel-by-voxel. The path to digital AM lies in being able to manufacture ‘things’ which *can’t be made any other way* and give a system level capability that *can’t be achieved any other way*. Digitally driven machines will additively fabricate heterogeneous objects with *spatial control of composition, macrostructure, texture, orientation and properties*. By this means, it is possible to achieve designer microstructures, graded compositions and coatings,

and multi-functional materials. ‘Programmable’, ‘adaptive’ and ‘biomimetic’ materials are possible. Such a capability will significantly expand the design space and provide more opportunities to push performance. Microstructural architectures with controlled spatial distribution of microstructure yielding properties at the extremes are achievable.

Additive manufacturing or 3D printing has entered the imagination of the general public. Not a day goes by without the popular media reporting on a new development in AM: “AM turns computer models into reality;” “AM techniques help assemble 3D nanostructures;” “AM capability is a must for a moon or Mars base;” “AM produces medical instruments for rural hospitals in India;” Many headlines begin with a “Print me a _____!” Phone, Stradivarius, Ear, Cruiser! You fill in the blank—anything is possible! AM is exciting and the possibilities are vast. ONR is pleased to be a player in this sandbox since the very beginning. What’s even more exciting for the Navy and our sister services, is this research has the potential to better equip and serve our future Sailors and Marines and that is a mission we are very proud to be a part of. Our AM program is dedicated to foster the science needed to overcome the challenges of quality, reliability, and consistency in AM production and to meet specific Navy needs. ■

The author would like to acknowledge the significant contributions that Dr. Ralph Wachter has made in support of the ONR Manufacturing Science Program. Dr. Wachter is a former ONR program officer who ran the Manufacturing Science Program since its inception. Dr. Wachter now works at the National Science Foundation.

BRIDGING THE NANO-BIO INTERFACE

ACTUALLY IT IS ALL ABOUT THE CHEMISTRY

**Igor L. Medintz¹, James B. Delehanty¹,
Alan L. Huston², Michael H. Stewart²,
Philip E. Dawson³ and Glyn Dawson⁴**

Nanotechnology is often thought of as the emerging discipline where new materials are engineered from the bottom-up by working at the atomic scale. This definition, however, overlooks one of the most promising areas under development, namely integrating vastly disparate materials to create new composites with previously unattainable capabilities. Okay, what exactly does this mean and why would it be important to the future warfighter? Let us explain using the example of biological molecules and inorganic nanoparticles because it is at this very crossroads that we have been steadily working.

Biomolecules, as epitomized by proteins and enzymes in particular, have the capability to do almost everything in biology. They can synthesize the most complex of drug such as the chemotherapeutic Taxol[®], which required Nobel Prize winning chemistry to be made artificially, or incredibly strong materials such as spider silk with a tensile strength *five-times* that of steel. We also often forget that antibodies, proteins with very specific recognition capabilities, are the first-line response in our immune systems and can be used as anti-venoms to protect us from poisons. Due to their ultrasmall size, nanoparticles synthesized from noble metals or semiconductors manifest many unique and

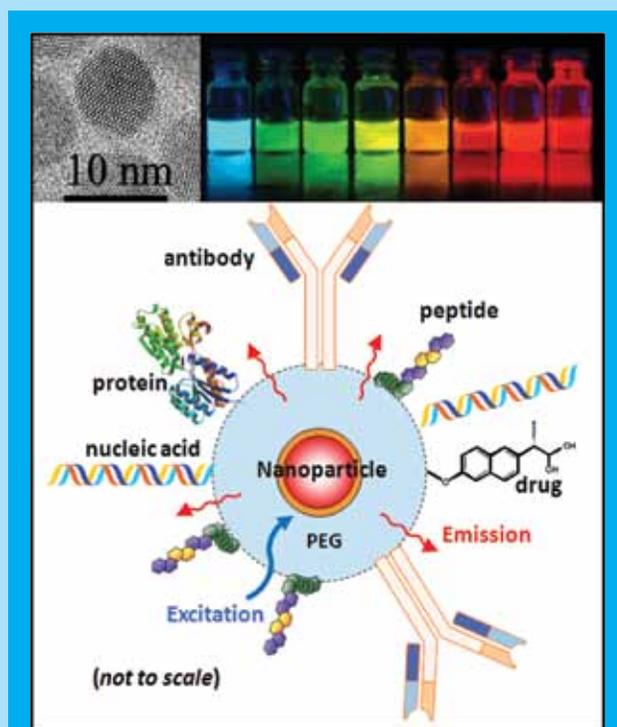


Figure 1. *Top left.* Electron micrograph of a semiconductor QD with a diameter of slightly less than 10 nanometers (courtesy of Dr E. Oh, NRL). *Top right.* Photograph of a series of QDs all excited by a single ultraviolet lamp. The only difference between each sample is its size. Note the clearly distinct color palette available. *Bottom.* Schematic of a nanoparticle-bioconjugate assembled around a central nanoparticle platform that is made soluble with a poly(ethylene glycol) or PEG ligand. Each biomolecule would provide a different intended function. For example, the antibodies would provide targeting to specific cells, the other protein could be used for sensing, the peptides could help the construct go into the cell and the drug and nucleic acid could be used for therapy. The intrinsic nanoparticle properties such as magnetic contrast or fluorescence would also be used to visualize the location of the construct inside the body.

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unexpected properties that are unavailable in the larger bulk regime. We work with semiconductor nanocrystals (termed quantum dots or QDs) as one of our model nanoparticles. QDs are known for their bright, size-tunable photoluminescence; where the physical size of the nanocrystal determines the emission color. Thus many differentially colored QDs can be visualized using just one excitation source and easily tracked in complex environments (*Figure 1*). As nanoparticle properties were elucidated, scientists and program managers quickly realized that if they could marry proteins or other biomolecules to nanoparticles, they could access unprecedented capabilities at the nanoscale. Future uses could include antibody/drug-nanoparticle hybrids that could patrol the body searching for new infection sites and would release a drug exactly where required rather than dosing the entire body with thousands of times more drug than needed. Even more exciting concepts were envisioned such as sensors for complex diagnostics, sensors for autonomous monitoring in almost any environment, ultralightweight biocomputers, and energy harvesting systems (*Figure 1*). As the critical components of all would be on the nanoscale (≤ 100 nanometers in size), the future warfighter would have access to myriad, self-powering incredibly-enabling technologies

with almost no weight penalty. The benefits of these and many other envisioned technologies to DoD are self-evident and, in essence, reflect the promise of bionanotechnology. However, in the excitement of new possibilities, one necessity was critically overlooked by almost all—the fundamental incompatibility between nanoparticles and biomolecules. To achieve these goals, chemistries that could seamlessly integrate these two almost polar opposite materials to yield the desired, functional composite were required. It was this lynchpin that we recognized and sought to address under the auspices of the Naval Research Laboratory (NRL) Nanosciences Institute. Success would not be instantaneous but would ultimately come from steady research in conjunction with key collaborations and a healthy dose of the unexpected.

Reflecting the inherent dichotomy of the two materials and ultimate goal, research began as a collaboration between NRL's Center for Bio/Molecular Science and Engineering and the Optical Sciences Division at the turn of the millennium. Initial work focused on using QDs as a model system and modifying their surfaces to make them biocompatible. QD ligands, organic molecules that can attach to the inorganic QD surface, were designed to provide both stability in water and present chemical

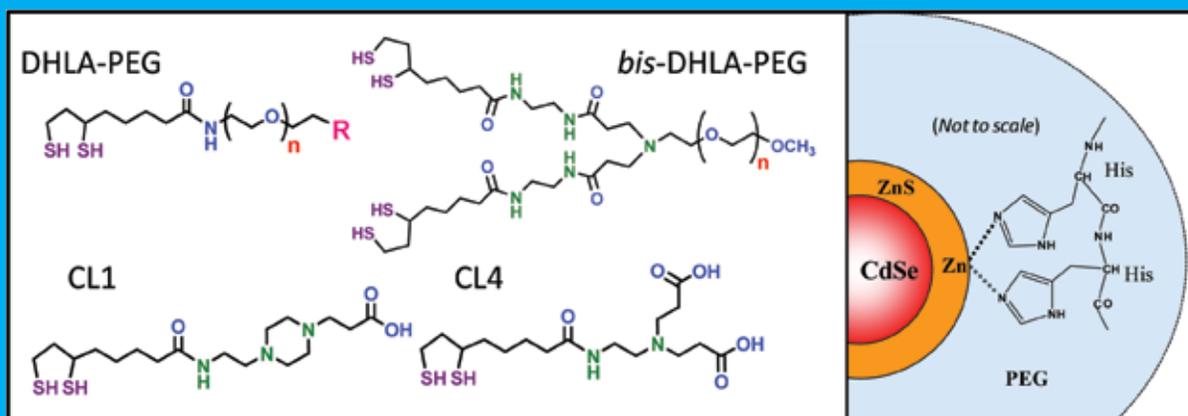


Figure 2. *Left*. Chemical structures of some of the nanoparticle-solubilizing ligands developed by the Optical Sciences Division at NRL. DHLA-PEG is dihydrolipoic acid attached to poly(ethylene glycol) or PEG – the group in brackets that is repeated n times. R stands for other functional groups such as amines, biotin, and carboxyls while CL is short for compact ligand. The DHLA-PEG would provide wide pH stability while the bis-DHLA-PEG extended this to extreme conditions. The CL structures also provide pH stability but with a much smaller overall size. The thiols (SH) are used to anchor the ligands to the nanoparticles. *Right*. Schematic of how histidines (His) coordinate to the Zn on the surface of a CdSe/ZnS core/shell QD coated with PEG.

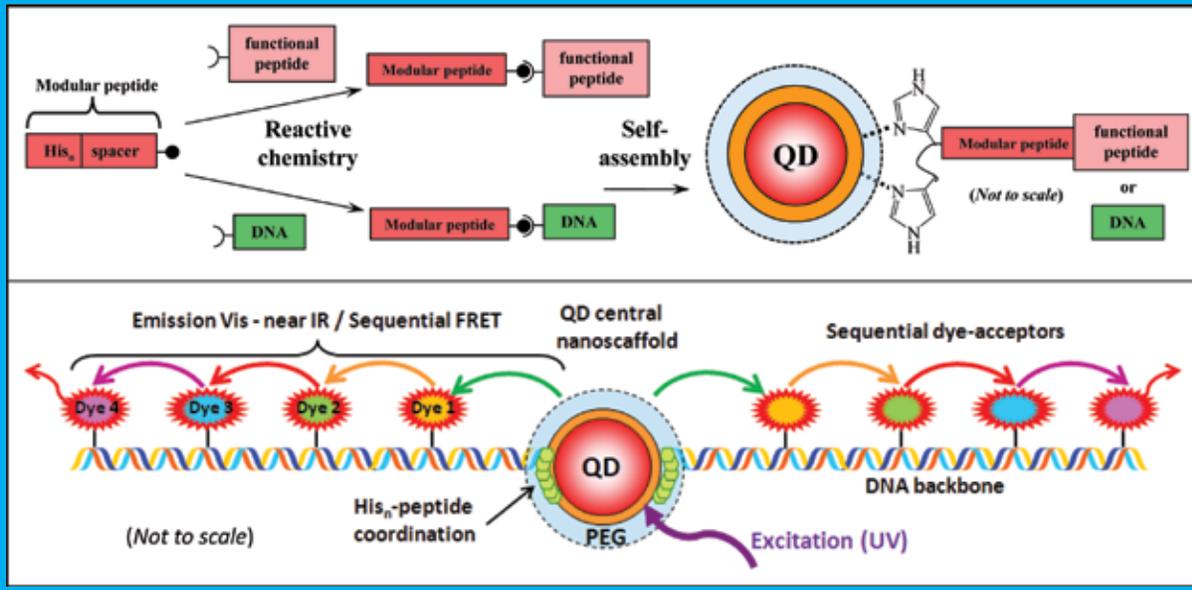


Figure 3. *Top*. Modular-reactive peptide concept. The peptide consists of a polyhistidine or His_n sequence (module 1), spacer sequence (module 2), and a reactive chemical group (module 3 – black circle). This peptide is then joined to another biomolecule such as a functional peptide, DNA or other biomolecule (module 4) which provides the desired bioactivity. The His_n then allows for direct self-assembly to the QD to create the final bioconjugate. *Bottom*. Schematic of a QD-DNA-dye composite energy harvesting system. The reactive peptide approach facilitates DNA attachment to the QD which acts as a central light harvesting component and then drives an energy transfer cascade through the dyes along the DNA. Continuing research has improved the end-to-end energy transfer efficiency in these constructs steadily from ~0.1 to ~10% and has also enabled other research programs which seek to focus and deliver light at the nanoscale.

functional groups that promote the attachment of biomolecules or bioconjugation. The Optical Sciences group led by Alan Huston and Michael Stewart synthesized an extended library of ligands that could address QD requirements in many different biological roles (Figure 2). These ligands would prove a critical advance as they made the QDs robust in water, an essential prerequisite for biological integration. Many of these ligands subsequently received patent protection and their utility has been steadily adopted within the field and extended to all other manner of nanoparticle materials. The next hurdle was bioconjugation. We needed a method by which we could consistently attach biologicals to the QDs—in technical jargon we needed a chemical handle. Ideally, this chemistry would also be easy to implement, precisely repeatable, be applicable to different biomolecules, have high affinity, and provide control over the number of biologicals attached per QD. The breakthroughs came in several steps. First, we fortuitously realized that when

several histidines (a common amino acid component of proteins) were placed at the end of a protein—they could facilitate the assembly of that protein onto the QD surface (Figure 2). It was also at this point (~2005) that we started working with Prof. Phil Dawson at the Scripps Research Institute in La Jolla. Prof. Dawson is a well known biochemist who invented many different types of peptide chemistry (peptides are the smaller building blocks of proteins made from multiple amino acids). Working with him, we conceived the idea of developing a modular peptide approach (Figure 3) consisting of:

1. borrowing that polyhistidine sequence from proteins to facilitate QD conjugation (module 1);
2. attaching a spacer sequence to move things away from the QD surface (module 2);
3. adding a reactive chemistry at the peptides terminus which would be used

Serendipity led to our “Eureka” moment when we reasoned that since this same lipopeptide was positively charged it might act to deliver quantum dots to target cells.

to attach the biomolecule of choice (module 3);

4. the added biomolecular component (module 4), which would provide a desire function.

To make this a reality, we incorporated chemoselective ligation chemistries that Dawson had just developed for module 3. These are specific reactions that do not affect anything else around them and yield a unique, clean product. Cumulatively, the modular-reactive peptide provided several intrinsic benefits for bioconjugation that included being able to switch the reactive chemistry to target almost any biomolecule, allowing us to do the chemical joining to the biomolecule away from the QD (which is a precious commodity), and most importantly, allowing the peptide-biomolecule construct to self-assemble to the QDs while also meeting all our initial criteria.

This modular approach would become our workhorse chemistry and enabled us to move to the next step—designing and engineering biomolecular-nanoparticle composites with new capabilities. One illustrative example was a QD-DNA-dye hybrid where we were able to control the placement of a series of dyes on the DNA which extended out from the central QD. This novel energy harvesting system allowed the QD to harvest UV light and propagate it down the DNA through a sequential fluorescence resonance energy transfer (FRET) cascade driven by the dyes (*Figure 3*). Many other constructs were assembled exploiting FRET and other electron transfer processes for use as cellular labels, myriad static and active sensors, for diagnostics, for optical encoding and even biocomputing. The numerous scientific papers describing these constructs have received thousands of citations and the cumulative result

can best be described by the adapted quote “if you build it—they will come.” These constructs, and in particular the underlying chemistries, were adopted by other government agencies (FDA and Army Corp of Engineers) for biothreat sensing, by private companies for creating new products and by many new collaborators to help solve their nanoresearch problems.

The most exciting adaptation would be unexpectedly found within our own “family.” Phil Dawson’s father, Prof. Glyn Dawson at the University of Chicago Kennedy Center studies inherited neuronal lysosomal storage diseases such as Batten disease. This is a devastating, degenerative and fatal condition involving peptide accumulation in the brain that strikes 2-4 children per 20,000 births. The Dawson father-son team had previously developed a prospective peptide therapy to treat a form of Batten and although it underwent intensive evaluation by the NIH, this sequence ultimately failed as a lead drug. Serendipity led to our “Eureka” moment when we reasoned that since this same lipopeptide was positively charged it might act to deliver QDs to target cells. Exploiting our chemistry, we attached the sequence (as module 4 on our peptide construct) and tested direct delivery to neurons in a rat brain hippocampal slice culture. Surprisingly, a unique combination of a specific compact ligand and this peptide provided for QD uptake by target neurons throughout the brain and not at all by glial cells. This achieved our goal of specific neuronal targeting and suggested the exciting possibility of a new treatment modality for many types of brain diseases from Alzheimer’s to traumatic brain injury (*Figure 4*). These results have now led to testing in other neuronal systems including the developing chick embryo brain, where chicks injected at day 3 with QDs carrying peptides

show diffuse delivery to many neurons and hatch normally at day 21. Since we have also shown that larger, bulkier proteins can be attached to QDs in the same manner, we are now attempting enzyme replacement therapy in mouse models in the hopes of relieving some of the suffering associated with these devastating diseases.

Coming back full circle to the exciting possibilities offered by melding nanomaterials to biology, we now find ourselves closer to making this goal a reality. However, it is important to remember some key lessons. Integrating bio to nano required borrowing from

a third partner, namely chemistry, reflecting that the heart of nanotechnology is really about multidisciplinary engineering at the intersection of materials. Lastly, something useful developed for one purpose (QD-bioconjugation chemistry) can often times lead to something unexpected, i.e., a potential disease treatment strategy in this case. As the chemical toolset used to assemble these technologies continues to mature, we will see the transition from just proof-of-concept to application and these empowering technologies may significantly change the battlespace environment and perhaps again have unexpected impact in other unrelated areas. ■

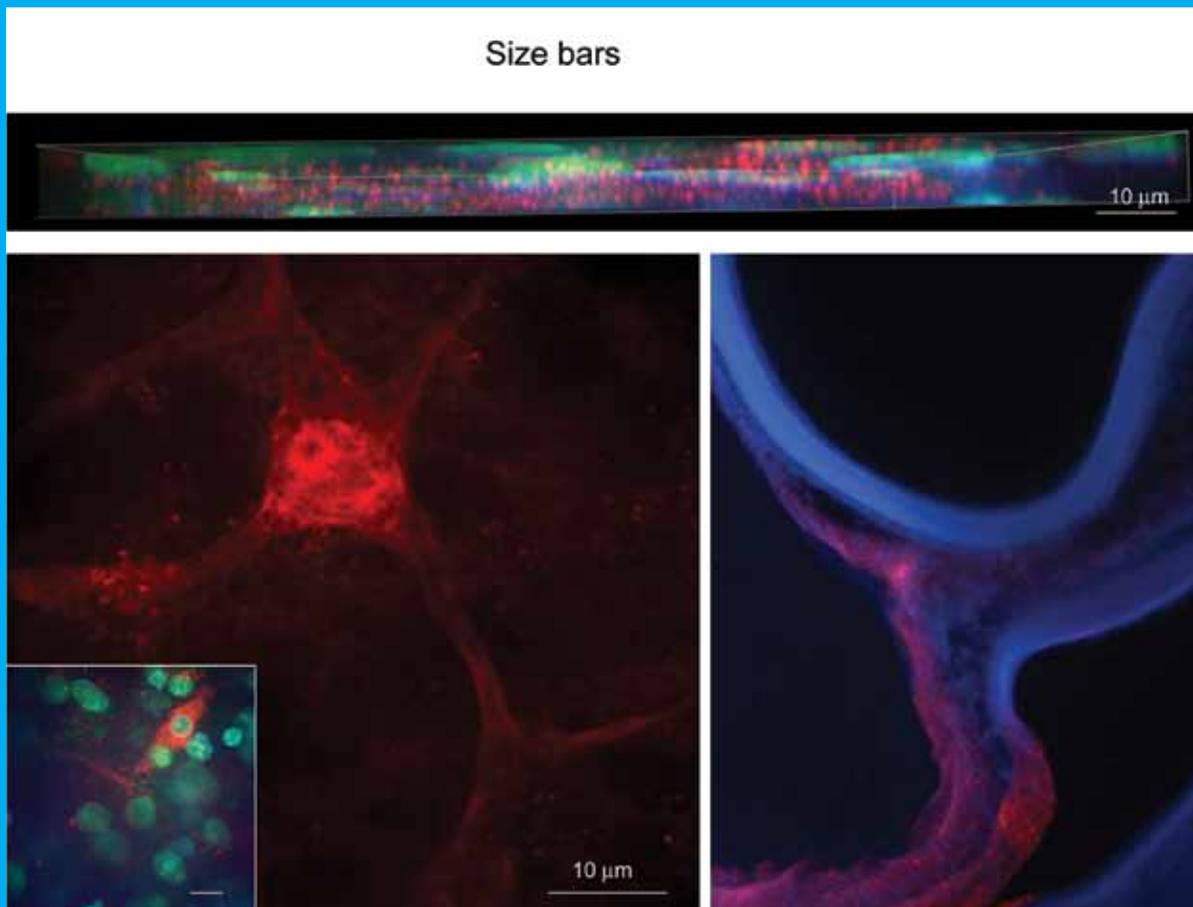


Figure 4. *Top.* Composite image looking across a rat brain hippocampal slice culture showing the presence of QD peptides (red) in neurons. The slice is 6 cell layers thick and achieves normal brain developmental milestones. The green and blue portions are other cellular components. *Bottom left.* Image of a neuron in the brain slice that has taken up the QD-peptides (red). The inset shows another neuron in the context of the other cellular components. *Bottom right.* Image of the developing spinal column in a chick embryo brain stained with QDs (red).

PROJECT MAGIC CARPET

A BREAKTHROUGH IN CARRIER AIRCRAFT LANDING

Mr. John Kinzer, Program Officer, Air Vehicle Technology, Office of Naval Research

Landing a jet aircraft on an aircraft carrier is very difficult on a good day, and when you add in darkness, bad weather, a heaving, pitching deck, and pilot fatigue from an extended combat mission, it is one of the most demanding challenges faced by Naval Aviators. And the consequences of failure are severe. Because of this challenge, the costs of training Naval Aviators are very high. Aircraft carrier qualification training is conducted during intense pilot undergraduate training, fleet replacement squadron training, and refresher training prior to deployment.

It's no surprise, then, that the idea of automating carrier landings has been around for some time. In fact, the first automated aircraft landing on an aircraft carrier was performed by an F-3D Skyknight in 1957 on the USS Antietam (Figure 2). So why aren't we routinely relying on this capability today? The answer is that because piloted landing skill is so difficult to develop and maintain almost all the landings a pilot performs are needed to make sure he or she is ready when challenging conditions occur. If an automated landing system cannot be 99.9999% reliable under the worst case scenario, then the pilot always has to be ready. There are a number of reasons why automated landing systems have insufficient reliability even today. Many of them have been addressed by steadily advancing reliability of the aircraft themselves. One is the need for a precision navigation system that can provide high quality information to the aircraft as to exactly where it is relative to the landing point, all the way to touchdown. This technology is still in development.

The real breakthrough then is to change the way pilots fly aircraft to landing. Traditionally, pilots



Figure 1. Carrier landing area as seen through the HUD. Pilots need to monitor glideslope using the Fresnel Lens, angle of attack (speed), and lineup simultaneously. (background photo: U.S. Navy photo by Petty Officer 3rd Class Kenneth Abbate)



Figure 2. An F-3D Seaknight conducts the first automated landing, aboard USS Antietam, using the radar equipment in the foreground.



Figure 3. F/A-18F engages the arresting wire during a carrier landing.

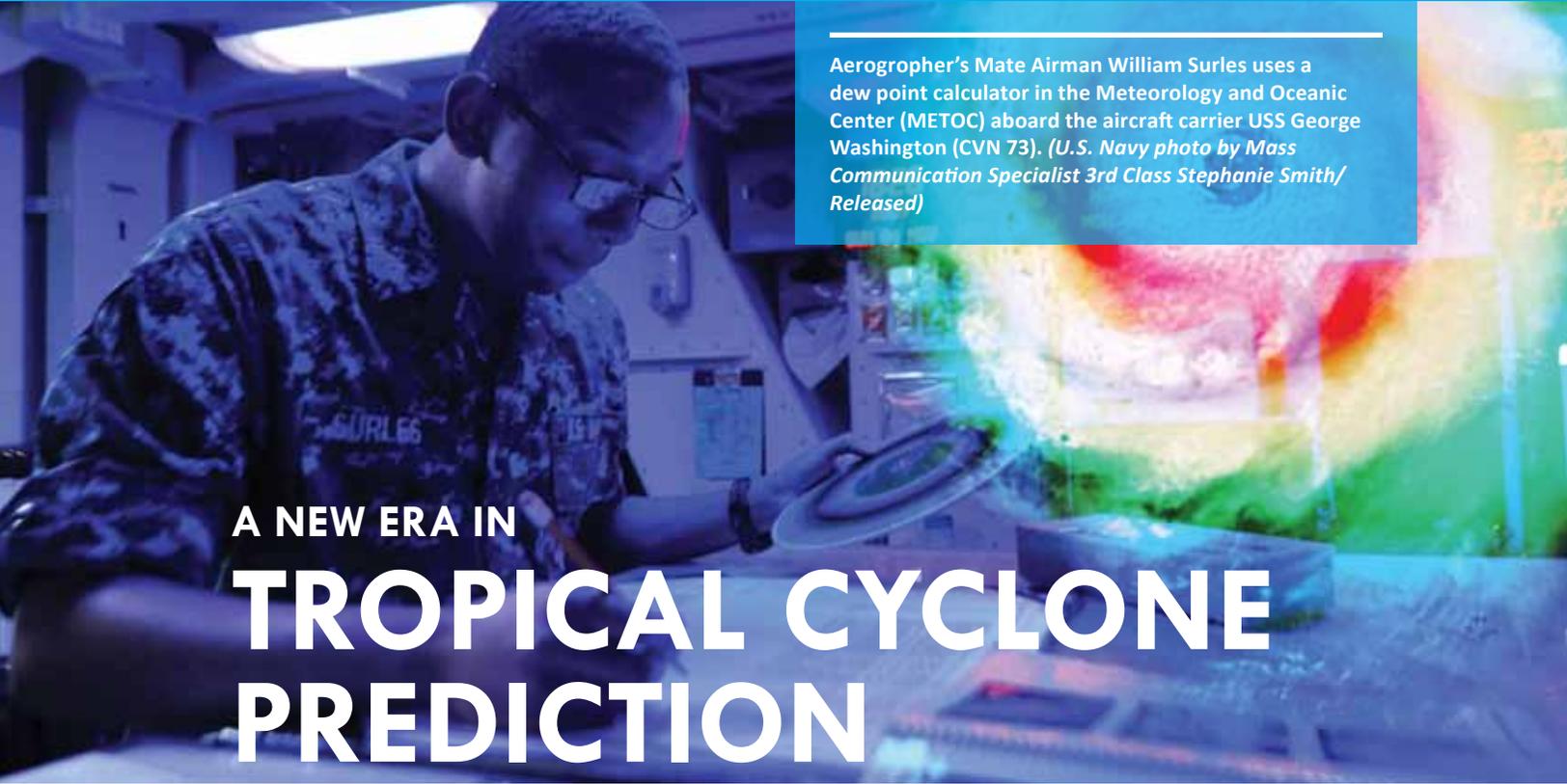
control rate of descent with power (left hand on the throttles), airspeed with pitch attitude (forward/aft stick), and heading with roll (left/right stick). It's hard enough to do these three things at once, but complicating the problem is that these control axes are cross-coupled and only indirectly influence what is really intended: glideslope and lineup. The pilot is required to integrate the disparate control problems and anticipate the need for adjustments. The change that is being developed is to reduce the number of controls, eliminate control cross-coupling, and provide direct control of glideslope and lineup (*Figure 1*).

At the Naval Air Warfare Center, Aircraft Division, Patuxent River, engineers under the leadership of James "Buddy" Denham, and with partial Office of Naval Research (ONR) sponsorship, this breakthrough change is becoming reality in a program called MAGIC CARPET. First, they incorporated the use of reliable automated approach power control to allow the pilot to control the entire landing with just the right hand on the stick. Second, they developed flight control laws which did two things: (1) utilized wing flaps and ailerons to instantly adjust lift on the wing, and (2) augmented aircraft stability to allow the pilot forward and aft stick inputs to directly control glideslope angle. Third, they provided displays to the pilot on the Head Up Display (HUD) with desired glideslope reference and actual glideslope flight path vector. The task for maintaining glideslope then becomes greatly simplified: fly level until the ship comes under the desired glide slope reference and push the stick forward until the actual glide slope vector matches the glideslope, and release the control. Slight adjustments high or low can be accomplished in a similar manner.

These breakthroughs have been tested and demonstrated in simulators with two different aircraft. In flight simulator evaluations in a Joint Strike Fighter configuration at BAE Wharton, the workload for carrier landing was reduced from a Handling Qualities Rating (HQR) 6 (extensive pilot workload), to 2 (minimal pilot workload)—a dramatic reduction! These results were confirmed in an F/A-18E/F simulator at Patuxent River in late 2012, in which landing touchdown performance was improved by over 50% (*Figure 3*).

MAGIC CARPET technology development is continuing. Flight control augmentation for lineup is being developed and tested in the flight simulator, and HUD displays are being refined. Planning is underway to conduct testing of the control laws and displays in both the F/A-18E/F and the F-35C.

Since training cost reduction as well as landing performance enhancement is needed, an ONR interdepartmental Air Warfare and Warfighter Performance collaboration has commenced. Experiments are being developed to assess the pilot's learning curve using these advanced controls and displays as well as performance. This will help to establish a basis for potential reduction of the amount of dedicated training needed to ensure continued operational effectiveness without compromising efficiency or safety. It is possible that integration of MAGIC CARPET technology in F/A-18 and F-35 could save hundreds of millions in training costs per year—that would be the real breakthrough. Of course, we may someday see the day when all aircraft landings aboard ship are fully automated and pilots no longer have to train for this part of the mission at all. Navigation systems and automated capability to enable this are already in work, but significant challenges remain. But that's another story. ■



Aerographer's Mate Airman William Surles uses a dew point calculator in the Meteorology and Oceanic Center (METOC) aboard the aircraft carrier USS George Washington (CVN 73). (U.S. Navy photo by Mass Communication Specialist 3rd Class Stephanie Smith/Released)

A NEW ERA IN TROPICAL CYCLONE PREDICTION

Ronald J. Ferek, Ph.D.

*Program Officer, Marine Meteorology,
Office of Naval Research*

Predicting tropical cyclones (TCs) has been a Fleet priority since at least as far back as Typhoon Cobra, or “Halsey’s Typhoon,” which struck the Navy’s Pacific fleet in December 1944, sunk three warships and claimed the lives of 790 Sailors. Accurate forecasts are still required for many decisions, including: avoiding damaging winds and seas; conducting safe operations; executing timely evacuations of vulnerable assets; setting appropriate conditions of readiness for threatened installations; and planning and executing humanitarian assistance and disaster relief.

Our ability to predict the path, or track, of tropical cyclones has improved dramatically since the 1940s. However, until recently our ability to predict a storm’s intensity, or strength, was minimal. While intensity predictions are not yet where they need to be, sustained research has led to breakthrough technologies in modeling prediction systems.

The TC story shows how basic research builds over time. The Department of Defense established the Joint Typhoon Warning Center (JTWC) in 1959; TC research has been a significant ONR

science and technology (S&T) thrust since 1980. A major goal of ONR-sponsored research was to reduce the 72-hour forecast track, or path, error to 150 nautical miles (nm)—typical forecast track errors had been about 400nm. Throughout the 1980s and ‘90s, much of ONR’s research focused on improving global numerical weather prediction (NWP) models for more accurate tracking forecasts. We have seen steady progress; the 150nm goal was finally achieved at JTWC in 2006.

The steady improvement of tropical cyclone track forecast skill in global NWP models over the past several decades is considered one of the greatest achievements in meteorology and science in general.

Over that same time period, however, there has been virtually no improvement in TC *intensity* forecasts, which remain stuck at plus or minus 20 knots average error for three-day forecasts. Global NWP models are very effective for predicting track, since they capture the large-scale steering flows in the atmosphere, but they remain blunt tools for intensity. This is because the models have insufficient resolution to capture important TC details such as energetic eyewall and inner core processes, deep convection and detailed surface wind fields, among other factors.

In view of these deficiencies, the United States Pacific Command (USPACOM) issued new TC forecasting goals in 2009: reduction of position errors to 75nm at three days, 150nm at five days and 200nm at seven days; prediction of the radius of 35- and 50-knot winds within 20 percent through seven days; development of products that display uncertainty in a dynamic and probabilistic sense; and forecasting the intensity (max winds) to within 20 percent at seven days.

These are challenging goals; current limitations of forecast accuracy show much work needs to be done to achieve them. Fortunately, ONR has focused S&T over the past decade on better understanding physical processes in TCs, and development of higher-resolution regional (mesoscale) models. Some of the first attempts more than a decade ago to use mesoscale models to forecast TCs generally gave poor results. Researchers initially suspected that surface friction (drag) in the models was being overestimated at high winds.

To address this, ONR sponsored Coupled Boundary Layers and Air-Sea Transfer (CBLAST) experiments from 2001 to 2005 to investigate the physics of heat, moisture and momentum exchange at the sea surface beneath TCs. Researchers from academia, the Naval Research Laboratory (NRL), National Oceanic and Atmospheric Administration (NOAA) and NASA conducted intensive field projects during two hurricane seasons in the Atlantic. They were supported by several “Hurricane Hunter” aircraft from the U.S. Air Force Reserve’s 53rd Weather Reconnaissance Squadron, and from NOAA’s Aircraft Operations Center, equipped with meteorological and oceanographic sensors.

CBLAST was a breakthrough experiment that yielded powerful new discoveries. Results proved that previous assumptions of increasing frictional drag with higher winds were wrong. Mesoscale modelers quickly created realistic pressure-wind relationship in TCs, allowing skillful intensity predictions for the first time. This breakthrough stimulated a great deal of new applied research. ONR began supporting NRL’s Marine Meteorology Division for development of an improved version of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS): the Navy’s workhorse operational mesoscale NWP

model would be optimized for TC forecasting (COAMPS-TC).

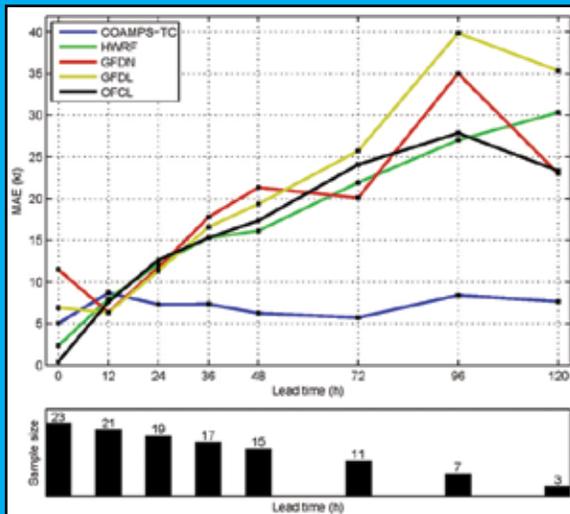
“Tropical cyclones continue to be the most disruptive and devastating peacetime threat affecting operations within the USPACOM AOR”

—Capt. John O’Hara,
Fleet oceanographer, 2009

Early investigations showed that COAMPS-TC forecasts had reasonable, sometimes remarkable, skill for certain storms. One of the major benefits of having a skillful model was that by comparing it to observations, remaining model deficiencies or missing physics became clear, and provided insight to future investigation. ONR formulated two subsequent research Initiatives: Tropical Cyclone Structure (TCS-08) and the Impact of Typhoons on the Ocean in the Pacific (ITOP) from 2008 to 2012. These were large field projects with research aircraft and oceanographic vessels investigating storm-scale processes to improve the understanding of the physics coupling TCs to the ocean. Discoveries from those experiments led to many model improvements.

Performance of COAMPS-TC became sufficiently skillful for it to be selected as a Rapid Transition Project in 2010, sponsored by ONR and the SPAWAR PMW-120 Future Meteorological and Oceanographic (METOC) Systems Program. Additionally, under sponsorship of NOAA’s new Hurricane Forecast Improvement Program (HFIP), COAMPS-TC and other experimental models have run in pseudo-real-time operations for the past three Atlantic hurricane seasons. COAMPS-TC has become the most skillful of the experimental dynamic models for TC intensity predictions, and significantly, has surpassed the skill of existing models for the first time at the 24- to 72-hour forecast lead times. For example, performance for Hurricane Irene was very accurate, far exceeding the skill of previous operational prediction tools because of its ability to capture the dynamically-driven influences that statistical models miss. COAMPS-TC will transition to operations at Fleet Numerical Meteorological and Oceanographic Center (FNMOC) this spring to support the JTWC and NHC. This will be a brand new capability for the Navy.

Figure 1. Wind speed mean absolute error (MAE) (knots) as a function of forecast time for Hurricane Irene for a homogeneous statistical sample. The numerical models included in this analysis are the Navy's COAMPS-TC, operational models run by NOAA (HWRP, GFDL), and the Navy's current operational limited area model (GFDN). The number of cases is shown at the bottom. Only forecasts after Irene has moved away from Hispaniola are shown here.



The work of the research community is still far from complete, however. New mesoscale models can still “bust” badly in certain storms. There are many things we do not understand about TCs, and there remain processes that models do not adequately represent. Additionally, we still do not have good understanding of the intrinsic predictability limits governing tropical cyclone intensity.

At a recent ONR workshop, a number of other gaps in our TC knowledge were identified. One involves the interaction of TCs with the large-scale environment, particularly at upper levels where TC outflow can interact with flows like the jet stream. The linkage of primary (rotational) and secondary (inward-upward-outward) circulation is poorly understood, and the limited range of available research platforms has meant that this has been largely unexplored territory.

However, ONR is taking important steps here as well. NASA's high-altitude Global Hawk research platforms now provide opportunities to explore this region for the first time. ONR began a partnership with NASA's Hurricane and Severe Storms Sentinel (HS3) project, jointly funding several members of the science team. Also, through the ONR Small Business Innovative Research program, an advanced, automated, rapid-fire dropsonde system has been developed for deployment on a Global Hawk in 2014 for collecting an unprecedented set of observations in the upper levels of TCs. (Dropsondes are

instrument packages with parachutes that provide much needed wind, temperature and moisture observations of tropical cyclones from inside the storm and its surroundings at higher levels than ever observed before.) In 2012, the first observations in the hurricane outflow region were made from a Global Hawk deployed from NASA's Wallops Flight Facility. When these high-altitude observations from Hurricanes Leslie and Nadine were assimilated into COAMPS-TC, it resulted in 20-40 percent improvements in the intensity forecast. This remarkable result is encouraging; further investigations as part of a new ONR research initiative (Tropical Cyclone Intensity, or TCI-14) start in FY14.

By improving our understanding of the dynamic processes governing hurricane outflow, we expect to fill significant knowledge gaps, and add important physical processes to predictive models like COAMPS-TC.

Much as global dynamic NWP models became skillful for TC track forecasts in the early '90s, we are on the threshold of an era in which mesoscale NWP models are becoming skillful for prediction of TC intensity, as well as many other operationally useful details of tropical storms. Decades of basic research discoveries led to these breakthroughs in forecast technology. Predicting intensity of tropical cyclones remains a hard problem. The general methodology—from process studies to model development, and advanced development into prediction systems—has proven to be robust, transitioning new operational capabilities to support the Navy and DoD. Civilian systems have also benefited through research collaborations and partnerships between agencies for common goals.

In the future, many forecasting capabilities are potentially achievable: the ability to predict rapid intensity changes; ensemble prediction systems that quantify uncertainty in hurricane structure and intensity forecasts; new observing systems that directly reduce forecast errors by targeting regions where the impact on forecast skill will be greatest; coupled systems that accurately predict storm-induced changes in the downstream atmosphere and ocean; more accurate, longer-range storm surge and flood predictions; and TC genesis and seasonal outlook. Such capabilities would offer tremendous benefit to the Navy and civilian population. ■



BACK TO THE FUTURE

BLOOD PLASMA FOR THE RESUSCITATION OF COMBAT CASUALTIES

Michael B. Given, Ph.D.
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BACKGROUND

The transfusion of whole blood as a treatment for shock was first introduced by the British Third Army during World War One (WWI), after military physicians realized that hemorrhage, and the lack of oxygen-carrying red blood cells, was the single most important factor causing shock. Plans were soon implemented to provide whole blood to far forward Aid Posts for the treatment of casualties, which was no simple task, as the blood needed to be packed in ice until used. The benefits of whole blood transfusion became more apparent during the Spanish Civil War (1936-39), in which over 18,000 units of blood were collected and administered to casualties in shock. Perhaps most importantly, it was noted that medical outcomes were better when casualties

were administered both whole blood and blood plasma.

THE EMERGENCE OF DRIED PLASMA

The fact that whole blood was highly perishable and required constant refrigeration prevented its use on the front line by medics/corpsmen. As a result, pharmaceutical companies began to separate whole blood into packed red blood cells (pRBCs) and plasma (the remaining liquid portion). The plasma was then dried by a process called freeze-drying, where the plasma was cooled and warmed in a cyclic nature under vacuum to draw off water. This new technology meant that plasma would be available for the treatment of casualties at the point of injury. Sharpe & Dohme produced the first units of dried plasma which were distributed in two glass bottles, one containing distilled water and the other approximately 18 grams of dried plasma. Prior to transfusion, the distilled water had to be added to the dried plasma by the medic to rehydrate the product. To protect the glass bottles they were distributed in tin cans, but breakage during transport was substantial.



Photo of WWII era plasma infusion set.

It became very apparent that the volume of plasma (400 mls) was insufficient for treating casualties with severe blood loss, requiring a medic to carry multiple sets, which greatly increased his burden. Production of 600 ml volumes began in 1943, which further contributed to weight/cube issues. During the Korean War, dried plasma was discontinued due to what was termed “serum hepatitis”, now known to be caused by a virus, the existence of which was unknown at the time.

DRIED PLASMA REVISITED

As in past wars, hemorrhage remains the leading cause of death on the battlefield. Also, as in past wars, the result of this blood loss is shock which, if untreated, results in multi-organ failure. While the ideal solution to replace lost blood is with new blood, the requirement for refrigeration prevents its use by expeditionary forces lacking that capability. Currently, lost blood volume in the field is replaced by salt or starch-solutions (e.g., normal saline, lactated Ringers (LR), Hextend™), but these lack any coagulation proteins. Military surgeons in Iraq and Afghanistan often complained that use of these fluids diluted the remaining blood to the point that their patients “were bleeding Kool-Aid” which made it very difficult to get bleeding under control. As in WWII, the nearly ideal replacement fluid is considered to be plasma which, not only replaces lost blood volume, but also replenishes coagulation factors required to stop bleeding.

The current method of storing plasma is in a frozen state, called fresh-frozen-plasma or FFP. FFP has a finite shelf-life and once thawed needs to be used. Thus, even if refrigeration was available at forward medical treatment facilities there would be a delay due to thawing, and in trauma, time is critical. Clearly a dried plasma product was needed, but which one? The use of FFP has recognized medical risks, such as infectious complications, allergic reactions, circulatory overload, transfusion related acute lung injury (TRALI), which can range from mild to severe. Therefore, simply drying FFP did not appear acceptable for naval expeditionary use since available medical assets may be limited and insufficient to effectively manage potentially serious adverse events.

THE ONR PRODUCT

The ONR focus is on safety, and the approach is to develop a pooled-donor, solvent-detergent treated, spray-dried, plasma product that can be safely administered to all casualties regardless of blood type (universal donor). The ONR performer is Entegriion (Research Triangle Park, NC), along with its European biopharmaceutical partner, Kedrion S.p.A (Barga, Lucca, Italy). Kedrion, is the second largest manufacturer of plasma-derived products in Europe.

The process starts using plasma collected from U.S. donors with type AB plasma (universal donor) after testing for infectious agents by Nucleic Acid Testing (NAT). NAT is considered superior to antibody testing since it detects genetic material in the pathogen itself and not antibodies to the pathogen, which take time to develop and may not identify an infected donor with a recently acquired disease.

The plasma is then kept for a period of time and retested before being combined into pools from 100-150 donors. All people have different levels of coagulation factors and this process smoothes those peaks and valleys resulting in uniform concentrations of factors which are known. The pooled plasma is then retested before further processing is begun. This retesting, combined with accurate record keeping, provides full “look-back” capability that allows recall of infected units should that ever be necessary.



Prototype of administration set for spray-dried, solvent-detergent treated, plasma.

The pooled plasma then undergoes a solvent-detergent treatment process licensed from Octapharma AG (Lachen, Switzerland) that effectively removes pathogens (viruses and bacteria), lipids, and cellular debris (microparticles), thought to cause potentially fatal transfusion reactions. Kedrion uses this same process for its liquid plasma product and has marketed over seven million units in Europe without any reported serious adverse events. This safety record cannot be matched by FFP.

The plasma is then dried, not by freeze drying as used in WWII, but by exposing a stream of plasma to high temperature nitrogen gas (131°F) for 15 milliseconds which removes the water without harming the plasma proteins. This approach has been developed by Entegrion for plasma, and can dry a unit (250 mls) of plasma in approximately 10 minutes compared to 48-72 hrs for freeze-drying. This reduction in processing time translates into cost savings. The dried plasma product will be distributed in

an intravenous administration set, representing considerable weight/cube savings over that used in WWII, and allows reconstitution in the field in less than 3 minutes. ONR is also working on a plasma concentrate as part of its Multifunctional Blood Substitute project. This approach provides more plasma in a smaller volume rather than giving more plasma in a greater volume as in WWII, and this translates into a weight/cube savings as well as decreasing the risk of transfusion associated cardiac overload (TACO).

The ONR product, which has Joint funding for advanced development, will begin FDA clinical trials in FY14 and is planned to be fielded in FY18, providing that it successfully navigates the FDA regulatory process. Since this blood product is highly processed, it has to meet the higher regulatory standards of a biologic pharmaceutical, but is a much safer than FFP. Naval expeditionary forces deserve nothing less. ■

COMPOSITE STRUCTURES

A VIEW FROM THE INSIDE

Judah Milgram, Ph.D.,
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Aircraft designers have long been interested in composite materials such as fiberglass, Kevlar, and carbon fiber. The ability to mold complex shapes and tailor the strength and stiffness of finished components makes composites naturally appealing for aircraft structures. Composites are an enabling technology in certain kinds of helicopter rotor systems, and the structural performance of composite dynamic components is an important problem for the Navy. A new experimental approach developed at the University of Texas, Arlington, under an ONR grant allows scientists to “look inside” composite structures to improve their understanding of the internal structural behavior of such materials.

Compared with metals, composites have been relatively slow in finding their way into airframe structures in part because of gaps in the understanding of composite material performance and, in turn, difficulties in establishing compliance with certification standards. This is especially

true with respect to airframe fatigue, the growth and formation of cracks due to long-term exposure to time-varying loads. For example, in jet transports the wing is subject to varying loads due to turbulence. The situation is even more critical with helicopters, whose bellcranks, pushrods, blades, and blade retention systems are subjected to vibratory loads upwards of 10,000 cycles per flight hour. In composites, fatigue cracks often appear inside the structure, becoming visible at the surface only after many flight hours. In addition to creating a challenge for routine inspections, this makes it difficult to develop a detailed understanding of how cracks form and progress through the structure. As a result, designers must apply overly conservative factors of safety, in turn leading to structures that are unnecessarily heavy. What is needed is a way to look inside the part to observe the details of fatigue crack development.

Efforts over the last few decades to develop analytical techniques capable of predicting the life of composite aircraft structures have not been successful because of poor understanding of the complexity of failure modes

in composite structures. For example, while components can be designed for overall strength, the detailed structural behavior between the layers of composite material is not well understood and it is precisely this interlaminar behavior that often governs the way fatigue cracks begin. Material discontinuities including the edges of composite plies and tiny air bubbles (“voids”) contribute to failure initiation but their effects have not been completely understood.

Variations inherent in composite materials and manufacturing processes contribute to this—inevitably, microscopic voids in the matrix and waviness in the fiber develop during layup and curing. Both of these effects impact our ability to predict internal loading details at the scale required to predict the formation and growth of cracks. X-raying, while useful for detecting major structural faults, is unable to characterize very small scale porosity, waviness, matrix cracking, and delamination. The lack of empirical and analytical understanding of composite structures results in designs that are overly conservative and unnecessarily heavy.

This challenge was very much in our minds in 2009, when ONR's Naval Air Warfare and Weapons Department (Code 35) initiated a new program, "Basic Research in Rotorcraft Technology." With relatively little ONR investment in rotorcraft S&T in the preceding years, it was hoped that this initiative would return focus rotorcraft dynamics, aerodynamics, and structures, technology areas of importance to rotorcraft development. The call for proposals included a research thrust area dedicated to advancements in Structures technologies, specifically including "Methods for determining and improving the durability and damage tolerance of composite structures."

Enter Professor Andrew Makeev, who leads the recently established Advanced Materials and Structures Lab (AMSL) at the University of Texas at Arlington (UTA). Prof. Makeev, who earlier had developed an interest in composites diagnostics and prognosis methods while he was in charge of risk assessment at Delta Air Lines, saw an opportunity to

advance the state of the art in the experimental assessment of composite structures. These rely upon three-dimensional imaging and performance prediction based on accurate computational tools. Makeev's project, "Integration of Design and Manufacturing Processes to Improve Performance of Composites," which was selected by ONR with the aid of a joint Navy/Army/NASA panel of subject matter experts, centered on three-dimensional imaging techniques together with finite element analysis to understand the effects of manufacturing irregularities on performance of composites. The project kicked off in July, 2009 at Georgia Tech, and moved to UT Arlington with Makeev in July, 2011 when he was invited to lead the AMSL.

Initial stages of the project involved development of Digital Image Correlation techniques to map the strain fields along the surfaces of standard composite test pieces ("coupons") subjected to various kinds of loading. In this approach, high-resolution stereoscopic cameras image

the structure before and after a load is applied. By tracking the minute translations of random texture features, the strain at the component surface can be computed, material stress-strain constitutive properties captured, and in some cases, internal cracks detected before they appear at the surfaces. This effort (undertaken initially by Makeev while he was at Georgia Tech) was also supported by a 2009 Defense University Research Instrumentation Program (DURIP) award.

Encouraged by these results, the UTA researchers moved to an even more sophisticated measurement technology: X-Ray Computed Tomography (CT). CT scanning has become almost commonplace in the medical field as a method for imaging three-dimensional structures within the human body. Makeev's group, however, employed a high-power industrial micro-focus CT system that provides a much higher resolution than medical CT scanners, albeit at the cost of increased scan time and radiation levels. This equipment



Figure 1. Typical CT image showing the interior of a 30-ply Glass/Epoxy laminate. Wrinkles and voids that are not evident from an exterior inspection are clearly visible in this high-resolution cross-sectional image.



Figure 2. The AMSL Director Professor Andrew Makeev and Research Associate Dr. Yuri Nikishkov discovered multiple delaminations initiated at manufacturing irregularities in the fatigue tested article.

allowed the researchers for the first time ever to develop images of the fine internal details of composite structures, including voids, wrinkles, and cracks.

A typical image (*Figure 1*) shows the “inside” of a 30-ply Glass/Epoxy laminate. Wrinkles and voids are clearly visible with high resolution. These features are at the same time invisible to external inspection. This new ability to characterize and quantify manufacturing variations in composite components allows the researchers to relate fatigue test results to statistical characterizations of manufacturing processes.

Makeev’s project also includes an effort aimed at improving finite-element modeling of composite microstructures. Within the past year, a more detailed understanding of the mechanisms of crack formation and occurrence of manufacturing variations have allowed his group to make advances in Finite Element Modeling (FEM) of composite structures that,

according to Makeev, represent somewhat of a breakthrough. “Traditionally we have relied on time-consuming trial-and-error experimentation in the design of composite materials and structures. Thanks to this technology we can develop more efficient diagnostic and predictive methods.” In other words, designers may one day be able to predict accurately the fatigue lives of composite components as they are actually manufactured, and not rely on excessive factors of safety in design.

More recently, Makeev was awarded a second DURIP to acquire and install a load frame inside the CT-system. This will allow CT measurements of components while under load, and should provide even more insight into the mechanics of structural damage initiation and progression in composite components.

Anisur Rahman, Advanced Structural Technologies Lead for the Naval Air Systems Command (NAVAIR) Airframes Technology Branch, is responsible for Research and

Development efforts in areas that will improve our use of composite materials in aircraft and is optimistic about the impact Makeev’s research will have on future rotorcraft. “This work will reduce the amount of testing required to qualify new rotorcraft components. Better knowledge of material structural characteristics will lead to weight savings and increased reliability and safety.” Ed Lee, Principal Engineer for Manufacturing R&D at Bell Helicopter Textron and a collaborator with Makeev on the project, agrees. “Andrew was the first to quantify the effects of porosity on component fatigue lives,” says Lee. “This improved knowledge will ultimately allow us to produce lighter, more reliable composite components at lower cost than at present.” With composite dynamic components likely to become more common in future Naval rotorcraft, this can be expected to result in improved operational capability and reduced cost to the fleet. ■

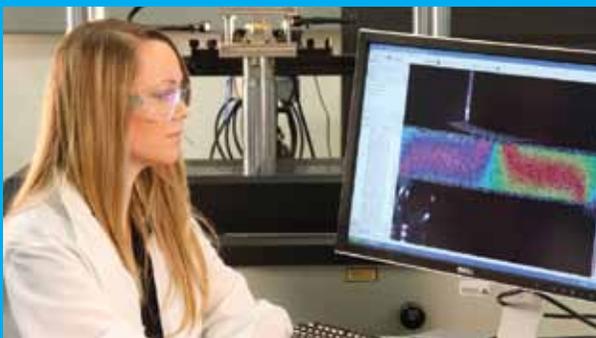


Figure 3. Ph.D. Candidate Paige Carpentier is conducting a short-beam test coupled with the digital image correlation (DIC) technique for the full-field 3-D measurement of surface deformation enabling the understanding of deformation and failure mechanisms for a composite material.



Figure 4. UTA/Bell Team working on the ONR project (*left to right*, Ms. Carpentier, Dr. Nikishkov, Graduate Assistant Ekatarina Bostaph, Research Associate Mr. Brian Shonkwiler, Prof. Makeev, and Mr. Lee) after reviewing CT reconstruction results at the AMSL facility.

SHINING SOME LIGHT

ON A SEEMINGLY IMPENETRABLE PROBLEM

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Air Systems Command
(NAVAIR)

Lightweight, fiber reinforced polymer matrix composites (PMC's) are an enabling structural material for naval aircraft. PMCs provide a combination of high strength to weight ratio, good fatigue properties, and saltwater corrosion resistance. Since the introduction of structural PMC's on Navy aircraft in the 1980's, their use has increased (as measured by percentage of aircraft total weight) from 2% to over 35% today. As the need for future aircraft with longer range, greater speed and maneuverability, and larger payload capacity increases, PMC's will continue to provide optimal solutions where the weight of the airframe will offset any additional loads associated with integration of these improved capabilities.

A serious drawback to PMCs, though, is their vulnerability to heat or fire damage. Of significant concern to the fleet is thermal degradation called "incipient" damage (such as from long-term exposure to moderate sources of heat or the extent and depth of the regions surrounding clearly visible heat damage). Incipient damage cannot be visually identified nor detected by any non-destructive inspection

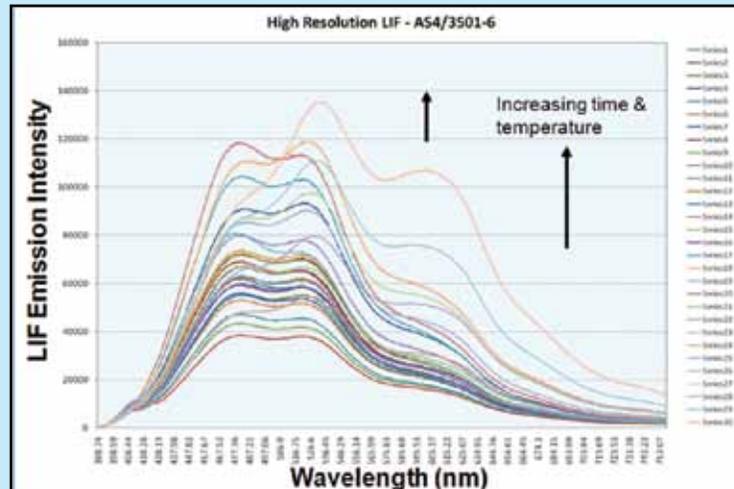


Figure 1. LIF spectral changes to epoxy based composite amples after exposure to elevated temperatures for increasing exposure times; (405 nm laser excitation).

(NDI) techniques currently used by the Navy, but can cause up to a 40% knockdown in the strength of a part. Such a large, undetectable knockdown is a significant safety issue for a deployed aircraft. Since the late 1980's, the Navy has funded evaluation of many NDI techniques for detection of incipient heat damage with limited success.

The difficulty in detecting incipient damage stems from the two component nature of the composite. In a PMC, the high strength, high temperature resistant graphite structural fibers are held together with a polymer, or plastic. The high temperatures during a fire degrades this polymer component. However, most standard inspection techniques used to detect polymer damage depth, are "blocked" by the opaque graphite fibers. Given

that a typical aerospace grade PMC is roughly 70% graphite fiber by volume, the material is essentially "opaque" to most optical inspection methods.

Recently, NAVAIR in collaboration with scientists from Oak Ridge National Lab (ORNL) and under ONR Code 332 funding, have made significant breakthroughs in developing a novel, laser induced fluorescence (LIF) based NDI technique for assessment of incipient heat damage of fielded composite aircraft components. Fluorescence results from the emission of lower frequency light by a substance that has absorbed light of higher frequency. A well known use of fluorescence is in crime scene forensics to detect blood or fingerprints with a UV black light, as often seen on TV police shows. Alternatively,

As is often the case with new technologies, success in demonstrating a novel concept in a lab environment frequently is tempered by practical considerations such as cost, reliability, procedural, or environmental factors when attempting to transition the idea to field use.

laser induced fluorescence (LIF) uses laser light to enhance “fluorescence” emission in a material instead of using a black light. What Navy funded researchers at ORNL discovered in the 1990’s was that as a plastic was gradually heat damaged, its laser induced fluorescence spectral content or color, changed and correlated monotonically to the degree of mechanical damage (see *Figure 1*). As the graphite fibers did not fluoresce from the same laser light, it was realized that LIF might be a novel way to track heat damage in polymers, and thus the degree of incipient

mechanical damage in the PMC parts.

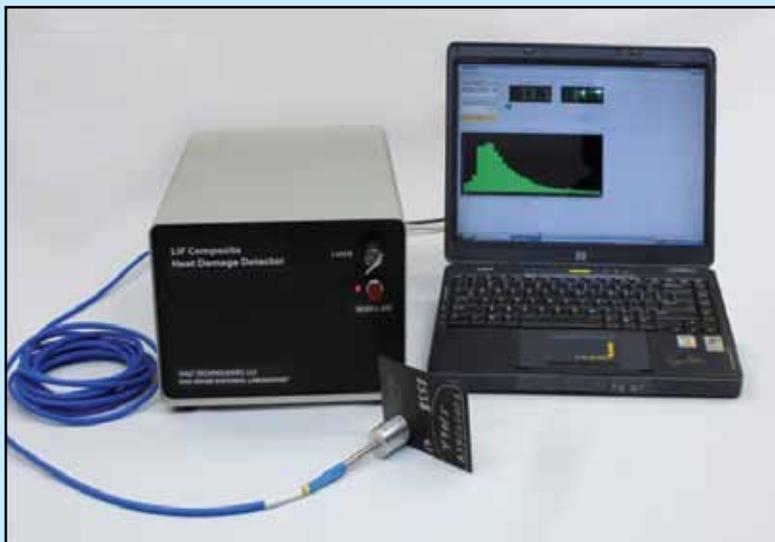
These original LIF studies by ORNL scientists were encouraging. The work, though, was performed with lab instrumentation that was not suitable for field inspections of real aircraft parts. As is often the case with new technologies, success in demonstrating a novel concept in a lab environment frequently is tempered by practical considerations such as cost, reliability, procedural, or environmental factors when attempting to transition the idea to field use. Such was the case for LIF technology.

For example, to “see” an object fluorescing with the naked eye, one needs to turn off the lights as the emission is extremely weak compared to daylight or interior lights. But in a large Navy aircraft maintenance facility, hangar, or deployed ship, turning off the lights to inspect an aircraft is not a viable option. In the lab one could also offset the weak fluorescence

signal from the opaque composite surface by increasing the laser power. But in a Navy fleet environment, for safety concerns, operational lasers are restricted to only Class IIIa, essentially the wattage of a laser pointer. Another obvious approach for detecting a weak fluorescence signal is simply to spend a longer time collecting the light with your sensor—from minutes to hours, if needed. But a fielded, portable LIF system was envisioned as being hand held and manually operated. As an individual usually can only hold a probe stationary for a minute or less, measurement times needed to be comparable. What this all means is that a fielded system has the seemingly impossible requirements of needing to measure the weak fluorescent signal emitted by an opaque, black surface in daylight and in real time, with a laser source comparable to a laser pointer.

The solution ORNL devised was to borrow from phase detection methods developed for laser-based RADAR, or LIDAR which needs to measure very weak reflected laser signals in real time. The approach is similar to how an AM (Amplitude Modulation) radio works, only instead of radio waves, light waves are used. With this approach fluorescent signals many orders of magnitude smaller than ambient noise can be recovered. As the system is tuned to detect only signals at the modulation frequency of the light (similar to a radio channel), measurements can be taken in daylight or ambient light conditions as these sources are not modulated.

Figure 2. Portable LIF NDI prototype.



The components of the LIF prototype are relatively simple comprising a diode laser, a mini-spectrometer/detector, and a fiber optic probe. The probe delivers the excitation light from the laser to the composite surface, then collects the emitted fluorescence and delivers to the spectrometer/detector. Unlike most commercial, portable fluorescence systems, the novel Navy LIF design incorporates a type of detector called a photomultiplier (PMT), instead of the customary CCD detector typically found in digital cameras. Though a CCD detector would provide a higher imaging resolution, PMT detectors are much faster at sensing small packets of light (photons). The Navy LIF prototype takes advantage of the much greater detection speed of a PMT to collect 100's of spectra in a few seconds which are then averaged to give data statistically comparable to that collected with a higher resolution CCD detector.

The portable unit also incorporates other, new electro-optic technologies not available in the 90's and early 2000's. Previous LIF lab systems utilized large, expensive ion (gas) lasers outputting green (514 nm) or red (633 nm) light. The current prototype design uses small, high quality blue diode lasers which have significantly decreased in cost with the advent of BlueRay DVD technology. A blue laser is critical for future fleet use of LIF as blue light excites fluorescence in all the different types of PMC's used on current Navy aircraft, as well as in many



Figure 3. Inspection of In Service composite aircraft parts with LIF NDE unit's fiber optic probe.

new high temperature PMC's being incorporated into next generation aircraft such as the F-35.

Over the last several years the prototype has undergone Demonstration/Validation (DEM/VAL) trials at Naval Air Warfare Center–Aircraft Division (NAWC-AD) Pax River, and associated NAVAIR Flier Readiness Centers (FRCs). These activities included evaluation of heat damaged components on In Service V-22, AV-8B, and F/A-18 C/D aircraft. In parallel, the benefit of the system in evaluating the degree of composite mechanical damage induced by short duration fuel fires also has been conducted by a NAWC-AD/Air Force team funded by the Joint Aircraft Survivability Program (JASP). A photograph of the ORNL prototype is shown in *Figure 2* and the unit being used for

inspection of several aircraft composite parts in *Figure 3*. The prototype has successfully supported structural inspection and repairs of heat damaged composite aircraft composites; in one example a composite wing with heat damage was successfully repaired (instead of scrapped) and returned to the fleet, saving the Navy roughly \$2M.

Based on the NAWC-AD DEM/VAL trials and feedback from the NAVY end users, ONR Code 332 is funding upgrades to the baseline prototype design to eliminate several deficiencies in the current system as well as to incorporate the latest improvements in electro-optic components. These upgrades will further increase the speed and accuracy of the electronics and durability of the system to produce a production ready design. ■

INNOVATION

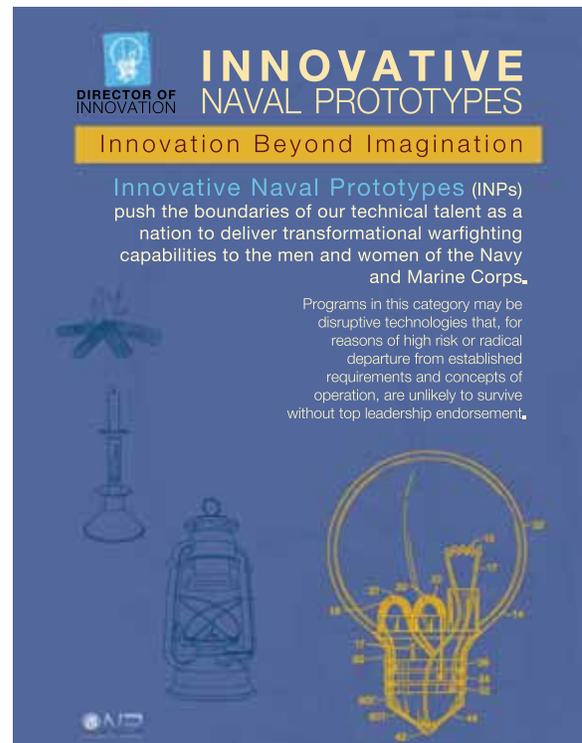
IT TAKES A VILLAGE

Mr. Craig A. Hughes

Acting Director of Innovation,
Office of Naval Research

When I first arrived at the Office of Naval Research five years ago, I was asked to take over managing the Innovative Naval Prototypes (INPs) portfolio. The INPs are a select group of high-risk, high-payoff technologies that are potential game changers for the Sailor and Marine. Because of their disruptive nature, there are a lot of people involved in the proposal development, evaluation and selection; the management and leadership; the research and development (to include government labs, commercial companies and government sponsored entities); the financial, contractual and program management execution; and eventually, the prototyping and relevant testing of these high-risk, high-payoff technologies. INP proposals fall into the 6.2 or 6.3 government research categories, otherwise known as applied research through advanced technology development. This ensures that the technologies selected are more mature and have concrete naval application and relevance. As someone with the thirty thousand foot view into this highly technical and leap ahead portfolio, what struck me as impressive was the entire system that is in play to support the development and execution of these INPs. *It literally takes a village.*

First, consider that before a technology even becomes an INP, we can't forget that at one point, the concept only existed inside of a researcher's brain as a notion. It sometimes takes years of research and exploration into these new concepts before a technology is even ready to be considered as an INP candidate. It would be impossible to document the number of contributors who provided insight into the development of a basic research program. Sure, you have the core research team—but what about their colleagues outside the program that they bounce ideas off of? What about the lab leadership that handles the management and administration of their research that make it



possible for them to focus on their work? What about the family members who support them when they stay up late working in the lab or are deep in thought at the dinner table, or are distracted by a challenge that they've run into? It takes a lot of smart and supportive people to deliver innovative basic research that is worth taking to the next level.

Second, consider the selection of these innovative technologies. Naval government program managers submit INP proposals from within, or to ONR, every other year. Because INP technologies are meant to dramatically change the way in which our naval forces fight, it is important that senior leadership has a role in the evaluation and selection of the INPs. The experience of the senior Admirals, Generals and Senior Executives who sign off on these proposals every other year is critical. Providing this INP oversight today is the Naval Research, Development, Test and Evaluation Corporate Board which includes the Under Secretary of the Navy; the Assistant Secretary of the Navy for Research, Development and Acquisition; the Vice Chief of





INNOVATIVE
 NAVAL PROTOTYPES

Large Displacement Unmanned Underwater Vehicle

LDUUV

Contact:
 Daniel Deitz
 Code 32

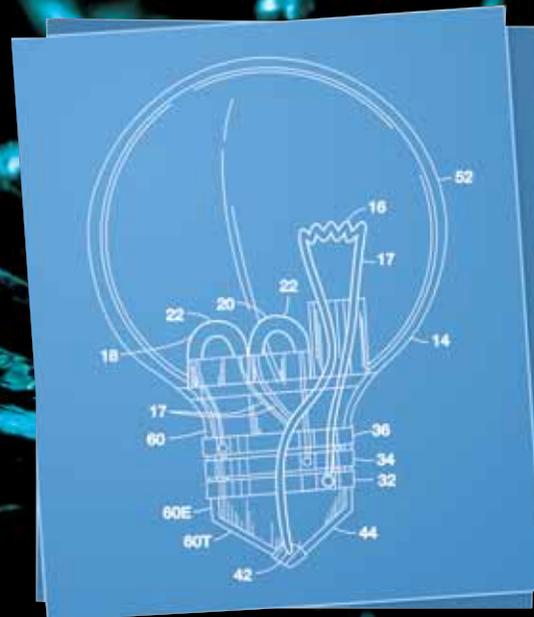
This Innovative Naval Prototype program will develop fully autonomous, long-endurance, land-launched unmanned underwater vehicles capable of operating near shore. It will extend and augment the Navy's current platform capability. The LDUUV program will develop new air independent energy systems and core vehicle technologies to extend unmanned underwater vehicles endurance into months of operation time. Advanced autonomy and sensing will enable operations in the cluttered littoral environment.

Naval Operations; and the Assistant Commandant of the Marine Corps. This team of senior decision makers, their staffs, science and technology (S&T) evaluators, ONR S&T technology program officers and department-level leadership, other stakeholders throughout the Navy and Marine Corps, and the Naval Research Enterprise spend considerable effort evaluating the value of each proposed INP before deciding which technologies will ensure our future Sailors and Marines have more capabilities than the generation that served before them. It takes a lot of people and their efforts to propose, evaluate and select our INPs.

Finally, consider that the collaboration efforts necessary to champion these innovative technologies doesn't stop once they become INPs. In fact, the team and their responsibilities only grow! Take our Large Displacement Unmanned Undersea Vehicle INP for example—at ONR alone, it receives the support from numerous departments: contracts, finance, public affairs, legal, security, information technology, the congressional liaison office, the ONR Directors, the Ocean Battlespace Sensing Department and Division Heads, Systems Engineering and Technical Assistance support contractors who work both on and off site, the Chief of Naval Research and his staff—and the list continues.

And that's **ONLY** the support and program management team members. Now imagine if you included all of the performers and their contractors and subcontractors, the decision makers at the Pentagon, and don't forget the eventual customers—our warfighters who help to shape the development of new warfighting capabilities. It takes a lot of people to manage the development of an innovative technology.

A large and diverse team is necessary for innovation to thrive. On one hand, we recognize that ideas and new technologies can come from anywhere and we value and look to bring those ideas in to ONR. On the other hand, and talked about far less often, we recognize that it takes a deep bench to actually *deliver* an innovative technology to our Sailors and Marines. Without the concerted efforts from all the stakeholders, these INPs would not have a chance to truly make a difference. And when you have the opportunity to watch this system from where I sit, it's truly an impressive thing to see. It may take a village, and when you see everyone coming together for the common goal of delivering new innovative technologies to our warfighters, you couldn't be prouder to be a part of such an important mission. ■



INNOVATION BEYOND IMAGINATION™

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