Lawrence Livermore National Laboratory

April/May 2022

Science & Technology REVIEW

LASER PROGRAM CELEBRATES 50 YEARS

Also in this issue:

Transuranic Waste Management and Transport

Isotope Hydrology Solves a Mystery

About the Cover

Lawrence Livermore established its unified Laser Program, bringing together researchers from across the Laboratory to develop high-energy laser systems for pursuing inertial confinement fusion. As the article beginning on p. 4 describes, over the program's 50 years, Livermore and collaborating institutions have been at the forefront of scientific and technological innovations, paving the way to a major fusion milestone in August 2021. The cover represents the evolution of the laser showing (back) an early tabletop system pictured with Laboratory physicists John Emmett (left) and John Nuckolls, and (front) an artist's rendering of a fusion experiment inside the National Ignition Facility.

Cover design: Mary J. Gines

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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April/May 2022

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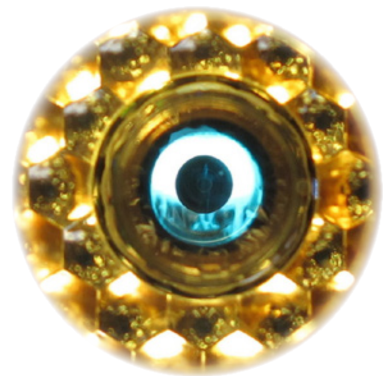

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Superionic Water Properties Deciphered

At a specific combination of extreme temperature and pressure, water can enter a "superionic" phase in which oxygen atoms retain a lattice structure, but hydrogen ions move fluidly with liquidlike behavior. Superionic water remained a hypothetical state for decades, thought to exist within massive planets such as Uranus and Neptune that contain substantially more water than all of Earth's oceans. Only recently have scientists confirmed the superionic phase's existence and accurately assessed its properties.

New research published September 23, 2021, in *Nature Physics,* applies machine learning to understand the behavior of atoms in water's superionic state. Experimentation with superionic water is complex, so quantum-based simulations of molecular dynamics are often used to help design an experiment and evaluate its results. However, these simulations become prohibitively expensive with large system sizes and timescales greater than a matter of picoseconds. Machine learning programmatically determines the nature of atomic interactions via quantum mechanical calculations so the team can infer atomic behavior over longer timescales with greater precision.

Identifying the phase boundaries of water in such an environment allows scientists to differentiate multiple superionic phases present within ice giants. Co-author Sebastien Hamel says, "Our quantitative understanding of superionic water sheds light into the interior structure, evolution, and magnetic fields of planets such as Uranus and Neptune and also of the increasing number of icy exoplanets."
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Livermore Optics for World's Newest Telescope

For the past decade, Livermore researchers have collaborated with international partners to design and fabricate major optical components for the world's newest telescope. Now complete, the 8.4-meter Simonyi Survey Telescope will take digital images of the southern sky using the Legacy Survey of Space and Time Camera (LSSTCam) at the Vera C. Rubin Observatory in Northern Chile. Livermore researchers made essential contributions to the optical design of LSSTCam's lenses and the Simonyi Survey Telescope's mirrors such as determining how the camera and telescope surveys the sky and how these components work together to compensate for temperature and gravity.


(Photo by Garry McLeod.)

The telescope's camera weighs more than 3 tons. Its six 76-centimeter-diameter filters are among the largest produced, and one of its three optical lenses is the world's largest, high-performance optical lens at over 1.5 meters in diameter. Inside the National Ignition Facility's optical assembly building, industrial partners fabricated the lenses and filters, which were then placed into Laboratory-developed mounts. (See image below, left.) Each filter transmits light from a segment of the electromagnetic spectrum, progressing throughout the entire visible range and moving from near-ultraviolet to near-infrared.

"The successful fabrication of these optical filters and lens assemblies is a testament to the Laboratory's world-leading expertise in large optics, built on decades of experience constructing the world's largest and most powerful laser systems," says Livermore physicist Scot Olivier. LSSTCam data will help researchers better understand the makeup of the universe, detect and study about 20 billion galaxies over a 10-year span, track potentially hazardous asteroids, and observe exploding stars.
Contact: Scot Olivier (925) 423-6483 (olivier1@llnl.gov).

Algorithmic Blackbox Takes on Black Holes

Black hole mergers are the only cosmic phenomena explosive enough to produce gravitational waves detectable by current instrumentation. Such a merger—in which binary black holes (BBH) fuse and expel mass as energy—was the source of the revelatory direct observation of gravitational waves at the Laser Interferometer Gravitational-Wave Observatory in 2016. Findings published November 9, 2021, in *Physical Review Research,* present new computational methods to rapidly decode the dynamics of the black hole systems responsible for gravitational disruptions.

Albert Einstein's field equations to describe black hole mergers require resource-intensive computation to solve for each unique combination of physical parameters, leading researchers to reduce them to more manageable, yet less precise forms for describing BBH motion throughout each merger stage. Livermore mathematician and computational scientist Brendan Keith led a collaborative effort with researchers from the University of Massachusetts, Dartmouth College, and the University of Mississippi to rethink the problem. The team devised a machine-learning model that intakes raw gravitational wave data to systematically learn and produce equations describing BBH motion.

Starting with a nonrelativistic physics model and a system of differential equations adjusted and refined by neural networks, the method algorithmically fills in the relativistic aspects of motion not accounted for in the basic model. "Our model takes astronomically fewer resources than conventional computational methods and can return highly accurate descriptive equations in mere minutes," says Keith. This predominantly data-driven approach may provide for accurate simulations of astrophysical dynamics even in scenarios with limited or low-resolution data.
Contact: Brendan Keith (keith10@llnl.gov).

Commentary by Kimberly Budil

A Remarkable Past and EXCITING FUTURE

THE feature article in this issue of *Science & Technology Review* celebrates 50 years of pioneering work on laser technology for inertial confinement fusion (ICF) and the important recent success at the National Ignition Facility (NIF). The Laser Program was launched on March 2, 1971, to consolidate ongoing laser development activities and explore the feasibility of ICF. Associate Director for Plans Carl Haussmann served as the first program leader and recruited John Emmett, who headed solid-state laser research at the Naval Research Laboratory, to lead laser development efforts as Y-Division leader in July 1972.

Y-Division took on the challenge to advance solid-state laser design in preparation for constructing Shiva, a 20-beam, high-power 10-kilojoule laser. Recognizing the strategic importance of ICF research, Atomic Energy Commission chairman James Schlesinger approved the proposal by Haussmann and future Laboratory Director John Nuckolls to build such a laser. It was an ideal, long-term undertaking for a national laboratory—requiring major scientific and engineering breakthroughs, enabling detailed exploration of high-energy-density (HED) conditions to support the weapons program, and offering the potential path to an unlimited source of energy. As the article beginning on p. 4 describes, the 50-year history of Livermore's Laser Program, now the NIF and Photon Science Principal Directorate, has greatly contributed to U.S. leadership in ICF research and, more generally, has made remarkable advances in solid-state laser technology and our understanding of HED science.

I started my career as a postdoctoral researcher conducting experiments on the Nova laser, NIF's predecessor, studying instabilities that arise in shock-driven materials and other HED phenomena and learning about the role these facilities play in our national security mission. My final Nova experiment was also, sadly, Nova's last experiment as Laboratory staff shifted attention to making NIF a reality. The bold step to construct NIF required revolutionary advances in solid-state laser and optics design and engineering. NIF's 192-beam laser provided the enormous capability leap needed for experimental HED science to support stockpile stewardship and moved the ICF program steadily toward achieving fusion ignition and burn—a goal given a 50–50 chance of succeeding at the time.

Today, working in partnership with countless collaborators, scientists and engineers at NIF provide crucial data to sustain the nation's nuclear weapons stockpile, make remarkable discoveries in HED science that help us understand the universe, and put us on the threshold of fusion ignition. Equally important, many outstanding young scientists test their skills and gain expertise in HED science—opportunities I had early in my career. NIF plays a crucial role in attracting, training, and challenging our scientists, helping them build knowledge and judgement to support our important responsibilities for the nation's nuclear deterrent.

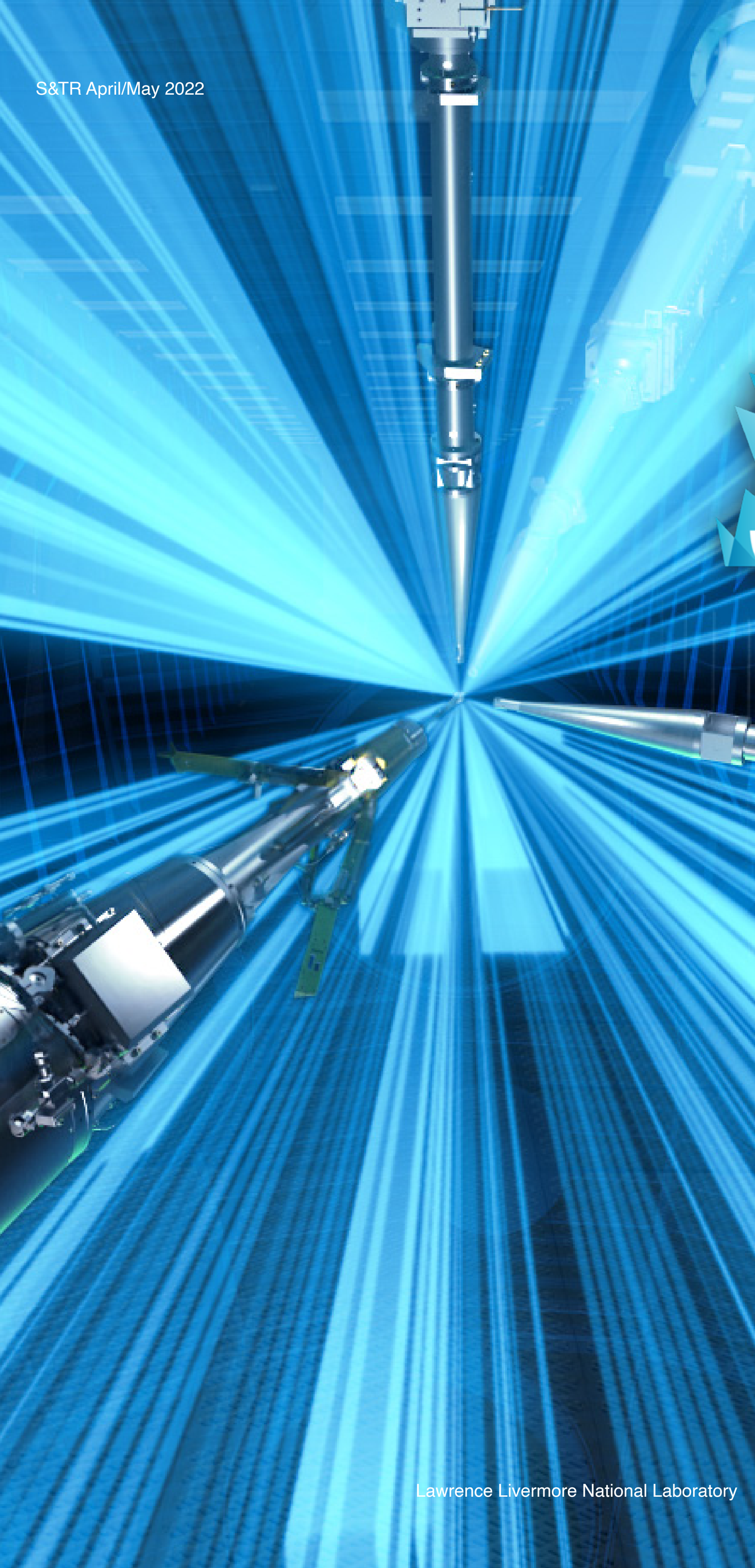
Our feature concludes with a summary of the Laboratory's record-breaking, near-fusion-ignition experiment in August 2021: a "shot heard round the world" achievement. But that's not the end of the story; in fact, it's a beginning. The success at NIF and recent advances in magnetic fusion energy research prompted a March 2022 White House Summit, "Developing a Bold Decadal Vision for Commercial Fusion Energy," in which I was honored to participate. This summit highlighted the many advances in fusion science over the past year. These advances make a vigorous approach to developing clean fusion energy a priority for the nation and one in which our Laboratory will play an exciting role.

The two highlights in this issue exemplify our Laboratory's commitment to environmental protection. The first article describes our exacting processes to safely characterize and ship transuranic waste generated by national security programs at the Laboratory to the U.S. Department of Energy's Waste Isolation Pilot Plant in New Mexico. The second highlight presents an unusual application of Laboratory expertise in isotope hydrology, often applied to inform public policy on water issues. In this case, we used our capabilities to solve the mystery of local flooding at a neighboring vineyard and to identify the water's source. While successes such as these may not always be "heard round the world," they illustrate the breadth of our capabilities to make a difference in the world.

■ Kimberly Budil is Director of Lawrence Livermore National Laboratory.

BEAMING WITH EXCELLENCE

After 50 years of pioneering laser research along with experimental and computational advances, the Laboratory and the inertial confinement fusion community stand at the threshold of ignition.



50 Years

HUMANKIND'S history is a tapestry of invention and application, both scientific and technical. From learning to make tools and control fire, to understanding complex astrophysical phenomena and developing ever-more advanced machines, people are continually striving to investigate, innovate, and discover in the pursuit of knowledge. In 2021, Lawrence Livermore researchers and colleagues from collaborating institutions working at the National Ignition Facility (NIF) added another stitch to this tapestry. After millennia of looking up at the stars, humankind now stands at the threshold of replicating one.

Recreating fusion, the process that powers the Sun, within a laboratory has long been a grand challenge of scientific research. On August 8, 2021, the research team conducted a shot that produced a record-breaking 1.3 megajoules (MJ) of fusion energy by imploding a deuterium-tritium (DT) fuel capsule with 1.9 MJ of laser energy. The capsule, located within a hohlraum that converted the laser light into x rays, produced about six times as much fusion energy as the x-ray energy it absorbed. The shot marks the first time in a laboratory that scientists have observed signs of a self-sustaining wave of nuclear reactions—thermonuclear burn—in the DT fuel, opening a fundamentally new regime to explore and advance the Laboratory's critical national security mission and future fusion energy applications.

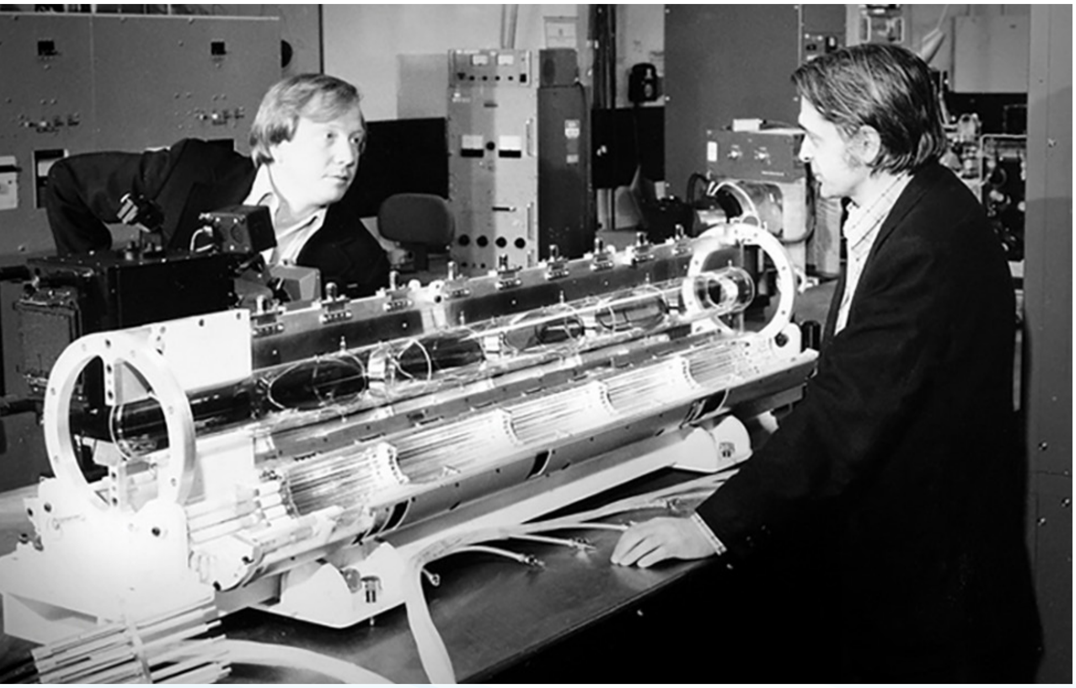
This monumental achievement was the culmination of painstaking efforts undertaken by a team of multidisciplinary experts over multiple decades. Since the inception of Lawrence Livermore's Laser Program 50 years ago, scientists and engineers from across the Laboratory have been at the forefront of scientific and technological innovations that have paved the way to the August 2021 milestone. These advancements were a concerted effort of Livermore and collaborators including industrial and academic partners, Los Alamos and Sandia national laboratories, the University of Rochester's Laboratory for Laser Energetics (LLE), General Atomics, and the Massachusetts Institute of Technology (MIT). Being at the threshold of ignition as defined by the National Academy of Sciences (NAS)—where more energy is produced by the fusion reactions inside the fuel capsule than the amount of laser energy delivered to the target—builds on the work of the entire team, including the people who pioneered inertial confinement fusion (ICF) research since the Laboratory's earliest days.

Driven by Purpose…and Lasers

In the 1950s, Laboratory physicist John Nuckolls and colleagues were investigating whether it was possible to ignite a fusion explosion without a fission bomb as a means of generating power for commercial applications. They ran the latest, state-of-the-art computer codes and found that radiation at temperatures of a few hundred electronvolts (eV) could implode a capsule of DT fuel and initiate a very small-scale fusion explosion. However, the process needed a driver. When physicist and engineer Theodore Maiman demonstrated the first laser in 1960, its implications for other fields of research began to take shape. Nuckolls, who later became Laboratory director, saw the laser as the tool for achieving fusion ignition through ICF, wherein the small mass of DT could be compressed and heated through the laser-driven implosion of the fuel capsule.

"In 1972, John and Livermore colleagues Lowell Wood, Albert Thiessen, and George Zimmerman published a defining set of challenges and requirements that would be faced in trying to achieve an ICF laser-driven implosion," says John Lindl, a senior scientist in the NIF and Photon Science (NIF & PS) Principal Directorate who has been part of Livermore's laser research since he joined the Laboratory in 1972. "Their calculations used an early version of the LASNEX code, which has been enhanced over the years for laser fusion predictions and developing ICF target designs."

Throughout the 1960s, nascent experimental laser research at the Laboratory was disjunct, and progress was slow to develop a high enough power laser for fusion applications. In 1971, Laboratory Director Michael May and Associate Director for Plans Carl Haussmann took steps to consolidate the distributed expertise in ICF code development, specifically LASNEX; laser–plasma interactions (LPIs); and high-power, short-pulse lasers into a single program. Haussmann, the program's first leader, built a crackerjack team with the help of John Emmett, who was head of solid-state laser research at the Naval Research Laboratory and became the Laboratory's Y-Division leader in 1972; and physicist William Krupke from Hughes Aircraft Company.



Physicists John Emmett (left) and John Nuckolls were two of the most influential pioneers of the Laboratory's Laser Program and inertial confinement fusion (ICF) science and technology.

Under their collective leadership, the scope of the Laser Program expanded, the workforce grew, and plans were initiated to construct a series of bigger, more complex, higher energy lasers for achieving ICF, with an eye on developing a 10-kilojoule (kJ) class, 20-beam, solid-state laser called Shiva.

In 1974, the Janus laser came online and was the first Livermore system to carry out target compression experiments for fusion research. Compared to the 1-joule (J), 1-nanosecond (ns, billionth of a second) infrared pulses of early 1970s lasers, Janus was a powerhouse. In its first iteration, the single-beam laser, made from commercially available silicate glass, produced 20 J and 0.2 terawatts (TW) in just 0.1 ns. Later, the addition of a second beam resulted in achieving 40 J. Experiments using Janus were instrumental in demonstrating direct-drive implosion of a spherical DT target—wherein the laser directly irradiates the capsule containing the fuel—and in helping researchers gain insight into the complex physics involved. Janus experiments also led to development of better diagnostics for measuring implosion characteristics and further improving LASNEX.

Janus was followed by the one-beam Cyclops laser in 1975 (developed as a prototype and test bed for Shiva components) and the two-beam Argus laser (designed for direct-drive experiments) the next year, both of which contained neodymium-doped phosphate glass amplifiers. Lindl says, “Neodymium’s anticipated flexibility in pulse format as well as its potential for light frequency conversion to a shorter wavelength were strategic reasons for its implementation.”

During this time, physicists were also making inroads in target design and, based on experimental data, pivoted to pursue ICF through indirect drive, wherein the laser heats the inside of a cylindrical enclosure called a hohlraum to produce x rays that then irradiate the spherical fuel capsule contained inside the casing. Argus produced up to 4 TW and enabled more extensive radiation-driven experiments, allowing scientists to study laser–plasma interaction (LPI) physics and laser propagation limits in more detail. Argus was also the first laser with integrated spatial filters that were made possible through technology developed by laser scientist John Hunt. The filters help maintain beam quality over long propagation distances, thus reducing optics damage.

Then in 1977, all that was learned from Janus, Cyclops, and Argus came together in the stunning $25-million, 20-beam Shiva laser. Nearly the size of a football field, Shiva delivered 10.2 kJ of infrared laser light in less than 1 ns during its first full-power firing. Overall, Shiva offered higher power and plasma temperatures, better control over experimental conditions, and greater fuel compression than any previous laser. Two years after it came online, Shiva compressed a fusion fuel capsule to a density 50 to 100 times greater than its liquid density, an unprecedented achievement in laser research.

The 20-beam Shiva became the world’s most powerful laser in 1977, delivering an unprecedented 10.2 kilojoules of energy in less than a billionth of a second in its first full-power firing. Shiva’s laser bay (shown here) captures the large scale of development taking place by the late 1970s.

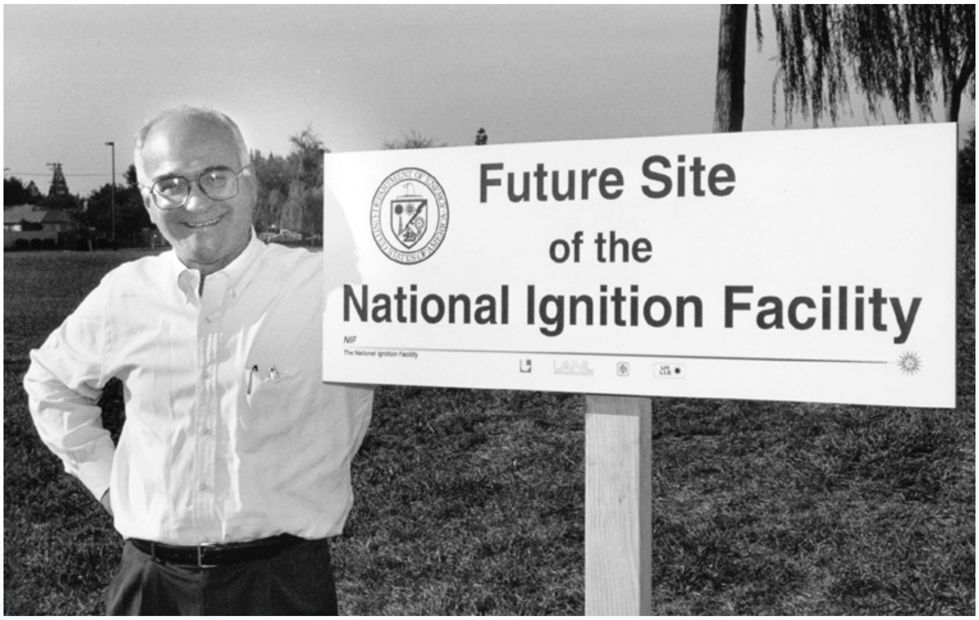
Notably, experiments with Shiva, and early research on Argus, confirmed that a more powerful laser utilizing a different light frequency would be needed to achieve ignition. Early theoretical work, including that by Bill Kruer and Livermore colleagues, indicated that the production of hot electrons from LPIs at the intensities required for ICF might well require laser wavelengths shorter than 1 micrometer (μm). Indeed, the interaction of Argus and Shiva’s high-power infrared beams with the hohlraum plasma generated physics that produced a large number of extremely hot electrons and disrupted control over implosion symmetry. Lindl says, “Through demonstration experiments performed on

Argus and additional scaling experiments with Shiva, we concluded a shift to shorter wavelength light was necessary to reach the hohlraum temperatures needed for ignition." Similar experiments on the laser direct-drive approach at LLE and other institutions also showed the need for shorter wavelength light.

With this finding, the Nova laser, in development, was reimagined. Nova's prototype, Novette, was the first multikilojoule system to include a subsystem of plates made of potassium dihydrogen phosphate (KDP) crystals for converting 1-omega (1.053-µm wavelength) infrared light to a higher frequency. Novette experiments carried out with 2-omega (0.53-µm wavelength) and 4-omega (0.265-µm wavelength) light showed that these shorter wavelengths facilitated coupling of the laser energy to the target and reduced laser–plasma instabilities. However, since optics damage becomes a greater challenge with shorter wavelengths, the decision was made to use 3-omega (0.351-µm wavelength) ultraviolet light for Nova. The 10-beam laser produced up to 30,000 J of ultraviolet laser light and 40 TW of power in 2.5-ns pulses. Nova generated the largest laser fusion yield in prior history—a record 11 trillion fusion neutrons—and achieved implosion symmetry sufficient to compress a fuel capsule to about one-thirtieth its original diameter. During this period, Lawrence Livermore's broader weapons program and other institutions began using Nova for a wide range of high-energy-density experiments, demonstrating the utility of lasers for understanding issues important to weapon physics.

Altogether, six large fusion laser systems were engineered and built in 10 years after the Laser Program's inception, and the pace of laser construction matched the growth of diagnostics and target fabrication capabilities, computer simulation tools, and theoretical understanding to continually improve laser capabilities and experimental results. Emmett attributes this success to the people. "We had several hundred people working together in amazing harmony to accomplish something that we all thought was terrifically exciting," he says. "I'd never seen a team work together the way we did."

Nova, which operated from 1984 through 1999, and additional experiments on the Omega laser at LLE, provided the primary experimental basis for the physics of laser-driven, indirect-drive implosions. Coordinated underground explosives tests with Los Alamos would further advance knowledge of the physics required for ignition and demonstrated that although no showstoppers were evident to achieving ICF ignition, an even bigger facility than Nova would be needed to make it a reality. Lindl says, "With Nova at energies below those needed for ignition and the experiments at much larger energies that could be conducted underground, our goal was to bracket the requirements for a future ignition facility."



Vic Reis, then Department of Energy Assistant Secretary for Defense Programs, visits the proposed construction site for the National Ignition Facility (NIF) in 1996. Reis played a key role in the development of the Stockpile Stewardship Program, including plans to build NIF.

A New Era in Laser Research

As the plans for NIF began to take shape, scientists concluded that if they could reach 300 eV hohlraum temperatures, stabilize hydrodynamic instabilities, maintain acceptable LPI effects, and adequately control the capsule's implosion symmetry, then ignition would be possible with a 1 to 2 MJ laser. To make this concept work, NIF would have to go far beyond the performance of what its predecessors could achieve. Laser Program scientists would have to develop an integrated hohlraum and capsule design that could be driven at the needed 300 eV temperatures, and the capsule design had to include a high-quality cryogenic DT layer inside a spherical shell—a central feature of ignition designs.

NIF's development was almost prescient as the changing global landscape of the early 1990s necessitated its delivery. The Soviet Union collapsed, the Cold War ended, and in 1992 U.S. President George H. W. Bush instituted a moratorium on underground nuclear testing—a decision that would have a profound impact on the nation's overall strategy for maintaining the U.S. nuclear weapons stockpile. In the wake of these world-changing events, Vic Reis, in his role as the Department of Energy's (DOE's) Assistant Secretary for Defense Programs, provided the imagination and political acumen to guide the nation's transition to the science-based Stockpile Stewardship Program (SSP).

The program endorsed an aggressive advance in computing capability and the development of key experimental facilities for testing and validating computational models—essential tools for maintaining the safety, security, and effectiveness of an aging and evolving nuclear weapons stockpile without nuclear testing. Nova had demonstrated the utility of lasers for studying weapon physics issues, and NIF would fill a critical mission need in support of SSP. (See *S&TR*, March 2021, pp. 4–11.) Reis's view was that if the Laboratory could sustain the SSP effort and commitment that would be required for ignition, then it would also demonstrate the kind of resolve needed to succeed in the broader SSP mission. Former Laboratory Director George Miller says, "Ultimately, confidence in the stockpile comes down to the confidence in the people making judgements about it. NIF is important both in terms of its ability to make measurements that are important to the stockpile, but equally—and perhaps in some ways more important—its ability to recruit and train people to make decisions about complicated subjects, particularly when you have inadequate knowledge."

Work began in earnest between Livermore and Los Alamos to formally establish the functional requirements and primary criteria for NIF: a laser design capable of providing 1.8 MJ and 500 TW at a laser wavelength of 0.351-µm light; a 192-beam, 4-cone beam geometry consistent with the required target symmetry; precision µm-scale pointing accuracy; and other power-dependent criteria. Scientists in the Laboratory's Laser Program built on their experience with Nova to develop Beamlet, which served as a prototype of the novel multipass architecture designed for NIF that increases the optical energy of each of the 192 laser beams from 1 J to 10 kJ. Beamlet demonstrated that the multipass laser architecture could meet the fluence (energy per unit area) requirements, an accomplishment prescribed by NAS as one of the key developments needed for approval of NIF construction.

Ultimately, given the evidence before it, the NAS committee responsible for reviewing the NIF proposal concluded that the facility had a 50–50 chance of achieving ignition given its specifications, and it would certainly be large enough to firmly establish the requirements for ignition and high gain. Construction had the green light, and groundbreaking began in 1997. Mike Campbell, associate director of the Laser Program at the time, says, "NIF faced many challenges in the early 1990s. We had to develop a strong technical, mission, and stakeholder-support strategy, one that ultimately resulted in official approval for NIF. I still remember after the groundbreaking, walking through building 381 thinking, 'We did it.'" The facility was completed 12 years later, and in March 2009 experiments began as part of the National Nuclear Security Administration's National Ignition Campaign (NIC) to facilitate NIF's transition from a construction project to a national user facility.

Necessity: The Mother of Invention

From a technology standpoint, NIF was a giant leap. NIF produces 60 times

Missions "Seemingly" Impossible

Lawrence Livermore was founded as a "new ideas Laboratory" in 1952. From the beginning, its purpose was to pursue innovative solutions to the nation's pressing needs, particularly to advance nuclear weapons science and technology during the Cold War. "The whole point of having places like the Laboratory is to do things that are incredibly difficult," says Lawrence Livermore Director Kimberly Budil. "We're here to take on the biggest, most gnarly technical challenges that our country and the world face." Indeed, Edward Teller, one of the founders of the Laboratory, proved early on that Livermore never shied away from tasks deemed impossible.

In the summer of 1956, the U.S. Navy sponsored an interagency study on antisubmarine warfare that led to discussion of whether it was possible to make a small, light, nuclear warhead in the 1-megaton range. When Teller recalled the event decades later, he said, "Everyone at the meeting, including representatives from Los Alamos, said it could not be done—at least in the near future. But I stood up and said, 'We at Livermore can deliver it in five years, and it will yield 1 megaton.'" Upon hearing the news, his Laboratory colleagues were incredulous. He continued, "They said, 'What have you done? We can't get a megaton out of such a small device, not in five years!'"

Yet, remarkably, in a three-year crash effort, Livermore scientists and engineers made sweeping technological breakthroughs to develop the highly effective W47 Polaris warhead in record time. Fast forward to today, and that same fighting spirit and superior ingenuity puts Livermore once more on the verge of a scientific accomplishment many deemed impossible: fusion ignition and gain.

as much energy with 10 to 20 times more power than Nova. The size of three football fields, NIF is the world's most energetic high-energy laser system, serving as a unique capability to advance ICF research, astrophysics, and planetary science; support stockpile stewardship and radiation effects experiments; and investigate the potential for controlled fusion as an energy source. The laser system accurately guides, amplifies, reflects, and focuses all 192 laser beams onto a centimeter-scale hohlraum containing a millimeter-scale fusion target in just 1 ns, delivering up to 2 MJ of ultraviolet energy and 500 TW of peak power. NIF implosions have generated temperatures in the target of more than 180 million degrees Fahrenheit (about 9,000 eV) and pressures of more than 300 billion Earth atmospheres, conditions that exceed those at the center of stars.

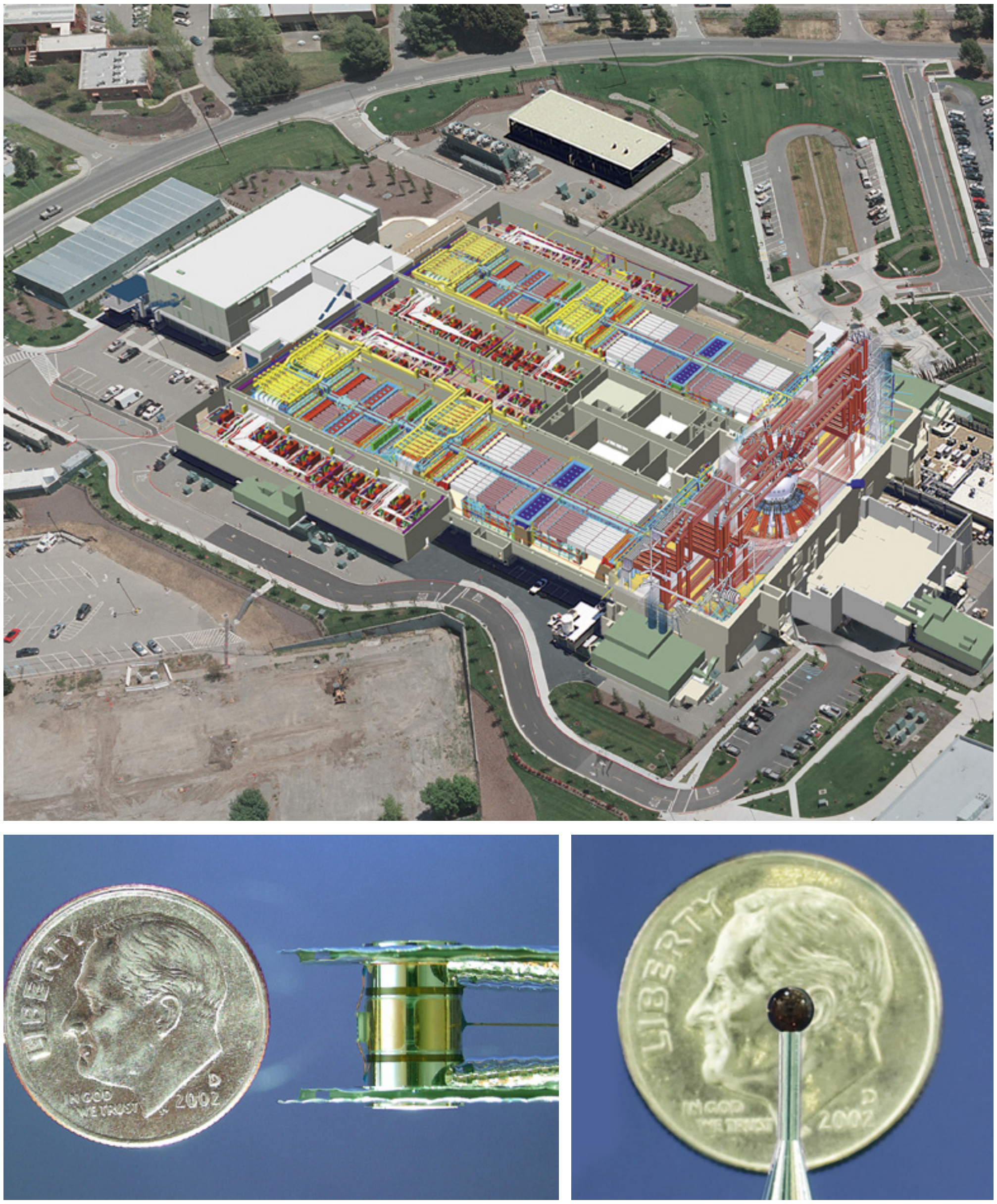
Ed Moses, NIF project manager from 1999 to 2005 and later Principal Associate Director for NIF & PS, says, "NIF was not an incremental advance. It was approximately a factor of a hundred more than Nova, and few institutions will take that kind of step. When I came to NIF, we looked at what NIF was; what it was being asked to do; and how it was being stressed from a science, technology, engineering, and management point of view; and we recognized important challenges that we had to face." The NIF team worked closely with industrial partners, in some cases for more than a decade before the project began, to advance technologies needed to complete NIF. Among those accomplishments are the so-called seven wonders of NIF: precision preamplifier modules that shape, smooth, and intensify

Beamlet, the single-beam prototype for NIF, demonstrated that the multipass laser architecture developed for NIF could meet the fluence (energy per unit area) requirements prescribed by the National Academy of Sciences.

laser light; continuous-pour laser glass for faster, less expensive glass production; rapid-growth KDP crystals; optical switches that work in conjunction with the amplifiers to increase the beams' energy; deformable mirrors to correct for wavefront errors; an integrated control system for conducting shots; and advanced manufacturing capabilities for target fabrication. In tandem with this work, the NIF team devised new experimental platforms and a vast array of optical, x-ray, and nuclear diagnostics for characterizing each experiment. (See *S&TR*, December 2010, pp. 12–18.)

In collaboration with partners including Los Alamos and Sandia; LLE; MIT; General Atomics; National Security Technologies, LLC; and the atomic energy agencies in the United Kingdom and France, Livermore scientists and engineers have created a suite of more than 120 diagnostics for characterizing experiments in unprecedented detail, and the number continues to grow. Vice President at General Atomics and NIF measurements lead Joe Kilkenny, says, "The quality of the diagnostics enables the high-quality science, and this is particularly true with NIF. We have achieved innovation and quality through a national diagnostic effort, drawing from the best ideas from each of the partner institutions."

Dedicated, collaborative research and development in target fabrication between Livermore, General Atomics, and Diamond Materials allowed major advances that ultimately led to production of ultrasmooth beryllium, high-density-carbon (HDC, or diamond), and plastic shells to provide ablators and stable uranium hohlraums, along with the associated precision metrology, which have all proven crucial for the ICF effort. Target engineering innovations led to the development of a robust platform for making full cryogenic targets while increasing cryo-target throughput to provide sufficient targets for the needed shots.



ICF requires perfecting technologies that span a dramatic range of spatial scales. The facility (top) is the size of three football fields and focuses 192 laser beams into a centimeter-scale hohlraum (bottom left) containing a millimeter-scale fusion capsule (bottom right), which is then compressed by a factor of 30 to a diameter comparable to that of a human hair. (U.S. dime shown for scale.)

Alongside these advances, the ICF team has also promoted the development of advanced computer codes that help guide experiments. For example, the Hydra code utilizes the unprecedented large-scale computing hardware and various software libraries developed by the Laboratory's Advanced Simulation and Computing (ASC) Program to generate 3D simulations of ICF capsules and hohlraums.

Hydra, together with exceptional ASC computational resources, has played a critical role in improving physics understanding on the path to ignition.

Another 10 Years of Innovation

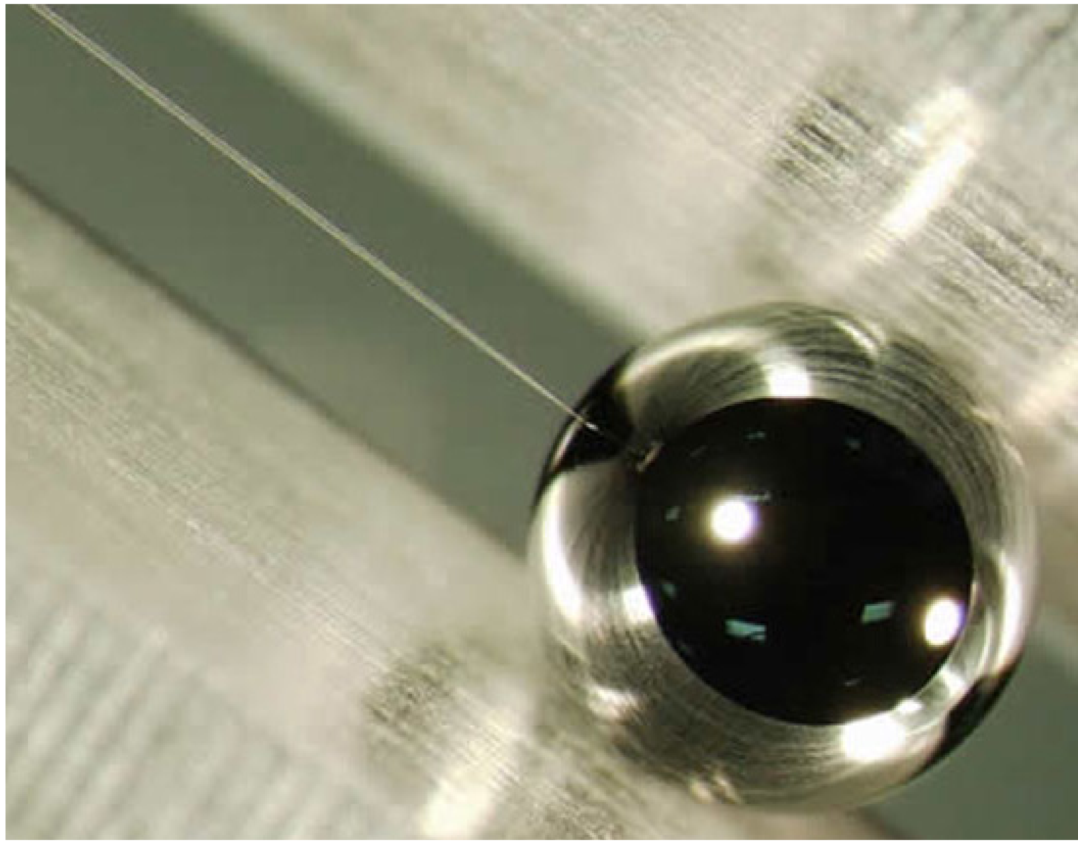
Since 2009, when experimental operations began, NIF scientists and engineers have continually improved the laser's performance, tuning, accuracy, and shot reproducibility, among other capabilities. (See *S&TR*, March 2013, pp. 10–17.) During NIC, which ended in 2012, the NIF team installed and qualified many target diagnostics, facility capabilities, and experimental platforms; implemented a target positioner diagnostic for fielding cryogenic DT layered targets; determined how to make high-quality DT ice layers; implemented target fabrication capabilities to meet the stringent requirements; and advanced the final optics sufficiently to deliver more than 1.8 MJ and 500 TW. Mary Spaeth, NIF chief technologist from 1999 to 2012, says, "NIF fully meets its original design requirements. After solving all the challenging design and engineering problems for building NIF, the final key for meeting its power and energy goals has been the ability to recycle and repair its damaged optics for continued use in the laser."

A large ICF laser system must provide both energy and power on target, while delivering that energy with wide variations in pulse shape. Follow-on experiments after NIC led physicists to investigate modifications to the laser pulse as a means of improving implosion symmetry and overall target performance. Researchers made a breakthrough in 2013 when they conducted an experiment using a "high-foot" pulse shape—three shocks characterized by a higher power initial pulse and shorter pulse duration (15 ns versus 20 ns) compared to the previous "low-foot" pulse specifications. (See *S&TR*, June 2014, pp. 4–10.) "The high-foot design tested the hypothesis that ablation Rayleigh–Taylor instability was a performance-limiting factor during the NIC experiments and that by better controlling it, we could make a step to higher fusion performance," says chief scientist Omar Hurricane. "These experiments were extremely exciting as we obtained more than an order of magnitude increase in fusion yield performance in a half-a-dozen DT experiments and obtained the first experimental demonstration of alpha-heating and fusion fuel gain."

Target Area Operator Bill Board removes an image plate from the NIF Dilation X-ray Imager (DIXI), the world's fastest x-ray framing camera. It produces images of an imploding target capsule with 10 times faster temporal resolution than previous systems. DIXI is one of 120 NIF diagnostics developed for characterizing experiments in unprecedented detail. (Photo by James Pryatel.)

Both the high-foot and earlier low-foot shots used hohlraums with helium gas fill to slow down the inward expansion of the cylinder's walls during the experiments. In 2013, experiments showed that reducing this gas fill by a factor of 3 to 5 dramatically reduces LPI effects in the hohlraum. However, a reduced gas fill shortens the pulse lengths that can be utilized for NIF before control over implosion symmetry is lost. To utilize the lower gas fill more effectively, scientists switched from plastic capsules to HDC ones. Reductions in the size of the tiny fill tubes used to inject the DT fuel into the capsule also paid dividends. To reduce the x-ray emissions from fill-tube material injected into the compressed fuel, scientists at General Atomics reduced the size of the fill tubes from 10 to 5 µm in diameter, and ultimately to 2 µm (for comparison, the diameter of a human hair is approximately 70 µm) and achieved up to double the neutron yield.

Through the tandem paradigm and iterative process of experiments and simulations, bolstered by data captured from the ever-growing number of diagnostics and techniques, scientists



Scientists reduced the size of the fill tubes—used to inject the deuterium–tritium fuel into the capsule—from 10 to 2 micrometers (µm) in diameter. Shown here is the 2-µm fill tube (thin needlelike object) inserted into a high-density-carbon capsule. The significant decrease in size improved the implosion symmetry of the target and doubled the neutron yield. (Photo courtesy of General Atomics.)

have and continue to make great strides in understanding and enhancing laser tuning, pulse shaping, and target components and construction. "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 programs," says NIF Director Doug Larson. Now, the insights and improvements made in the last 10 years have brought NIF to the edge of what it was built to do.

A Major Fusion Milestone

On August 8, 2021, NIF laser beams imploded a target capsule to create a central hot spot of dense DT fuel and trigger a self-sustaining wave of fusion reactions. This historic experiment achieved a record ICF yield of more than 1.3 MJ of fusion energy, a yield from the imploding capsule about six times the x-ray energy it absorbed. As defined by NAS, ignition occurs when the fusion energy produced exceeds the amount of laser energy delivered to the target chamber. The measured fusion yield

Hybrid-E experimental lead Alex Zylstra (left) and target design lead Annie Kritcher stand in the NIF target bay holding a Hybrid-E target. This target design was used in the record-breaking fusion shot at NIF on August 8, 2021. (Photo by Mark Meamber.)

was about 70 percent of that goal. The laser system delivered 1.9 MJ, which squeezed the central DT fuel within the capsule to eight times the density of lead and generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second.

This experiment brings NIF shots into a fundamentally new physics regime with signatures of a hotspot undergoing rapid self-heating and beginning to propagate burn into the surrounding dense shell, which causes increases in fusion yield, temperature, hotspot mass, and energy. This shot produced eight-times higher yield than the previous NIF record and 25-times higher yield than was achieved prior to November 2020. "An incredible amount of teamwork got us to this point," says former NIF Director Mark Herrmann, now director of the Laboratory's Weapon Physics and Design Program, "from conceiving of ICF 60 years ago in the revolutionary work by John Nuckolls to developing a series of lasers; advancing optics, target fabrication, computer simulations, and designs; understanding the science; and fielding the diagnostics that allow us to measure these extraordinary events."

The success of the result relied on extensive efforts during the year to improve the target design (called Hybrid-E), which includes a large HDC capsule and the 2-µm-diameter DT fill tube. NIF Target Fabrication Program Manager Abbas Nikroo says, "Changes to the HDC deposition and polishing processes allowed major improvements in the quality of HDC shells where capsule defects were reduced by two orders of magnitude—a key target fabrication improvement that, combined with the innovative hohlraum drive, enabled this significant achievement."

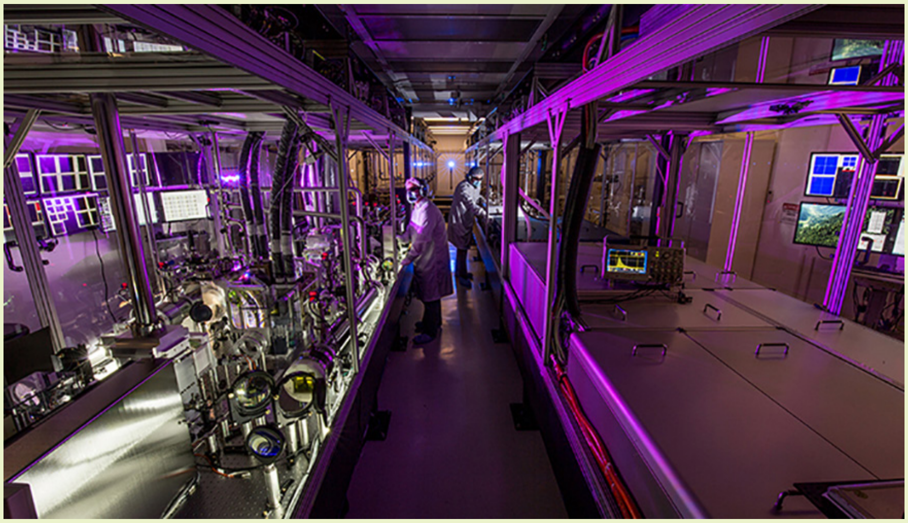
Compared to earlier NIF experiments, Hybrid-E uses a larger capsule and a more efficient hohlraum to couple more energy to the compressed fuel resulting in an increase in hotspot pressure and temperature. "A major challenge in increasing the coupled energy to the hotspot by making the implosion larger with the fixed laser energy and not reduce the hotspot pressure was to carefully balance and optimize many design parameters simultaneously," says Hybrid-E lead designer Annie Kritcher. To achieve a symmetric implosion with the larger capsule, the wavelength of each laser beam is slightly adjusted to help balance x-ray energy that drives the implosion. The entrance holes that let

Technology Development through Fusion Research

Over its 50-year history, the Laboratory's Laser Program has developed many high-profile spin-off technologies from inertial confinement fusion (ICF) research. The field of laboratory astrophysics was born during Nova's era (1984–1999) and has enabled scientists across the world to study astrophysical phenomena in greater detail. The emergence of short-pulse lasers, including the world's first petawatt laser on Nova, extended astrophysics work to relativistic regimes and other applications including plasma-based, high-energy particle acceleration. Short-pulse lasers also spurred the broader area of high-field physics.

Extreme ultraviolet lithography—developed from Livermore's early work with precision engineering, metrology, and coatings—supported the continuation of Moore's Law, driving ever-smaller and faster microprocessors. Optical technologies developed by the Laser Program include high-damage-threshold silica, gratings, and coatings. Laser applications advanced metal conditioning (peening) to increase the strength and lifetime of high-stress components such as jet turbine blades. An outflow of target diagnostic work on Nova led to micropower impulse radar, which was extensively licensed for use in automotive cruise control, tape measures, stud finders, and many other products.

The rich history of the Laser Program includes many other examples that illustrate the contributions of ICF research. In the years to come, continuing to improve the flexibility, power, and precision of the National Ignition Facility will spur further technology advances that will impact science and industry well beyond ICF.



High-repetition-rate lasers, such as the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS)—the world's most advanced and highest average power diode-pumped petawatt laser—have been made possible through ICF research.

laser light into the hohlraum were also reduced in size to increase the coupled energy. The experiment used one of the highest quality target capsules ever shot at NIF, with a surface virtually free of pits and voids and 99.7 percent shell thickness uniformity.

With the August 8, 2021, shot, improvements to establish better reproducibility enabled the laser to deliver a pulse very close to the target design specifications. "There was a certain amount of serendipity in the 1.3-megajoule experiment. It required more than a good design concept. It needed a high-quality target, a precise laser pulse, and uniform energy delivery—all those things coming together synergistically to achieve the result," says Laboratory Director Kimberly Budil. "We are squarely on the threshold of ignition, and well positioned to take the next steps toward target gain greater than one and beyond. The goal is to create a stable, repeatable, robust, igniting platform, and our entire team is hard at work to make this possible."

Lawrence Livermore Director Kimberly Budil (far left) served as moderator for the opening panel of the White House Fusion Summit on March 17, 2022. The first-of-its-kind summit convened leaders in fusion from government, industry, and academia to showcase the latest fusion achievements and technologies and discuss an inclusive, equitable 10-year strategy for developing commercial fusion energy.

The Future of Fusion

NIF's breakthrough experiment factored heavily in discussions during a recent White House Fusion Summit. Hosted by the White House Office of Science and Technology Policy and by DOE, the first-of-its-kind summit convened leaders in fusion from government, industry, and academia to showcase the latest fusion achievements and technologies and discuss a 10-year strategy for advancing development of commercial fusion energy.

Director Budil was requested to host a panel as part of the event. "We discussed where we are with fusion research based on results from NIF, tokamaks, new kinds of superconducting magnets, progress on ITER, and the work that still needs to be done," says Budil. "Several billion dollars in investments have been made in this area over the last year, and the goal is to build a demonstration plant to show that commercial fusion energy is viable. We have the only facility on the planet right now that can pursue the science to develop a stable, repeatable, igniting platform in the laboratory."

Together, the NIF team has constructed, tested, and fine-tuned an unprecedented laser facility. This achievement is the result of the decades of work in laser technology, target fabrication, diagnostics, and computer modeling developed through each of Livermore's major laser systems over 50 years of programmatic research. NIF Operations Manager Bruno Van Wonterghem says, "We've all made sacrifices to get here, but it is worth it to stand here now in a structure that many said could never be built, as it performs on a day-to-day basis what many believed it couldn't."

Producing an ignited fusion plasma in a laboratory is indeed a scientific grand challenge but when attained will provide new avenues of scientific exploration. "Fusion is one of those fundamental processes of mother nature. It's the energy source of the universe," says Jeff Wisoff, principal associate director for NIF & PS. "Being able to control that process in a laboratory and use it someday would be one of the major milestones of human history, like gaining fire."

—Caryn Meissner

(Additional resources provided by John Lindl and Paul Chrzanowski)

Key Words: Argus, Beamlet, computer simulation, Cyclops, deuterium–tritium (DT), diagnostic, fusion, hohlraum, Hybrid-E target, inertial confinement fusion (ICF), Janus, laser, laser–plasma interaction (LPI), megajoule (MJ), National Ignition Facility (NIF), Nova, Novette, Shiva, terawatt (TW), White House Fusion Summit.

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TRULY Well-Managed Waste

RESEARCH experiments generate data, publications, new scientific discoveries, and—almost always—waste. For special nuclear materials (SNM) research supporting the Laboratory's stockpile stewardship mission, handling that waste safely requires expertise and diligent care.

The Laboratory is tasked with modernizing two aging nuclear warheads, as well as conducting annual assessments of three others. Scientific expertise with SNM is a key element in Lawrence Livermore's ability to conduct these assessments and certify modernized warheads as safe, secure, and effective without conducting an underground nuclear test. Laboratory scientists study the physical, chemical, and metallurgical qualities of SNM, such as highly enriched uranium and plutonium, as well as tritium. Tests analyze existing nuclear components, duplicate the mechanical motion and temperatures expected over a weapon's lifetime, and review approaches to replace components in the future. Along with research results come clothing, tools, debris, and residues contaminated with very small amounts of plutonium and other human-made radioactive elements.

Transuranic (TRU) waste shipments departed Lawrence Livermore National Laboratory last fall for permanent storage at the Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) in New Mexico.

Waste from elements with an atomic number greater than uranium and radioactivity exceeding a specific limit is labeled "transuranic" or "TRU" waste. The National TRU Program in the Department of Energy (DOE) Office of Environmental Management is charged with the safe disposal of TRU waste accumulating at DOE sites dedicated to SNM research, weapons production, and cleanup. "Lawrence Livermore takes special care to properly manage and dispose of all hazardous and radioactive waste," says Reggie Gaylord, manager of the Laboratory's Radioactive Hazardous and Waste Management (RHWM) Program. "Handling TRU waste adds another level of detailed planning and execution." Adding to the complexity of this task, only one location can accept the material: DOE's Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico.

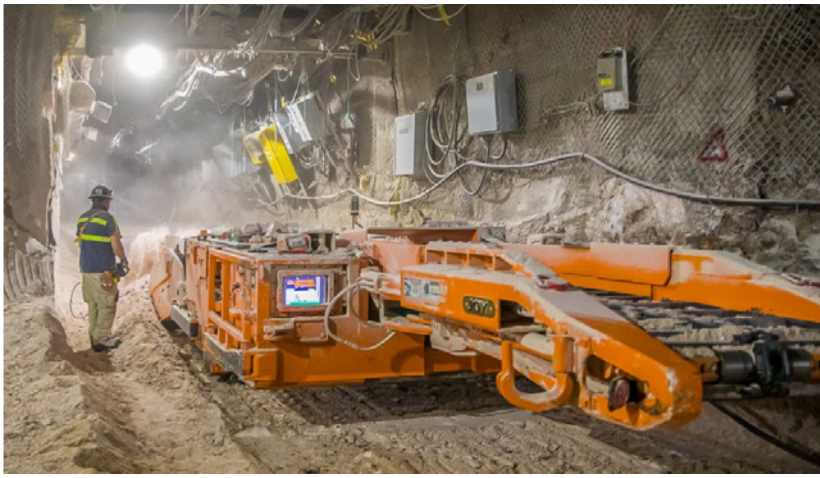
One-of-a-Kind Mine

Located in a nearly 610-meter-deep mine within a salt dome, storage areas at WIPP isolate and entomb TRU waste. Evaporation cycles 250 million years ago created WIPP's salt beds, and the fact that salt remains today indicates a lack of groundwater intrusion. To support the nation's nuclear defense programs, the National Academy of Sciences determined that geologically stable, impermeable salt beds were the best option to isolate radioactive waste to protect human health and the environment for millions of years. The salt rock is easily mined to create disposal rooms yet creeps slowly to seal all fractures and naturally close openings.

Construction of WIPP started in the 1980s, and TRU waste was first accepted there in 1999. Since its commissioning, WIPP has accepted TRU waste from 22 sites in the DOE complex. The bulk of the waste has come from former weapons production sites such as the Rocky Flats Environmental Testing Site and Los Alamos and Idaho national laboratories. Smaller amounts have arrived from the Savannah River Site, the Nevada National Security Site, and national laboratories such as Lawrence Livermore.

WIPP stores two types of TRU waste: contact-handled (CH) TRU waste—about 96 percent of the total at WIPP (and the only TRU waste generated at Livermore)—or remote-handled (RH) waste. The radiation dose of CH TRU waste, measured at the waste container's surface, does not exceed 200 millirem (mrem) per hour compared to RH TRU waste's dose rate of up to 1,000 rem per hour. The average American is exposed to 200 mrem annually from natural radiation in the environment and diagnostic x rays. During transportation, lead shielding around all TRU waste shipping casks reduces radiation doses to very low levels. Once inside WIPP, CH TRU waste barrels and boxes are stacked in rows in underground disposal rooms, while higher dose rate RH TRU waste canisters are placed in boreholes drilled into WIPP's salt walls.

Shipments of radioactive waste from DOE facilities ceased between 2014 and 2017 following the 2014 accidental leak of TRU waste from a storage drum generated at a DOE site and emplaced a year earlier. Although the public was never at risk, DOE enacted improved storage and monitoring practices. The Environmental Protection Agency (EPA) recertified WIPP as safe for radioactive waste disposal in 2017, and the facility regained DOE accreditation for high safety and health performance. WIPP operates under stringent controls to prevent the release of radioactive materials.



WIPP, located in a New Mexico salt mine, isolates and entombs TRU waste in storage chambers carved into salt walls. (Photo courtesy of WIPP.)

Staff in Lawrence Livermore's Radioactive Hazardous and Waste Management Program sort contaminated debris in the onsite Centralized Waste Processing Line, a large glovebox.

Meticulous Process

Operations staff in the Laboratory's Weapons and Complex Integration (WCI) Principal Directorate consider waste management strategies during experiment design and facility startup to ensure the waste has a disposal path. Day-to-day, TRU waste generated onsite is segregated into mixed debris such as gloves, tape, tools, paper, and aluminum foil; solidified inorganics and organics (liquids transformed to solids by clay); and salts. Debris, the largest component of this waste stream, is broken down into individual pieces of metal, plastic, even balls of tape. This painstaking task is performed in a large glovebox located in the Laboratory's plutonium facility—the Centralized Waste Processing Line—by RHWM program personnel. "The level of training required at every stage of this process is incredible," says Gaylord. "To become a Certified

Fissile Material Handler takes many months, and handlers are overseen by supervisors with multiyear training and experience."

After sorting, waste characterization ensures TRU waste can be shipped safely to WIPP. First, waste that cannot be accepted at the disposal site, such as liquids, batteries, and sealed containers, is identified and segregated. Trained visual inspectors examine waste during generation while older waste undergoes radiographic testing. In the next step, gamma-ray spectroscopy performed with high-purity germanium detectors identifies and measures radioactive isotopes present in waste containers. Finally, container headspace sampling using gas chromatography–mass spectrometry looks for flammable volatile organic compounds and other gasses, such as hydrogen and methane, that can form from the interaction between radiation and plastics or organic waste. Acceptable Knowledge, defined as a combination of waste generation process knowledge, data analysis, and facility records, complements the three-part waste characterization process. "The level of detail required to complete each waste characterization step has increased tremendously since the 2014 accident at WIPP," says Rod Hollister, the Laboratory's TRU waste subject matter expert. "The biggest challenge has been meeting the level of Acceptable Knowledge associated with each waste stream."

Following characterization, waste drums are stored under tightly controlled conditions in RHWM's nuclear facilities. When enough certified containers accumulate to warrant shipment, Laboratory and WIPP experts collaborate to ensure TRU waste is packaged and shipped in compliance with EPA and Department of Transportation regulations. TRU waste is shipped in a specially designed shipping container called the TRUPACT II, certified by the Nuclear Regulatory Commission to provide the highest level of safety and the capability to withstand severe accidents. Trucks en route to WIPP are tracked by satellite and come equipped with redundant communication systems.

Enduring Shipment Model

Removing TRU waste has priority for DOE's National Nuclear Security Administration (NNSA) to ensure workplace and public safety as well as uninterrupted SNM research. However, shipments to WIPP must be paced to avoid overtaxing limited shipping resources and overwhelming the facility. Prior

(a) Waste characterization includes head space testing for flammable gasses that can form when radiation from radioactive waste interacts with plastics and organic materials.

(b) The inner lid of a TRUPACT II container is certified for the safest possible shipment of waste from DOE sites to WIPP.

(c) Inspectors check the seal of a TRUPACT II container before use.

The 2020 shipping campaign safely transported waste containers that had accumulated for 10 years. Images show a container storage area before (left) and after (right) the shipping campaign.

to 2020, the Laboratory shipped TRU waste in 2004 and again between 2009 and 2010. Recognizing that Laboratory waste storage capacity limits would be reached after approximately 10 years, WCI operations staff started planning in 2016 for a 2020 campaign. "Approaching waste storage capacity in Superblock laboratories impacts programmatic work, since the drums of waste often must be stored in laboratories and work areas," says Hollister.

Hollister and project manager Clint Conrad, with more than 60 years in waste management experience between them, developed a detailed, multiyear plan to execute a 2020 TRU waste shipment to WIPP. "With that plan in hand, we obtained $16 million from NNSA for activities culminating in a 2020 shipment campaign," says Conrad. "Experts from WIPP's Central Characterization Program (CCP) partnered with us to make the plan a success."

The Laboratory and CCP share TRU waste management responsibilities during a campaign: the Laboratory ensures safe operation and handles any required remediation, and CCP is responsible for characterizing the waste. CCP inspectors relocate to the site for the duration of characterization activities. "Nothing leaves without our say," says Jackie Hulse, a CCP inspector who has worked with TRU waste since 2009. She and her CCP colleagues participate in several hours of training each day. In fact, each CCP inspector's credentials and training records in visual examination, nondestructive assay, or gas sampling are verified daily to qualify them for characterization activities.

For the 2020 campaign, the Laboratory–CCP team established onsite waste characterization capabilities by 2018, and the site was certified by DOE's Carlsbad Field Office, which manages WIPP, as well as the State of New Mexico and the EPA. From summer 2019 through early 2020, 874 drums and waste boxes were characterized onsite with only a few containers requiring follow-up analysis or repackaging.

Despite the 2020 shelter-in-place orders issued for San Francisco Bay Area counties, review and approval of Laboratory processes related to generating, evaluating, and characterizing waste continued. NNSA, DOE, and WIPP coordinated eight-week rolling WIPP shipments for Livermore's TRU waste. WIPP's Mobile Loading Team arrived in September 2020 and began placing characterized waste into TRUPACT II containers for shipment to WIPP. Laboratory staff including riggers, material handling technicians, and Environmental Safety and Health staff supported the loading effort. California and Nevada Highway Patrol officers inspected the vehicles, and the first shipment left Livermore on September 21, 2020. In the months that followed, 18 shipments comprised of 624 waste drums and 13 standard waste boxes made their way to the New Mexico facility.

Following the 2020 campaign, the Laboratory team capitalized on the training efforts and characterization facilities created for the shipping effort and pursued an enduring TRU waste certification model. "With the enduring program, staff remain in a trained and ready state rather than gearing up for a new shipment campaign every 10 years," says Gaylord. "Costs are lowered, and efficiency is increased." Laboratory and CCP personnel established a certified visual examination process, eliminating the necessity of radiographic examination since all waste would be examined when generated. Inspected waste can be transferred directly to waste drums at the Centralized Waste Processing Line. The non-destructive assay is performed using a CCP-certified process, and CCP personnel conduct flammable gas analysis once waste is packaged and moved to the RHWM storage facilities.

In October 2021, two shipments consisting of 70 drums were successfully shipped to WIPP. The Laboratory is continuing to accumulate containers for additional shipments approximately every 9 to 12 months. "We have successfully shifted from a periodic to an enduring model for TRU waste generation, characterization, and shipping," says Gaylord. "Not only have we increased our TRU waste-handling capabilities, we have created a more streamlined environment for the nuclear material testing and research that directly supports the Laboratory's stockpile stewardship mission."

— *Suzanne Storar*

Key Words: Acceptable Knowledge, Central Characterization Program (CCP), radioactive waste, special nuclear material (SNM), transuranic (TRU) waste, TRUPACT II, waste characterization, Waste Isolation Pilot Plant (WIPP).

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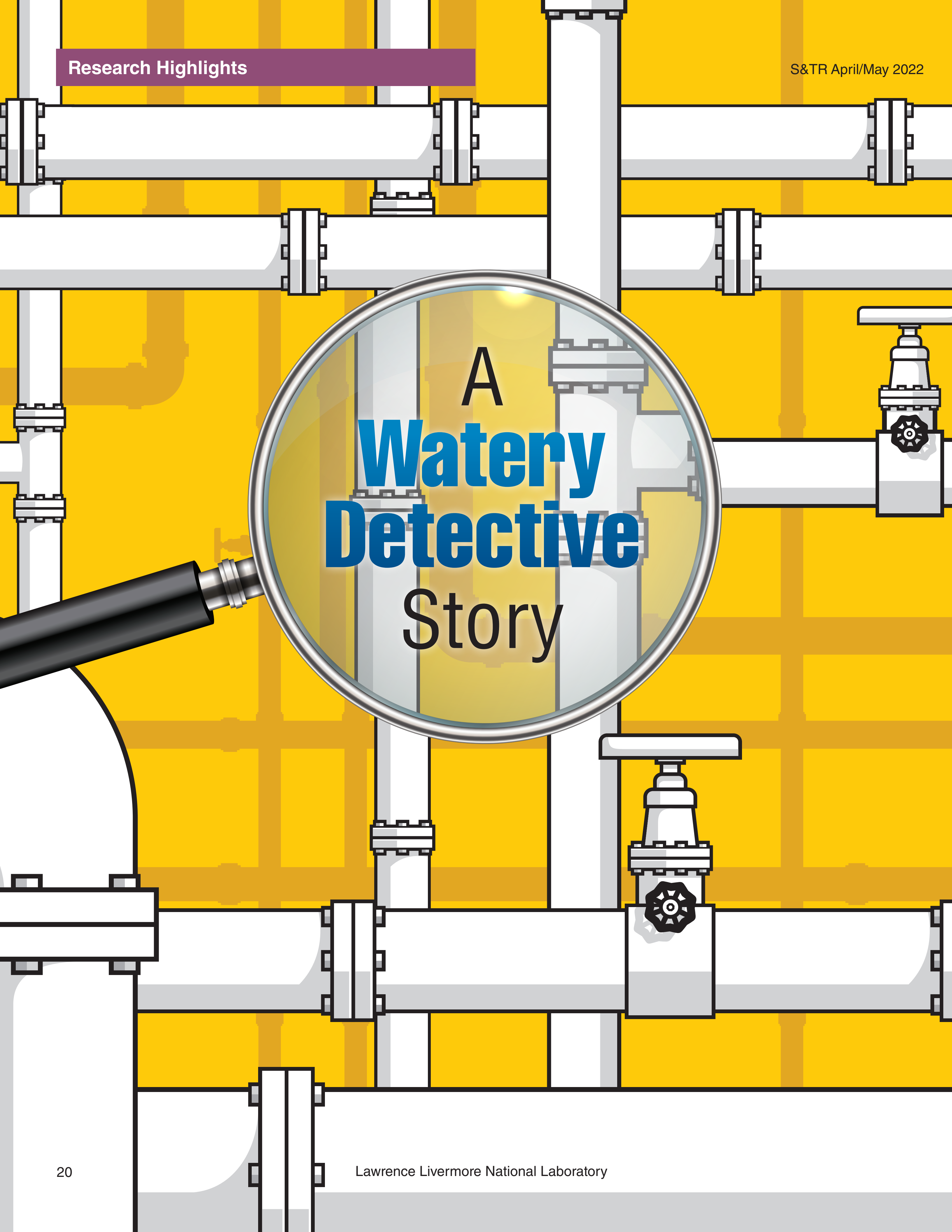


A Watery Detective Story

As with most mysteries, this one starts with a puzzling scene: a waterlogged field situated near Lawrence Livermore and Sandia national laboratories in Livermore, California. The property belongs to Wente Vineyards, a winery in the region, whose establishment predates the Laboratory by nearly 100 years. How the water got there and why was unclear, but the most likely suspect was a water pipeline running underneath the land—a pipeline that supplies water to both laboratories.

The laboratories' pipeline taps the Hetch Hetchy Aqueduct, which supplies water to 2.6 million people in the San Francisco Bay Area and runs north several miles through the Wente property to water tanks on Sandia/California land. In February 2021, Howard Depew, leader of the Laboratory's Mechanical Utilities Division, received a call concerning the flooded Wente field. As part of Lawrence Livermore's Infrastructure Maintenance and Utilities Department, Depew's division is responsible for overseeing the complex's water, compressed air, natural gas, and sewage lines, and for fixing any leaks. Depew's charge: investigate if the pipeline was the culprit or an innocent bystander.

The Hetch Hetchy water system carries water from the Hetch Hetchy Valley in Yosemite National Park in California's Sierra Nevada mountain range more than 250 kilometers to San Francisco, supplying water to 2.6 million people. (Photo courtesy of the National Park Service. Photo by Clarisa Flores.)

A Sopping Field, No Smoking Gun

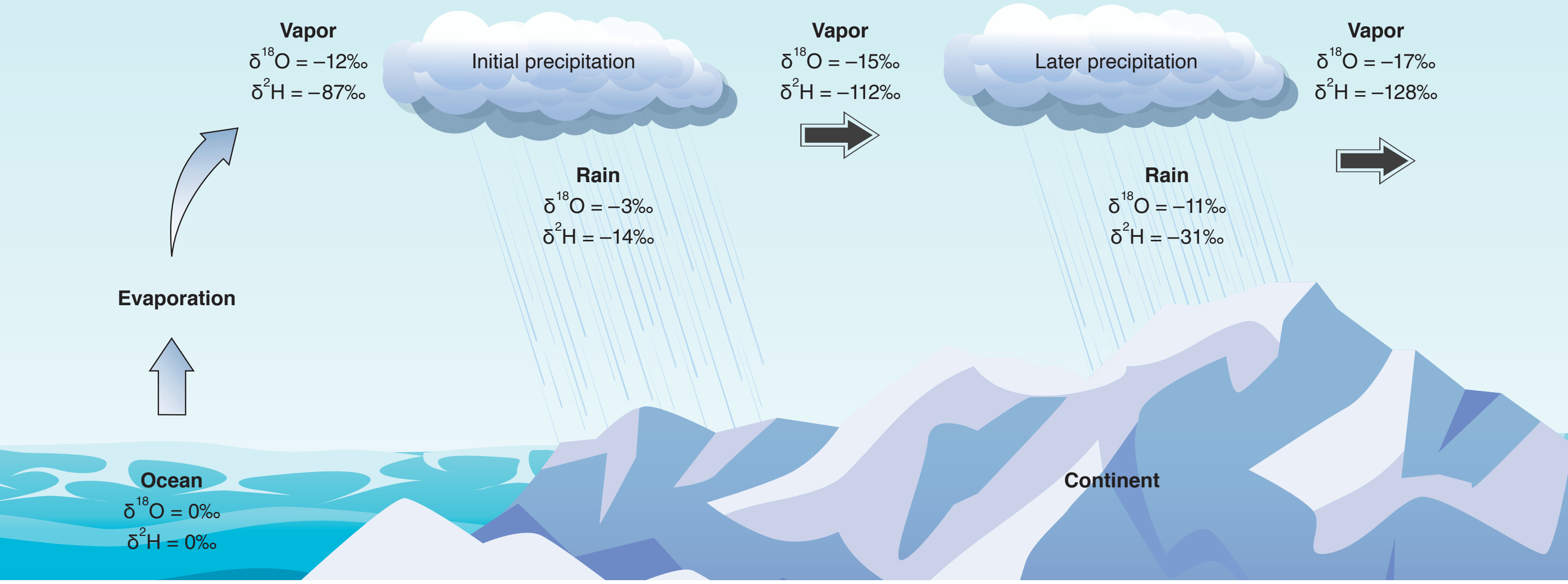
Depew's team met with Wente officials and with their permission began digging down at several locations along the laboratories' pipeline looking for the source of a leak. After months of fruitless digging and more than $100,000 expended, no leaks were discovered. Depew was frustrated. He was faced with the prospect of unearthing the entire pipeline to find the leak's location, a project that would cost the Laboratory and the Department of Energy (DOE) 10 times more money. Seemingly out of options, a serendipitous connection pointed the way to a solution.

Depew's colleague, Stephanie Bibby, group leader for Water Resources and Environmental Planning in the Environment, Safety, and Health Division, had a lead. She put Depew in contact with her husband, Richard Bibby, lead of Livermore's Environmental Radioanalytical Monitoring Laboratory, whose group specializes in analyzing radioisotopes in environmental samples. His colleague, Erik Oerter, a scientist in the Environmental Isotope Systems Group of the Nuclear and Chemical Sciences Division, uses isotope hydrology to identify sources of water as it travels through the water cycle, from precipitation to surface water to shallow groundwater to deep aquifers, and into our food and other materials. The Bibbys thought that Oerter could determine whether water samples from the field were linked to the Hetch Hetchy system or to some other source—confirming or eliminating the laboratories' pipeline as the perpetrator.

Early in his career, Oerter was a Colorado ski instructor and river rafting guide. He developed an appreciation for the water cycle in those jobs, and eventually obtained a doctorate in environmental science from the University of California at Berkeley. At Lawrence Livermore's Light Stable Isotope Geochemistry and Hydrology Laboratory, Oerter measures isotopic ratios of oxygen, hydrogen, and other elements in environmental samples to gain clues as to where materials in the sample—including nuclear materials, agricultural products, and water—originated. In the case of water, oxygen and hydrogen are key elements in determining a source's location.

Just the Chemistry Facts

Oxygen-16 (^{16}O) contains 8 neutrons and 8 protons and is the most common stable isotope of oxygen. In fact, the oxygen in Earth's water is 99.8 percent ^{16}O. Oxygen-18 (^{18}O), with 8 protons and 10 neutrons, forms only 0.2 percent of Earth's water supply. "Oxygen-18 is heavier, so it behaves differently," says Oerter. "Water molecules containing oxygen-16 are lighter than those with oxygen-18, so they will evaporate more readily. As a result, the vapor that evaporates from the ocean has less oxygen-18 than the liquid water from which it evaporated." Hydrogen in water molecules can form ^{1}H (protium), ^{2}H (deuterium), or ^{3}H (tritium)—containing no neutrons, one neutron, or two neutrons in its nucleus, respectively.



As water moves from the ocean to become rainwater that fills freshwater sinks on land, the isotopic ratios of oxygen-16 to oxygen-18 ($\delta^{18}O$) and hydrogen-1 to hydrogen-2 ($\delta^{2}H$) change. Each time the clouds (formed by evaporation from the ocean) travel and produce rainfall, the water becomes more depleted as it loses the heavier isotopes. The isotopic ratios are measured as negative parts per thousand, the relative depletion of the isotopes compared to a standard sample of seawater.

As rain clouds move across the North American continent from the Pacific Ocean, the rain that falls on land becomes more isotopically depleted (less ^{18}O) as it travels east, so its ^{16}O to ^{18}O ratio (expressed in units of negative parts per thousand) is different than that of ocean water. Rainwater's hydrogen isotopic ratio also shows depletion of ^{2}H compared to ^{1}H. The lower the ratio, the lower the quantity of the heavy isotope in the sample. Thus, water in the streams, lakes, and aquifers of different regions—from Livermore over the Sierra Nevada to the Rocky Mountains—each carry characteristic isotopic ratios. The oxygen and hydrogen isotopic ratios have been mapped in water across the United States and throughout the world, providing scientists with a way to trace the source of water should the need arise.

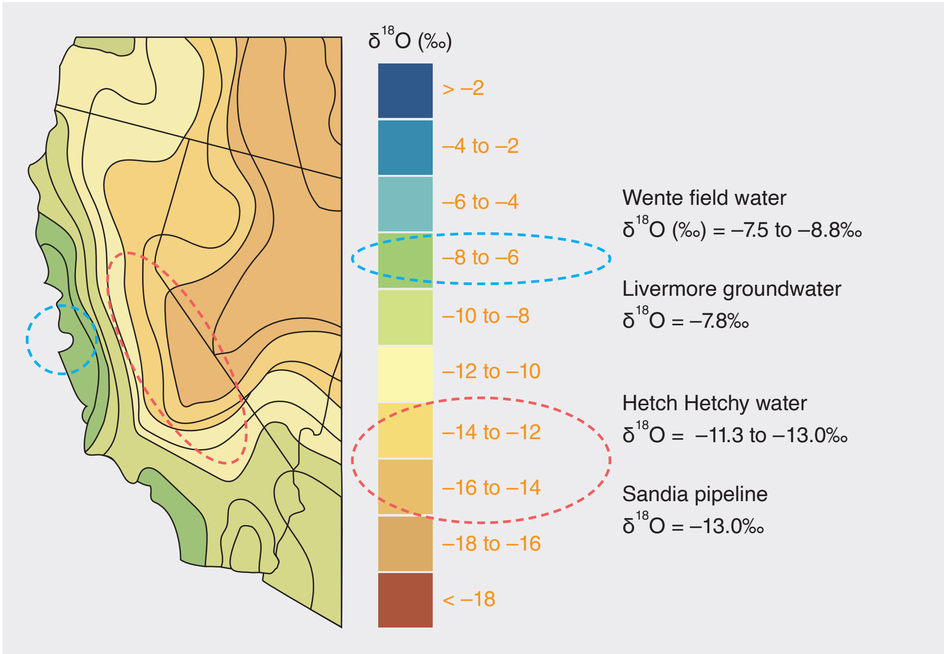
Earlier, Oerter and colleagues had conducted a study to better understand what water sources bioenergy crops, such as switchgrass, use to grow. Switchgrass is a potential source of carbon-neutral biofuels and a possible means to increase carbon sequestration in soil. However, commercial growers need to know how this crop, which has deep, subterranean roots that extend nearly 2 meters, could affect groundwater resources. By comparing the oxygen isotopic ratios in water extracted from under corn crops, which draw rainwater from soils close to the surface, to that of switchgrass, the researchers confirmed that switchgrass draws on the deeper, older, more isotopically depleted water underground. Oxygen isotopic ratios can also reveal the provenance of food sources, enabling agricultural officials to detect counterfeit labeling, where crops grown in regions that fetch a lower price are sometimes labeled as a more valuable crop variety from elsewhere.

Isotope hydrology also has value to the Laboratory's national security mission. When iron rusts, it transforms chemically as hydroxide (hydrogen and oxygen) ions combine with atoms of the metal. Uranium also reacts with water to form various uranium oxide hydrates. Oerter and his colleagues have developed methods to remove the water hydrating such metals so that their isotopic ratios can be measured. This work allows researchers to identify where in the world a nuclear material may have been stored.

In the Trenches

Oerter knew that water in Livermore is supplied by several sources. He deduced that by measuring the isotopic ratio of water in the Wente field he may be able to identify the source. He asked Depew to supply several samples from the trenches and holes in the field that were dug to find the source of the leak. He trained Lawrence Livermore utilities engineers Michael Favalora and Temple Steadman to collect samples properly. (Samples had to be clear, not muddy, with sediment allowed to settle, and they had to be sealed to prevent evaporation). Oerter measured the oxygen isotopic ratio using a cavity ring-down spectrometer, which vaporizes a sample and streams it into a chamber containing two mirrors at either end. A laser pulse shot into the chamber bounces between the mirrors. The beam decays as it is absorbed by the vapor sample, and the rate of decay provides a measure of the oxygen and hydrogen isotopic ratios.

For the Laboratory, knowing the isotopic composition of the water used in research is necessary to preserving the integrity of results. To that end, Oerter's laboratory already had data on the isotopic composition of water at Lawrence Livermore and the surrounding local area. He had data on Hetch Hetchy water, Laboratory tap water, as well as water supplied to the city of Livermore, which comes from the San Joaquin Delta area of California. By comparing results from the field tests with the existing isotopic data, Oerter would shed light on this watery mystery.



Isotopic ratios measured from the laboratories' pipeline, Hetch Hetchy Aqueduct, and groundwater in the city of Livermore, California, confirmed that the source of the water in the Wente field could not be from the laboratories' pipeline, as Hetch Hetchy water is considerably more depleted in oxygen-18 than water samples taken from the field.

A Positive Identification

"The samples from the Wente field had isotopic ratios that were identical to Livermore groundwater, which is similar to local rainwater," says Oerter. "With that result, we knew that the water could not have come from the Hetch Hetchy Aqueduct, which has isotopic ratios derived from Sierra Nevada snowfall." So, the pipeline wasn't the problem. As any good gumshoe isotope hydrologist would do, Oerter conducted additional tests to determine whether a hypothetical "missing" water source with a sufficiently high oxygen isotopic ratio could be mixing with Hetch Hetchy water (which has a very low ratio) to deliver the same isotopic depletion observed in the Wente field water. However, no such source could be found anywhere in the region. An innocent suspect had been cleared through Oerter's detective work.

Howard Depew invited Oerter to meet with Karl Wente, the chief operating officer for Wente Vineyards, and other members of his staff, in the flooded field. Oerter gave them an explanation of his work and showed them his results. They were satisfied with his findings. Oerter later measured water samples taken from an aqueduct at the south side of the Wente field that supplied water to the city of Livermore. The isotopic ratios from this water were an identical match to those obtained from the Wente field—the true culprit was identified.

Karin King, senior technical advisor in the Livermore Field Office, which helps oversee the Laboratory for DOE, later thanked Oerter, suggesting that he may have saved DOE and U.S. taxpayers a substantial amount of money by solving this puzzle without needing to dig along the entire pipeline. Identifying the true source of the leak also allowed local authorities to fix the problem and eliminate the water loss, an important action made more necessary given the drought California faces. Although the proverb "dead men tell no tales" rings true, happily for all, water's a high-tech stool pigeon.

—*Allan Chen*

Key Words: Hetch Hetchy Aqueduct, hydrogen isotopic ratio, isotope hydrology, cavity ring-down spectroscopy, Light Stable Isotope Geochemistry and Hydrology Laboratory, oxygen isotopic ratio, Wente Vineyards.

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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

High Power Handling Digitizer Using Photonics
Peter Thomas Setsuda DeVore, Apurva Shantharaj Gowda, David Simon Perlmutter, Alexander Thomas Wargo, Jason Thomas Chou
11,159,241 B2
October 26, 2021

Optical Encoder Devices and Systems
Brandon Walter Buckley, David Simon Perlmutter, Peter Thomas Setsuda DeVore, Apurva Shantharaj Gowda, Jason Thomas Chou
11,184,087 B2
November 23, 2021

Solid-State Integrated Real-Time Optical Monitoring of Biochemical Assays
N. Reginald Beer, Steven W. Bond
11,209,423 B2
December 28, 2021

Radio Frequency Passband Signal Generation Using Photonics
Apurva Shantharaj Gowda, Jacky Chak-Kee Chan, Peter Thomas Setsuda DeVore, David Simon Perlmutter, Jason Thomas Chou
11,209,714 B2
December 28, 2021

Method and System for Locating the Source of Events in Power Distribution Systems Using Distribution-Level PMU Data
Hamed Mohsenian-Rad, Mohammad Farajollahi, Alireza Shahsavari, Emma Mary Stewart
11,211,800 B2
December 28, 2021

Plasma Confinement System with Outer Electrode Having Liquifiable Material and Methods for Use
Uri Shumlak, Harry S. McLean, Brian A. Nelson
11,219,117 B2
January 4, 2022

Hohlraum Used as a Single Turn Solenoid to Generate Seed Magnetic Field for Inertial Confinement Fusion
Lindsay John Perkins, Jim H. Hammer, John H. Moody, Max Tabak, Burl Grant Logan
11,227,693 B2
January 28, 2022

System and Method for X-Ray Compatible 2D Streak Camera for a Snapshot Multiframe Imager
Matthew S. Dayton, John E. Field
11,240,433 B2
February 1, 2022

Operando Nuclear Magnetic Resonance Rotor Insert
Maxwell Marple
11,255,933 B2
February 22, 2022

Apparatus and Method for Hybrid Opto-Electrical Multichip Module
Susant Patra, Razi-Ul Muhammad Haque, Komal Kampasi, Ian Seth Ladner
11,262,514 B2
March 1, 2022

Synthetic Apolipoproteins, and Related Composition Methods and Systems for Nanolipoprotein Particles Formation
Paul D. Hoeprich, Jr., Julio A. Camarero
11,279,749 B2
March 22, 2022

Selective High-Affinity Polydentate Ligands and Methods of Making Such
Sally J. DeNardo, Gerald L. DeNardo, Rodney L. Balhorn
11,285,165 B2
March 29, 2022

Awards

A Lawrence Livermore computing science team received the first-ever **Best Reproducibility Advancement Award** at the **2021 International Conference for High-Performance Computing (HPC), Networking, Storage, and Analysis (SC21)**. The award recognized the team's High-Performance Approximate Computing (HPAC) framework for exploring advantages of different approximation techniques to improve HPC performance and addressing accuracy requirements for scientific applications. Team members include **Harshitha Menon, Konstantinos (Dinos) Parasyris, Giorgis Georgakoudis, James Diffenderfer, Ignacio Laguna, Daniel Osei-Kuffuor**, and **Markus Schordan**. HPAC's development was funded by the Laboratory Directed Research and Development Program as part of Livermore's ApproxHPC project.

Omar Hurricane, chief scientist for Lawrence Livermore National Laboratory's inertial confinement fusion program, received a **2021 Edward Teller Award** for his work at the Laboratory's National Ignition Facility. The award, named in honor of the physicist, Laboratory director emeritus, and Hoover Institution senior research fellow, recognizes other pioneers of inertial fusion science. In presenting the award, the **Fusion Energy Division of the American Nuclear Society** recognized Hurricane's leadership and insights contributing to experiments that achieved fuel gain, an alpha-heating-dominated plasma, and a burning plasma.

Abstract

Beaming with Excellence

Since the inception of Lawrence Livermore's Laser Program 50 years ago, Laboratory researchers, with colleagues from collaborating institutions, have been at the forefront of advancing fusion research. In the program's first 10 years, a remarkable six large fusion laser systems, each one bigger, more complex, and higher energy than its predecessor, were engineered and built with the goal of achieving inertial confinement fusion. The pace of laser construction matched the growth of diagnostics capabilities, computer simulation tools, and theoretical understanding to continually improve laser capabilities and experimental results. Now, the Laboratory's flagship National Ignition Facility, the world's most energetic laser, stands at the threshold of an unprecedented fusion milestone. On August 8, 2021, the research team conducted a shot that produced a record-breaking 1.3 megajoules (MJ) of fusion energy by imploding a deuterium–tritium (DT) fuel capsule with 1.9 MJ of laser energy. The shot marks the first time in a laboratory that scientists have observed signs of a self-sustaining wave of nuclear reactions—thermonuclear burn—in the DT fuel, opening a fundamentally new regime to explore and advance the Laboratory's critical national security mission as well as future fusion energy applications.
Contact: Patti Koning (925) 423-4332 (koning3@llnl.gov).

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

Operationalizing Audacious Goals

The Adaptive Computing Environment and Simulations Project brings new software and state-of-the-art computing to model the enrichment of fissile material and reduce nuclear proliferation.

Also in this upcoming issue...

- *Virtual Beamline (VBL)++, the latest generation of Livermore's workhorse laser physics code, promises full integration across applications including high-performance computing.*
- *Optics for advanced extreme ultraviolet lithography systems shed light on the habitability of exoplanets, the sun's magnetic field, and solar weather.*
- *Livermore's additive manufacturing and materials science expertise yields transparent ceramics with novel properties.*

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