Lawrence Livermore National Laboratory

Science & Technology Review

December 2022

W87-1 INVIGORATING the Enterprise

Also in this issue:

About the Cover

The W87-1 Modification Program presents a complex, transformative technological and programmatic challenge. As the feature article beginning on p. 4 describes, researchers at Lawrence Livermore are cultivating dynamic partnerships across the Nuclear Security Enterprise to innovate materials development, manufacturing techniques, and modeling and simulations to deliver and certify the first newly manufactured warhead in 30 years without the need for additional underground nuclear testing.

Cover design: Mary J. Gines

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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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NNSA
National Nuclear Security Administration

LAWRENCE LIVERMORE NATIONAL SECURITY LLC

Prepared by LLNL under contract DE-AC52-07NA27344

Science & Technology REVIEW

December 2022

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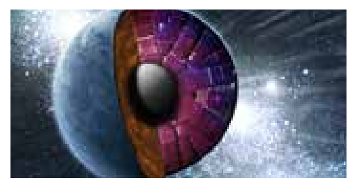
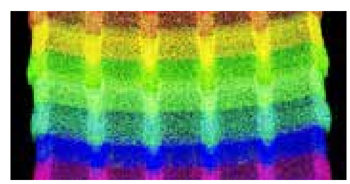
Contents

Feature

Research Highlights





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S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Planning and Special Studies.

S&TR is available on the Web at str.llnl.gov

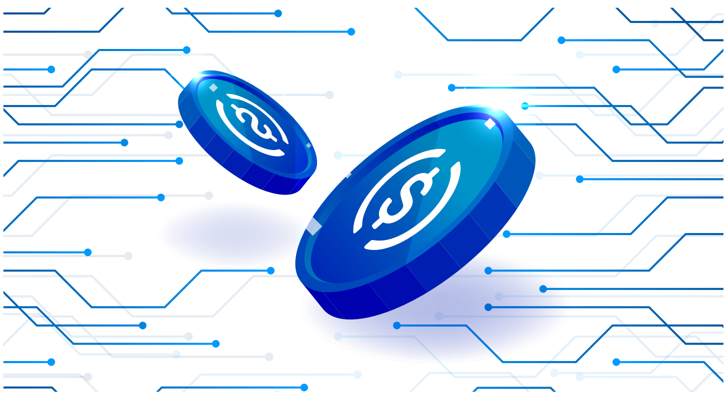
Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-22-12
Distribution Category UC-99
December 2022

Electricity-Collateralized Blockchain Technology

Lawrence Livermore researchers have conceived of a physics-based cryptocurrency that could one day transmit electricity in addition to information. Their "Electricity-Collateralized Stablecoin," or "E-Stablecoin," represents the first blockchain concept to be both fully decentralized and collateralized by a physical asset–in this case, electricity. Unlike other cryptocurrencies, energy is not consumed following transaction; instead, the currency can be "burned" to redeem its associated energy input.



Livermore researcher Maxwell Murialdo explains the innovation linking financial and energy transfer: "Any anonymous party can mint an E-Stablecoin token with the input of roughly one kilowatt-hour of electricity. They can then transact with the digital token like any other cryptocurrency, or even turn it back into usable electricity—all without the need for electrical power companies, electrical transmission lines, permissions, or authorities. It is a trustless system from top to bottom."

At present, E-Stablecoin provides a theoretical proof of concept for potential blockchain technologies. Looking forward, minting E-Stablecoin using, for instance, the ambient temperature in a warm location and redeeming it in a cooler location would effectively create a remote heat engine. Similar principles could eventually be exploited to distribute electricity to areas lacking requisite infrastructure or to intermittently channel renewable energy across the power grid to maintain efficiency in the face of climate change.
Contact: Maxwell Murialdo (925) 422-2577 (murialdo1@llnl.gov).

Developing Responsive Materials

Livermore researchers have created responsive, architected materials that react to changing environments. According to their paper, published June 20, 2022, in *Nature Reviews Materials*, the materials are highly programmable, meaning their reactions to different stimuli can be preset during fabrication. Staff scientist and lead author of the study Xiaoxing Xia explains, "Architected materials… can respond to various forms of stimuli—be it mechanical, thermal, electromagnetic, or chemical—and transform their shape, change properties, or navigate autonomously."

Classical materials exhibit dynamic properties—for example, phase transition—at naturally occurring thresholds; applying processes of heating, chemical reaction, and / or physical deformation permanently alters these properties until another process occurs. Architected materials "are not stagnant after fabrication," says Xia. Using computational logic and machine learning, architected materials can be structurally encoded to respond in unique ways under specific conditions.

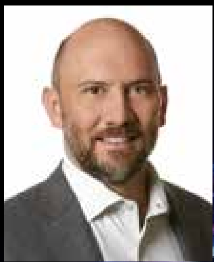
Potential applications utilizing these responsive materials are vast. Programmable, adaptable form and function is highly advantageous in embedded medical devices and drug delivery. Other uses include secure information storage and performing inference or recognition tasks. "The burgeoning research space raises fundamental questions about the future of technological development: logical, transformable, and autonomous structures will lead researchers to reevaluate standard definitions of agency and sentience," says Xia.
Contact: Xiaoxing Xia (925) 423-6489 (xia7@llnl.gov).

High-Power, Solvent-Free 3D-Printed Lithium Batteries

Lawrence Livermore has partnered with American electrolyte materials company Ampcera, Inc., to develop next-generation lithium–ion battery fabrication methods. The selected technique would allow for 3D-printed batteries featuring greater energy and power densities than feasible using current means. Lead investigator Jianchao Ye explains that the team plans to adapt the process of laser powder bed fusion—originally conceived for 3D printing small-scale metal parts—to produce 3D-structured lithium battery cathodes without the use of solvents. "The environmentally benign process allows for thick, high-capacity 3D-cathode structures to be processed, enabling lithium–ion batteries to charge up to 80 percent in 15 minutes or less," says Ye.

The additive manufacturing method will thermally bind mixtures of cathode powder onto the aluminum current collector to produce unique battery architectures with heightened performance. Using a laser-powered process avoids the use of harmful solvents that are routinely employed in the standard battery manufacturing technique of slurry casting and coating. In light of significant advantages in efficient and clean energy storage offered by the venture, the project has received $1.5 million in funding from the Advanced Manufacturing Office of the U.S. Department of Energy (DOE). The effort is one of a host of DOE-funded projects that support domestic-energy resilience while minimizing environmental impact.
Contact: Jianchao Ye (925) 423-6696 (ye3@llnl.gov).

Commentary by Brad Wallin



Science and Technology on a Mission for the Future

As we celebrate the Laboratory's 70th anniversary, it is an excellent time to appreciate the incredible contributions we are currently making to support the U.S. nuclear deterrent and to strengthen U.S. security through the development and application of world-class science and technology. Our adversaries are developing and deploying new technologies and capabilities that underscore the need for the United States to aggressively execute its stockpile modernization efforts as well as re-establish its production infrastructure for all nuclear weapon components.

Building on the design, reuse, and manufacturing innovations identified by the W80-4 Life-Extension Program, the W87-1 Modification Program, featured in the article beginning on p. 4, will produce the first 100 percent newly manufactured nuclear warhead since the end of nuclear testing in 1992. It will replace the aging W78 warhead, meet military requirements, and improve safety and security. As a lead design agency for these two systems, we are finding that our efforts are also transforming the Nuclear Security Enterprise in important, lasting ways.

The changes we are making to the W87-1 are possible due to the unique, diverse tools of science-based stockpile stewardship, allowing the new warhead to be confidently certified without nuclear testing. We are using high-performance computing and calculations in innovative ways and will be among the first to leverage our new exascale supercomputer, El Capitan. Recent results from the National Ignition Facility promise to increase the fidelity of extreme-condition experiments to provide certification data. We are also pursuing innovative, transformational partnerships across the Nuclear Security Enterprise to introduce new materials, manufacturing techniques, and processes to meet W87-1 and future stockpile systems requirements.

The three research highlights in this issue examine how scientists and engineers are also utilizing the Laboratory's unique, diverse tools to produce unprecedented findings, generate novel materials, and explore the potential impacts of emergent technologies.

As part of the National Ignition Facility Discovery Science Program, scientists have performed a series of 12 experiments over the past three years to understand the properties of iron under the extreme conditions in the core of massive terrestrial planets. Previous theoretical predictions and extrapolations from relatively low-pressure data generated in laboratory settings were used to predict iron properties at extreme conditions. The highlight starting on p. 12 describes how this recent set of experiments presented the first opportunity to collect data on melting and crystallization of molten iron in the extreme conditions that approximate those at planetary cores.

The highlight beginning on p. 16 describes a three-year exploratory research project funded by the Laboratory Directed Research and Development Program that shows, for the first time, that 3D biomaterials with embedded microbes can be printed using additive-manufacturing techniques. The Laboratory's combination of bioengineers possessing unique understanding of bacteria and microbiology and access to sophisticated 3D-printing systems make the Laboratory one of the few places capable of advancing this technological breakthrough with a range of potential applications, including remediating hydrocarbons, recovering critical metals, and serving as chemical biosensors.

Finally, the Laboratory's Center for Global Security Research (CGSR), with its exceptional ability to tackle questions at the intersection of technology, national security, and public policy, has positioned Livermore to take a lead role in creating and developing the emerging field of strategic latency—the inherent potential for technologies to bring about significant shifts in the military and/or economic balance of power. As described in the highlight on p. 20, CGSR has brought together a diverse stakeholder community to explore how emerging technologies will affect national security and transform our understanding of deterrence 10 to 20 years from now.

Delivering on the W87-1 and making lasting transformation for the enterprise will require the expertise and extraordinary dedication of our workforce. Their efforts inspire me to do all I can to help enable the changes that are necessary to deliver the nation's nuclear deterrent and science and technology on a mission for today and the future.

■ Bradley K. Wallin is principal associate director for Weapons and Complex Integration.

W87-1

The Modification that Invigorated an Enterprise

Lawrence Livermore will deliver the first newly manufactured nuclear warhead in three decades, which will replace the aging W78, meet military requirements, improve safety and security, and transform the Nuclear Security Enterprise through innovative collaborations.

WHEN the Cold War ended, so too did nuclear testing and the need for ongoing nuclear weapon design and production. In the ensuing decades, the U.S. stockpile of nuclear weapons aged beyond its designed service life, and the national laboratories were tasked with conducting Life-Extension Programs (LEPs) to refurbish existing designs and reuse existing parts to the maximum extent possible. Because of the nature of LEPs, key production technologies were allowed to atrophy or disappear completely from the Nuclear Security Enterprise (NSE). The W87-1 Modification Program is reinvigorating and transforming the production complex such that NSE can once again produce all of the components typically required for modern nuclear warheads. This work will give the nation expanded options for maintaining an effective nuclear deterrence posture for decades to come.

The W87-1 Modification Program marks the first time since the end of the Cold War that the nation's NSE will be putting a 100 percent newly manufactured nuclear warhead into the stockpile. "For decades, nuclear deterrence has been foundational to U.S. national security, enabled by our ability to field innovative solutions on relevant timescales," says Laboratory Director Kimberly Budil. "Over the last two decades, our adversaries have rapidly modernized and expanded their nuclear capabilities, while the U.S. lost its ability to manufacture critical warhead components as facilities aged and capabilities atrophied without a consensus on the path forward. The W87-1 Modification Program changes that. Relearning to design, engineer, and produce a warhead presents a tremendous challenge, but we are working side-by-side with our partners to deliver for the nation and transform the Nuclear Security Enterprise in multiple critical areas."

As the design agency for the nuclear explosive package for the W87-1, Lawrence Livermore researchers are spearheading new partnerships to innovate materials development and manufacturing techniques. They are leveraging decades of advances in science and engineering to certify the first newly manufactured warhead without conducting a nuclear test. Laboratory researchers benefit from concurrent work on the W80-4 LEP, which began before the W87-1. "The W80-4 LEP kick-started the modernization process and has had significant ramifications in terms of skills, materials development, workforce training. It's been challenging, but we've learned a lot and developed first-of-its-kind protocols and standards. The W87-1 came in right behind, and thanks to the W80-4, we're hitting the road running," says Derek Wapman, deputy principal associate director for stockpile modernization. "U.S. warheads were designed and manufactured until the late 1980s and early 1990s," says Juliana Hsu, Livermore physicist and W87-1 program manager. "Since then, we have not designed any new nuclear components. When the warheads needed repair, we remanufactured the existing designs and reused components that we were not able to manufacture. That's no longer an option. For the W87-1, every part will be newly manufactured using well-established design knowledge. W87-1 requires different thinking, different problem solving, and close collaboration with the production agencies to construct entirely new components. W87-1 also requires training a new generation of weapons designers and engineers."

Subject matter experts from the Kansas City National Security Campus and Lawrence Livermore work together to hone production processes at the Polymer Production Enclave in Livermore. (Photo by Garry McLeod.)

Rewriting the Playbook

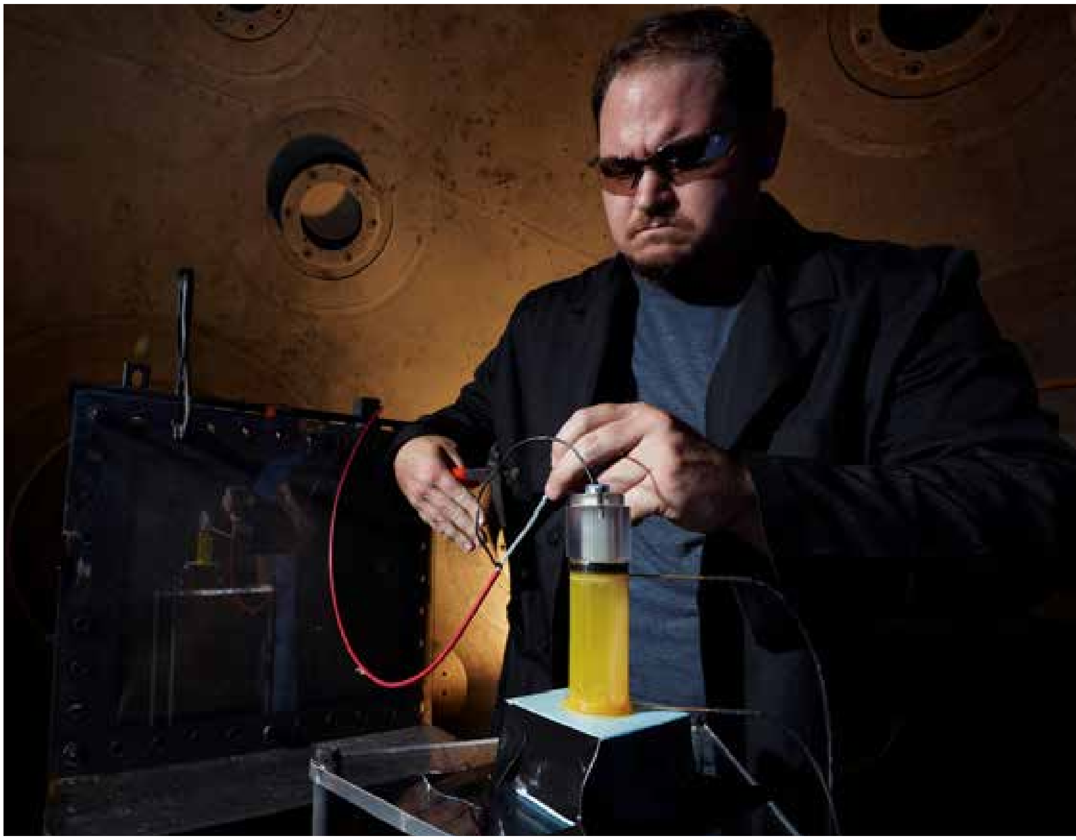
Building on the progress of past LEPs, the design and production agencies—Lawrence Livermore and Sandia National Laboratories (SNL)—and the production agencies—Los Alamos National Laboratory (LANL), Savannah River Site (SRS), Kansas City National Security Campus (KCNSC), Y-12 National Security Complex, Pantex Plant, and key NNSA material supplier—Holston Army Ammunition Plant—are collaborating more closely than ever. This includes enhancing the integration across National Nuclear Security Administration (NNSA) to establish appropriate project controls. Strong partnerships with the U.S. Air Force, Lockheed Martin, and Northrop Grumman are key to having a reliable deterrent based on the Sentinel intercontinental ballistic missile and the Mk21A reentry vehicle that will deliver the W87-1 warhead.

"As the design agency for the W87-1 nuclear explosive package, our responsibility is to make sure our designs meet the Department of Defense (DOD) requirements for safety, security, reliability, and nuclear yield. The production agencies are responsible for making the parts. Lawrence Livermore could design amazing parts, but if the production agencies can't make them, it's moot, so we work collaboratively with the production agencies to ensure our designs are manufacturable so that we can ultimately deliver the system," says Alicia Williams, W87-1 project engineer.

Over the past few decades, scientific and engineering communities have made significant progress in the area of materials science and technology. The Laboratory has been at the forefront of some of these advances and has been actively leveraging new materials science and associated engineering know-how to develop new materials and production methods to support the NSE. "In the past, design agencies might throw drawings over the fence to the production agencies and assume they could manufacture the parts," says Peter Raboin, W87-1 deputy program manager at the Laboratory. "It's too easy, however, to design 'excellent' parts that can't be manufactured. We are rewriting the playbook with our production partners by collaborating on the creation of designs optimized for manufacturing the W87-1 components. We're constantly in contact with our collaborators across the enterprise."

A good example is the development of additively manufactured polymer components for the stockpile, which began in the early 2000s with a handful of Laboratory Directed Research and Development (LDRD) projects to support high-risk, high-potential-reward additive-manufacturing (AM) techniques. As these short-term LDRD projects ended, some approaches showed promise for NNSA-funded programs at the Laboratory to further explore the technology.

Inks or feedstocks were developed and optimized to offer desirable properties at the molecular level for use in modern AM machines. Completely new capabilities were developed to efficiently determine how the ink can be deposited to produce unique components providing the necessary macroscopic properties. Computational scientists developed models to predict how variables would impact performance at the part and system levels. In addition, in situ spectroscopy was applied to scan each layer of an object as it was printed, allowing for real-time assessments of part integrity and performance. By the time the W80-4 LEP was underway, AM had matured enough for stockpile use and the concept for a Polymer Enclave materialized.



Senior explosives handler Anthony Olson crimps a shot wire to a firing cable to prepare for an explosives test inside the spherical tank at Lawrence Livermore's High Explosives Applications Facility. (Photo by Garry McLeod).

The Polymer Enclave is a new approach to taking a polymer-based design from concept to realization via a joint effort between Lawrence Livermore and KCNSC. Both sites have procured the same AM equipment and have essentially the same work environment. Close integration of the design, development, and production teams from Lawrence Livermore and KCNSC are central to the effort to advance the technology and accelerate iterative loops that optimize both component performance and manufacturability. The Polymer Enclave came online in early 2022 to support the W87-1 Modification Program and provide necessary development hardware for some of the nuclear components. (See *S&TR*, November/December 2021, pp. 12–15.) "The enclave concept is a remarkable example of a collaborative commitment to innovation through partnership," says Raboin.

Lawrence Livermore and Pantex Plant—the Department of Energy (DOE) and NNSA's primary facility for the final assembly, dismantlement, and maintenance of nuclear weapons—northeast of Amarillo, Texas, are also exploring novel technologies to develop reliable high-explosive parts, some of which could reach maturity for inclusion in the W87-1 Modification Program. Similar to polymers, these high-explosive technologies have been researched and developed over the past decade, and a new Energetic Materials Development Enclave has been established. To support this collaborative effort, new facilities have been constructed at Lawrence Livermore's Site 300. (See *S&TR*, August 2021, pp. 16–19.)

The Laboratory is also working closely with DOD's Holston Army Ammunition Plant, in Kingsport, Tennessee, which supplies the NNSA with explosive materials, to perfect the insensitive high explosives that will serve as the main charge for the W87-1. "It's an old recipe, but the equipment has changed," says Raboin. "We learned with the W80-4 that explosive properties were specific to the equipment. Mixing tank sizes and types during the Cold War were different than the tanks available today. The difference in tank geometries changes stirring patterns, which in turn, alters the crystalline morphology and the properties of the explosives." Researchers have been modeling newer synthesis processes and conducting experiments at Lawrence Livermore's High Explosives Applications Facility (HEAF) to hone explosive behavior models, which inform product requirements and specifications for the production agencies. "I support the product realization team in their mechanical properties work, specifically with establishing an experimental capability for essential testing," says Rowan Baird, an early career mechanical engineer and high-explosives mechanical properties lead at HEAF. Working with stakeholders across the enterprise, communication is both essential and challenging. "I have to ensure the message I'm communicating is received by all the parties and take all areas of concern into consideration. I'm listening and thinking from a variety of perspectives," says Baird.

The Y-12 National Security Complex in Oak Ridge, Tennessee, focuses on processing and storing uranium and is responsible for producing the components for a nuclear explosive package. The W87-1 team in Livermore is working closely with Y-12 to modernize technology and production methods for manufacturing components more efficiently. One example is the installation of an electron-beam cold-hearth melter (EBCHM)—a machine that can melt various metals—in Tennessee so that Y-12 personnel can work directly with the new technology. The EBCHM has the potential to improve materials usage, reduce waste, and shorten the time for producing metal ingots. "By working collaboratively, the joint Livermore and Y-12 material team is able to test and rapidly mature the EBCHM technology, with the goal of making it a standard production method for some key stockpile components across the National Security Enterprise," says Tom Goodrich, W87-1 design lead responsible for overseeing product development.

Y-12 and Lawrence Livermore are also partnering on a key innovation that the W87-1 is introducing into the stockpile. Some of the materials used in Cold War weapon systems are hazardous and no longer producible in the modern safety environment. In the case of one particularly toxic material, Lawrence Livermore researchers invented an alternative that provides nearly the same material properties without the health hazards for workers. Researchers at the Laboratory have also developed a manufacturing process using a massive hot press to turn this new material into the needed weapon component. Y-12 has fielded a similar hot press, and a joint Livermore–Y-12 team is working to optimize the production process.

The W87-1 will also contain newly produced plutonium pits, which initiate the nuclear reactions when compressed by high explosives. LANL has been reconstituting pit manufacturing with SRS—a DOE industrial complex responsible for disposition of nuclear materials, waste management, environmental cleanup, and environmental stewardship—near Aiken, South Carolina. Lawrence Livermore designers are working closely with partners from LANL and SRS to establish pit specifications and evaluate the impact potential defects might have on the system. "These pits are a big deal," says Hsu. "If they don't work, the system won't go nuclear. The enterprise must get this right."

Experimental capabilities contribute to addressing W87-1 pit assessment and certification challenges. The JASPER two-stage gas gun at the Nevada National Security Site (NNSS) has played a central role in Laboratory designers' evaluation of plutonium under extreme conditions. In addition to these focused experiments at JASPER, Lawrence Livermore designers are conducting a series of hydrodynamic experiments that integrate relevant materials in warhead configurations. (See *S&TR*, November/December 2021, pp. 16–19.) These integrated tests at the Laboratory's Site 300 and LANL's Dual-Axis Radiographic Hydrodynamic Test Facility guide pit design to meet military requirements.

Modern Tools for Certification

Certification of a redesigned and fully rebuilt weapon is a formal process by which NNSA laboratory directors assert that the system meets requirements. In addition, modernization programs go through a process by which the DOD accepts the Final Weapon Development Report, which is based on the expert judgment of weapons designers, chemists, and engineers and supported by a comprehensive set of calculations and experiments. Historically, this process included nuclear explosive tests. Today, Lawrence Livermore designers leverage decades of advanced simulations and nonnuclear-testing capabilities to resolve nuclear weapons performance queries. This meticulous understanding of weapons physics, engineering, materials science, and manufacturing processes gives the Laboratory's W87-1 team the confidence to design and deliver a safe, secure, effective, and fully modernized nuclear warhead that meets requirements.

Modeling and simulation in support of the W87-1 Modification Program is underway using the Sierra high-performance computer, currently ranked the sixth fastest in the world. The Laboratory is working with industry partners to develop NNSA's first-ever exascale supercomputer—El Capitan, which is scheduled for delivery in 2023 and projected to offer more than 15 times the peak compute capability on average over Sierra. El Capitan will facilitate regular use of high-resolution 3D simulations of W87-1 warhead performance.

Ensuring Longevity

Lawrence Livermore researchers must ensure new materials installed in the W87-1 will last. While it is impossible to produce a part that will not age over time, Laboratory engineers, materials scientists, and chemists work together to evaluate and predict how materials will age and interact as they age. "We need to know how long a material will last when it's exposed to environmental stressors," says Sarah Chinn, W87-1 materials science and chemistry lead. "If you put a rubber band in the sun for a week and stretch it out, it will break. That's an extreme example, but we want to understand long-term behavior of the materials going into the W87-1."

To predict material longevity, researchers use a variety of techniques to accelerate aging, including increasing the levels of thermal and radiation exposure,

Lawrence Livermore materials scientists prepare to consolidate raw materials into test components using a hot press.

as well as performing mechanical and chemical testing. Material compatibility across components must also be considered. For example, if a polymer in one component releases gases or produces moisture, the researchers need to ensure adjacent metal components will not corrode.

Prototypes are heated in ovens at Site 300 and compared with predictive models as well as actual legacy stockpile parts. Similar to the development of AM techniques, the foundation for this work—the ReSorT model (Reaction Sorption and Transport)—began as an LDRD project 10 years ago by materials scientist Libby Glascoe. After showing promise at a fundamental-science level, Lawrence Livermore's Aging and Lifetimes Program continued to mature the model through data gathered while evaluating legacy warheads in support of annual assessments of the stockpile. ReSorT benefited the W80-4 program and now informs component design decisions for the W87-1. "Livermore has a reputation for making high-quality weapons that last. One reason is those ovens. The others are our models and simulations," says Raboin.

Stockpile-to-Target Sequence

The W87-1 must operate as expected despite exposure to hostile environments including antiballistic missile attacks. Many experiments are underway across the enterprise to evaluate the stockpile-to-target sequence challenges in detail. They range from focused experiments on the new materials for the W87-1 to integrated tests to evaluate the reliability of the entire system.

At the National Ignition Facility (NIF)—the world's most energetic laser—researchers are bombarding the newly designed materials for the W87-1 with x rays and neutron fluxes. During the Cold War era, researchers bored tunnels beneath the mesas of the Nevada Test Site—now NNSS—and conducted nuclear explosive tests to evaluate a material's ability to survive hostile nuclear environments. Today, NIF recreates some of the extreme conditions that the designers previously could only create with nuclear detonations. The record-breaking neutron yields achieved at NIF in 2022 opened the door to

El Capitan, an exascale supercomputer, will facilitate regular use of high-resolution 3D simulations of the W87-1 warhead in operation. The Laboratory has completed infrastructure improvements to support the larger system while developers prepare codes to run on the exascale architecture.

creating additional experimental conditions not produced since the days of nuclear testing. "Now that NIF is producing higher yields, we are getting closer to replicating the actual hostile environments the W87-1 must operate in," says Hsu.

The Air Force, in partnership with Lawrence Livermore and Sandia researchers, will conduct flight tests to provide insight into the warhead's ability to withstand the extreme forces associated with intercontinental ballistic missile (ICBM) liftoff and reentry. Launched from the Vandenberg Space Force Base in southern California, Air Force ICBMs carry mock warheads of Lawrence Livermore's design with diagnostics that relay essential data about system performance. As the ICBM traverses the ocean, a flotilla of rafts packed with the Laboratory's diagnostics scans the night sky off the coast of Kwajalein Atoll in the South Pacific. Within minutes of launch, these rafts—known as the LLNL Independent Diagnostic Scoring System—lock in on the incoming mock warhead. Data from these flight tests will inform assessments and make it possible for the Laboratory to certify the warhead.

A Key Milestone

With the Laboratory's submission of its input to the Weapon Design and Cost Report (WDCR), the W87-1 Modification Program passed a key milestone in November 2022. With the conceptual design for the warhead complete, this cost report details the scope of work required and provides a cost estimate. The next phase of the program is development engineering, where the Laboratory will continue to work with production partners to manufacture prototypes at the plants and start to qualify their manufacturing processes as well as executing experiments with increasing fidelity to verify that the design will meet requirements. Every component in a nuclear weapon has a product realization team (PRT), which is a collaboration between Livermore and one or more production agencies. As components come off the production line, the PRT and the broader W87-1 team at Livermore will evaluate whether they meet requirements through testing and assessments. PRTs also work to improve manufacturability and minimize production risks.

Active risk management is crucial in executing such a complex program. Hiccups in fielding new manufacturing processes or unexpected experimental results will stress the project's timeline and budget. Risk also arises from the program's challenges in staffing appropriately. The program is hiring additional people, and along with the hiring push comes the need to train and develop this next generation of stockpile stewards. Another source of risk is the parallel development approach—in lieu of developing components one at a time—which is necessitated by the program's tight timeline.

To actively manage these risks, the W87-1 team is employing a set of strategies, including close collaboration between design and production agencies and project management techniques such as the implementation of an earned value management system (EVMS)—a method of breaking a program down into manageable work elements and defining key steps within those work elements that provide indicators of how the program is progressing. In implementing EVMS for the W87-1, Lawrence Livermore is applying lessons learned from the W80-4 LEP. "Many of us worked on the W80-4 program, and we learned a tremendous amount," says Rachael Weinbrecht, project controls manager for the W80-4 LEP and the W87-1 Modification Program.

During the COVID-related lockdowns, the W87-1 team adapted to working in a different way as the program entered its second year of work. This presented additional challenges because as a program enters its second year, staffing and the pace of work both typically increase as deliverable deadlines approach. Despite having to adapt to less in-person time and other related adjustments, the W87-1 Modification Program met all of its objectives and accelerated timelines in several areas. With the acceptance of the WDCR in November 2022, the W87-1 enters phase 6.3—the development engineering phase—where the Laboratory works closely with the production plants to ensure that the manufacturing process delivers parts that meet requirements. "This is an immensely challenging program to execute, both technically and from a project management perspective," says Williams. "The complex has never been busier. It's an exciting time to be here. We're breaking new ground with our collaborators across the enterprise. Technologies that started as just an idea, like additive manufacturing or longevity modeling, we've seen them evolve and advance, lay the groundwork, and provide the tools we need to design and build the W87-1. We've also seen our partnerships grow and change, and we're cultivating and benefiting from a more agile, collaborative enterprise."

As teams design, develop, and deliver the materials for the W87-1 Modification Program, the contemporary challenges generate questions about future capabilities. "We need to think about the future and explore the AM innovations, NIF upgrades, high-energy-density physics advances, and exascale computing possibilities," Budil says. "We are tasked with advancing weapons and weapons systems and developing the next generation of an expert workforce to fulfill our mission as a national security laboratory."

—Amy Weldon and Nolan O'Brien

Key Words: Additive manufacturing (AM), El Capitan supercomputer, electron beam cold hearth melter (EBCHM), earned value management system (EVMS), hot press, Laboratory Directed Research and Development (LDRD), National Ignition Facility (NIF), National Nuclear Security Administration (NNSA), Nuclear Security Enterprise (NSE), plutonium, ReSorT model, Sentinel, W80-4 Life-Extension Program (LEP), W87-1 Modification Program.

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Iron under
EXTREMES

THE rotation and convection of liquid iron within the Earth's core generates the magnetosphere, an expansive magnetic field that stretches across 12 million kilometers and protects us from harmful solar winds and cosmic radiation, allowing life to flourish. Many super-Earths—planets outside our solar system more massive than Earth, yet lighter than ice giants like Neptune and Uranus and made of gas, rock, or a combination of both—could also contain dynamos that generate their own magnetospheres. The lifetime of a dynamo depends on how and when its molten core crystallizes. By understanding the melting and solidification curve of iron under extreme conditions, scientists can characterize the potential for these exoplanets to have a sustained dynamo-generated magnetosphere that could support life.

Lawrence Livermore scientists have performed a series of experiments through the National Ignition Facility's (NIF's) Discovery Science Program to replicate the extreme conditions within super-Earth cores and answered many questions posited by theoretical predictions and extrapolations from previously established relatively low pressure–temperature experimental data. This series of 12 experiments at NIF have also opened new pathways for future research that will increase our understanding of the properties and performance of materials under extreme temperatures and pressures that contribute to the Laboratory's stockpile stewardship mission.

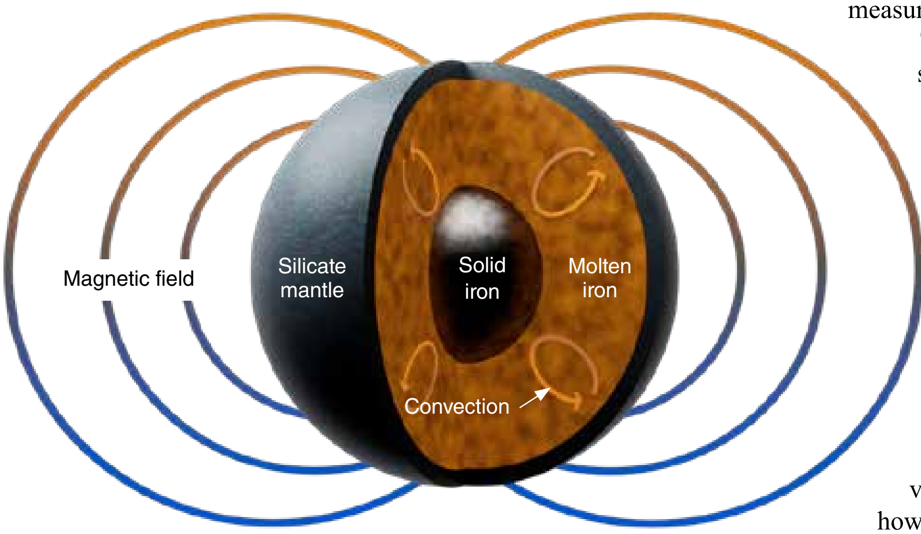
Intense Temperatures and Pressures

NIF Discovery Science Program researchers, led by Livermore physicist Rick Kraus, have been working to determine how and when cores of super-Earths solidify and their magnetospheres cease. Building on decades of developments at NIF including exquisite laser pulse shaping, plasma x-ray source generation, and the TArget Diffraction In Situ (TARDIS) x-ray diffraction diagnostic, the team determined the high-pressure melting curve and structural properties of pure iron up to 1,000 Gigapascals (GPa), a pressure nearly four times greater than any previous experiment and three times the pressure at the center of the Earth. For these experiments, the team aimed pulses of 16 NIF laser beams on a sample package of beryllium, germanium, pure iron, and lithium fluoride, shocking the iron into a liquid state between 220 and 300 GPa. Following the initial shock, the team carefully increased the laser power, so as to compress the iron with only a small temperature increase, which drives the iron back toward the solid state at high pressure. Finally, using x-ray diffraction, the team assessed whether the compression wave had resolidified the iron.

An artist's rendering of the cross section of a super-Earth with the National Ignition Facility (NIF) target chamber superimposed over the mantle. (Image credit: John Jett.)

Expert target fabrication played a critical role in the success of the experiments and required NIF's technological capabilities as well as the expertise of its researchers. Each sample package was designed to subject an iron sample to a single, steady shockwave. "As the shock from the NIF lasers moved from the iron to the lithium fluoride window, the iron decompressed slightly, ensuring a completely liquid iron sample for all but the lowest shock pressure experiment. Then we precisely increased the laser power to isentropically compress the sample to the desired peak pressure, up to 1,000 Gigapascals in about 10 nanoseconds, where we measured the initial shock pressure and peak pressure in the sample," says Kraus, who was recently awarded the inaugural American Physical Society's 2023 Neil Ashcroft Early Career Award for Studies of Matter at Extreme High-Pressure Conditions. To document the structure of iron at peak pressure, another 24 beams of the NIF laser illuminated a germanium or zirconium foil, producing a hot plasma, which emitted a nanosecond burst of radiation, allowing the team to record an x-ray diffraction snapshot within the TARD IS diagnostic. The pinhole of palladium or platinum attached to the sample package collimated or aligned the x rays and cast a known diffraction pattern.

Jon Eggert, chief scientist in the High-Energy Density (HED) section, led the development and fielding of the NIF TARDIS diagnostic, which uses x-ray diffraction to determine crystal structures, measure density, and evaluate strain-induced texturing of iron at extreme conditions. "This campaign required determining the precise pressure history and distribution within a target. To predict and control the sample pressure, we used advanced radiation hydrocode simulations similar to those used for inertial confinement fusion and the Laboratory's Weapons and Complex Integration computational models. We then improved our predictive tools by reconciling our results with each successive shot," says Eggert.



A dynamo of molten iron generates the Earth's magnetic sphere that protects the planet from lethal solar rays and cosmic radiation. Understanding the melting curve of iron under conditions similar to the core of rocky planets and super-Earths helps scientists characterize the potential for these planets to have sustained dynamo-generated magnetospheres and the potential to support life. (Renderings by Eric Smith).

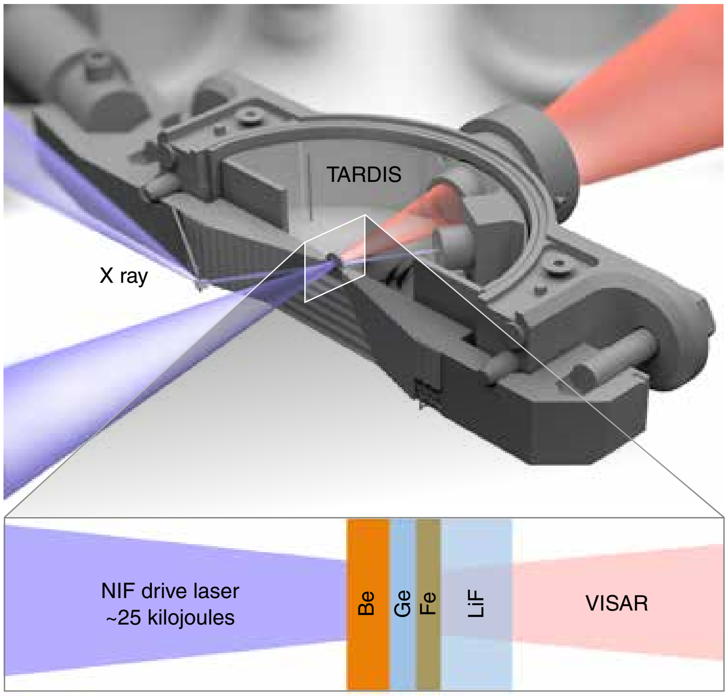
Solid in a Nanosecond

By harnessing the ultra high-power laser capabilities and diagnostics of NIF, Kraus and his team produced unprecedented pressures and temperatures, tracing the melt curve and crystallization process of iron at the extreme conditions within a super-Earth. At approximately both 550 and 1,000 GPa, the team observed a transition from liquid iron at high entropy states to a solid-hexagonal, close-packed (hcp) crystalline structure as the pressure rose, which means that the cores of exoplanets solidify from the bottom up and produce stronger magnetic fields that do a better job of protecting planetary surfaces from charged particles. "Although our data are focused on iron melting in super-Earth cores, our results also provide accurate determination of iron melting at the pressure-temperature conditions from the bottom of Earth's core through the inner core boundary, which has been controversial because of the lack of ability to directly take measurements in these conditions," says Kraus.

The fundamental processes for nucleation—the first step in the solidification of iron—and crystal growth at extreme conditions remains a challenging theoretical field. Jon Belof, group leader in the Materials Science Division and project lead for the theoretical and simulation studies of phase transformation kinetics, explains, "The timescale of planetary formation of an iron core is considerably slower than those we've attained with the very short timescale of compression experiments on the NIF. The development of a physics-based model for the nucleation process, considering this change in compression rate, has been a multiyear effort at the Laboratory." By applying extremely fast compression via laser drivers, the limits of theoretical understanding for how phase transformations occur at extreme conditions shed new light on this complex, dynamic process.

Livermore has also determined through these experiments that iron solidification happens very quickly, rather than over long periods of time. At Earth's core, scientists have questioned how it is possible for the Earth to have a solid inner core, hypothesizing based on previous experiments that iron must be supercooled by 2,000 Kelvin before it solidifies, implying Earth should not have a solid inner core even on a few billion-years' timescale. The NIF experiments, however, revealed that iron solidifies at near equilibrium and on a timescale of nanoseconds. "The fact that you can observe near-equilibrium solidification of iron at such short timescales addresses an interesting paradox. People questioned why Earth has a solid inner core if it required significant supercooling before solidifying, but we can take the results from our experiments and show that this theory of long cooling times is incorrect. Rather than taking billions of years to solidify iron, it takes only billionths of a second," says Kraus.

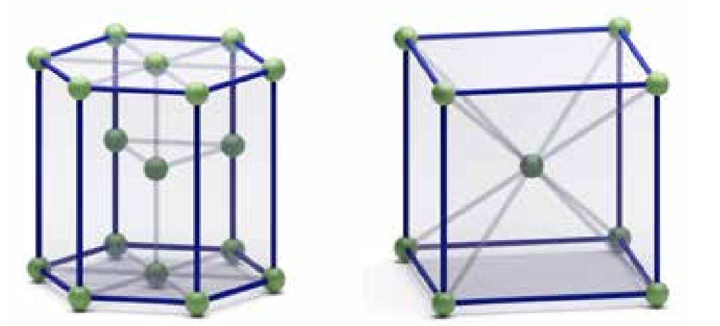
The team's observations of pressure-driven solidification indicate super-Earths will undergo bottom-up solidification, which will produce stronger magnetic fields than outside-in solidification. With nascent liquid iron cores and a nominal core-mantel boundary heat flux, the team found that super-Earth cores will take up to 30 percent longer to solidify than Earth's core, while cores of planets smaller than Earth will solidify faster. "Assuming solidification sets the timescale for dynamos, our results lead to the notable finding that super-Earths are likely to have a longer duration of magnetically shielded habitability than Earth," says Kraus.



Livermore's research team used NIF and in situ x-ray diffraction to discriminate between phases of matter at extreme conditions using the TArget Diffraction In Situ (TARDIS) diagnostic, with a zoomed-in view of the sample package with layers of Beryllium (Be), germanium (Ge), iron (Fe), and lithium fluoride (LiF) that is attached to a collimating pinhole at the front of the TARDIS. The Velocity Interferometer System for Any Reflector (VISAR) produces data that determines the initial shock pressure.

What's Next?

Documenting the melting temperature of iron in the Earth's core is important because it sets our understanding of the heat balance and physical conditions within the Earth as well as how it impacts the core's structure. "Determining that the structure of solid iron near the melt point is hcp rather than body-center cubic (bcc) is a huge deal because it helps geologists and geophysicists understand key inferences about the Earth's core," says Kraus. "Seismologists infer that sound waves move faster in the core depending on their direction, or anisotropy." Scientists are working to put the puzzle pieces together regarding fundamental anisotropy within hcp and bcc crystals versus what is seen in the core and what that reveals about the composition of the inner core and its thermal history.



The Livermore team determined that iron near the melt point transitions from liquid to a mixture of liquid and solid hexagonal close-packed (left) crystalline structures rather than body-centered cubic (right). This finding will help geophysicists and seismologists understand more about the Earth's core.

Despite the significant results that Livermore has uncovered through these experiments, questions persist. The team plans to explore what factors contribute to the stability of materials under extreme conditions, whether those materials behave as insulators or metals, as crystalline solids or liquids, and whether they form mixtures or segregate. "We've been able to put together a more complete understanding of how iron solidifies over a range of super-Earth masses, the timescales for core solidification as well as how long a planet could have a magnetosphere, but this is just the beginning," says Kraus.

—Sheridan Hyland

Key Words: body-centered cubic (bcc), dynamo, hexagonal close-packed (hcp), magnetosphere, National Ignition Facility (NIF), super-Earth, TArget Diffraction In Situ (TARDIS), Velocity Interferometer System for Any Reflector (VISAR).

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3D-Printed Microbes
ENHANCE BIOMATERIALS

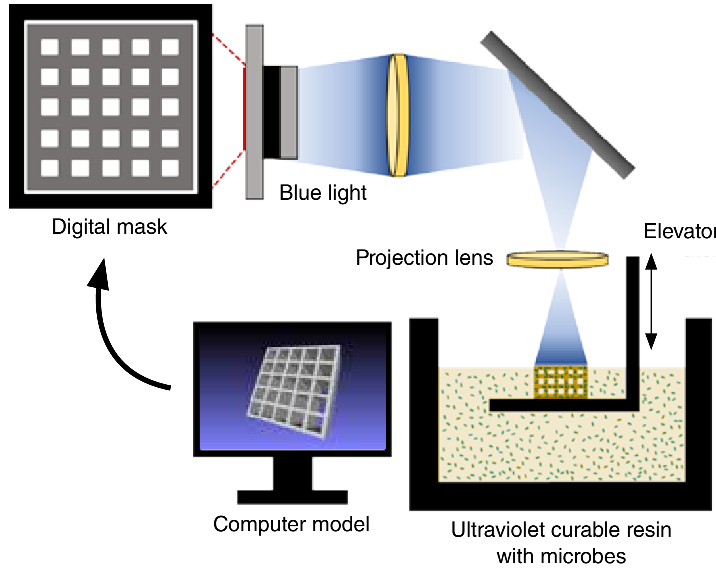
DESPITE their size, microorganisms represent a majority of biomass on Earth. Most microbes are contained in biofilms—thin accumulations of opportunistic microorganisms that form on virtually any surface that harbors basic ingredients for survival, whether the hull of a ship or the hard-to-reach spaces between one's teeth. Far from motley clumps of microbes, these microcities boast elaborate, interconnected ecosystems whose collective behavior drives fundamental biogeochemical reactions.

From a human standpoint, however, biofilms are often intrusive and pathogenic. Persistent accretions of microbes rapidly colonize medical devices, developing antibiotic resistance along the way and jeopardizing patient health. They also coat fresh produce, create food waste, and glaze surfaces of industrial machinery and transport vessels, adding billions of dollars to shipping costs. A multidisciplinary effort at Lawrence Livermore is underway to better understand the dynamics of microbiome differentiation and how certain biological processes might be harnessed through additive manufacturing (AM).

Staff engineer William "Rick" Hynes heads an exploratory research project investigating how microbial growth is tied to host-surface properties. "In the wild," explains Hynes, "microbial colonies develop their own structures through a mix of competition and symbiosis, so species partitioning and geometry come naturally; behavior and growth are a direct result of their orientation in space." Understanding the growth pattern of a lone species in a petri dish may not be too challenging, but biofilms that harbor tens or hundreds of species in unique arrangements exhibit complex behaviors which are difficult to parse, much less predict.

To understand how biological relationships within biofilms (and other microbiomes) are affected by spatial geometry, Hynes's team is utilizing the 3D printing process of biological projection microstereolithography (BioPμSL) to build intricate, living structures for studying and directing microbial growth. "Typical 3D-printing processes require melting a thermoplastic polymer and tracing out the desired shape layer-by-layer as it cools," explains Jesse Ahlquist, staff engineer and co-technical lead. "That method does not work when live cells are embedded in the material because exposure to high temperatures would kill them." As part of Livermore's Laboratory Directed Research and Development Program, Hynes's team has developed a customized stereolithographic apparatus for microbial (SLAM) bioprinting that produces complex structures at higher resolution than other microscale methods while sustaining living organisms.

This confocal image of 3D-printed grid structure (left), viewed from the side, consists of two different, alternating molecular weight bioresins. Each layer contains differing ratios of microbe-sized, polymeric-fluorescent beads to achieve 10 different colored sections, each 500 micrometers tall, in a single build.



Overview of the biological projection micro stereolithography (BioPμSL) system used to produce printed structures with embedded microorganisms.

Reciprocally Enabling Bacteria

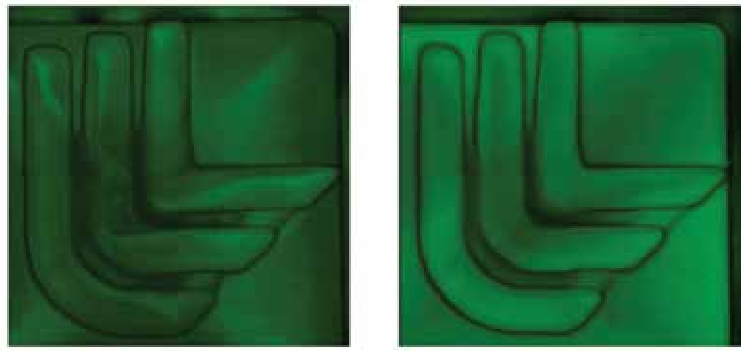
Developed at Livermore's state-of-the-art Micro Nano Bioengineering Laboratory (MNBL), the group has already used SLAM bioprinting to generate complex lattices and whorls that can accommodate over a dozen bacterial species. With these sophisticated structures, researchers will be able to conduct controlled experiments to extend basic scientific understanding of microbial interaction from the flat, unnatural setting of Petri dishes to dynamic, 3D environments that reflect natural patterns.

Artificial biofilms are not new, but until now, efforts to characterize the biodiversity and community stability of micro-environments have been constrained by lack of control over growth geometry. Microbes systematically grown on the same agar resort to interspecies competition over nutrients rather than expand in new directions to exhibit colony spacing and nuanced biological relationships. Exerting precise control over microbial cultures in increasingly complex settings will reveal insights into behaviors that have so far eluded researchers. "We're developing the tech that synthetic- and microbiologists don't even know they need yet," says Hynes. "We're not just trying to mimic the geometry and growth found in the wild, but as we come to better understand natural microbial behavior, we can begin thinking about functionalization, which can often require division of labor within cellular communities and can hinge on their structure."

"This is where things get really interesting," says Ahlquist. "We can use the waste products from one species to power the processes of another. By linking different layers and different species, we achieve a consortium of reciprocally enabling bacteria." Microbes make ideal components in emerging technologies because they function in ways manufactured products cannot.

Harnessing microbes' natural metabolic processes will hasten the development of new technologies across diverse fields. By exploiting special metabolic processes—oftentimes via fermentation—bioplastics and energy-rich biofuels such as ethanol and biodiesel could be more efficiently derived from biomass, relieving dependence on finite petroleum resources. Encasing cells in printed bioresins could effectively capture and neutralize pollutants as part of bioremediation efforts in contaminated areas. Similarly, printed microbial structures could be used to absorb and purify rare-earth elements during mining operations, a capability that promotes resource independence for substances critical to U.S. defense technologies. Microorganisms even show promise as remote chemical biosensors by detecting carefully monitored substances like uranium. Any of these nascent applications' success, however, requires deeper understanding of microbial biology and behavior.

While Hynes aims to equip scientists with tools to probe these dynamics, staff engineer and co-technical lead Javier Alvarado is working on other applications. Alvarado, who studied neuroscience and tissue engineering, sees great potential for Livermore's bioprinting research in medical innovation. "One of the leading causes of infection is invasive cells' ability to form biofilms and develop antibiotic resistance," he explains. Once pathogens infect an individual, their quorum-sensing ability allows them to lurk within biofilms, evading immune detection until their numbers are sufficient to mount a full-scale attack. "Putting an artificial construct into a body, for example, is risky because there's uncertainty about how it will hold up in a new environment. Having precise control over cell growth parameters reveals how biofilms behave in different settings and how to disrupt their formation."



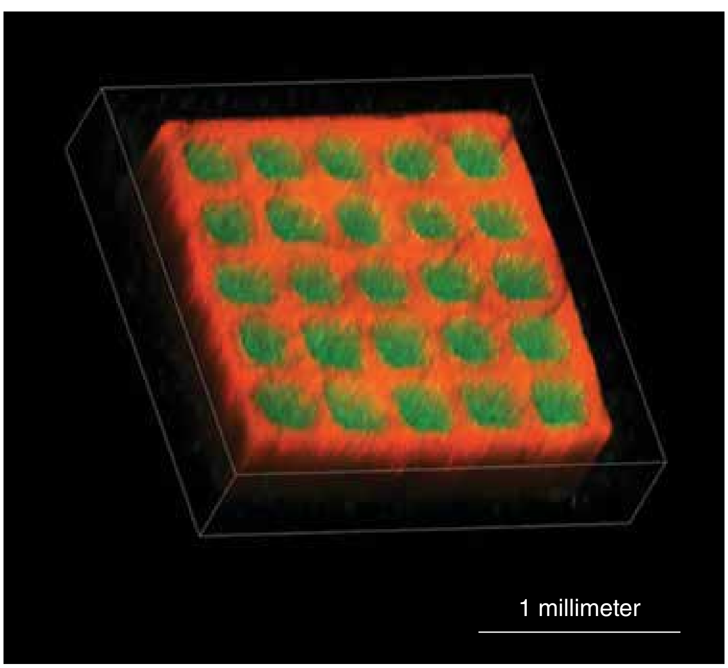
A printed version of the Laboratory's logo harbors *C. crescentus* within the material (left). The suspended bacteria fluoresce upon exposure to 10 micromolar uranium, brightening the construction (right).

An Ideal Molecular Structure

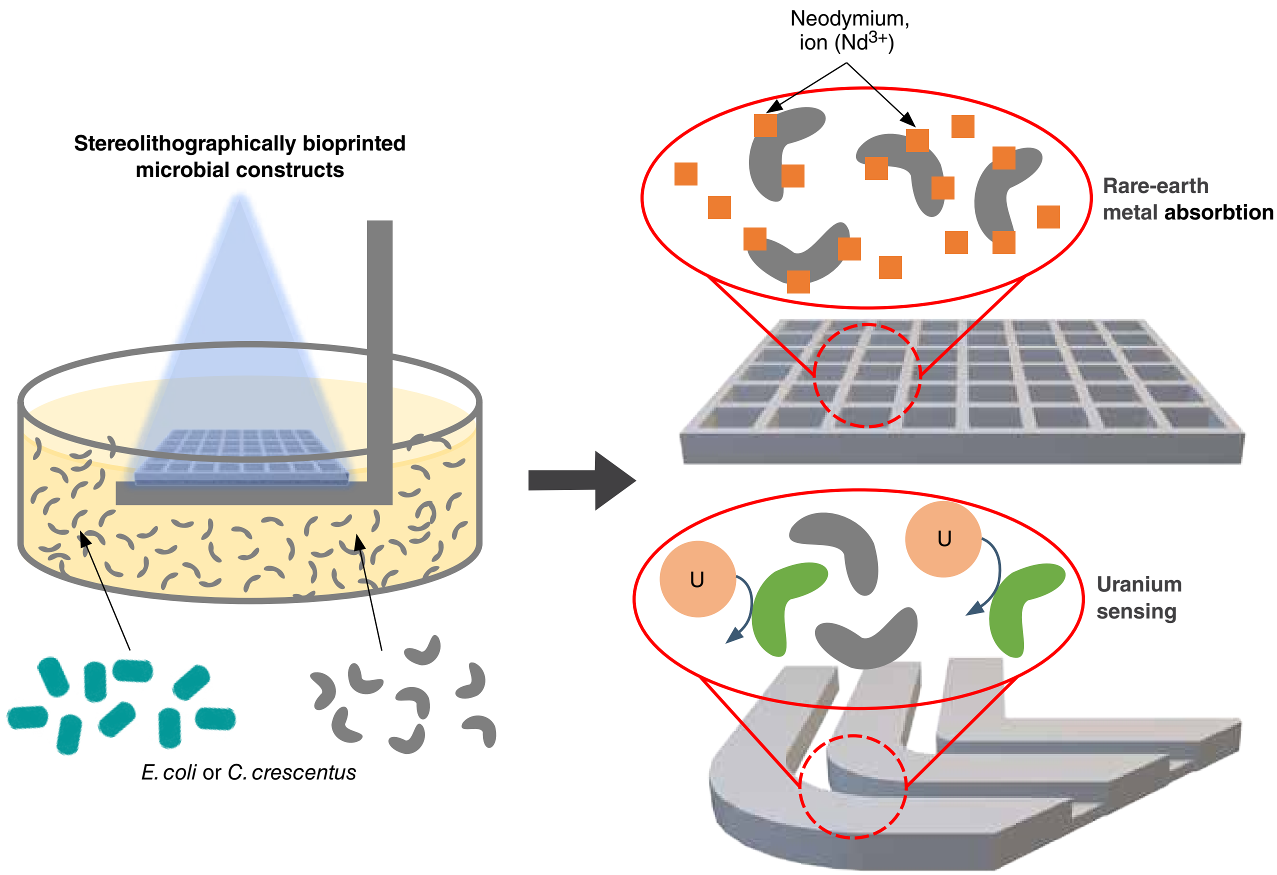
Ordinary stereolithography functions by selectively exposing layers of photosensitive liquid resin to ultraviolet light, which cures it into the desired shape. Slices of a 3D image are serially projected onto the resin, and as the top layer solidifies to form a translucent polymer hydrogel, a mechanical stage lowers the hardened layer to just below the liquid surface. Subsequent projections cure layer after layer of resin until the entire object is produced. In the case of SLAM bioprinting, the resin begins saturated with microbes, then a 405-nanometer wavelength light hardens the bioresin into hydrogel, and the organisms become living parts of the structure.

Hynes explains that SLAM Bioprinting itself is not a large-scale manufacturing technique. "It serves as a rapid prototyping method to test cells under different conditions," he clarifies. The technique will enable researchers to realize more efficient, economical, and environmentally friendly processes once scaled.

Refining large-scale production methods demands technical sophistication at the research level. For instance, wieldy



Oblique view of a printed grid structure containing *Escherichia coli*, which express either green fluorescent protein or mCherry in red.



The BioPμSL printing process can encapsulate multiple bacterial species and lends itself to numerous functionalities.

microbes favored by bioengineers, like *Rhodopseudomonis palustris*, which Alvarado dubs "the Swiss Army knife of bacteria," require an electron source to synthesize bioplastics. Providing electricity to bioprinted architectures necessitated embedding carbon nanotubes inside the printed structures, a challenging task given the sensitive manufacturing method.

Ahlquist utilized MNBL's capabilities to help develop an ideal microbe-bearing resin for bioprinting experiments, ensuring compatibility between the cells and the resin's conductivity. "The process is essentially a funnel," he explains. "We look at all the possible materials we could use, and then narrow it down to one that keeps microbes healthy and performs well during the printing process." Bioresins come in a spectrum of formulations, each providing a unique combination of porosity, stiffness, molecular weight, and other properties that must harmonize for cells to thrive. The team identified a blend of polyethylene glycol diacrylate with an ideal molecular structure for cells to take root, absorb vital nutrients, and dispel metabolic waste products through passive gradient diffusion.

Ahlquist and Hynes credit Lawrence Livermore's new additive manufacturing (AM) facilities with making their work possible. "MNBL was finished just as I started at Livermore, giving us access to a breadth of AM capabilities and expertise," recalls Hynes. "This would have been incredibly difficult to pull off in academia, but at a national laboratory so many tools are readily available." For Alvarado, the Laboratory's exceptional capabilities go beyond instrumentation. "It's the people. Having mentors and mentees with diverse backgrounds makes it possible to investigate these emerging fields. Nature is the best engineer, and we're still figuring out all of its tricks."

—*Elliot Jaffe*

Key Words: Additive manufacturing (AM), bacteria, biofilm, biological projection microstereolithography (BioPμSL), bioplastics, bioprinting, Micro Nano Bioengineering Laboratory (MNBL), *Rhodopseudomonis palustris,* stereolithographic apparatus for microbial bioprinting (SLAM).

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DETERRENCE THROUGH STRATEGIC LATENCY

LAWRENCE Livermore National Laboratory is perhaps best known for its work in maintaining the country's nuclear deterrent. Emerging technologies have always been central to the deterrence mission. Today, deterrence is more complex than ever, and emerging technologies continue to play a critical role in the Laboratory's support of national security. Beyond keeping the nation's stockpile of nuclear weapons safe, secure, and reliable, emerging technologies in the realms of space, cyber, artificial intelligence, and quantum computing are defining the full range of complex, multidomain and integrated deterrence options. Anticipating how emerging technologies will be applied to military requirements is the goal of the Strategic Latency Program at the Center for Global Security Research (CGSR).

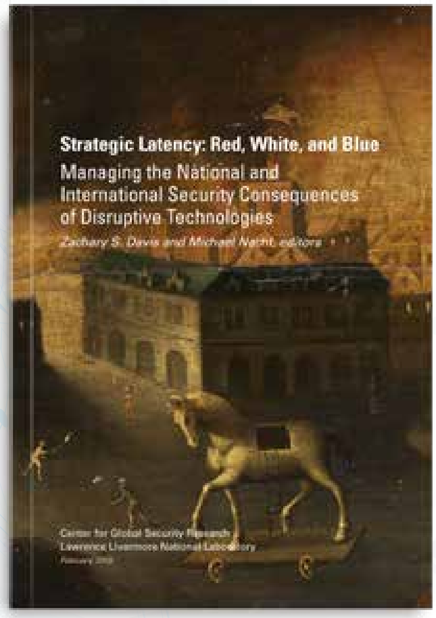
The Laboratory's CGSR was established in 1996 to serve as a bridge between the science, technology, and national-security policy communities, and focuses on emerging challenges in the areas of deterrence, assurance, and strategic stability.

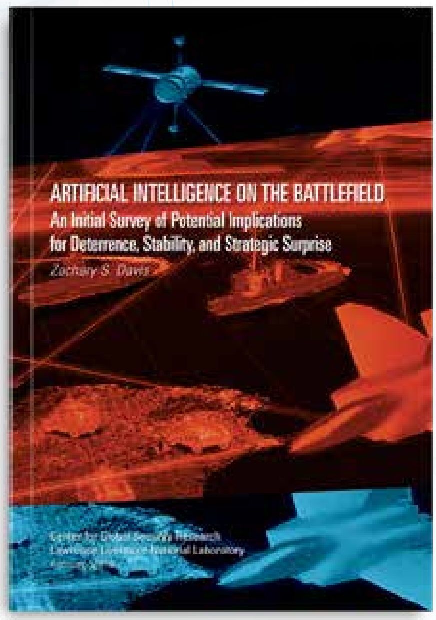
Strategic latency refers to the potential for science and technology to shift the economic and/or military balance of power through innovations that could threaten national security, as well as the impetus to harness and leverage emergent, untapped technologies that could give the United States an economic as well as military advantage.

One of CGSR's thrust areas is understanding the future of long-term competition, where the analytical lens of strategic latency offers insights about the threats and opportunities associated with novel technologies. The program draws on the full portfolio of Livermore's expertise, from threat analysis

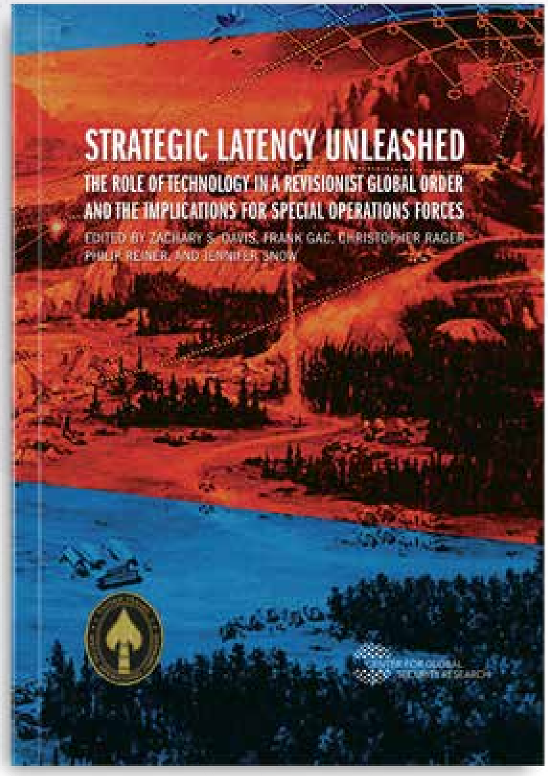
to fundamental and applied sciences, to assess how nascent technologies shape national and international security. Zachary S. Davis, senior fellow and South Asia specialist who leads CGSR's Strategic Latency Program, explains, "Technology is transforming the face of warfare and will directly impact warfighters across the spectrum of conflict from strategic deterrence to special operations forces and the gray zone. CGSR's exploration of strategic latency in all its facets speaks to the need to relentlessly anticipate future technological applications."

CGSR has made substantial contributions to creating and growing the field of strategic latency through the development of intellectual analyses that address complex questions about the impact of scientific advancements on security and society at large. The analytical frameworks examine strategic latency through the perspective of (1) threat analysis of how different countries apply science and technology to military





Strategic Latency: Red, White, and Blue: Managing the National and International Security Consequences of Disruptive Technologies, which was published in 2018 and edited by Zachary S. Davis, senior fellow at the Center for Global Security Research (CGSR), and Michael Nacht, Schneider Chair Emeritus and professor of the Goldman School of Public Policy at the University of California, Berkeley, examines how seemingly harmless or beneficial technological innovations can precipitate political, military, or economic disaster. The 2019 CGSR occasional paper, *Artificial Intelligence on the Battlefield, An Initial Survey of Potential Implications for Deterrence, Stability, and Strategic Surprise*, poses questions and provides first-order arguments developed by Davis for a CGSR workshop on the emerging roles and consequences of artificial intelligence.



CGSR's *Strategic Latency Unleashed: The Role of Technology in a Revisionist Global Order and the Implications for Special Operations Forces* was edited by Davis; spans 38 chapters written by contributors from the government, military, intelligence, academic, and private sectors; and includes a chapter on forensic science coauthored by Lawrence Livermore's Brad Hart and Brian Souza. (Cover artwork by Mark Gartland.)

purposes; (2) the origin and trajectories of individual technologies; and (3) how the United States government develops and acquires the technology it needs. Brad Roberts, CGSR director and deterrence expert, asserts that strategic latency is "a hedge against a future deterrence shortcoming. With a solid scientific grasp of emerging technologies, states can develop bleeding-edge military applications and innovate strategic advantages in response to a compromised security environment."

Measuring a country's latency toward possessing nuclear capabilities—how close it is to developing nuclear weapons—is the key to measuring proliferation risk. Emerging technologies, such as additive manufacturing, might shorten the timeline. As a strategy, latency can be looked at from two sides—either by potential proliferators who assemble the necessary elements needed to acquire nuclear weapons, but without "crossing the line," or from a nonproliferation perspective, which seeks to extend the time it takes before a nation-state has the technological means and resources to successfully develop weapons of mass destruction. "Strategic latency—as an analytical lens—can also be an applied strategy that deploys export controls, safeguards, and treaties to incentivize countries to maintain their latent state," says Ronald Lehman, CGSR fellow and counselor to Laboratory Director Kimberly Budil. For example, the Atoms for Peace Program in the 1950s sought to provide the benefits of nuclear technology without spreading the means to acquire or develop nuclear weapons. Another example is Iran, which pushes the limits of nuclear latency, while the Joint Comprehensive Program represents multilateral efforts to keep Iran from turning its latent capabilities into weapons.

"The globalization and democratization of technology is a double-edged sword," says Davis. "Superpowers can't control access to technology like they used to. Our challenge is to understand the technology, predict its unforeseen applications, and then figure out how to control it—if that's even possible. National and international controls on nuclear, chemical, and biological weapons depend on verification and enforcement mechanisms that don't yet exist for cyber, space, or other emerging technologies."

A Tactical Approach

CGSR employs a multistep approach that first brings leading experts in science, technology, military, and policy together on a range of issues including missile defense, nuclear strategy, regional conflict, and peer competitors such as Russia and China to focus on a specific topic area. "The complexity of today's problems demands an interdisciplinary approach," says Davis. "Assembling the technical and policy expertise is essential." Increasingly, it is equally important to include insights from the private sector as well as groups such as In-Q-Tel and the Defense Innovation Unit that were established to help the United States government acquire cutting-edge technologies from private industry.

The information gleaned from these gatherings is documented in workshop proceedings and bibliographies published on the CGSR website. The discussions and presentations often evolve into CGSR occasional papers, Livermore papers, or larger edited volumes. They can also result in journal publications by CGSR staff and fellows. The latter category is a diverse group comprised of postdoctoral researchers and short-term fellows, which include internal Laboratory scientists and specialists of all disciplines that spend several months focusing on a research question that falls within CGSR's key thrust areas.

Strategic Latency in Practice

A key benefit of conducting this analytical work at Lawrence Livermore is the immediate access CGSR researchers have to scientists and engineers working on cutting-edge science and technology. "You can go directly to the technology experts who share their first-hand, work-bench insights and knowledge," says Davis.

One major example that highlights how the Laboratory is realizing strategic latency is its work in additive manufacturing—the innovative layer-by-layer technique of printing 3D objects from a digital model—and the development of new feedstocks or inks and manufacturing techniques that have produced components with unprecedented characteristics and geometries. Additive manufacturing opens a new world of design possibilities in medicine, aeronautics, energy, and many other industries. The Laboratory's Polymer Production Enclave, a collaboration with the Kansas City National Security Campus, was established to accelerate the design, development, and production of additively manufactured parts for the Nuclear Security Enterprise and has already realized several early technological advances. (See *S&TR*, November/December 2021, pp. 12–15.) "The Laboratory's work in additive manufacturing is already having a strategic impact. When we look at it through the lens of strategic latency, however, we're not just evaluating it for what it does or how we're using it, we're also taking into consideration how it *could* be used," says Davis.

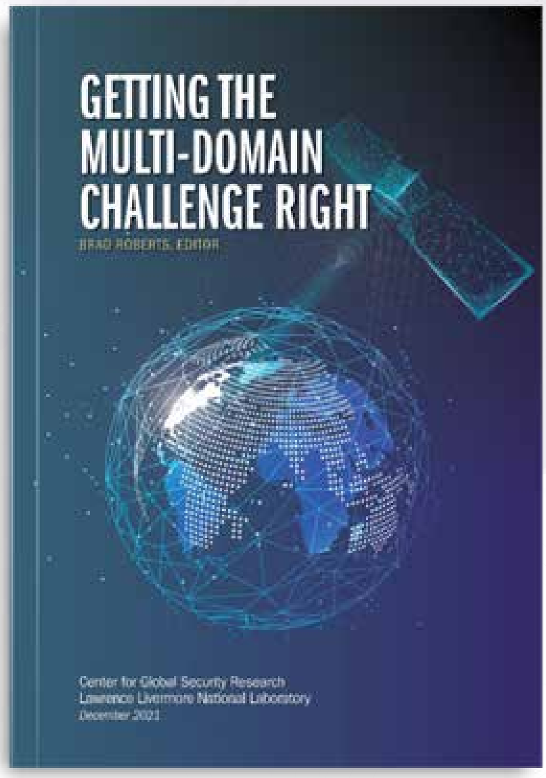
Another example of the Laboratory's pioneering work is the National Ignition Facility's development of nuclear-fusion energy. Realizing fusion—the reaction that produces energy by joining the nuclei of two atoms—could be revolutionary. It could slow climate change, as this type of nuclear energy would not release carbon emissions or other greenhouse gases into the atmosphere. "Once commercialized," Davis says, "fusion energy will have major strategic benefits for the United States and the world. The latent potential is very promising."

Cultivating the Next Generation

CGSR has cultivated widespread recognition of strategic latency. It has also expanded the field through its research associates and internship program that provides participants with opportunities for research, publication, and connections with a diverse set of technical experts. CGSR fellows were instrumental in the recent National Nuclear Security Administration's Strategic Outlook Initiative on technology futures studies and have complemented the Laboratory's highly respected series of edited volumes on strategic latency with publications of their own. Early career scholars at CGSR have studied the strategic potential of lasers, drones, artificial intelligence, genetics, social media, space, and other technologies, leveraging Laboratory scientists' unique insights.

Today, the Strategic Latency Program's network encompasses "hundreds of people with diverse expertise and seniority working across dozens of institutions." Roberts says, "As a foremost leader in strategic latency, CGSR has attracted a new generation of scholars determined to uncover and think critically about how these emerging, disruptive technologies will affect our future security."

—*Kristine Wong*



CGSR occasional paper, *Getting the Multidomain Challenge Right,* explores the implications of emerging technologies such as artificial intelligence, hypersonic missiles, and biotechnology on U.S. defense planning, as well as strategies to support strategic stability. (Cover artwork by Tom Reason.)

Key Words: additive manufacturing, Center for Global Security Research (CGSR), deterrence, disruptive technology, emerging technology, fusion, multidomain deterrence, National Ignition Facility, Polymer Production Enclave, strategic latency.

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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 (uspto.gov).

Patents

Cylindrical Microelectrode Array for Neural Stimulation and Recording
Kedar G. Shah, Supin Chen, Sarah H. Felix, Satinderpall S. Pannu, Susant Patra, Vanessa Tolosa, Angela C. Tooker, Jason Jones
U.S. Patent 11,357,975 B2
June 14, 2022

Laser-Driven Hydrothermal Processing
Raymond P. Mariella, Jr., Alexander M. Rubenchik, Mary A. Norton
U.S. Patent 11,358,237 B2
June 14, 2022

Water Purification
Ryan P. Brisbin, Jenny Zhou, Allan S. Chang, Tiziana C. Bond, Aaron J. Simon, Lars Voss
U.S. Patent 11,358,880 B2
June 14, 2022

System and Method for Using Ultramicroporous Carbon for the Selective Removal of Nitrate with Capacitive Deionization
Patrick Campbell, Maira Cerón Hernández, Steven Hawks, Colin Loeb, Tuan Anh Pham, Michael Stadermann
U.S. Patent 11,358,883 B2
June 14, 2022

System and Method for Liquid Crystal Display System Incorporating Wire Grid Polarizers for Large Scale and Large Volume Stereolithography
Eric B. Duoss, James Oakdale, Nicholas Anthony Rodriguez, Hongtao Song, Richard Crawford, Carolyn Seepersad, Morgan Chen
U.S. Patent 11,360,348 B2
June 14, 2022

Heat and Fire Resistant Gel Seal
Erik P. Brown
U.S. Patent 11,364,398 B2
June 21, 2022

Photoconductive Charge Trapping Apparatus
Stephen Sampayan, Paulius Vytautas Grivickas, Krisin Cortella Sampayan
U.S. Patent 11,366,401 B2
June 21, 2022

Awards

Three Livermore scientists received the **Department of Energy's (DOE's) Office of Science Early Career Research Program Award**. Awardees typically receive $500,000 annually for five years to support promising research projects. **John Despotopulos**, a staff researcher in the Nuclear and Chemical Sciences Division, was recognized for work investigating heavy elements and stellar nucleosynthesis. **Timofey Frolov**, physicist in the Materials Science Division, was nominated for research into computationally modeling material interfaces of alloys. **Mimi Yung**, deputy group leader within the Biosciences and Biotechnology Division, was recognized for research into protein compartmentalization systems and genetically engineered microorganisms.

The **DOE** granted two Livermore scientists—**Sofia Quaglioni** and **Jennifer Pett-Ridge**—the **E. O. Lawrence Award** for exceptional achievement among mid-career researchers in DOE focus areas. Quaglioni, who has been with the Laboratory over 15 years, serves as Nuclear Data and Theory group leader in the Nuclear and Chemical Sciences Division. She was recognized for substantial contributions in quantum and computational physics that bear strong implications to inertial fusion and astrophysics understanding. Senior staff scientist Pett-Ridge, who has been at the Laboratory for 17 years and is a group leader for the Environmental Isotope Systems Group in the Nuclear and Chemical Sciences Division, was lauded for her research in quantitative microbial ecology and for heading efforts to understand the impact of climate change on the environmental biogeochemical roles of microorganisms.

Abstract

W87-1 The Modification that Invigorated an Enterprise

Lawrence Livermore is fulfilling its mission to strengthen U.S. security and global stability and resilience by delivering the first newly manufactured nuclear warhead since the end of nuclear-weapons testing in 1992. The W87-1 Modification Program is a massive collaborative effort to replace the aging W78 warhead, and relies on the Laboratory's partnerships for success. After three decades of conducting only Life-Extension Programs (LEPs), which refurbish weapons with existing parts, the Laboratory and its partners are collaborating to optimize the manufacture of new components for the W87-1 warhead. The W80-4 LEP, started in 2018, provided the W87-1 program with a blueprint to navigate the challenges of designing, developing, manufacturing, and certifying nuclear-weapon components with entirely new materials, infrastructure, and technology. By utilizing advances in nonnuclear experiments, computational modeling, in situ diagnostics, and new resources like the Polymer Enclave, the W87-1 Modification Program is setting new precedents for collaboration across the Nuclear Security Enterprise and the next generation of the nuclear deterrent.

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U.S. Government Printing Office: 2022/670-075-20024

Coming Next Issue

Disruptive Research

Outside-of-the-box research reveals new approaches for lasers, food production, energy storage, hypersonic flight, and cybersecurity.

Also in the next issue:

- *Lawrence Livermore receives three 2022 R&D 100 awards for technologies advancing additive manufacturing and high-power lasers.*
- *A past Laboratory R&D 100 award winner tracks food in the supply chain for improved food safety.*

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Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

Printed on recycled paper.