Lawrence Livermore National Laboratory

Science & Technology Review

June 2019

NIF 10 YEARS OF HIGH-ENERGY INNOVATION

Also in this issue:

Synthesizing Nerve-Agent Antidotes

Lecture Series Stimulates Interest

Validating Weapons Performance

About the Cover

In 2019, the National Ignition Facility (NIF)—the world's most energetic laser—celebrates 10 years of operation. As the article beginning on p. 4 describes, every year, researchers conduct experiments at NIF that are essential to the National Nuclear Security Administration's science-based Stockpile Stewardship Program. In doing so, they advance national security and the field of high-energy-density science. They also enable advances in astrophysics, planetary physics, hydrodynamics, and materials science. NIF conducts approximately 400 shots per year. The cover image shows one of NIF's target positioners (bottom left) being inserted into the target chamber for an experiment.

Cover design: Mark Gartland; Cover photo: Philip Saltonstall

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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June 2019

Lawrence Livermore National Laboratory

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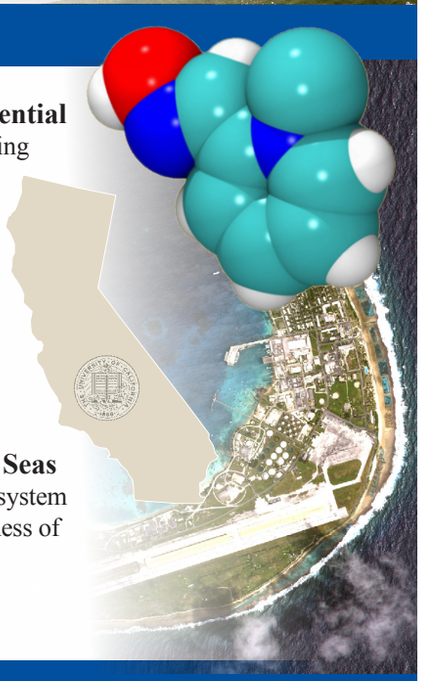

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Implants Record Widespread Brain Activity

In collaboration with researchers at the University of California at San Francisco (UCSF), Lawrence Livermore scientists developed a novel system for recording widespread brain activity using high-density, implantable electrode arrays. The research appears in the January 2, 2019, edition of the journal *Neuron*. As described in the paper, the system is capable of continuously recording the activity of nearly 400 single neurons over a period of at least five months from devices distributed in multiple brain regions.

UCSF scientists implanted 16 arrays (each consisting of 64 electrodes) across four distant regions of the brain: the hippocampus, ventral striatum, orbitofrontal cortex, and medial prefrontal cortex. The multielectrode arrays, which are made from a biocompatible, flexible polymer material, were fabricated at Livermore and combined with electrical hardware built by neuroscience tool manufacturer SpikeGadgets. Using an automated spike-sorting system developed at UCSF, the researchers concluded the recordings are stable enough to allow them to track large numbers of individual neurons for more than a week.

The team says the system provides a new tool for understanding brain activity and makes it possible to examine how different regions of the brain interact. "The ability to record activity from multiple regions of the brain for long periods of time with high fidelity allows us to start looking at patterns of learning and how memory changes," says Livermore researcher Angela Tooker, a co-author on the paper. Such a capability could make it possible to understand how the brain processes information that can take days, weeks, or even months, such as forming, consolidating, and retaining memories.

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Researchers Predict Reaction Data for Fusion Research

For decades, nuclear scientists have been trying to harness the energy produced by the thermonuclear fusion of deuterium (D) and tritium (T) nuclei to power reactors of the future. Now, a Livermore team has for the first time used validated models of the interactions of neutrons and protons (the constituents of nuclei) and an ab initio reaction method to accurately predict the properties of polarized DT thermonuclear fusion. The research appears in the January 21, 2019, edition of the journal *Nature Communications*.

Thermonuclear fusion is a type of nucleosynthesis in which lighter elements, such as hydrogen and helium, are converted into heavier ones, and in the process release large amounts of energy. In the study, Livermore researchers combined a first-principles approach with high-performance computing to model thermonuclear reactions. By using a state-of-the-art approach for studying the structure and dynamics of atomic nuclei—the ab initio no-core shell model with continuum—they were able to predict how the DT fusion rate changed based on spin polarization and temperature. The team is interested in polarized DT thermonuclear fusion wherein the D and T nuclei "spin" in the same direction, which could enhance the fusion rate by as much as 50 percent. The charged helium nuclei produced in the fusion reaction could be more efficiently focused to heat up reactor fuel.

Thermonuclear fusion occurs naturally in stars, which are fueled by nucleosynthesis, and also plays an important role in explaining the primordial abundances of elements after the Big Bang. Thus, thermonuclear reactions are of great interest to astrophysicists who seek to answer some of the most fundamental questions about the origins of the universe and the evolution of stars. Livermore physicist Sofia Quaglioni, one of the authors of the paper, says, "In the future, analogous calculations could be used alongside available experimental results to provide the thermonuclear reaction data and level of accuracy required to improve the predictivity of astrophysics simulations."

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Bioprinted Cells Enhance Catalytic Efficiency

Laboratory researchers have used three-dimensional (3D) printing to produce live cells that convert glucose to ethanol and carbon dioxide gas (CO_2)—a substance that resembles beer. The research, which appears as an ACS (American Chemical Society) Editors' Choice article in the January 31, 2019, edition of *Nano Letters*, shows that additively manufactured live whole cells can assist in studies of microbial behaviors, communication, interaction with the microenvironment, and new bioreactors with high productivity.

Microbes are extensively used in industry to convert carbon sources into valuable end-product chemicals that have broad applications. In the Livermore case study, the team incorporated freeze-dried live biocatalytic yeast cells into porous 3D structures using a new bioink material. The printed structures are large-scale and self-supporting, with high resolution, tunable cell densities, high catalytic activity, and long-term viability. More importantly, if genetically modified yeast cells are used, high-value pharmaceuticals, chemicals, food, and biofuels can also be produced.

"The bioprinted 3D geometries developed in this work could serve as a versatile platform for process intensification of an array of bioconversion processes using diverse microbial biocatalysts for production of high-value products or bioremediation applications," says Livermore materials scientist Fang Qian, the project lead and corresponding author on the paper. Engineer and co-author Eric Duoss adds, "This approach promises to make ethanol production faster, cheaper, cleaner, and more efficient. Now, we are extending the concept by exploring other reactions, including combining printed microbes with more traditional chemical reactors to create 'hybrid' or 'tandem' systems that unlock new possibilities."

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Commentary by Jeff Wisoff

Ten Years of Pioneering Science with the World's Largest Laser

IN 2009, the first time that the National Ignition Facility (NIF) fired all 192 of its laser beams at a single point inside a vast, spherical target chamber, it was 60 times more energetic than any laser ever built. Now, 10 years and nearly 2,800 shots later, NIF still dominates the world of high-energy lasers by a factor of 10 and continues to help the Laboratory achieve its mission objectives, offering unparalleled laser performance and precision.

NIF is a testament to the scientific and technical excellence of the people working at Lawrence Livermore and our partners across the United States and around the world. From the beginning, the facility has fostered an elite workforce and generated far-reaching innovation that has allowed us to lead in many areas of science critical to the Department of Energy and its National Nuclear Security Administration (NNSA). The article beginning on p. 4 describes NIF's success over the last decade and how our efforts support NNSA's science-based Stockpile Stewardship Program (SSP) and advance a broad range of applications.

Twenty-five years ago, SSP was formally established to maintain the safety, security, and effectiveness of the U.S. nuclear deterrent in the absence of underground nuclear testing. NIF was built with this approach in mind, and the facility routinely creates extreme conditions that allow unprecedented experimental access to the physics of nuclear weapons. Data from these experiments materially contribute to life-extension programs that are under way, helping inform immediate decisions to ensure the longevity of today's modernization projects. NIF data also validate the ever more complex and sophisticated simulations used for SSP.

Achieving ignition of a self-sustained nuclear fusion reaction is one of the most difficult grand challenges of our age. However, over the past 10 years, inertial confinement fusion (ICF) experiments at NIF have provided extensive insight into the most viable paths for making ignition a reality, which would open a gateway toward higher pressures, temperatures, and yields that are relevant to the weapons program. Although we continue to make significant progress, ignition is the one element of underground testing that has not yet been reconstituted.

The last decade has certainly demonstrated how dedication to mission and innovative thinking at NIF has led to scientific and technical breakthroughs. From the beginning, facility advancements enabled NIF to reach its designed laser energy of 1.8 megajoules (MJ). Continued enhancements resulted in NIF setting a new facility record in 2018, firing 2.15 MJ to its target chamber. Additional diagnostics have led to more data being measured from experiments. The Advanced Radiographic Capability, for example, which is built into the NIF laser, allows researchers to probe dense conditions of matter during experiments, providing more insight into the evolving plasmas created with NIF's laser beams. Operational efficiencies have also led to an increased shot rate—NIF conducts approximately 400 shots per year. With more shots being made available, discovery science and national security applications have grown and contribute back to high-energy-density science and ICF programs.

Operating NIF and fulfilling the Laboratory's missions require expertise that extends throughout the Laboratory, from physics and engineering to computation, safety, security, and operations. This team is further enhanced through NIF's ability to attract talented engineers and scientists to Lawrence Livermore that replenish and broaden our capabilities. Our resulting laser advancements will enable new technologies that will help strengthen our country, such as advanced directed-energy laser systems.

Recognizing the importance of NIF, other nations are building NIF-like facilities aimed at achieving ignition. We must maintain our lead in the face of this growing competition. National laboratories serve the United States through execution of their challenging missions. Over the last 10 years, we have made continued, substantive progress in areas essential to our national security mission. Through this demonstrated excellence and innovative spirit, we will continue to improve NIF's capabilities to overcome challenges in the future and be prepared for what comes next.

■ Jeff Wisoff is principal associate director for NIF and Photon Science.

NATIONAL IGNITION CELEBRATES 10 YE

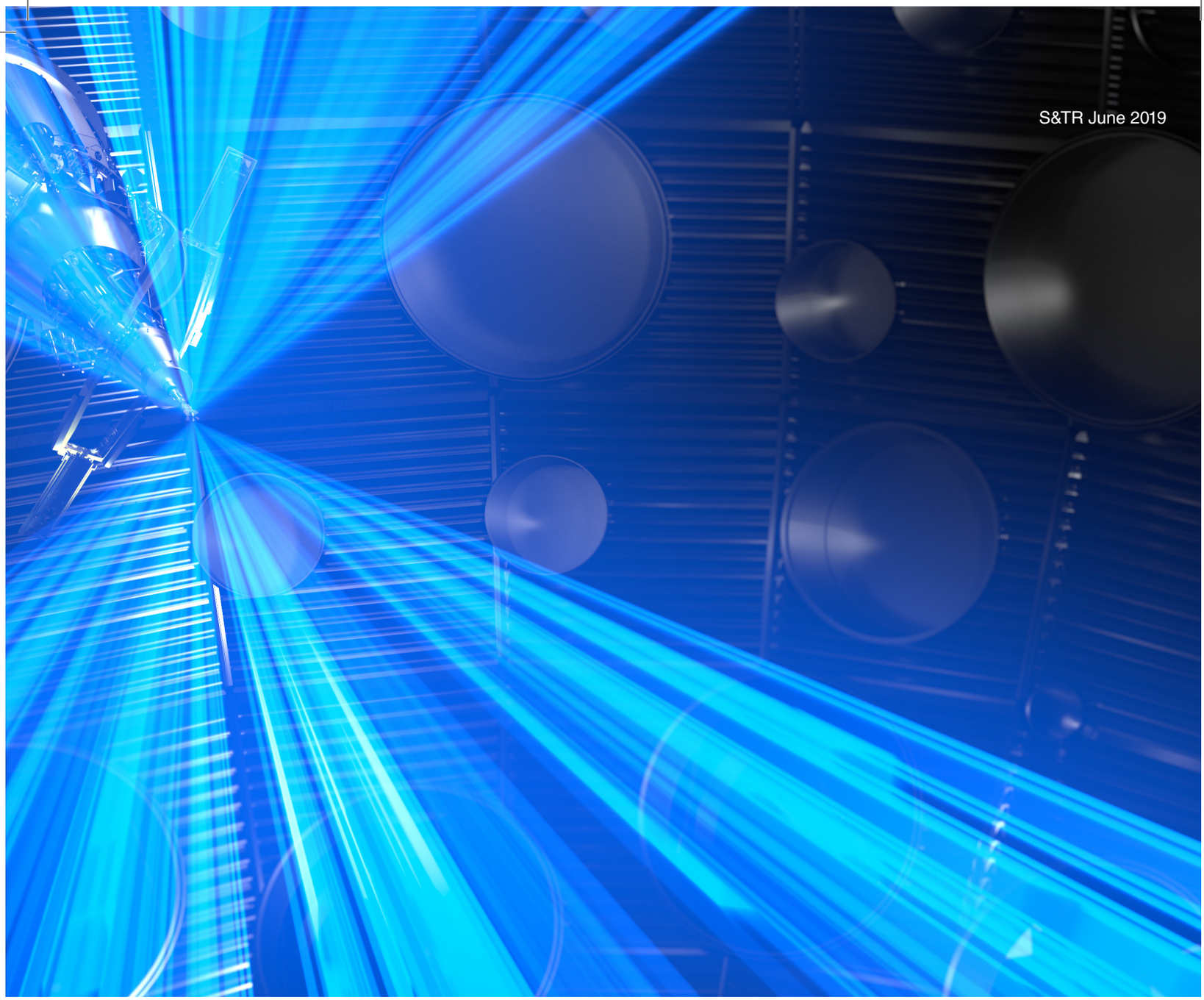
Over the last decade, the world's most energetic laser has been making important contributi

ON March 9, 2009, a staggering 2 trillion watts of electrical power—4 times more power than the United States uses at any instant in time—surged through the National Ignition Facility (NIF) to generate the intense light that powers the laser. At that moment, 192 laser beams raced down the beam path and converged to deliver an immense blast of energy onto a tiny target. This test shot was a key milestone for NIF, fulfilling one of its first critical design specifications. Five months later, in August, Livermore scientists began executing experiments at NIF aimed at ensuring

FACILITY
ARS OF OPERATION

ons to the Stockpile Stewardship Program, national security, and high-energy-density science.

The size of three football fields, the National Ignition Facility (NIF) is the most energetic laser in the world—offering unparalleled laser performance and precision for critical scientific applications. (Photo by Damien Jemison.)



Inside NIF, 192 high-energy laser beams converge onto a tiny target to create extreme conditions. (Rendering by Jacob Long.)

the Laboratory could deliver on one of its key missions: to maintain the nation's nuclear deterrent in the absence of further underground nuclear weapons testing.

This exceptional laser system makes it possible for scientists to explore physical regimes never before seen in a laboratory setting. Every year, researchers conduct experiments at NIF that are essential to the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program (SSP). In doing so, they advance our national security and the field of high-energy-density (HED) science. They also enable advances in astrophysics, planetary physics, hydrodynamics, and materials science. NIF's unique capabilities include flexible and repeatable experimental configurations, precision target fabrication and metrology, and advanced diagnostics. Such capabilities enable stockpile stewards from all three NNSA laboratories to execute experiments that deliver data in relevant regimes previously inaccessible to SSP. Weapons researchers are now able to measure the phase, strength, and equation of state of plutonium and other weapons-relevant materials at extreme pressures, densities, and temperatures. The data from those experiments are used to validate three-dimensional weapons simulation codes and inform life-extension programs (LEPs), the regularly planned refurbishments of nuclear weapons systems to ensure long-term reliability.

Much of NIF's success can be attributed to the Livermore scientists and engineers who have driven significant enhancements

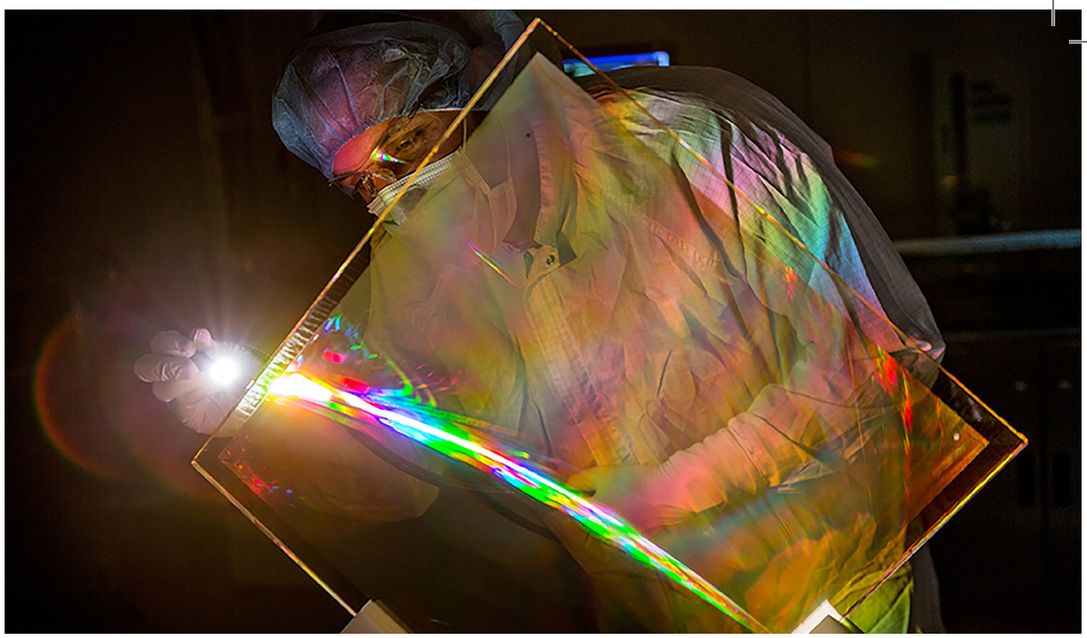
to NIF operations and experimental capabilities over the last 10 years. Their accomplishments have made the facility more efficient while expanding the depth and breadth of scientific applications. Such innovation has led to outstanding contributions in HED science and groundbreaking experiments in many of the Laboratory's mission areas.

NIF's chief engineer Doug Larson says, "We're constantly improving the capability of the laser from the standpoints of how much energy and power we can generate, the precision with which we can deliver it, and how we can diagnose the experimental output. We also continually engineer improvements to operational efficiency, identifying anything that will make NIF more productive for the Stockpile Stewardship Program." An ever-expanding list of target and diagnostic platforms in addition to continued efficiency gains sets the stage for NIF to continue to advance the Laboratory's missions further into the 21st century.

From Concept to Reality

As early as the 1970s, scientists at Livermore began to explore using powerful lasers to achieve ignition of a self-sustaining nuclear fusion reaction. Toward this end, the original NIF concept called for a larger, more complex laser named the Laboratory Microfusion Facility (LMF) that could deliver 10 megajoules (MJ) to a target. Based on data from Livermore's earlier laser systems and other experiments, 10 MJ would be sufficient to exceed the ignition threshold and to achieve higher efficiency and high gain—where more energy is produced from the reaction than the amount of energy used to initiate it.

When asked by the U.S. Congress to evaluate the feasibility of LMF, the National Academy of Sciences recognized the merit and importance of the endeavor and, in 1989, endorsed an ambitious plan to move forward, but with a substantial change. "According to the academy, LMF would probably work, but it viewed 10 MJ as a step too far," recalls John Lindl, NIF's chief scientist during its development. "It would cost too much and be too big an advance in technology. Instead, we were asked to consider something in the 1- to 2-MJ range, which would be closer to the onset of ignition. This revised concept became NIF." Extensive planning followed to determine the facility's design and performance specifications, and in 1996, authorization was given to proceed with full construction.

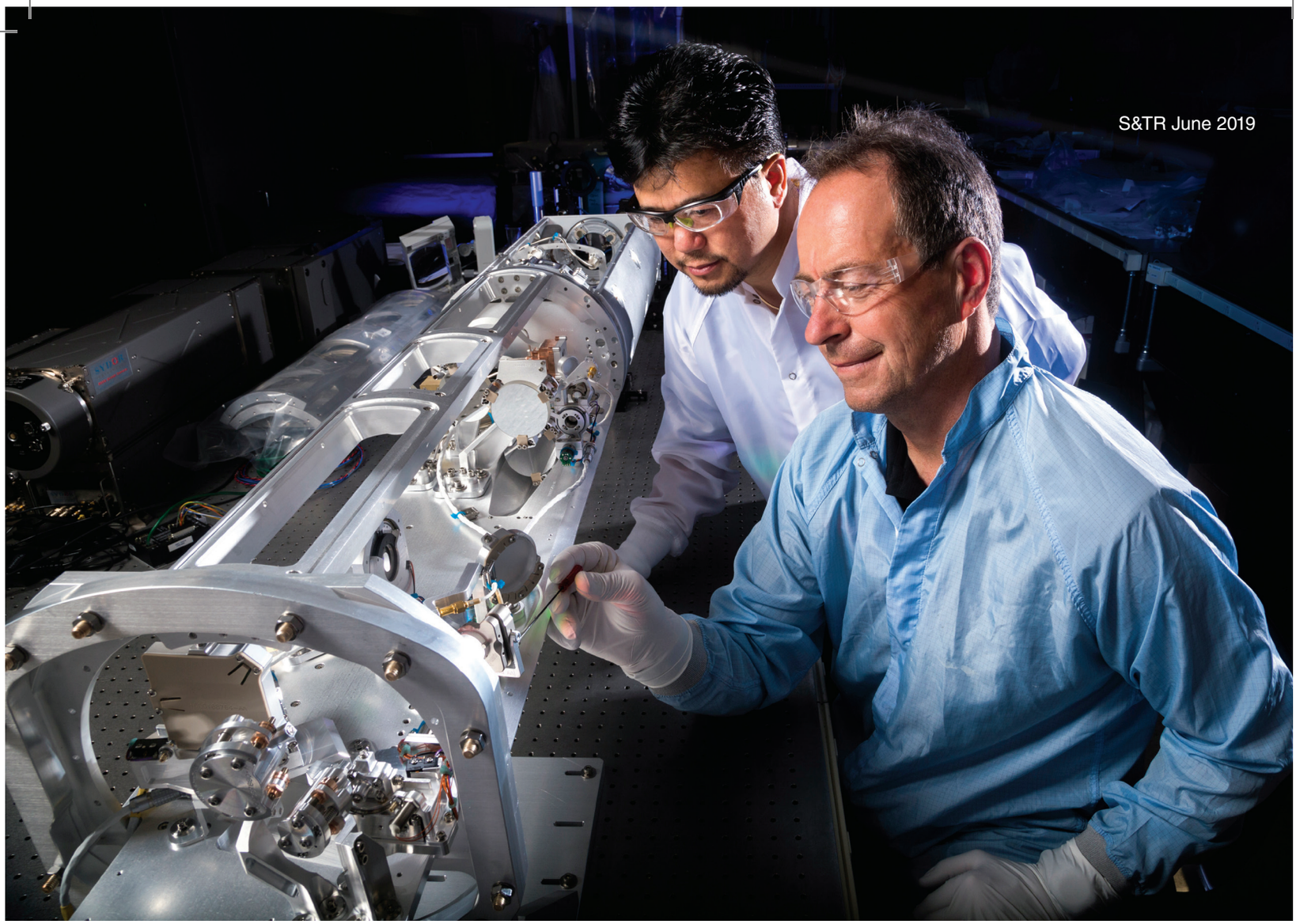


Laser-induced damage to the thousands of optics within NIF can limit the system's performance. Here, Livermore processing engineer Marcus Monticelli inspects the antireflective coating on a NIF grating debris shield. The coating helps reduce optics damage and improve laser performance. (Photo by Jason Laurea.)

In June 1999, after careful preparation, a rotating crane hoisted NIF's target chamber and gently moved it to the facility's target bay, a breathtaking event that took only about 30 minutes to complete.

Scientists, engineers, and technicians encountered and overcame daunting technical challenges to realize NIF, from developing one of the world's most sophisticated computer control systems to perfecting rapid-growth processes for the large single crystals of potassium dihydrogen phosphate (KDP) and deuterated KDP used in NIF optics. (See *S&TR*, September 2002, pp. 20–29.) One of the most important innovations was developing a means for limiting and repairing damage to optics sustained from repeated exposure to the laser's high-energy beams.

Laser and system engineer Mary Spaeth joined the team to address the threat of optical damage greatly hindering NIF's performance. "NIF's specification was 1.8 megajoules and 500 terawatts. If we'd have come up with only a fraction of that output, we'd be nowhere close to our goal," says Spaeth. Rethinking the science behind the issue, Spaeth was able to lay the groundwork for the optics-recycling loop now in place at NIF. This process offers a novel way to evaluate, refurbish, replace, and reintroduce optics, as needed.



An extensive suite of diagnostics is required at NIF to accommodate its diverse experiments. Shown here, engineering technical associates Gene Frieders (front) and Gene Vergel de Dios work on the optical Thomson scattering diagnostic for recording time-resolved spectra from experiments. (Photo by Randy Wong.)

In 2018, the NIF laser system set a new facility record, firing 2.15 MJ to its target chamber—a more than 15 percent improvement over NIF's design specification. The achievement is the result of sustained science and technology investment in NIF to realize a fundamental understanding of optical damage and develop the processes to overcome it. "By reaching higher energies, we can enhance the science NIF delivers in support of the Stockpile Stewardship Program," says NIF director Mark Herrmann. "This demonstration serves as the first step on a path that could allow NIF to operate at substantially higher energies than ever envisioned during NIF's design."

NIF Continues to Evolve

Livermore staff has greatly increased NIF's operational efficiency by building on their knowledge of the laser system and the complex interplay of targets, positioners, and diagnostics within the target chamber. Early on, the NIF team had to perform lengthy verification procedures before a single experiment could be executed. This process was needed to ensure the experiment would yield useful data and that it would not result in or lead to subsequent damage to the system. Over time, upgrades such as automation of time-consuming manual activities, an advanced laser alignment system, an integrated suite of online tools, and methods for gleaning more data from a shot, have steadily increased the rate of data generation at NIF.

Between 2014 and 2016, the NIF team achieved more than a 100 percent increase in the number of experiments through efficiency improvements. As an example, the team instituted "mini-campaigns," wherein similarly configured experiments are grouped together to minimize changes between shots. (See *S&TR*, March 2015, pp. 20–22.) Workflow tools were also developed to guide teams throughout an experiment, from proposal submission and project reviews to scheduling and data analysis. In recent years, NIF has conducted about 400 shots per annum. Notably, in 2017, NIF celebrated its 2,000th shot. Additional improvements, such as the Advanced Tracking Laser

Alignment System (see *S&TR*, March 2017, pp. 16–19) and the Target Alignment Sensor now work together to streamline the alignment of diagnostic instrument manipulators with the target, further increasing shot accuracy and repeatability.

Development of advanced diagnostic capabilities is required for measuring and characterizing a broad spectrum of experiments. Experimenters rely on an array of nuclear, optical, and x-ray diagnostic instruments to record vital data from NIF shots at micrometer and picosecond (trillionth of a second) scales. (See *S&TR*, April/May 2018, pp. 21–23; December 2010, pp. 12–18.) More than 90 diagnostic systems are available to experimenters, and researchers develop roughly a dozen target diagnostics each year to support needed measurements. One key addition to the NIF suite of tools is the petawatt-class Advanced Radiographic Capability (ARC) laser, commissioned in December 2015. (See *S&TR*, September 2018, pp. 4–11.) ARC's main purpose is to diagnose complex hydrodynamic experiments and improve the quality of inertial confinement fusion (ICF) implosions. It also serves experiments for the Discovery Science Program that investigate fundamental physics, such as matter–antimatter pair creation.

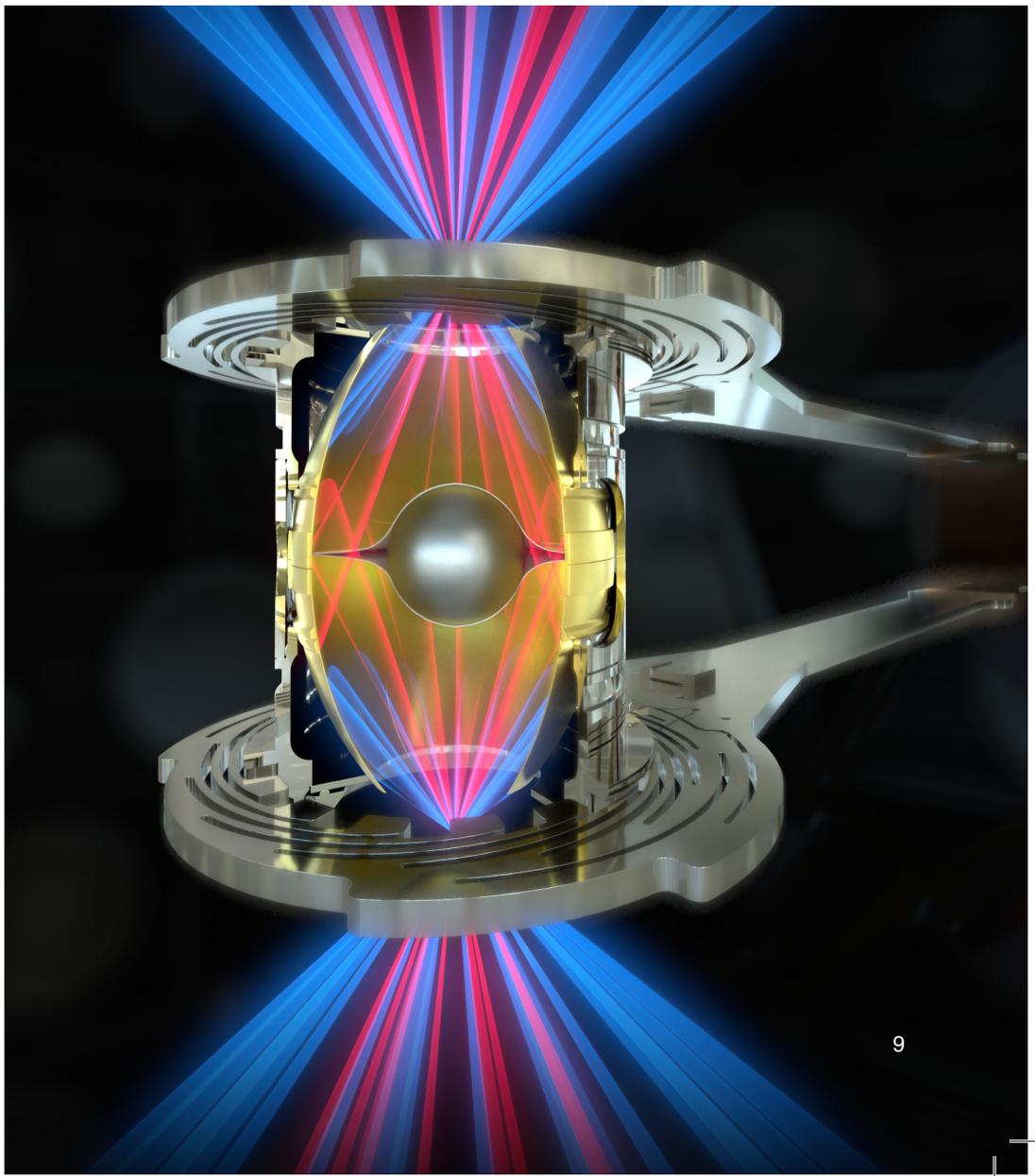
Fusion and Ignition

Over the past decade, ICF experiments at NIF have shown exciting progress and have provided extensive insight into the most viable paths for achieving ignition. As outlined at the beginning of SSP in the 1990s, achieving ignition at NIF is a significant goal, as it will enable the study of important weapons physics issues. In indirect-drive ICF experiments at NIF, a deuterium–tritium (DT) fuel capsule is seated inside a hohlraum, a cylindrically shaped device with open ends. When NIF's laser beams strike the hohlraum walls, a bath of x rays is generated that causes the capsule to implode, heating and compressing the DT fuel into a central hot spot wherein fusion occurs.

Debbie Callahan, the ICF program associate division leader, worked on a series of experiments—called the High-Foot Campaign—to investigate whether changing the laser pulse shape and making some performance concessions would reduce the hydrodynamic instabilities that dampen the fusion reaction in the target capsule. (See *S&TR*, June 2014, pp. 4–10.) Callahan says, "Ignition is a hard, complex problem. If we make one change, that adjustment can affect other aspects of the experiment, for better or for worse." In this case, the tradeoff was worth it, as Livermore scientists demonstrated fuel energy gain—more thermonuclear yield than energy delivered to the compressed fuel by the laser—a major milestone on the path to ignition.

Livermore researchers have been systematically exploring how to maximize the amount of energy that reaches the fuel capsule and implode the fuel symmetrically to achieve higher fusion yields. Options are under study

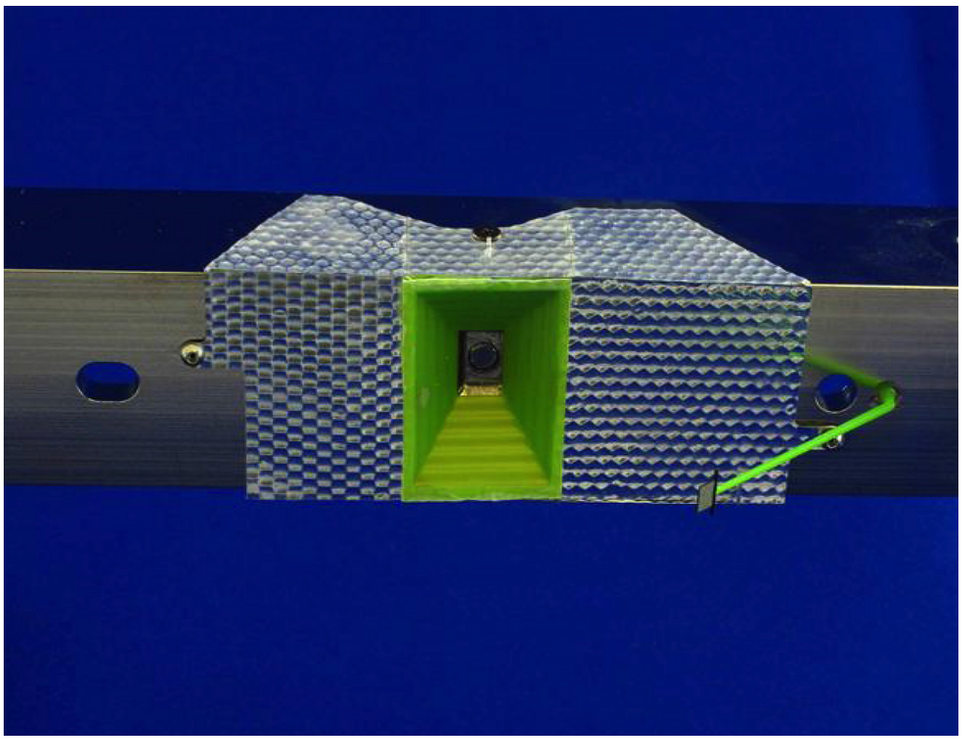
Rugby hohlraums are wide at the center and tapered toward the ends like a rugby ball. This shape is one of several under development for improving the energy efficiency and symmetry of inertial confinement fusion implosions. (Rendering by Jacob Long.)



to improve the design of both the fuel capsule and the hohlraum.

Hohlraums are typically filled with helium gas to help slow the expansion of plasma from the cylinder's walls that interferes with the propagation of the laser beams. However, a high gas concentration increases laser–plasma instabilities (LPI). Thus, some new hohlraum designs feature a much lower helium gas concentration, while others include a specialized foam liner on the hohlraum's inner walls, reducing LPI and increasing the conversion efficiency from the laser energy to x rays. Livermore scientists found that changing the target capsule material to high-density carbon, rather than plastic or beryllium, enabled the most efficient use of the low-gas-density-filled hohlraum while maintaining good implosion symmetry—a key factor for ignition. Reduced radiation loss from the hot compressed fuel, as well as some improvement in symmetry, was also realized by reducing the size of the microscopic fill tube used to transfer the fuel into the capsule from 10 to 5 micrometers in diameter. (See *S&TR,* March 2018, pp. 16–19; January/February 2016, pp. 4–11.)

To provide better control of the plasma or to accommodate a larger fuel capsule, changes to the hohlraum's shape are being explored, such as the rugby hohlraum. This hohlraum shape, which is wide at the center and tapered toward the ends like a rugby ball, may allow for a capsule with a radius about 50 percent larger than usual, exposing more surface area to capture energy.



The TARDIS (Target Diffraction In-Situ) diagnostic package has a tantalum and tungsten target body, which houses the material sample; an x-ray source target mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the sample's x-ray diffraction pattern.

Supporting Our Nuclear Deterrent

All NIF experiments serve SSP, which ensures the safety, security, and effectiveness of the nation's aging nuclear stockpile in the absence of underground testing, by advancing knowledge of HED physics. NIF makes it possible for Livermore scientists to acquire stockpile-relevant data at greater pressures and temperatures than other facilities. The information gathered from NIF experiments also helps improve and validate physics models in simulation codes. Physicist Alan Wan, who leads the Weapons and Complex Integration Principal Directorate's HED weapons-science effort, explains, "HED physics experiments help to assess, design, and provide confidence in the nation's nuclear stockpile today and prepare for the challenges that our country will face in the future."

Information from NIF experiments, combined with existing underground test data and validated computer simulations, are used to make judgments on the stockpile. HED experiments have helped scientists identify important material behaviors and properties that improved understanding of complex phenomena. As an example, NIF experiments contributed to resolving a long-standing issue with energy balance that had plagued weapons physicists for more than 40 years. (See *S&TR*, July/August 2015, pp. 6–14.) A second major success relates to NNSA's complex-wide program to study plutonium under stockpile-relevant, high-pressure conditions. Over more than 4 years, NIF has safely executed 18 experiments for this program.

NIF also supports Livermore's LEPs, which aim to prolong the service life of various nuclear weapons systems. As part of an LEP effort, NIF scientists were tasked with evaluating the efficacy of a material to replace a legacy material whose manufacture posed significant environmental and safety considerations. By adapting an existing HED platform, the NIF scientists successfully assessed the material on an accelerated

timeline—2 years, instead of the typical 5 to 10 years. Wan says, "The HED program has proved its worth in delivering for SSP."

A Universe Brought to Earth

NIF promotes a robust Discovery Science Program in addition to its core national security portfolio. Physicist Bruce Remington, who leads the program, adds, "NIF offers 8 percent facility time, or roughly 18 days per year, to researchers at the Laboratory, in the United States, and abroad to propose open, basic science experiments. The proposals are judged on scientific merit and how well they fit with NIF's capabilities." (See *S&TR*, January/February 2012, pp. 4–11.)

Remington's program receives between 20 and 40 proposals a year, of which roughly 65 percent come from outside the Laboratory. Principal investigators for selected proposals (about a quarter of the time requested) are paired with Livermore personnel, who help them design and conduct successful experiments. Over the years, experiments have delved into a range of fundamental scientific areas, including nuclear reactions under HED conditions; the interiors of planets, stars, and supernovas; and relativistic antimatter–matter plasma energy bursts from black holes. (See *S&TR*, April/May 2016, pp. 12–14.)

Remington views NIF's Discovery Science Program as much more than a way to conduct cutting-edge research. He says, "We attract highly regarded scientists outside of Livermore to engage with us, which keeps a steady flow of new ideas and approaches coming into NIF and helps us establish connections to leading institutions around the world. When we open up the laser to other scientific endeavors, we find ourselves conducting research that is interesting scientifically and overall beneficial—directly or indirectly—to NIF's other core missions."

One such example is the target diffraction in-situ (TARDIS) diagnostic, which was developed to investigate the phase changes between states of matter that occur in materials under pressures and temperatures comparable to those believed to exist in the cores of "super-Earth" extrasolar planets (those that are 3 to 20 times more massive than Earth). Researchers have used TARDIS to quantify the changes in materials' crystal structures as a function of applied pressure, providing clues to planet formation as well as to the exotic behavior of materials at high densities. Refinements made to TARDIS during discovery science experiments have made the platform applicable to its newest use—examining the properties of critical materials for SSP needs.

"We attract highly regarded scientists outside of Livermore to engage with us, which keeps a steady flow of new ideas and approaches coming into NIF and helps us establish connections to leading institutions around the world."

Lighting the Path

Years of dedicated planning, problem-solving, and innovation resulted in NIF delivering the requested capabilities from the start. "The first time we fired all 192 beams at 1 megajoule, the whole system worked," says operations manager Bruno Van Wonterghem, who also led development of NIF's prototype beamline during the preconstruction phase. "We achieved 1.1 megajoules and had good beam quality. The success was an incredible testament to the design, systems engineering, and overall effort."

Looking back over NIF's accomplishments to date, great advances have been made in the areas of target fabrication, optics, and diagnostics, enabling more frequent, varied, and complex experiments to be performed and greater amounts of high-precision data to be collected. The future of NIF includes additional enhancements that will bring increased laser power and diagnostic capabilities, keeping the facility at the forefront of laser science. Jeff Wisoff, principal associate director for the NIF and Photon Science Principal Directorate, is quick to acknowledge the people who make such breakthroughs in capabilities possible. He says, "NIF fundamentally depends upon the talent and skill of a small army of scientists, engineers, technicians, and many other types of support staff from all across the Laboratory and other institutions to address and adapt to current and future challenges."

Other countries are recognizing the scientific and national security payoff that a NIF-sized facility delivers. Large laser facilities designed to challenge NIF's capabilities are being built in other countries, including France, China, and Russia. Their collective goal is similar to NIF's: to understand matter at high-energy densities and obtain fusion ignition. "We must maintain our lead," says Wisoff. "Our plan is to continue to provide NIF with greater capability through investments that give experimenters more precision, more energy, and more power so that we can continue to reach our mission goals in the coming years."

—Dan Linehan

Key Words: diagnostic, Discovery Science Program, high-energy-density (HED) science, hohlraum, ignition, inertial confinement fusion (ICF), laser, megajoule (MJ), National Ignition Facility (NIF), nuclear fusion, Stockpile Stewardship Program (SSP), target, target diffraction in-situ (TARDIS) diagnostic, terawatt.

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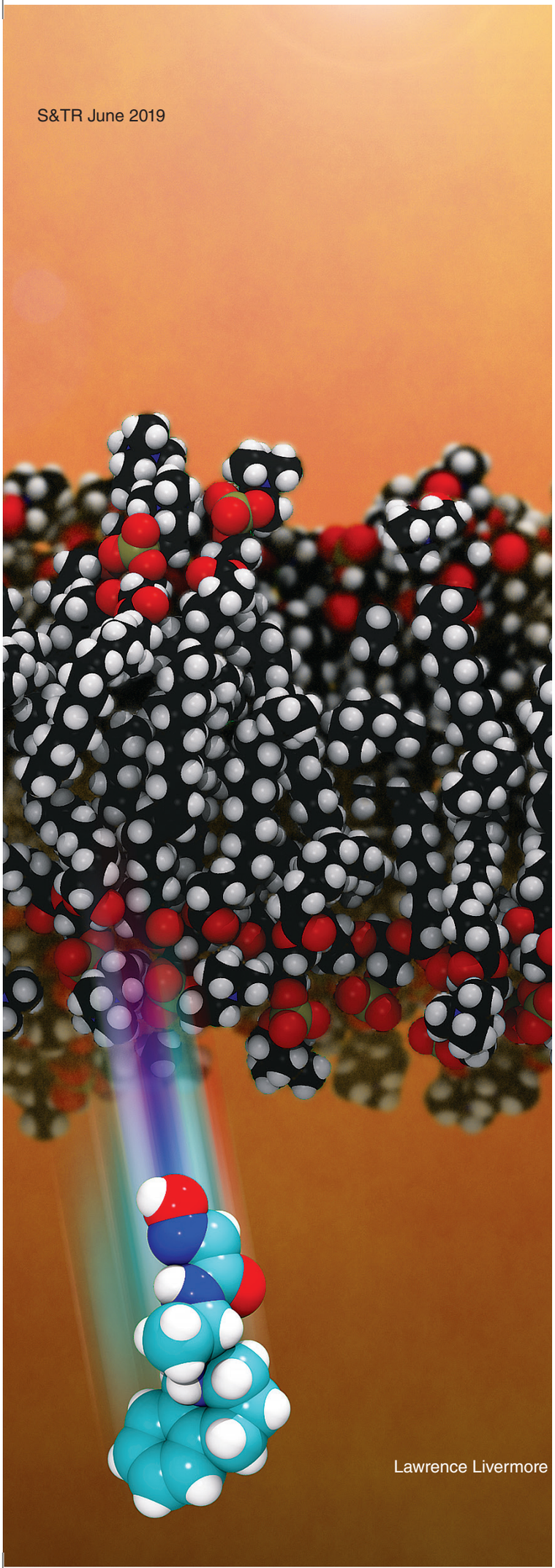
NERVE-AGENT ANTIDOTE SHOWS GREAT POTENTIAL

A model of the blood–brain barrier shows the permeability of three different compounds: 2-PAM (top left), RS194B (center), and LLNL-02 (lower right). Of the three compounds, only LLNL-02 successfully permeates the membrane.



IN the late 1930s, German scientists developing pesticides accidentally discovered a substance that not only effectively killed insects, but inadvertently also affected humans. Named "tabun," this substance, an organophosphate, would eventually be considered the first synthesized nerve agent. In subsequent studies, it proved lethal to animal test subjects—causing death within 20 minutes or less.

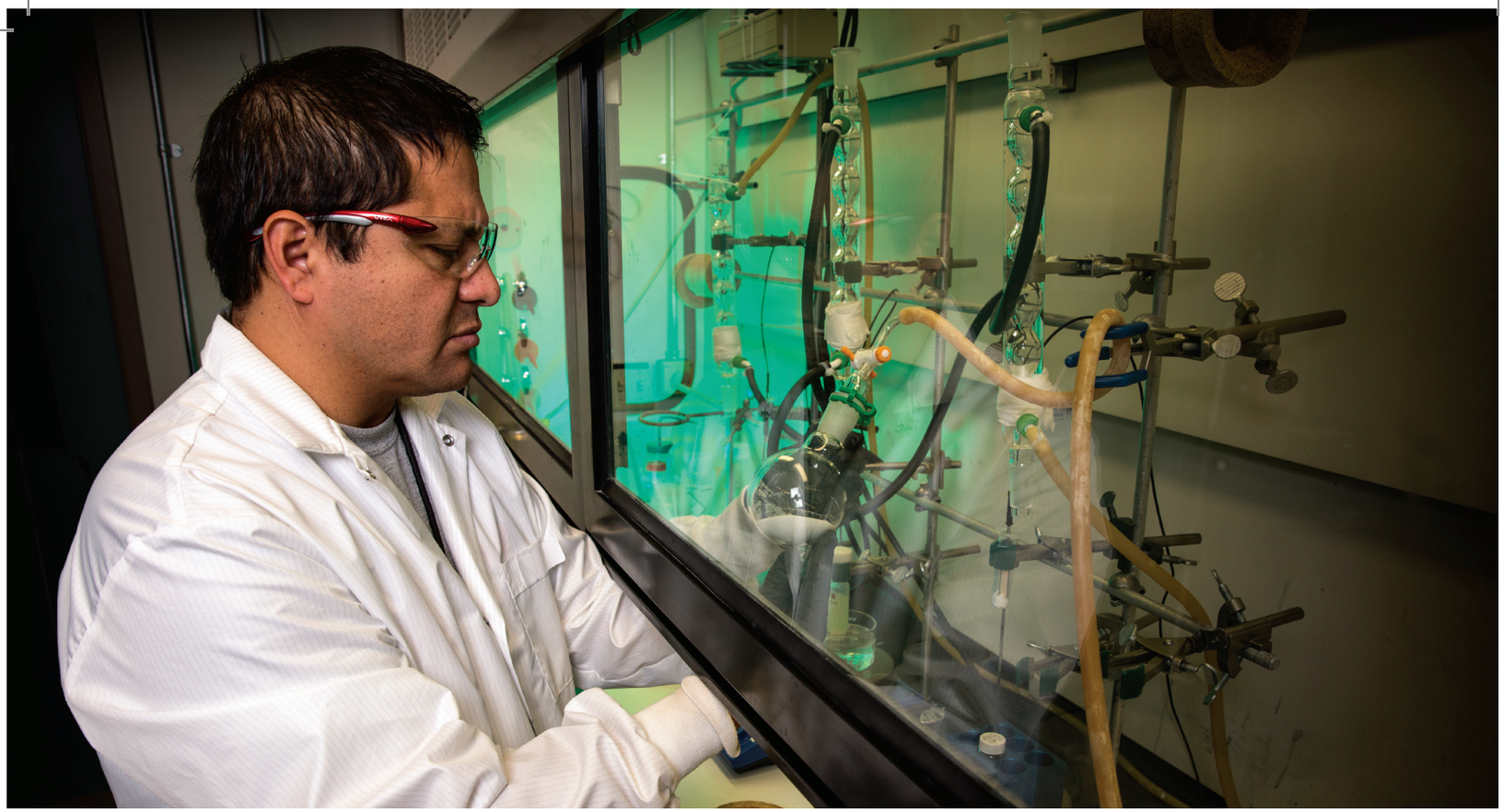
Nerve agents were formally banned by the Chemical Weapons Convention in 1997, but their illicit use has been detected as recently as 2018. To counteract the effects of nerve agents, military forces administer an antidote-injection device known as DuoDote. Similar to the way an epinephrine pen introduces adrenaline to the body, DuoDote simultaneously injects 2-PAM, a drug designed to restore the body's nerve function, and atropine, a medication that minimizes the symptoms of nerve-agent poisoning. The 2-PAM drug successfully reverses the effect of the nerve agent on the body's peripheral nervous system (PNS), but its chemical composition inhibits it from protecting the central nervous system (CNS), specifically the brain. Alarmingly, nerve agents reach the brain rapidly and have long-lasting effects.

A significant challenge for researchers developing nerve-agent antidotes is creating a drug that simultaneously protects both biological systems. Such a drug must be able to cross the semipermeable, protective blood–brain barrier (BBB), which separates the brain's blood supply from the CNS extracellular fluid. In a government-funded effort, scientists at Lawrence Livermore's Forensic Science Center (FSC) and Biosecurity Center (BSC) have formulated molecule LLNL-02, the first molecule capable of this dual protection.

Deconstructing a Nerve Agent

Nerve agents work by interrupting the activities of neurotransmitters in the body. For example, when a human attempts to lift an arm, the neurotransmitter acetylcholine (ACh) present within PNS transmits a signal to the corresponding muscle receptor to trigger that movement. Afterwards, an enzyme known as acetylcholinesterase (AChE) arrives to remove the ACh molecule. Without AChE, ACh molecules build up and cause uncontrolled muscle contractions, spasms, and eventually death. Within CNS, excess ACh degrades neural functions, resulting in conditions such as memory loss.

Nerve agents wreak havoc on the body by deactivating the AChE "cleanup" enzyme. The body is affected almost immediately, and an antidote must be administered within two minutes to halt the agent's physical effects on PNS. However, since 2-PAM cannot penetrate BBB, victims often suffer long-term neurological damage. The BBB membrane comprises a complex lipid bilayer, made up of fatty acid molecules and export proteins, which prevent lipophilic molecules from diffusing across BBB. These export proteins act like gatekeepers for the brain, catching



Chemist Carlos Valdez develops compounds in a synthesis laboratory. (Photo by George Kitrinos.)

any foreign substances and ejecting them back into the body's systemic circulation. In addition, BBB contains tight cell junctions that hinder even small molecules, foreign or not, from permeating the membrane. Thus, an effective nerve-agent antidote must be able to confer PNS protection while simultaneously penetrating CNS to reactivate AChE.

The Path to Antidote Development

Scientists at Lawrence Livermore turned to supercomputers to help tackle the antidote challenge. Timothy Carpenter, a scientist in the Laboratory's Biochemical and Biophysical Systems Group, developed a BBB computer model to simulate the effectiveness of potential antidotes prior to their creation. He explains, "Our organic chemist couldn't afford to waste time making compounds that were not going to work, so we vetted compounds computationally first."

Carpenter and the team used a barrier-crossing compound identified in a study from the University of California at San Diego to inform multiple simulations of potential antidotes. "Essentially, I input the drug molecules into the model and observe their interaction. I do not direct them at all—their movement is informed by physics." The team's focus is two-fold: screening millions of drug activities (a task performed by Livermore scientist Brian Bennion) to see if the antidote counters the nerve agent and assessing the drug's effectiveness at crossing BBB.

Each potential drug requires hundreds of simulations, and each simulation involves 5 quadrillion equations. Remarkably, the Laboratory's supercomputers can model a potential compound's effectiveness in a couple of days, whereas a laptop would take a couple of years to complete the same task. In tandem with computational efforts, lead chemist and project principal investigator Carlos Valdez synthesizes preliminary compounds to build the simulation library. Valdez tests these compounds for BBB permeability and feeds them (successful or not) into the library as a way of both validating simulation results and establishing a baseline of compound effectiveness.

The most successful compounds are iterated and eventually synthesized for thorough in vitro testing. Valdez explains, "Our biochemist Nicholas Be screens synthesized compounds in a lipid-bilayer assay that strongly mimics the blood–brain barrier. Scientists have the extremely difficult task of balancing the molecule's overall lipid content with its activity, as well as making sure the molecule is not intercepted by one of the blood–brain barrier's export proteins. The assays are set up to test these qualities." Adds Valdez, "Size is important here. Small molecules have a much better chance of crossing cell boundaries and reaching their targets than do large molecules." Critical factors such as the administration method and the commercial availability of materials used in the compound are also considered.

In addition to validating permeability and reactivity characteristics, Valdez helps determine if a molecule would

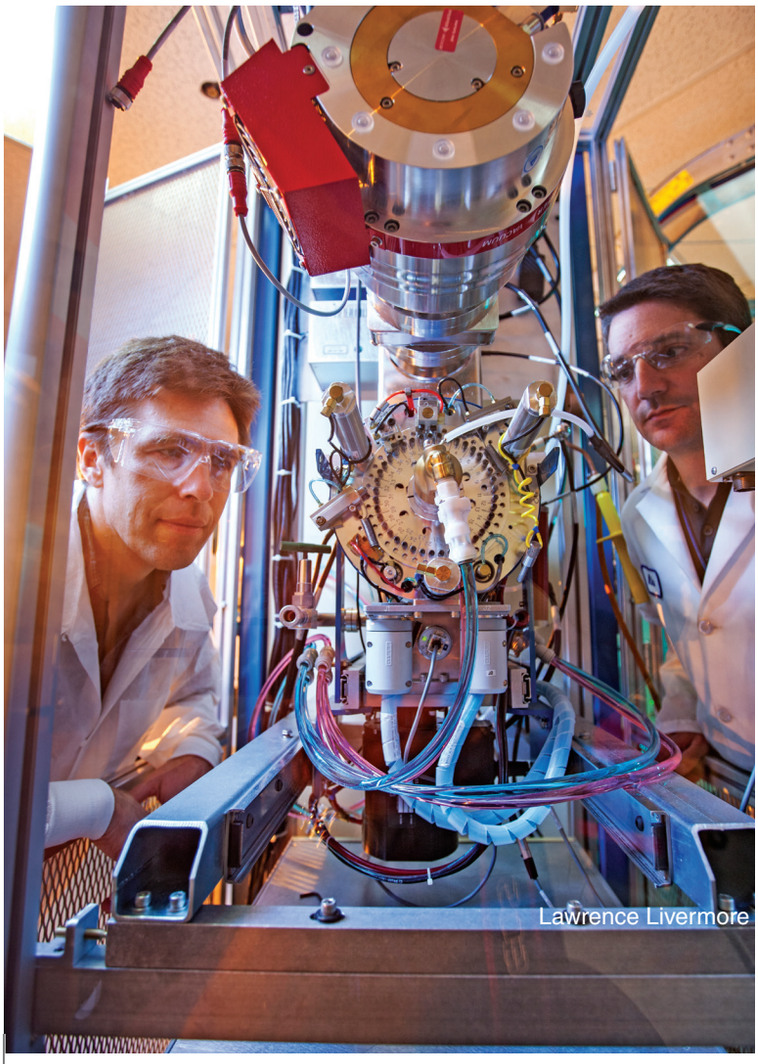
Mike Malfatti (right) and Ted Ognibene use accelerator mass spectrometry to identify carbon-14 in biological tissues. (Photo by George Kitrinos.)

be toxic to humans. In partnership with Livermore colleagues, scientists at the United States Army Medical Research Institute of Chemical Defense run in vitro assays on liver cells to assess potential toxicity, and whether a compound blocks critical ion channels—those involved in heart function, for example. Says Carpenter, "The team's extensive modeling, synthesis, and testing efforts confirmed the potential of LLNL-02, a small molecule. Although LLNL-02 is slightly less active than 2-PAM, it has a much higher effectiveness because 20 times more of it penetrates the blood–brain barrier." All LLNL-02 toxicology results came back clear, allowing the team to move into the final stage of antidote development—in vivo animal testing.

Theory Meets Practice

Livermore biomedical staff scientists Heather Enright and Mike Malfatti led the in vivo animal studies and tested the molecule's pharmacokinetics. Says Malfatti, "During in vivo testing, we look at how the compound is metabolized and excreted. We also look at whether it gets through the blood–brain barrier, if it's toxic, and if it eliminates at a good rate."

During tests, animal subjects are given a dose of the antidote, which is tagged with carbon-14. At predetermined time intervals, tissues from various parts of the subject are collected and quantified using accelerator mass spectrometry (AMS)—a technique that separates carbon-14 from other carbon isotopes in the body. (See *S&TR*, December 2012, pp. 18–20.) "The extreme sensitivity of AMS to detect carbon-14 allows us to identify the antidote in tissues at very low levels with high accuracy. With this technique, we can determine where the chemical goes and how it's metabolized," says Malfatti.



In the next stage of in vivo tests, the scientists administer a nerve agent (in this case, sarin) to the subject, followed by the antidote approximately a minute later—a process that replicates how an antidote would typically be administered in the field. The scientists look for overall survivability and then, within an eight-hour window, they look at the enzymes present in the blood and the brain. "Our primary goal is survivability," explains Enright. "Then, we evaluate whether the antidote is reaching the brain quickly enough to mitigate the negative effects of a nerve agent and whether it reactivates the enzyme. If these initial tests are promising, we'll move onto additional testing to evaluate toxicity and dose refinement," says Enright. Initial in vivo test results for LLNL-02 have been positive, demonstrating that the molecule reaches the brain within five minutes of administration and provides test subjects with a 100 percent survivability rate.

Journey to Field Use

The combined scientific capabilities provided by Lawrence Livermore's supercomputers, AMS instrument, and in vivo testing resources uniquely equip researchers to conduct work relevant to antidote development. Notably, Livermore is the only institution other than the Army cleared to use actual nerve agents during testing. "The ability to use real nerve agents in conjunction with computational simulations and AMS analysis has been incredibly valuable for this effort," says Valdez. In fact, similar techniques are now being applied to other Livermore research endeavors.

The next step for the team, which also includes Edward Kuhn, Victoria Lao, Saphon Hok, and Tuan Nguyen, is continued testing and refinement of the LLNL-02 antidote and identifying a second potential candidate molecule. The team ultimately hopes to get LLNL-02 approved by the Federal Drug Administration (FDA), which would be a first for the Laboratory. "Drug approval by the FDA is a long and arduous process," says Valdez. "It would be a significant, and potentially life-saving, accomplishment."

—Lauren Casonhua

Key Words: acetylcholine (ACh), acetylcholinesterase (AChE), accelerated mass spectrometry (AMS), Biosecurity Center (BSC), blood–brain barrier (BBB), central nervous system (CNS), computer model, Federal Drug Administration (FDA), Forensic Science Center (FSC), LLNL-02 molecule, nerve-agent antidote, peripheral nervous system (PNS).

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AMBASSADOR LECTURE SERIES STRENGTHENS ACADEMIC TIES

AT the heart of Lawrence Livermore's long history of outreach lies the University Relations and Science Education Office, which oversees a multitude of informative programs for everyone from kindergarteners to doctoral students. (See *S&TR*, September 2017, pp. 20–23.) Whereas the younger members of this audience benefit from improved scientific literacy and community commitment, university-targeted outreach directly enhances the Laboratory's employee pipeline and research collaborations. Annie Kersting, the office's director, states, "University relations increase the quality of our research while seeding the workforce. We want to inspire faculty to work with us and encourage their students to do the same."

Since its inception, Lawrence Livermore has been affiliated with the University of California (UC) system, which has served as both a managing entity for the Laboratory and an academic partner. A new program launched by University Relations—the Ambassador Lecture Series—seeks to increase the Laboratory's visibility at UC campuses and build connections with faculty and students. Patricia Falcone, Livermore's deputy director for Science and Technology (DDST), notes, "With this lecture series, the Laboratory is putting its best foot forward and offering an open invitation for collaboration. We benefit from greater visibility of the scientific areas in which we excel, and this program helps us tell the stories of our exciting research and talented staff."

Funded by DDST, a four-ambassador pilot program was launched in 2018, wherein scientific staff were nominated to give invited lectures at all 10 UC campuses (each ambassador visits at least three) showcasing some of Livermore's prominent research investments. This inaugural group of ambassadors included Frank Graziani, director of the High-Energy-Density Science Center; National Ignition Facility (NIF) physicist Tammy Ma; Michael Pivovaroff, who leads the Laboratory's Space Science and Security Program; and Christopher Spadaccini, director of the Center for Engineered Materials and Manufacturing. Working with DDST communications manager Kevin Melissare, these distinguished individuals developed presentations on the Laboratory's work in modeling hot dense matter, ignition experiments, the search for dark matter, and additive manufacturing capabilities, respectively. "Our ambassadors are experienced, senior scientists with a broad viewpoint of their specialty's role in the Laboratory's mission," says Kersting. "We encourage academic engagement in these research areas."

In 2018, the Laboratory's Ambassador Lecture Series began as a pilot program with four scientists and has since expanded to include two more. Pictured here (left to right, standing) are ambassadors Frederick Streitz, Christopher Spadaccini, and Frank Graziani. Annie Kersting (seated) is the director of Livermore's University Relations and Science Education Office, which spearheads the program. (Not pictured: Tammy Ma, Michael Pivovaroff, and Benjamin Santer.) (Photo by Randy Wong.)

Thanks to enthusiastic responses from students and faculty across the UC system, the Ambassador Lecture Series was expanded in 2019 with the addition of two new ambassadors: climatologist and MacArthur Fellow Benjamin Santer and Frederick Streitz, director of the Laboratory's High Performance Computing Innovation Center.

Ambassadors have visited all 10 University of California (UC) campuses, giving presentations to undergraduates, graduate students, and faculty.

From Scholars to Scientists

Students may not intuitively understand a national laboratory's mission or application-driven programs, let alone consider starting a career at one. Likewise, universities do not offer majors in national security or stockpile stewardship and may not approach the application of scientific and technological breakthroughs to real-world problems. Sending scientists to speak to faculty and students is an important way to bridge this knowledge gap, potentially bringing new expertise and competencies to the Laboratory in highly specialized, rapidly evolving fields.

Livermore's lectures are aimed at academic departments, so undergraduates, graduate students, and faculty are all invited to attend. Each ambassador explains the Laboratory's role among Department of Energy (DOE) laboratories and how his or her subject matter relates to national security. The talks then delve into technical content before concluding with a summary of internship and postdoctoral opportunities. As an example, Spadaccini's presentation focuses on the Laboratory's advanced manufacturing capabilities with an overview of architected materials and new material structures. His talk incorporates videos of processes such as large-area projection microstereolithography and computed axial lithography. "Audiences include many graduate students, and the talks have to strike a balance of technical depth and breadth," states Spadaccini, whose presentations to UC engineering and materials science departments have drawn as many as 150 attendees.

Attendees also have the opportunity to meet the ambassadors while they are at a specific campus, either outside the lecture hall or during tours of laboratories or other departmental areas. "Attendees often wait to chat after the presentation, or they contact me later," says Spadaccini. "They want to know all about the Laboratory, and the conversations can become quite technical. Face-to-face interaction and seeing students in their laboratory environments strengthen our ties."

Valuable Connections

A key goal of the Ambassador Lecture Series is to expand Livermore and UC scientific communities beyond existing relationships. Kersting teamed up with June Yu, executive director of National Laboratories Programs at UC National Laboratories, a division of the UC Office of the President (UCOP), to implement the program. Altogether, UC's campuses educate more than 280,000 students on a $36.5 billion annual operating budget. Each campus has its own research focus, collaboration potential, and growth trajectory. Yu, who coordinates the speaking invitations from university departments, says, "We are taking advantage of California's rich academic environment. All UC campuses conduct research relevant to DOE missions."

From the Laboratory's perspective, the connections made through the series help ensure that the best scientific and technological approaches underpin mission programs. Moreover, Ma says, "Livermore's amazing technical work is critical to our nation. Showcasing that aspect is important to knowledge sharing, to demonstrating that we are responsibly stewarding taxpayer money, and to engender support for our mission, as well as to inspire the next generation of scientists and engineers." The lecture series has also allowed Spadaccini to introduce Livermore's newly constructed Advanced Manufacturing Laboratory (AML). (See *S&TR*, March 2019, pp. 12–15.) He notes, "AML is an outward-facing facility with an industry and academic focus. We want UC to have a strong presence there. University partners routinely help us develop our capabilities."

Physicist Tammy Ma, shown here during a presentation at UC San Diego, has explained the National Ignition Facility's scientific advancements to students and faculty at four UC campuses. (Photo by Mingsheng Wei.)

Climatologist Benjamin Santer joined the lecture series in 2019, giving presentations that provide insight into climate modeling and Livermore's contributions to the Intergovernmental Panel on Climate Change's assessment reports.

For scientists, the lecture series introduces them to UC faculty whom they may not otherwise meet. "Ambassadors can build on their own research by collaborating with academic experts in their fields," states Kersting. Meeting students also opens up mentoring opportunities. Graziani adds, "I enjoy working with young people. Their energy level and enthusiasm for science are infectious. I get as excited as they do." Santer hopes to motivate students by sharing the joy of discovery and innovation, noting, "They come to realize science matters and they have a stake in the future. That some young researchers shift their focus to climate science is humbling."

The series also provides professors and students a glimpse of the Laboratory's unique position in advancing both basic science and national security. Attendees gain awareness of real-world applications relevant to California and to the United States. "UC is a significant player in the state's research goals, which overlap with some of Livermore's efforts," says Yu. Furthermore, visiting scientists can help fulfill academic needs beyond classroom instruction by introducing UC departments to large-scale scientific problems, experiments, and user facilities.

Paying Dividends

One year into the program, both Livermore and UC describe the Ambassador Lecture Series as a win–win. Falcone, who has received feedback from representatives of UCOP and the Laboratory's Board of Governors, says, "The response to this new avenue of university-level engagement has been incredibly positive." Graziani notes, "UC faculty have been warm and welcoming, but the best part has been the students. They are eager to learn and enthusiastic."

Ambassadors hear from students interested in applying for internships, and they invite professors to give seminars at Livermore. For instance, Ma hosted UC Davis students for a day, arranging for a career panel and tours of NIF and other facilities. She states, "The UC campuses I visit are incredibly dynamic and filled with enthusiastic students and supportive faculty. We share a common drive for innovation and excellence. Together, this lecture series and our other outreach efforts pay dividends down the road."

For evidence of this enduring effect, one need look no further than the ambassadors. Ma was motivated to study physics after attending the Laboratory's Science on Saturday lecture program. She earned her Ph.D. at UC San Diego and is now the associate program leader for High-Energy-Density Laboratory Physics. Graziani interned at NASA, SLAC National Laboratory, and Fermi National Accelerator Laboratory. He states, "The students we reach out to are future leaders of the national laboratories. I owe my successful career to the many patient mentors I had as a student and postdoc."

Now no longer a trial program, the Ambassador Lecture Series will continue to grow through the addition of speakers and topics, including those that span multiple academic departments. "Future lectures will cover fertile research areas where Livermore and UC overlap. Moving forward, we encourage ambassadors to connect with other colleges and universities," explains Kersting, noting Ma's recent invitation to visit Sacramento State University. Santer, who regularly speaks to campuses across the country, affirms, "A lecture is like a stone thrown into a pond. This simple act can produce positive results we may not be able to foresee."

—Holly Auten

Key Words: additive manufacturing, Advanced Manufacturing Laboratory (AML), Ambassador Lecture Series, climate science, high-energy-density science, National Ignition Facility (NIF), national security, outreach, Space Science and Security Program, University of California (UC).

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TESTING MISSILE TECHNOLOGY ON THE HIGH SEAS

MAKING a high arc southwest over the Pacific Ocean, a Minuteman III test missile with no nuclear materials aboard aims at a point just offshore of a small island in the Kwajalein Atoll. Launched from Vandenberg Air Force Base on the California coast, the warhead detonates just above the water. A little more than a dozen rafts packed with diagnostic instrumentation are waiting in a scattered array around the target area.

Measuring crucial impact parameters, these rafts form the core of the LLNL (Lawrence Livermore National Laboratory) Independent Diagnostic Scoring System (LIDSS). Designed, built, and deployed by a Livermore engineering team, LIDSS is unique in the flight-testing community—assisting the U.S. Air Force and Navy in evaluating the accuracy of intercontinental ballistic missiles (ICBMs) and other conventional delivery systems that are crucial to maintaining a viable U.S. deterrent.

Lawrence Livermore's foremost responsibility is to ensure the safety, security, and effectiveness of the nation's nuclear arsenal. LIDSS helps the Laboratory fulfill this mission, as the collected data are provided to the Department of Defense (DOD) for validating that the missiles carrying the warheads perform to expectations. "Imagine building a car and parking it in a garage for 30 years and then suddenly needing to drive it across the country," says Livermore mechanical engineer Steven A. Jensen. "The question is 'will it work?' We help provide the answer."

A Test of a Stockpile Element

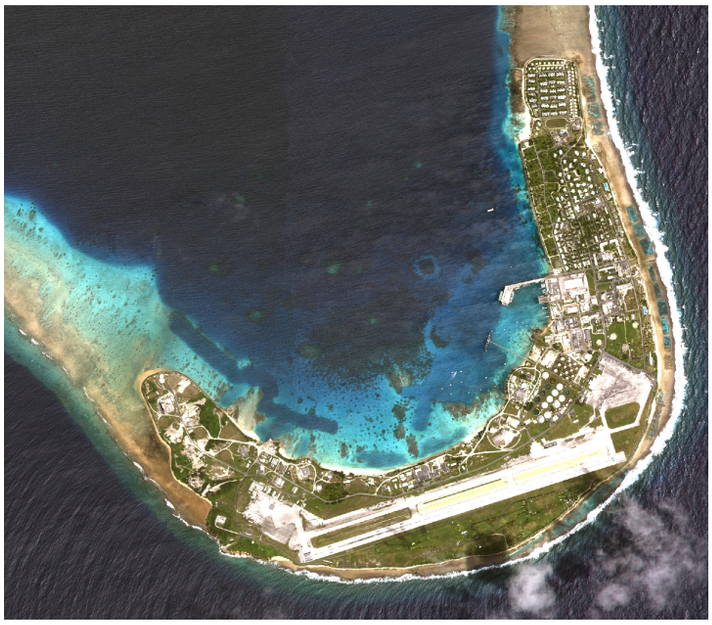
Jensen is the leader of Livermore's Flight Test Group, better known to its DOD customers as the LIDSS team. "Every year, warheads and missiles are randomly pulled from the stockpile as part of system surveillance. The special nuclear material is removed from the warheads and then they are reassembled for flight tests," says Jensen. "We work with the Air Force and Navy to test them. The Air Force, for example, fires three to four ICBMs per year from Vandenberg toward the Marshall Islands. The surveillance program ensures that the systems function as designed and arrive at the designated target area as expected." The Livermore group also works with the Air Force to score cruise missile tests at the Dugway Proving Grounds in Utah. (Cruise missiles fly close to the ground at relatively low constant speeds, while ICBMs such as the Minuteman missile are designed to fly to long-distance targets.) Since 1990, the Flight Test Group has participated in more than 60 missions.

Back in the early days, ICBM tests targeted points on land, and rafts were not needed. Eventually, the targets were relocated to water entry points, and the need for autonomous rafts to carry the diagnostics was born. In addition, LIDSS allowed the Air Force to vary the distance the missiles traveled and adjust the reentry parameters.

In a typical test, a Minuteman III missile travels more than 7,700 kilometers toward the island of Illeginni in the Kwajalein Atoll. As the last of three stages drops off during the missile's trajectory, only the missile bus, carrying the warhead, is left. By design, the warhead spins up after release from the bus and heats up as it enters the atmosphere. Most often the warhead is designed to detonate its high explosives just before it enters the water.

Prior to detonation, LIDSS rafts capture images that aid in assessing such parameters as the warhead height of burst, reentry angle, location relative to target, and other performance criteria. The rafts are outfitted with equipment such as high-speed, streak, and high-definition video cameras, as well as hydrophones, microphones, and telemetry equipment that record key information about the overall performance. LIDSS rafts maintain their position in the water thanks to a global positioning system–based control setup developed by members of the team.

Within two hours of reentry, the Livermore team can provide its DOD customers with a preliminary score of the missile–warhead performance and accuracy. The team then retrieves the rafts, takes the data back to Lawrence Livermore, and provides a more detailed report in the following weeks. Although the performance score was once measured in terms of how close the warhead landed to its target, today it consists of various



(Left) Crew aboard the United States Army Vessel *Great Bridge* lower an LLNL (Lawrence Livermore National Laboratory) Independent Diagnostic Scoring System (LIDSS) raft into the water prior to a flight test. Kwajalein Island (right), which is part of the Kwajalein Atoll in the Republic of the Marshall Islands, is home to U.S. Army Garrison Kwajalein Atoll and the Ronald Reagan Ballistic Missile Defense Test Site. (Image courtesy of USGS.)

The LIDSS rafts at Kwajalein Island await transport to the area where they will gather data during the next test of a Minuteman III missile.

performance indicators from different LIDSS instruments. Says Jensen, "The 'independent' in the LIDSS name stands for the fact that different types of measurements provide an independent check on scoring accuracy and build a more robust picture of a system's performance."

Life on a Remote, Tropical Island

Three or four times a year, Jensen and other members of his group spend 48 hours traveling to the Kwajalein Atoll, one of the largest coral reef atolls in the world. Part of the Republic of the Marshall Islands (RMI) in Micronesia, Kwajalein Island within the atoll is home to U.S. Army Garrison Kwajalein Atoll and the Ronald Reagan Ballistic Missile Defense Test Site. The island base, leased from the RMI government, is populated by more than 1,200 U.S. military staff and contractors. A crescent-shaped reef about 2.5 square kilometers in area, Kwajalein Island is home to a complete community with housing, a post office, a bank, and a modest grocery store, but not much else. "You can bike from one end of the island to the other in about 15 minutes," says Jensen. Biking and walking are the island's primary modes of travel.

A Livermore team deployment to Kwajalein Island usually lasts 18 to 20 days. Setting up a test requires 7 to 10 days, a process that includes preparing the test equipment, evaluating the rafts, and loading them aboard the United States Army Vessel (USAV) *Great Bridge*, an Army landing craft used to transport cargo around the atoll. "Significant planning goes into these tests—for example, where to place the rafts, the diagnostic setup, and camera coverage. Extensive preparation is done before leaving on the mission and for setting up all the mission logistics," says Jensen.

USAV *Great Bridge*, with several Livermore team members aboard, sails to ocean test sites near the island of Illeginni, which is about 48 kilometers from Kwajalein Island. The ship lays out

the LIDSS rafts at the test-site location and then sails at least 16 kilometers away to a safe position during vehicle reentry.

Many things can happen during the setup for a test beyond uncooperative equipment, including weather delays. During a 2015 mission targeted to an area of open ocean far from any land (referred to as broad ocean area or BOA), the Navy mobile instrumentation ship, tasked with delivering the LIDSS rafts, encountered a tropical storm on the way to the test site and then had to ride out a super typhoon on the way back. Delays can also happen when civilian ships, such as fishing vessels, pass too close to the reentry point for their safety, necessitating a hold on the test until they leave the area.

Eventually, a missile flies, measurements are taken, and the USAV *Great Bridge* sails back into the area to collect the rafts. The conclusion phase lasts three or four days while equipment is disassembled and stored before the team flies home. Livermore team members can be aboard the vessel during these BOA missions for as long as two weeks.

Enhancing LIDSS with Drones

As DOD begins to develop hypersonic delivery systems for conventional weapons, the demand for LIDSS continues to increase. "Originally, we developed this capability primarily to support the nation's nuclear weapons community," says Jensen. "However, our capabilities also cater well to the conventional side." Over the next several years, the Flight Test Group, currently about a dozen members in size, will grow to meet the needs of its customers.

Jensen and his colleagues are also working to add new technologies to LIDSS. For example, the team is looking to expand LIDSS diagnostic vehicles to include drones, which are smaller, nimbler, and more cost-effective than the rafts. These devices would be used to augment the existing raft fleet on key missions. Jensen says, "The rafts provide a nice platform from which to field diagnostics. We are always looking to leverage current technology to provide even more data for our customers."

—Allan Chen

Key Words: drone, hydrophone, Illeginni Island, intercontinental ballistic missile (ICBM), Kwajalein Atoll, LLNL Independent Diagnostic Scoring System (LIDSS), Minuteman III, Republic of the Marshall Islands, stockpile stewardship, telemetry.

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The reentry of a Minuteman III missile without its nuclear package—launched from Vandenberg Air Force Base in California—occurs near Illeginni Island in the Kwajalein Atoll.

Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven- or eight-digit number in the search box at the U.S. Patent and Trademark Office's website (http://www.uspto.gov).

Patents

Techniques for Release of Material into an Environment
William C. Floyd, III, Roger D. Aines, Eric B. Duoss, John J. Vericella
U.S. Patent 10,207,001 B2
February 19, 2019

Additive Manufacturing of Semi-Solid Metal Alloys Using Ultrasonic Agitation
Andrew J. Pascall, Eric B. Duoss, Ryan M. Hunt, Joshua Kuntz, Christopher M. Spadaccini, John Vericella
U.S. Patent 10,207,317 B2
February 19, 2019

Highly Crystalline 3D Graphene
Marcus A. Worsley, Leta Woo, William Mickelson, Alex Zettl
U.S. Patent 10,233,087 B2
March 19, 2019

Hemorrhage Management System
Duncan J. Maitland, Todd Lawrence Landsman, Tyler Joseph Touchet, Elizabeth L. Cosgriff-Hernandez, Thomas S. Wilson
U.S. Patent 10,265,433 B2
April 23, 2019

Bi-Directional, Transformerless Voltage System
Stephen E. Sampayan
U.S. Patent 10,270,368 B2
April 23, 2019

Broad Band Half Vivaldi Antennas and Feed Methods
David M. Benzel, Richard E. Twogood
U.S. Patent 10,276,946 B2
April 30, 2019

Awards

The **National Nuclear Security Administration** (NNSA) has awarded **John Nasstrom**, Lawrence Livermore's chief scientist for the National Atmospheric Release Advisory Center, with the **NNSA Administrator's Distinguished Service Gold Award**. Nasstrom was recognized for his service to U.S. national security, particularly in the areas of atmospheric dispersion modeling and incident response. In part, Nasstrom's award citation reads, "For leadership, technical excellence, and impact in the efforts of the Office of Nuclear Incident Response to manage the consequences associated with the release of hazardous material into the atmosphere and mitigate the nuclear threat."

Research scientist **Paul Durack** from Livermore's Program for Climate Model Diagnosis and Intercomparison has been awarded the **World Climate Research Programme** (WCRP) **2018 Data Prize** for his leadership of the input4MIPs (input data sets for Model Intercomparison Projects), which began in 2016. The prestigious WCRP prize is awarded annually by the prize committee, which consists of representatives from the Global Climate Observing System, Atmospheric Observation Panel for Climate, Terrestrial Observation Panel for Climate, and the Ocean Observations Physics and Climate Panel, for an outstanding contribution to data product generation, data management, data preservation, data monitoring, and other data-relevant activities by an early- to mid-career researcher. Durack received the award for his strong professional portfolio and the outstanding quality of his contributions to the development of documented climate data sets.

Lawrence Livermore and three Laboratory employees—**Charity Follet**, **Candice Gellner**, and **Quentin Vaughan**—have garnered the **"Best in Class" Award** from the **Department of Energy's** (DOE's) **Technology Transfer Working Group** (TTWG) for their innovation in partnering to develop the four-institution Accelerating Therapeutics for Opportunities in Medicine, or ATOM, consortium. The goal of the ATOM consortium, which includes Lawrence Livermore, the pharmaceutical firm GSK, the National Cancer Institute's Frederick National Laboratory for Cancer Research, and the University of California at San Francisco, is to create a new paradigm of drug discovery that would reduce the time from an identified drug target to clinical candidate from the typical six years to one year. The TTWG awards, which were inaugurated this past year, are selected by a team of representatives from the national laboratories and the DOE Office of Technology Transitions.

The online high-performance computing (HPC) news publication ***HPCwire*** has named Lawrence Livermore's **Lori Diachin**, the Computing Directorate's deputy associate director for science and technology, as one of its **"People to Watch"** in 2019. The honor recognizes key people who are likely to propel the HPC industry forward in the coming year. Diachin was one of 12 people honored by the publication.

Over the past 16 years at the Laboratory, Diachin has held several leadership roles including the director for the Center for Applied Scientific Computing and director for the Department of Energy's (DOE's) HPC4Manufacturing and HPC4Materials programs. In 2018, Diachin took over the role of deputy director for DOE's Exascale Computing Project (ECP), which involves 15 DOE laboratories, numerous university partners, and more than 1,000 researchers. Her primary focus over the next year will be preparing for a critical ECP review that will set the technical baselines for the remainder of the project.

Abstract

National Ignition Facility Celebrates 10 Years of Operation

Twenty-five years ago, the Department of Energy formed the science-based Stockpile Stewardship Program (SSP) to maintain the safety, security, and effectiveness of the U.S. nuclear deterrent in the absence of underground nuclear testing. To meet this challenge, Lawrence Livermore leveraged its decades-long expertise in laser development and inertial confinement fusion to establish the National Ignition Facility (NIF)—the most energetic laser in the world. A decade after the facility's commissioning in 2009, NIF continues to enable the Laboratory to achieve its mission objectives by offering unparalleled laser performance and precision. Every year, researchers conduct experiments at NIF that are essential to SSP. In doing so, they advance national security and the field of high-energy-density science. They also enable advances in astrophysics, planetary physics, hydrodynamics, and materials science. Over the last 10 years, Livermore scientists and engineers have driven significant enhancements to NIF operations and experimental capabilities. Such advances have dramatically improved the facility's performance, operational efficiency, shot rate, and data collection processes. An ever-expanding list of target and diagnostic platforms in addition to continued efficiency gains set the stage for NIF to advance scientific discovery further into the 21st century.

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Working toward a New Carbon Economy

Livermore's Carbon Initiative aims to understand, develop, and implement technologies for removing carbon dioxide from the atmosphere.

Also in July/August

• From astrophysics to energetic materials, data analysis and interpretation techniques play a vital role in advancing fundamental science.

• At the National Ignition Facility, a specialized team assesses the risk of damage from target debris and shrapnel dispersal during high-energy laser shots.

• A new design for diamond anvil cells puts the extreme squeeze on materials of interest for physicists and stockpile scientists.

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