

December 2016

Science & Technology

REVIEW

The National Ignition Facility **EXPLORES** the **COSMOS**

Also in this issue:

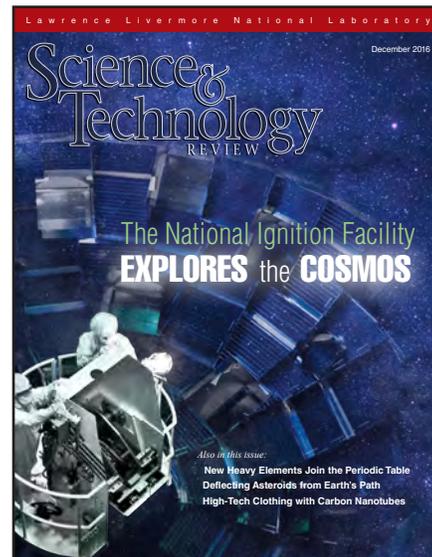
New Heavy Elements Join the Periodic Table

Deflecting Asteroids from Earth's Path

High-Tech Clothing with Carbon Nanotubes

About the Cover

With 192 beams, the National Ignition Facility (NIF) at Lawrence Livermore is the world's largest and most energetic laser. NIF allows scientists to test materials in high-energy-density (HED) regimes not accessible by any other means—temperatures and pressures found only in stars, giant planet cores, and detonating nuclear weapons. NIF's Discovery Science Program provides academic users access to the facility to conduct experiments in fundamental HED science. The article beginning on p. 4 describes some Discovery Science experiments and the mysteries they are probing, such as the source of ultrahigh-energy cosmic rays, the formation of collisionless astrophysical shocks, and the likely composition of exoplanet cores. The cover shows workers setting up a target for one such experiment inside NIF's 10-meter-diameter target chamber.



Cover design: Acen Daturin

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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Livermore Garners Three R&D 100 Awards

Three technologies developed by Livermore researchers and their collaborators have been named winners in the 2016 R&D 100 awards. The awards, sponsored by the trade journal *R&D Magazine*, are given annually for the top 100 industrial inventions worldwide. This year's award winners are as follows:

- The GLO transparent ceramic scintillator dramatically increases the throughput of megaelectronvolt-level radiography to provide images seven times faster than glass scintillators and with a lower x-ray dose, nondestructively obtaining detailed, three-dimensional images of complex objects.
- Polyelectrolyte-Enabled Liftoff technology fabricates freestanding polymer films for National Ignition Facility experiments that are larger, stronger, and thinner than what conventional methods can produce.
- The Carbon Capture Simulation Initiative Toolset is a suite of computational tools and models to accelerate the development of carbon capture technology for industry.

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Fracture-Healing Gene Identified

Fracture healing involves communication between bone, muscle, vasculature, and the thin membrane (periosteum) covering the outer surface of bones. The periosteum contains stem cells that migrate to the fracture site and differentiate into chondrocytes (cartilage-forming cells) or osteoblasts (bone-forming cells). Until now, little was known about the interaction between the periosteum stem cells and the bone cells during fracture healing, but a team of scientists from Lawrence Livermore, the University of California at Merced and Davis, Indiana University, and Regeneron Pharmaceuticals has identified the *Sostdc1* gene as a regulator of periosteum stem cell activity during fracture repair. The

research appears in the April 19, 2016, edition of the journal *Bone*. The study suggests that *Sostdc1* plays an important role in stem cell self-renewal and differentiation, which may be useful for developing novel therapeutics for difficult-to-heal

fractures. Mice lacking the gene, despite having a lower density of trabecular bone, had thicker, denser cortical bone, which healed at an accelerated rate relative to their genetically normal counterparts. The team also showed that suppression of *Sostdc1* induces a population of stem cells to rapidly expand and invade the fracture and help repair it.

“Future studies may allow us to harness the behavior of these stem cells in other parts of the body where they may do even more good,” says Nicole Collette, a Livermore biologist and lead author of the study. “This regulator is expressed all over the body, including in other tissues where stem cells are found.”

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Clue to Electrical Conductivity in Earth's Mantle

A team of scientists has found that the dehydration of chlorite is likely crucial in explaining the anomalously high electrical conductivity (EC) observed in Earth's mantle (see the image below). The high EC, observed in mantle wedge regions at depths of 40 to 100 kilometers, had often been attributed to the aqueous fluid released from descending slabs, but until now laboratory-based measurements of EC were significantly lower and could not readily explain the geophysically observed high EC.

The new research, appearing in the May 6, 2016, edition of *Science Advances*, shows that the EC of chlorite is similar to that of other hydrous silicate minerals. “We have measured the EC of a natural chlorite at pressures and temperatures relevant for the subduction zone setting,” says former Livermore geophysicist Davide Novella. “In our experiment, we observed two distinct conductivity enhancements when chlorite is heated to temperatures beyond its thermodynamic stability field. The initial increase in EC can be attributed to chlorite dehydration and the release of aqueous fluids. This is followed by a unique, subsequent enhancement of EC.”

The team found that the further increase in EC is also related to the growth of an interconnected network of highly conductive and chemically impure magnetite mineral phases, in addition to chlorite dehydration. Novella explains, “Chlorite dehydration in the mantle wedge provides an additional source of aqueous fluid above the slab and also could be responsible for the fixed depth of melting at the top of the subducting slab.”

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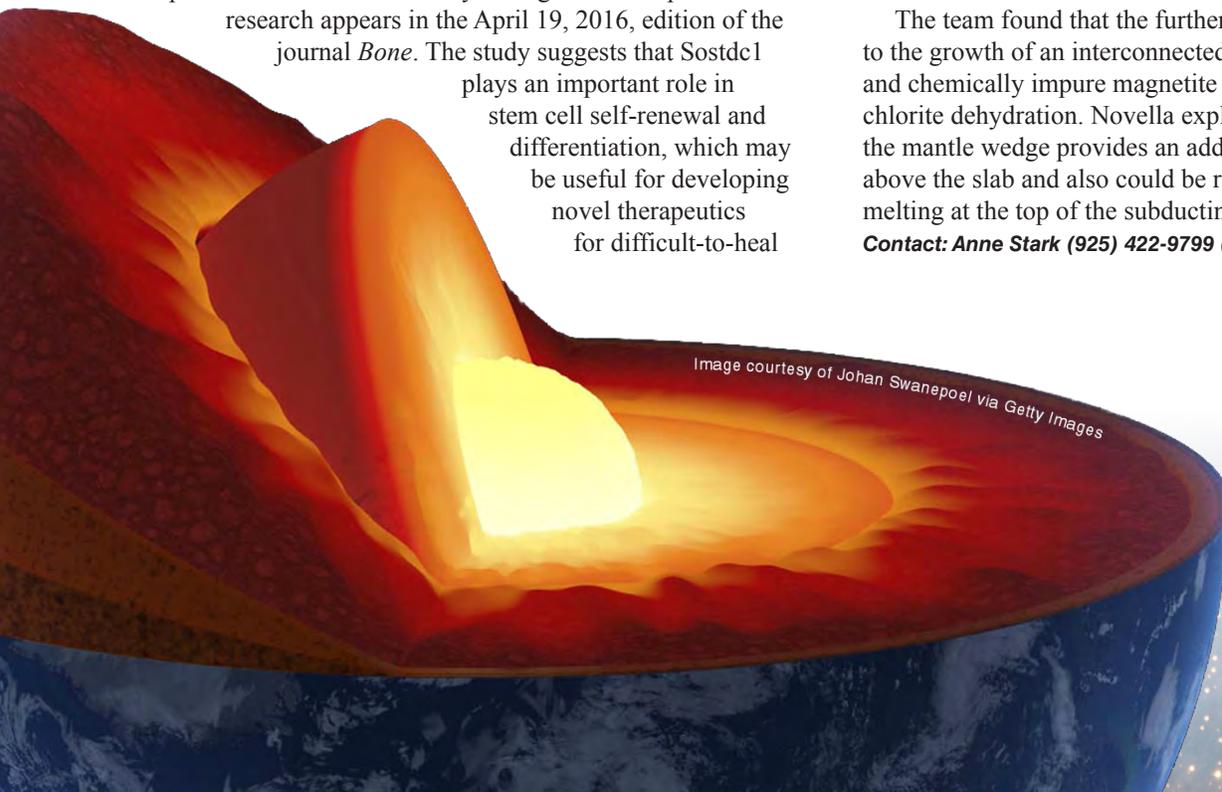


Image courtesy of Johan Swanepoel via Getty Images



A Stellar Experimental Facility for Stockpile Sustainment and Fundamental Science

ONE of the nation's most challenging scientific endeavors of the past two decades has been the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program, the science-based effort to ensure the safety, security, reliability, and effectiveness of the nation's nuclear weapons without additional explosive nuclear testing. The program's outstanding success has been due in large part to the enduring expertise of stockpile stewards at the three NNSA national security laboratories—Lawrence Livermore, Los Alamos, and Sandia national laboratories—in addition to the extraordinary capabilities of high-performance computing and the unsurpassed experimental research facilities maintained by NNSA.

Lawrence Livermore's National Ignition Facility (NIF), the largest and most energetic laser in the world, is NNSA's preeminent high-energy-density (HED) stockpile stewardship experimental facility. For a few millionths of a second, NIF's 192 lasers duplicate the same temperatures, densities, and pressures found in the interiors of stars and planets and detonating nuclear explosives.

Even before NIF began operation in 2010, researchers recognized that in addition to stockpile stewardship, fusion energy research, and national security applications, NIF would be invaluable in advancing fundamental HED science and that a portion of experimental time should be devoted to such research. As a result, Lawrence Livermore launched an experimental research effort that evolved into the Discovery Science Program in 2014. This program enables scientists from academic institutions and government laboratories from within the United States and abroad to perform HED experiments under conditions that only NIF can generate. These experiments include studies of material properties, hydrodynamics, and the interactions of intense radiation fields with matter. As described in the article beginning on p. 4, the studies have direct applications to disciplines such as astrophysics and planetary physics.

Approximately 8 percent of NIF shots are dedicated to the Discovery Science Program. Thanks to a concerted effort to increase operational efficiency, NIF scientists are currently conducting more than 400 shots a year—more than doubling the annual number of shots from only three years ago. This achievement makes more shots available for Discovery Science experiments than ever.

Competition for time on NIF is keen. Out of 26 proposals received this year, only about 6 will be accepted for shot time

in fiscal year 2018. Once a proposal has been accepted, NIF scientists provide feedback on all aspects of the experimental design. Because every experiment is unique, experts in a broad array of fields—including target fabrication, laser configuration, and diagnostics—typically become involved to help guide the researchers. Teams often conduct preparatory experiments at Livermore's Jupiter Laser Facility or at the Omega laser at the University of Rochester's Laboratory for Laser Energetics.

NIF's Discovery Science experimenters bring with them new ideas for experimental techniques, targets, and diagnostics, and their enthusiasm is infectious. Stockpile stewardship scientists at Livermore sometimes join a Discovery Science team, gaining the opportunity to publish their findings in the open literature, strengthen ties with colleagues in academia and other national laboratories, and keep current with the latest scientific discoveries all over the world.

Discovery Science experimenters often include young scientists who are among the best and the brightest researchers of their generation. These talented people are a natural pipeline for future stockpile stewards, and in fact so far about 10 young researchers from Discovery Science projects have been hired by the NNSA national security laboratories. Many other Discovery Science researchers form long-lasting relationships with Livermore colleagues. They can often be found on academic "red teams" charged with evaluating the Laboratory's scientific findings and experimental approaches.

Lawrence Livermore is excited to be helping grow the international HED community. One important element is the NIF User Group, to which more than 500 scientists around the world belong. In February 2016, the annual NIF User Group meeting took place here, bringing together nearly 180 people from around the world, including 41 graduate students and postdoctoral researchers.

Thanks to NIF, the Laboratory is expertly assessing the nuclear stockpile and re-creating remote parts of the universe with experiments once considered impossible. National security—and fundamental science—are indeed fortunate to have such an extraordinarily powerful and versatile facility.

■ Charles Verdon is principal associate director for Weapons and Complex Integration.

LASER EXPERIMENTS **ILLUMINATE** THE COSMOS

At the National Ignition Facility, scientists are creating extreme pressures and temperatures that mimic conditions on alien worlds.

THE most extreme conditions that can be created in the laboratory are in the high-energy-density (HED) regime, where materials often behave in unexpected ways. HED research involves examining materials under pressures and densities found until recently only in the cosmos—in stars and the cores of giant planets—or on Earth only in detonating nuclear weapons. The advent of Lawrence Livermore's 192-beam National Ignition Facility (NIF), the world's largest and most energetic laser, now makes it possible to test materials in HED regimes that are inaccessible to scientists by any other means.

Inside NIF's 10-meter-diameter target chamber, laser beams converge on meticulously engineered targets to obtain extremely accurate data on the HED conditions created. The pulses in a NIF beam typically last only a few nanoseconds (billionths of a second) and are spaced at intervals of less than 20 picoseconds (trillionths of a second). Together, the beams can deliver a combined energy of up to 1.8 megajoules and a peak power of 500 terawatts (trillions of watts), creating

pressures greater than 100 terapascals (1 billion times Earth's atmospheric pressure), temperatures of up to 100 million kelvins, and densities up to 500 grams per cubic centimeter. Not only can scientists define total laser energy and power by selecting the number of laser beams to use and the energy of each individual beam, but NIF's pulse-shaping ability allows them to vary the power of an individual pulse over time. Furthermore, some beams can be separately targeted at thin foils or other secondary targets to generate diagnostic streams of x rays, protons, or other particles that assess what is occurring in the primary target.

NIF has assembled a specialized team to carry out these HED materials experiments, which fall broadly into three categories: equation of state (EOS), or the relationship between pressure, temperature, and density; strength, that is, the speed and extent of the deformation of a solid; and phase changes, such as from a solid to a liquid. Livermore scientist Tom Arsenlis, who heads the team, explains, "No previous data exist for these very difficult regimes we are accessing."

Physicist Damian Swift notes that although NIF creates HED conditions of extremely short duration, the same physics apply to the long-lasting conditions found in stars and planets. Indeed, NIF provides the ability to reproduce the extreme conditions in myriad celestial phenomena, such as magnetic fields that stretch hundreds of light years, the interiors of stars, and the cores of planets inside and outside our solar system.

Program Key to Collaborations

Such fundamental HED experiments on NIF are conducted as part of the Discovery Science Program, which provides academic users access to NIF's HED regimes and enhances collaborations between Livermore scientists and academia. The program constitutes about 8 percent of NIF's more than 400 annual shots. A review committee of outside experts from different branches of physics advises NIF managers on the relative scientific merit of proposals submitted by investigators.

Discovery Science participants include researchers from other national laboratories and from leading universities worldwide. They include graduate students and postdoctoral researchers. Many prepare for years to conduct experiments at NIF. Discovery Science teams typically are allocated a few days of access each year, with two to three laser shots conducted in a 24-hour day. "The entire facility is theirs, so they can, within safety limits, fire any kind of laser energy and pulse shape and power they would like," says Bruce Remington, head of the Discovery Science Program. The program encourages Livermore HED researchers to engage the broader academic community in planning and executing Discovery Science experiments, publish their research in the open literature, and elicit comments from their peers. Collaborations also serve to attract the next generation of HED scientists to Livermore.

Discovery Science experiments are conducted on such materials as hydrogen, carbon, iron, copper, magnesium, and various silica compounds. (See *S&TR* December 2015, pp. 4–12.) Physicist Jon Eggert says, "It is important that we do experiments on a wide variety of materials to make sure our results are consistent." An experiment is conducted on a "platform," which comprises the laser configuration (energy, power, and duration), an extraordinarily precise target measuring a few centimeters in size, and ultrahigh-resolution diagnostic instruments, all tailored to an experiment's needs.

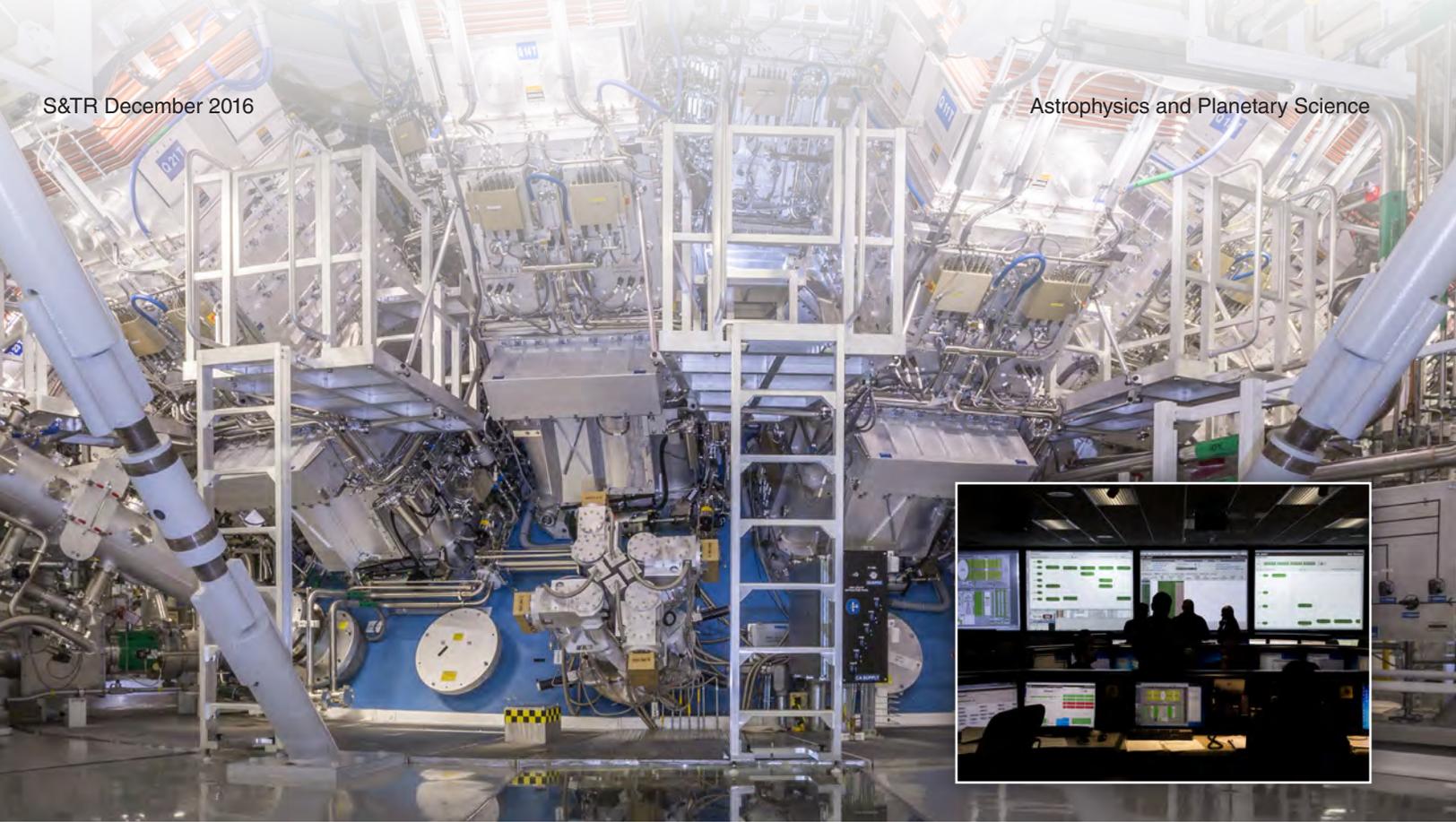
Preliminary experiments are often conducted at lower energy research centers such as the Omega Laser Facility at the University of Rochester and the Z Pulsed Power Facility at Sandia National Laboratories in Albuquerque, New Mexico. "Omega allows us to conduct many experiments in one day," explains Arsenlis. "We can test an idea there before graduating to NIF. Despite fielding more than 400 shots per year, demand for NIF shots always exceeds supply." The Z facility uses high magnetic fields associated with high electrical currents to produce powerful x rays and extreme temperatures and pressures that last 100 times longer than NIF's. Arsenlis explains, "NIF experiments are over in tens of nanoseconds. Z offers a valuable window into a longer timescale, although at somewhat lower energy densities."

Discovery Science experiments probe such mysteries as the source of ultrahigh-energy cosmic rays; the formation and evolution of collisionless astrophysical shocks; the creation mechanisms for the magnetic fields that thread the universe; nuclear reactions in HED plasmas; how the elements of the universe are forged in the interiors of stars; how stars form in molecular hydrogen clouds, such as the famous "Pillars of Creation" in the Eagle Nebula; and the likely composition of the cores of exoplanets, those planets located outside our solar system.

Duplicating Cosmic Rays in the Lab

One series of experiments is devoted to understanding ultrahigh-energy cosmic rays. Most cosmic rays are protons or helium nuclei—two protons bound to two neutrons—originating mainly from outside the solar system. Scientists do not know the origin of these rays or how they gain their incredible energy, which is largely dissipated when they enter Earth's atmosphere. In the experiments, conducted by an international collaboration called Astrophysical Collisionless Shock Experiments with Lasers (ACSEL), researchers are investigating the possible role of collisionless shocks and related magnetic fields in the acceleration of cosmic rays.

In collisionless shocks, clouds of rapidly moving plasma particles pass through each other largely without colliding but create shocks by means of collective plasma instabilities, such as the Weibel instability. Collisionless shocks appear in violent solar flares, outbursts from galaxies, supernova remnants, protostellar jets, and gamma-ray bursts. NIF is the only facility capable of creating plasma streams with sufficiently high density (greater than 10^{20} particles per cubic centimeter), velocity (greater than 1,000 kilometers per second), and temperature (greater than 1,000 electronvolts) to approximate these energetic astrophysical conditions. "We are seeing that magnetic fields can be generated from these high-velocity interacting plasmas. The magnetic fields definitely play an important role in the acceleration of cosmic-ray particles," says Hye-Sook Park, leader of the ACSEL experimental team. The NIF targets used in the experiments consist of two opposing plastic foil discs spaced 10 millimeters apart. When struck by NIF laser beams, the foils emit high-velocity plasma flows that generate shock, largely without ion-ion collisions. The associated magnetic fields produced by the interpenetrating plasmas are probed with protons created



by other NIF beams imploding a tiny capsule known as an “exploding pusher,” which is filled with a mixture of helium-3 and deuterium (a hydrogen isotope with one neutron).

A related series of experiments, called Turbulent Dynamo, or TDyno, is aimed at understanding how magnetic fields created in the early universe grew to their current size and strength. Led by a team from the University of Oxford in the United Kingdom, the TDyno researchers are studying how small “seed” magnetic fields are amplified by a turbulent dynamo—a kind of plasma characterized by turbulent eddies. Collisionless shocks are thought to be one of the mechanisms that create seed magnetic fields, which a turbulent dynamo then amplifies. The NIF experiments are re-creating the dynamos on a much smaller scale by striking two parallel plastic foils in a fashion that produces highly turbulent plasmas. As with the collisionless shock experiments, an exploding pusher creates a proton source to diagnose the magnetic fields as they are amplified by the turbulent plasma.

The Discovery Science Program at Livermore’s National Ignition Facility (NIF) provides academic users access to the high-energy-density regime found in stars and the cores of giant planets. (top) NIF’s target bay houses the 10-meter-diameter target chamber (partially obscured blue sphere), inside which up to 192 beams converge on a precisely engineered target. (inset) Researchers in the NIF control room monitor preparations for an experiment.

Thousands of Exoplanets

Other Discovery Science experiments are aimed at understanding the upwards of 4,000 exoplanets discovered to date orbiting more than 2,600 stars. Scientists aim to determine exoplanets’ internal structure, including whether they could have plate tectonics and a magnetodynamo, both considered essential to supporting some form of life. Indeed, identifying habitable planets has been deemed one of the top three scientific goals for both astrophysics and planetary science. Livermore physicist Robert Rudd states that the search aims to find a “Goldilocks” exoplanet that is not too hot or cold, has some water, and possesses a magnetosphere—a magnetic field generated by a magnetodynamo, shielding potential life forms from damaging cosmic radiation. Scientists

may have found one such exoplanet in August 2016—a roughly Earth-sized planet orbiting Proxima Centauri, the star nearest to our solar system. The planet, Proxima b, is located at a distance from its parent star that allows temperatures mild enough for liquid water to exist on its surface.

Exoplanet-related experiments on NIF are designed to replicate the conditions believed to exist in exoplanetary cores, where estimated pressures range from 350 gigapascals to 7 terapascals—the pressures found inside Earth and Jupiter, respectively. “Deep inside a planet, the properties of the constituent materials are strongly modified by extreme density, pressure, and temperature,” explains Livermore physicist Marius Millot. Even those conditions can be re-created using NIF.

The experiments also seek to accurately determine an exoplanet's composition, which is largely a matter of comparing its mass and radius—deduced from dips in the parent star's light as the planet crosses in front—to the composition suggested by the planet's distance from its star. The mass–radius relationship relies heavily on the EOS, which in turn is determined experimentally from a material's compressibility under HED conditions. Squeezed to extreme pressures by a single shock wave or a sequence of staged shocks, the material changes to a new state at higher density, temperature, and pressure. The resulting EOS data refines computational models. “We need data from NIF experiments to validate our calculations,” says Swift.

An extremely useful technique for obtaining EOS and material strength data is ramp compression, in which a material is pressurized gradually, so that it heats to lower temperatures and thereby retains its structural integrity. In contrast, a standard, nearly instantaneous shock raises temperatures significantly, limiting the study of fluid properties to those beyond 200 gigapascals. A realistic model of a planet's interior cannot be

based on an EOS ascertained at high temperatures because compression in these planets is caused by shock-free gravitational forces acting over millions of years, leading to high densities at relatively low temperatures.

Iron a Major Focus

Because iron is a major component of Earth and other planets, understanding the phases and melt curve of the metal at high pressure advances our understanding of Earth and Earthlike exoplanets. Studying iron at Earth-core conditions requires pressures of 130 to 360 gigapascals and temperatures of over 6,000 kelvins. These conditions are near melting, and in fact Earth's core is separated into a solid iron inner core surrounded by a rapidly convecting liquid iron outer core. The magnetosphere that protects life on Earth from cosmic radiation is generated by a magnetodynamo driven by this convective flow of electrically conducting molten iron. Iron's melting transition is therefore extremely important for determining the habitability of large terrestrial exoplanets, the so-called “super-Earths” that have up to 10 times the mass of our planet.

(Beyond this mass, planets tend to be gas giants such as Jupiter.) Super-Earths are calculated to have core pressures of up to 3.6 terapascals, but researchers presently have no idea whether such exoplanets will also have a liquid outer core and a magnetosphere.

A team of scientists led by Livermore physicist Richard Kraus is conducting experiments to measure iron's melting curve at pressures from 500 gigapascals to 2 terapascals, an area where no experimental data currently exist. If the iron core of a super-Earth is completely solid, it may not generate a magnetosphere, making it more difficult for life to evolve on the planet's surface. Kraus explains, “We need to know more about the liquid–solid transition in iron cores to determine whether rocky planets larger than Earth could have a protective magnetosphere.”

NIF has also advanced investigations of the phase changes of materials under HED conditions. Kraus and his team are using a novel experimental technique, developed at Omega, in which a sample is initially shocked into the liquid phase with high heat and low pressure and then subsequently ramp-compressed back into the solid phase at high pressure, with



(left) This target used in collisionless shock experiments conducted at NIF under the Discovery Science Program consists of two nickel- and iron-doped plastic foil discs 10 millimeters apart. The green plastic caps are light shields. Laser beams striking the discs create plasmas that interpenetrate at high velocity, thereby generating on a small scale the collisionless shocks that are believed to govern many large-scale astrophysical phenomena.

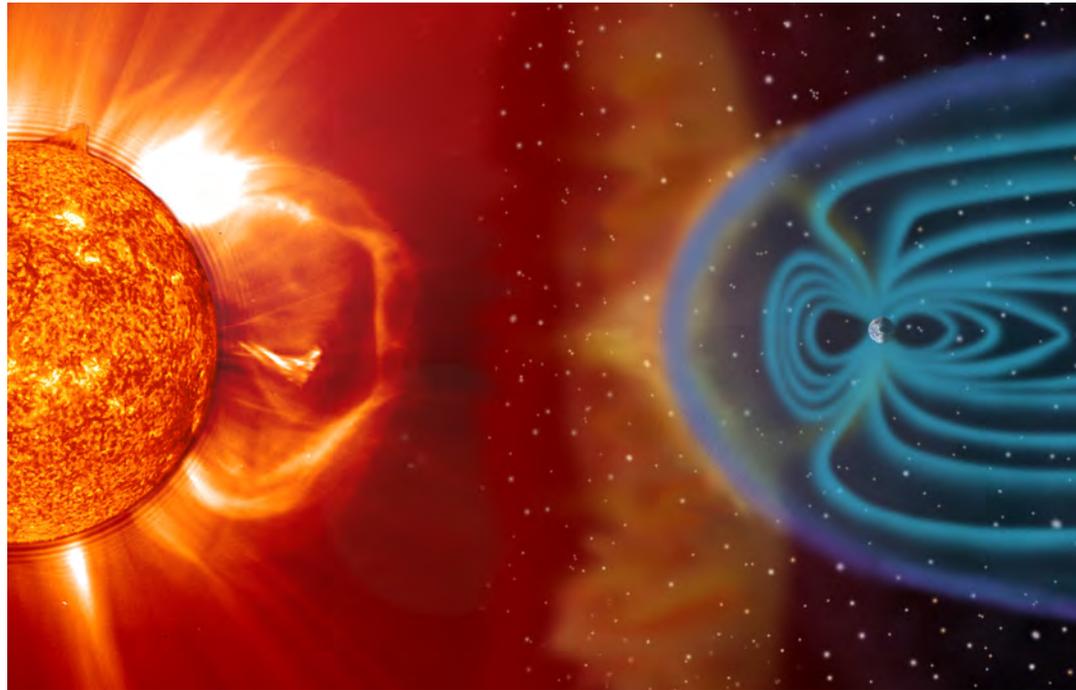
(right) The Turbulent Dynamo experiments at NIF produce the same turbulent plasma conditions that generate the vast magnetic fields permeating the universe. As in collisionless-shock experiments, a deuterium-filled exploding pusher (at the end of the L-shaped arm below the target) produces protons that probe the magnetic fields that are generated.



only a small increase in temperature. They use x-ray diffraction to confirm whether a 20-micrometer-thick iron foil was melted by the initial shock and then resolidified by the ramp-compression wave. This technique was proven on Omega at pressures lower than 500 gigapascals, but now researchers need access to higher pressures along the melting curve. Upcoming tests on NIF will provide the crucial data.

The integrated platform used in these experiments features a target and a diagnostic named Target Diffraction In Situ. In this setup, as many as 24 NIF laser beams strike an iron sample, followed nanoseconds later by up to 16 additional beams that illuminate a backlighter metal foil mounted on a stalk. Collimated x rays from the backlighter probe the sample, producing a diffraction pattern that serves as a “fingerprint” revealing the structure (phase) of the iron. (See *S&TR*, January/February 2016, pp. 4–12.) Kraus notes that the experiments are highly sensitive to the laser pulse’s temporal shape, that is, how its power varies over time. He reflects that a pulse lasting all of 30 nanoseconds provides reliable data on processes that occur in the cosmos over tens of thousands of years.

In previous experiments on the Z facility, Kraus and colleagues determined the impact conditions needed to vaporize iron in meteors and other objects that collided with an ancient Earth. “We need to model iron during impact events because it is a major component of planets, and its behavior is critical to how we understand planet formation,” explains Kraus. The experiments showed that these violent collisions generated significant amounts of iron vapor, and that iron vaporizes at much lower impact speeds than previously thought. As a result, more iron was probably vaporized during Earth’s period of formation and spread over the young planet’s surface instead of immediately sinking down to Earth’s incipient core.



Earth is surrounded by a magnetosphere (blue), which is generated by the planet’s molten outer core acting as a dynamo. The magnetosphere protects the planet from the Sun’s solar wind (white to light yellow lines) and magnetic storms (yellow cloud). When the solar wind collides with the magnetosphere, a bow shock (purple) forms. The shock is collisionless, forming not from the collision of particles but from collective instabilities of the interpenetrating plasmas. (Image courtesy of NASA.)

Hydrogen as a Metallic Liquid

Most exoplanets discovered so far are gas giants similar to Jupiter and Saturn, along with even larger “hot Jupiters,” so called because of their proximity to the stars they orbit. Gas giants are believed to be composed largely of hydrogen and helium. Hydrogen is the simplest element (one proton orbited by one electron) yet exhibits complex behavior under HED conditions, with at least four different solid phases, perhaps two different liquid phases, and a gas phase.

Some scientists postulate that the hydrogen and helium swirling around together in gas giants could separate when hydrogen becomes metallic under terrific pressures. Such a separation could affect the internal core structure and influence how the planets evolved over the past 4.5 billion years. Previous

experiments and models produced conflicting results about hydrogen’s sudden transition from an insulating molecular fluid to a metallic atomic fluid at around 100 to 300 gigapascals and at a relatively cool 1,000 to 2,500 kelvins.

Looking for signs of this transition was a goal of Discovery Science’s experiments on NIF conducted by Marius Millot, Peter Celliers, and other Livermore researchers, together with colleagues from the University of California (UC) at Berkeley, the Carnegie Institution, France’s Alternative Energies and Atomic Energy Commission, and the United Kingdom’s Edinburgh University. A series of small shocks of increasing strength was fired at cryogenic liquid deuterium positioned between a copper plate and a lithium fluoride window. This technique kept

the temperature lower than would be possible with one large shock, allowing access to unprecedentedly high densities. The team used a diagnostic called the Velocity Interferometer System For Any Reflector (VISAR) to record the velocity of reflected laser light by measuring the light's Doppler shift. Through VISAR's transparent lithium fluoride window, they also observed dramatic changes in the optical properties of deuterium. "During these 30-nanosecond-long dynamic compressions, we clearly see hydrogen transitioning from transparent to opaque and then becoming as reflective as a metal foil," says Millot. Further analysis and comparison with state-of-the-art simulations at Livermore will likely enhance understanding of the behavior of hydrogen and other matter at extreme density.

A research team led by Livermore physicist Ray Smith and including researchers from UC Berkeley and Princeton University has used ramp compression on diamond, the hardest known material and a form of carbon, the fourth most abundant element in the universe. Diamond may reside in the cores of Neptune and Neptune-sized giant planets, which are common in

our galaxy. The experiments achieved pressures as high as 5 terapascals—15 times the pressure at Earth's core and comparable to pressures at the center of Jupiter and Saturn. This pressure was achieved by ramp-compressing diamond to almost four times its normal density and more than six times the pressure previously achieved in similar experiments by the same team at the Omega laser. Eggert notes that at pressures exceeding 1 terapascal, diamond is theorized to transition to a different solid phase called BC8, which may be harder than ordinary diamond. NIF experimenters are attempting to create that phase in the laboratory for the first time.

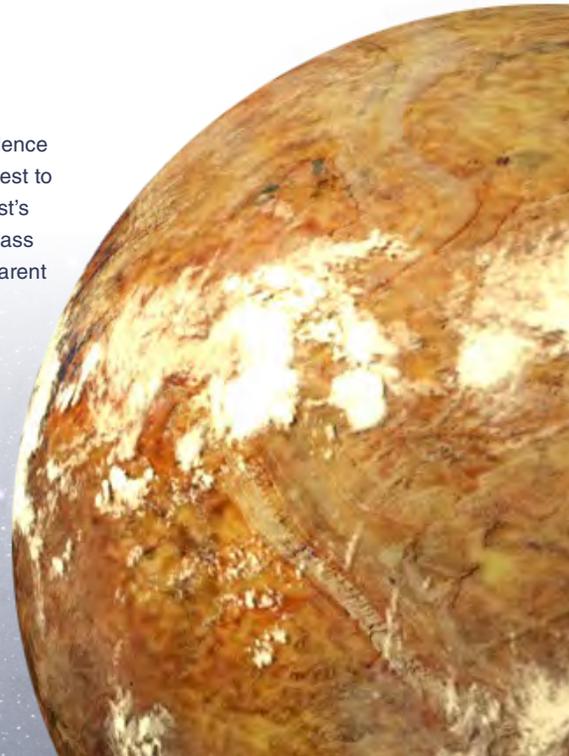
Models Keep Improving

"We are now measuring material properties on NIF at pressures up to a billion Earth atmospheres," notes Swift. The improvement in HED understanding has not come without surprises, in part because materials can behave entirely differently under HED environments, whereas materials science theories have been based on experiments conducted at much lower pressures and temperatures. "We sometimes fail to predict complex

material behavior," says Swift. "For example, we're discovering crystalline structures we didn't know existed but which have a bearing on material strength." In addition, some materials can be stronger than simulation codes predict because a shock can damage the crystal lattice, making the material stiffer.

Remington, Rudd, and Justin Wark of the University of Oxford reflected on the growing importance of HED experiments in a paper they published in 2015. "Regimes of science hitherto thought out of reach in terrestrial settings are now being accessed routinely," they wrote. "There are a multitude of new regimes of science that are now accessible in laboratory settings. Matter can now be studied experimentally with precision at very high pressures and over very short timescales."

Physicist Alan Wan observes, "Thanks to these NIF experiments, we have obtained much greater understanding of HED physics." He adds, "In HED science, the United States is clearly out front in the world. Lawrence Livermore and the nation need to remain the center of excellence for HED science. We're doing things no one

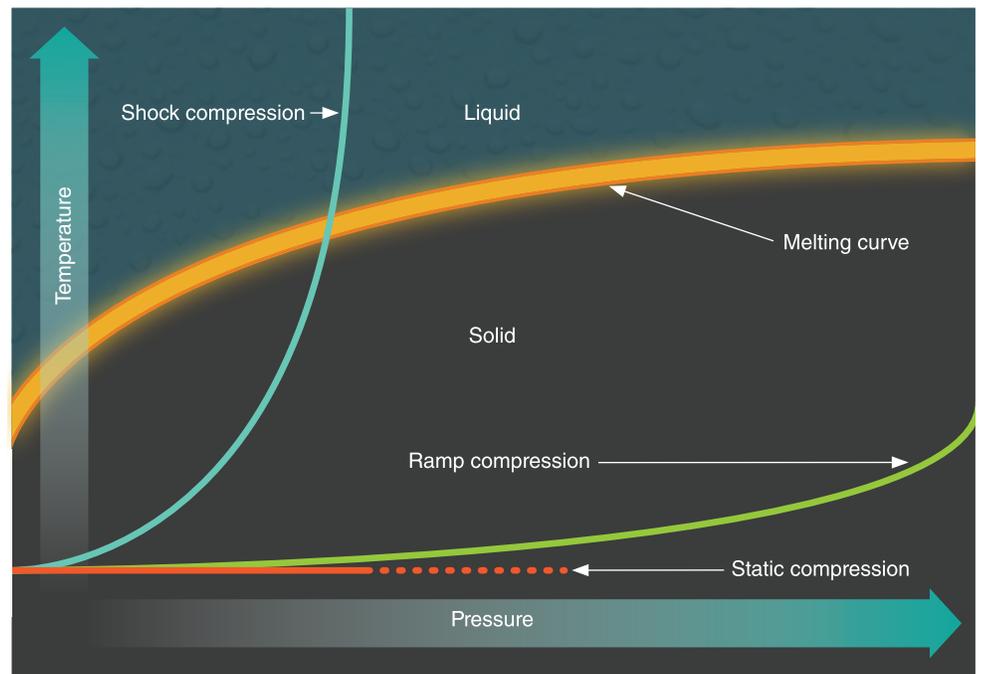


An international team of astronomers has found evidence of a potentially habitable planet orbiting the star closest to our solar system, Proxima Centauri. Seen in this artist's depiction, this exoplanet, named Proxima b, has a mass approximately 1.3 times that of Earth and orbits its parent star every 11.2 Earth days.

else can do. It's a way to leverage the nation's scientific prowess."

NIF can transform astronomy into an experimental science to better interpret observations and refine the latest models of the evolution and composition of stars, planets, and cosmic rays, as well as the dynamics of asteroid and meteor impacts, the response of space hardware to dust and debris impacts, and the effect of prolonged radiation exposure on nuclear reactor components. These are indeed exciting times for the astrophysicists, planetary physicists, and materials scientists who are pioneering new directions in HED science and regularly announcing exciting new discoveries. NIF's rising shot rate—increased from 194 in fiscal year 2014 to more than 400 in fiscal year 2016—is enabling more Discovery Science experiments, shorter down time between them, and greater opportunities to explore new ideas.

Remington credits Discovery Science campaigns with bringing new ideas, science, and diagnostic techniques to NIF through the many outside collaborations. "We inevitably have a better facility and better science coming out of NIF when we have new people coming in with new ideas, creative instincts, and challenges."



Ramp compression is used on NIF to obtain crucial data on the strength and equation of state of a material. This technique preserves the material's structural integrity as it is subjected to enormous pressures, while keeping temperature lower than is possible with conventional shock compression, as the figure shows. This advantage is essential to investigating the cores of planets, including those located outside the solar system.

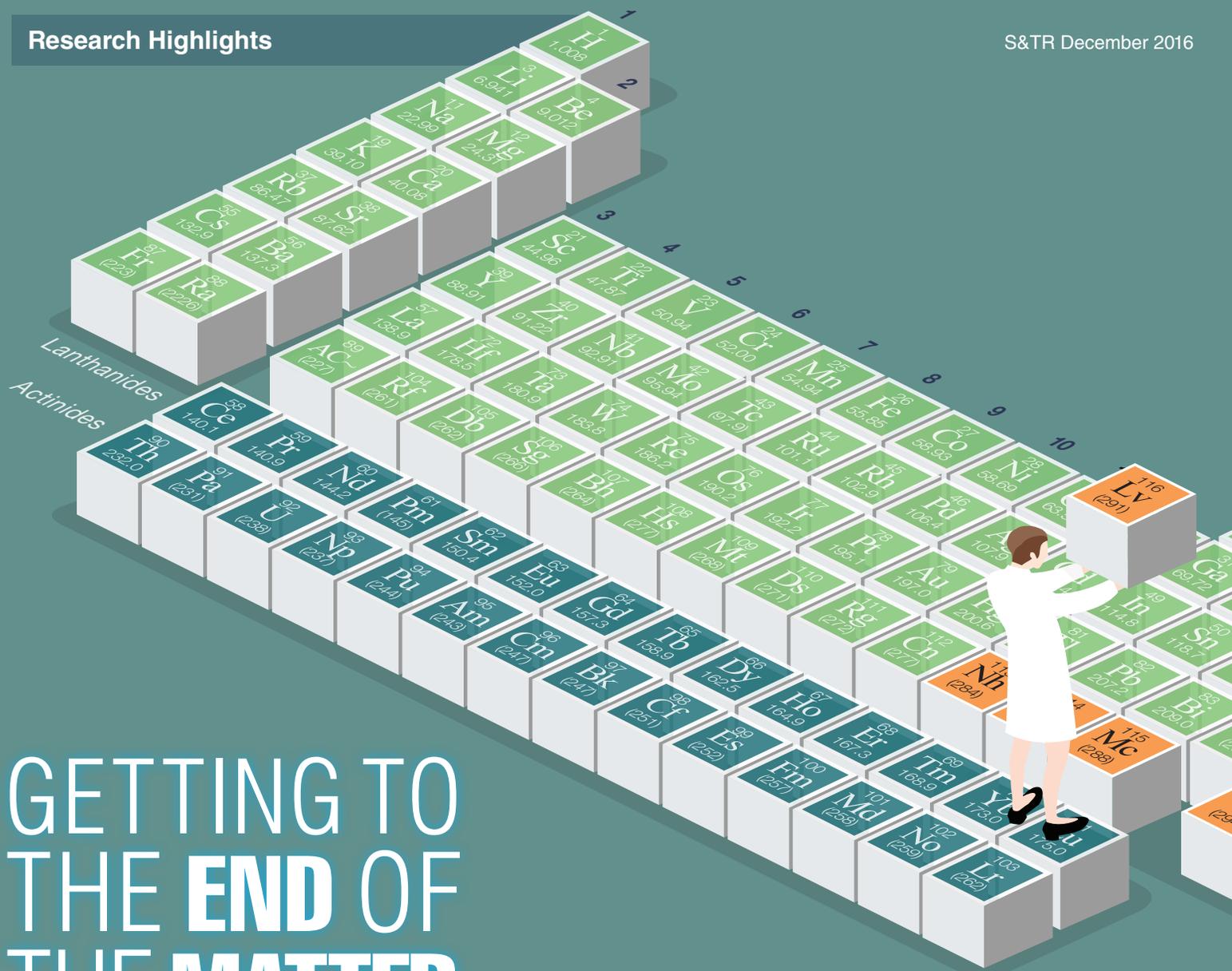
Arsenlis adds that the experiments help recruit, retain, and train a new generation of HED researchers. By their very nature, the experiments attract talented physicists and challenge theories in ways that can be experimentally tested. HED experiments at NIF, he says, are often extremely complex and require researchers to exercise the full range of modern computational and experimental capabilities. "A lot of physics is happening in every experiment, and we have to make sure the conditions are right," he notes. "At the same time, a huge engineering effort is underway to build the required targets and diagnostics.

All this creates a lot of opportunities for talented young researchers."

—Arnie Heller

Key Words: Astrophysical Collisionless Shock Experiments with Lasers (ACSEL), astrophysics, collisionless shock, cosmic ray, Discovery Science Program, exoplanet, high-energy-density (HED) science, hydrogen, Jupiter, National Ignition Facility (NIF), Omega Laser Facility, Neptune, planetary science, super-Earth, Target Diffraction In Situ, Velocity Interferometer System for Any Reflector (VISAR), Z Pulsed Power Facility.

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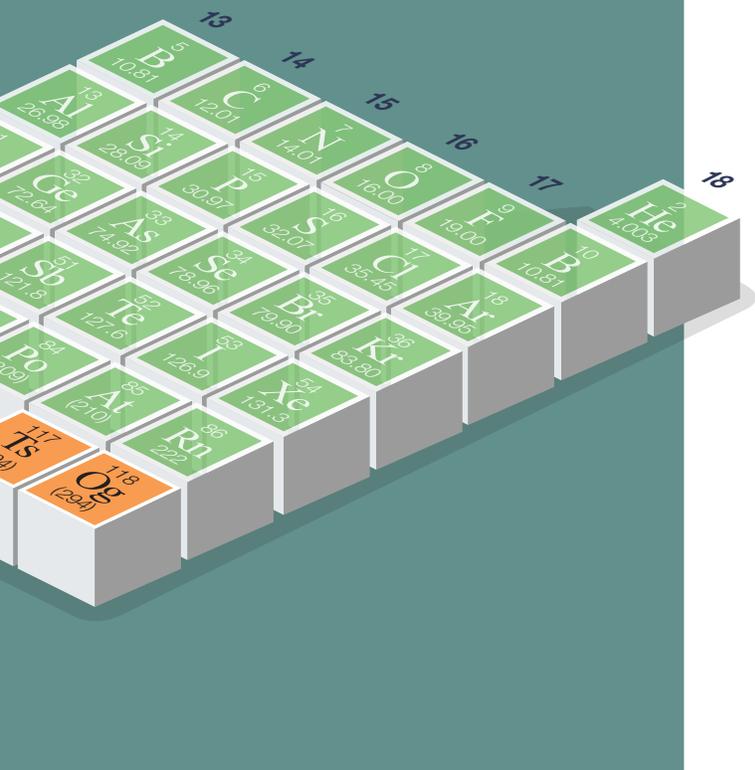
GETTING TO THE END OF THE MATTER

THE number 118 is higher than 117, but the search for superheavy element 117 may have tested the ingenuity and resolve of the scientific community more than did element 118. Finding these and other superheavy elements of the periodic table—those with an atomic number (Z) greater than 104—is a matter of close international scientific cooperation, experimental creativity, and pioneering and exacting data analysis. Synthesizing and investigating these elements expands

scientists’ knowledge of the chemical and physical behavior of matter.

Six Russian and American research institutions, including Lawrence Livermore National Laboratory and Russia’s Joint Institute for Nuclear Research (JINR), located in the city of Dubna, collaborated on the discovery of element 117. The paper announcing 117’s detection was published in April 2010, whereas evidence for the heavier element 118 had come out four

The current periodic table of the elements shows the newly named elements (numbers 113–118) in the lower right. With the naming of elements 113, 115, 117, and 118, discovered by the Livermore–Dubna collaboration, the seventh row of the table is complete. If heavier elements were to be discovered, element 119 would begin a new row.



years earlier, the result of work done by Livermore and Dubna, in part because the target isotope used to generate 118 is longer-lived and easier to obtain.

Superheavy elements have very brief half-lives—the time required for a quantity of the element to decay by one-half, often measured in seconds to milliseconds. Synthesizing these elements requires accelerating beams of neutron-rich ions at a target coated with a high-Z element. Among the collisions that follow, a few—less than a dozen out of 10 billion billion

(10^{19})—will form atoms that promptly decay by emitting alpha particles—helium ions containing two neutrons along with the two protons. For instance, an atom of element 117 decays into 115 by emitting an alpha particle, thereby losing two protons, then 115 decays to 113, and so on, until the nucleus fissions into two fragments. Each alpha particle's position, energy, and formation time can be measured. The whole cascade produces a set of decay products unique to the element created during the initial collision. From the decay products researchers can thus determine the original element.

To generate just a few atoms of 117, the team needed to bombard a target coated with berkelium-249 with a neutron-rich beam of calcium-48 ions. Oak Ridge National Laboratory's High-Flux Isotope Reactor (HFIR) generated the berkelium-249, a rare isotope with a half-life of 320 days, producing just milligrams. HFIR shipped the isotope to the Research Institute of Atomic Reactors, which made berkelium-coated targets and sent them to Dubna, where the experiments were performed. The clock was ticking—everything had to be completed before too much of the short-lived berkelium decayed.

Finding One Event in a Billion Billion

Now the ion beam bombards the target for months, during which the collected data are analyzed in real time. Proving a decay chain observed during an experimental run represents atoms of a new element is as much a matter of mathematical analysis and ruling out other possibilities as of observation. “In general, it takes about one billion random events before you see something that looks like the first true event,” says nuclear chemist Nancy Stoyer, a member of the team focusing on superheavy elements since 1995. “Our concern was the event's random probability—was it real or random error? We wondered if we could use the data itself. Could it tell us the chance that the event was a random one?” Stoyer and her husband, nuclear chemist Mark Stoyer, along with other members of the Livermore team, pioneered the development of probability-based analysis methods for the superheavy element search.

“Element 117 has a long decay sequence,” says Mark Stoyer. “It decays rapidly, so its random probability is very low. One of Livermore's most important contributions to the collaboration was the use of independent data analysis to verify the claim of discovery—a group at Dubna and one at Livermore checking each other's results. We also introduced random probability analysis.” For 117, Livermore was joined by colleagues at Oak Ridge, Vanderbilt University, and the University of Nevada at Las Vegas. The team developed methods of simulating

billions of nuclear events by generating them randomly using Monte Carlo calculations. Thanks to the careful analysis, the Livermore and Dubna groups were able to demonstrate that the decay chains observed in Dubna were real events, not random error of the detection method. Livermore's Roger Henderson conducted the data analysis that identified element 117.

Introducing Oganesson, Tennessine, and Moscovium

Following a multiyear, multilaboratory process of verifying results, the International Union of Pure and Applied Chemistry (IUPAC) agreed that the evidence added up to the detection of new elements. After an IUPAC release last June listing proposed names for public comment, the elements' new names have now become official. Oganesson, 118, is named for Yuri Oganessian, the leader of the Dubna team credited for discovering six elements altogether. Tennessine, 117, honors Tennessee, the home state of Oak Ridge, which has provided nuclear materials in superheavy element discovery for many years. Element 115 is now moscovium, also observed during the Dubna–Livermore collaboration. For element 113 the IUPAC approved the name nihonium, giving credit to a Japanese laboratory for a different isotope than that observed in the Livermore–Dubna experiments.

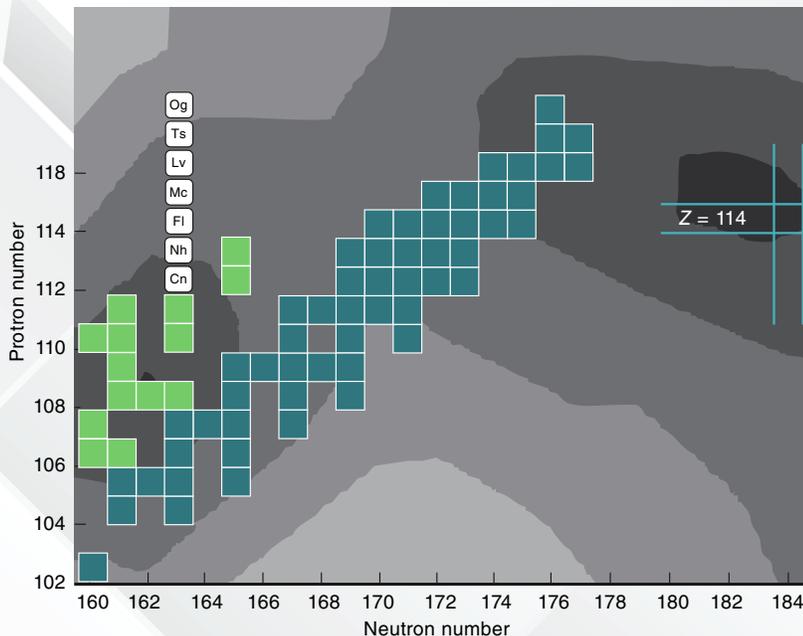
The island of stability is where nuclear chemists from Livermore and Dubna hope to find superheavy elements with half-lives longer than the millisecond timescale—perhaps long enough to be chemically useful. A portion of the table of isotopes focusing on the heavier isotopes is shown. Each colored box represents a synthesized isotope, with darker green representing the over 50 isotopes observed by the Livermore–Dubna collaboration, which was involved in the discovery of new elements nihonium (Nh), flerovium (Fl), moscovium (Mc), livermorium (Lv), tennessine (Ts), and oganesson (Og). [Copernicium (Cn) was discovered by Germany's GSI Helmholtz Centre.] A darker gray background indicates a longer half-life. Heavier, more stable isotopes are theoretically possible near a proton number (Z) of 114.

These four elements now join livermorium (116), named for the city where Lawrence Livermore is located, and flerovium (114), named for Georgy Flerov (the Russian founder of the Dubna laboratory), as the newest additions to the periodic table. The six elements, all discovered or observed by the Russian–American collaboration, fill out and complete the seventh row of the table.

The predominance of American and Russian names in the newest elements reflects the strength of collaboration between Livermore and JINR that began in 1989. Ken Hulet founded the group at Livermore, and over the years leadership passed to Ron Lougheed, Ken Moody, and then Dawn Shaughnessy, currently leader of Livermore's Nuclear and Radiochemistry Group. The Laboratory Directed Research and Development (LDRD) Program funded much of the research, while the Department of Energy's Office of Science funded some Livermore work, as well as Oak Ridge efforts to produce the isotopes needed for the 117 experiment. (See *S&TR*, October/November 2010, pp. 16–19.)

The Future of Superheavy Element Research

The discovery of these new elements is part of a larger puzzle. Many fundamental questions remain about the limitations of matter and its chemical behavior at the far end of the periodic table. Shaughnessy and her colleagues are focusing on the



chemistry of the new elements. Shaughnessy says, “Element 114 [flerovium] is the Holy Grail, because of the many predictions about its chemistry—some say a metal, some say a noble gas—and because one of its isotopes has a half-life of about two seconds, long enough to enable study. Performing the experiments would not be trivial, but ways exist to do the chemistry.” In 2017, an LDRD-funded project led by Livermore postdoc John Despotopoulos will study the aqueous chemistry of flerovium to establish the techniques for studying the chemistry of isotopes that are manufactured in a particle accelerator and subsequently transported into a liquid-containing reaction chamber.

“As we get to this region of the periodic table, a nucleus has so many protons that relativity affects the behavior of the electrons,” explains Shaughnessy. “The electrons move at speeds approaching a fraction of the speed of light, which increases their mass and causes them to bond differently from other elements in the group. If these predictions of relativistic quantum chemistry are correct, and 114 is not reactive, then science may need to rearrange the periodic table itself to reflect the nature of that bond.”

However, the physics also beckons. Scientists would like to know where the table ends. At what atomic number is it no longer possible to make a new element? Physicist Richard Feynman suggested the periodic table could go to element 137, whereas Finnish chemist Pekka Pyykkö calculates that the elements could range as high as 172. The elements beyond oganesson will fill out the eighth row of the periodic table, where the outermost electrons will begin to populate the eighth shell and its subshells, known as orbitals. Oganesson’s electrons populate the eighth shell’s outermost orbital, $7f$, and some elements in the eighth row would have electrons in the g orbital, which has never been observed and which would introduce new and unknown chemical behaviors.

The Livermore team is working with its Russian colleagues to find more isotopes of 118, with the Russians building an additional dedicated accelerator at Dubna. “This will increase the production rate of the superheavy elements by more than an order of magnitude—from 30 to 50 atoms per year to thousands,” says Mark Stoyer. Their hope is to eventually find elements in the island of stability—a zone of the periodic table where elements with much longer half-lives may exist. However, getting there will require collisions between beams of heavier neutron-rich ions and targets coated with actinides, producing new isotopes with far more protons and neutrons, or collisions transferring multiple neutrons or protons between projectile and target—a new technique for super heavy element production. Dubna’s new accelerator will allow the collaboration to try these techniques and



Livermore nuclear chemist Nancy Stoyer stands in front of the U-400 Cyclotron during a maintenance period at the Joint Institute for Nuclear Research in Dubna, Russia, where many superheavy elements were first synthesized and observed.

open up novel experiments in chemistry, atomic physics, and mass measurement—and perhaps also leading to yet more names on the periodic table.

—Allan Chen

Key Words: berkelium-249, calcium-48, decay chain, flerovium, half-life, livermorium, moscovium, nihonium, oganesson, periodic table, superheavy element, tennessine, trans-actinides, transuranics.

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MAKING AN **IMPACT** ON ASTEROID DEFLECTION

WHEN it comes to asteroids—rare but potentially cataclysmic threats to global security—the best defense is a good offense. The most hazardous planetary objects are near-Earth asteroids (NEAs), those found to be in orbits that allow them to enter Earth's neighborhood. Most large NEAs have been identified and plotted, but much remains unknown about smaller bodies, including how many exist. NEAs ranging in size from only tens to hundreds of meters are difficult to detect because they are often too small and dim for telescopic observation. The National Aeronautics and Space Administration's (NASA's) Planetary Defense Coordination Office oversees detection and follow-up investigations of these objects as they move through the solar system, watching for one that could potentially collide with Earth.

Earth-bound objects only a few kilometers across have already caused global catastrophes, such as the impact that wiped out all

nonavian dinosaurs and many other species 66 million years ago. More recently, the Chelyabinsk meteor measured only 20 meters in diameter before it exploded over the eponymous Russian city in 2013, injuring hundreds of people and damaging many structures. Livermore's planetary scientists Megan Bruck Sval, Paul Miller, Michael Owen, and other members of their interdisciplinary team are researching ways to prevent asteroids from reaching Earth in the first place. The strategy is known as asteroid deflection.

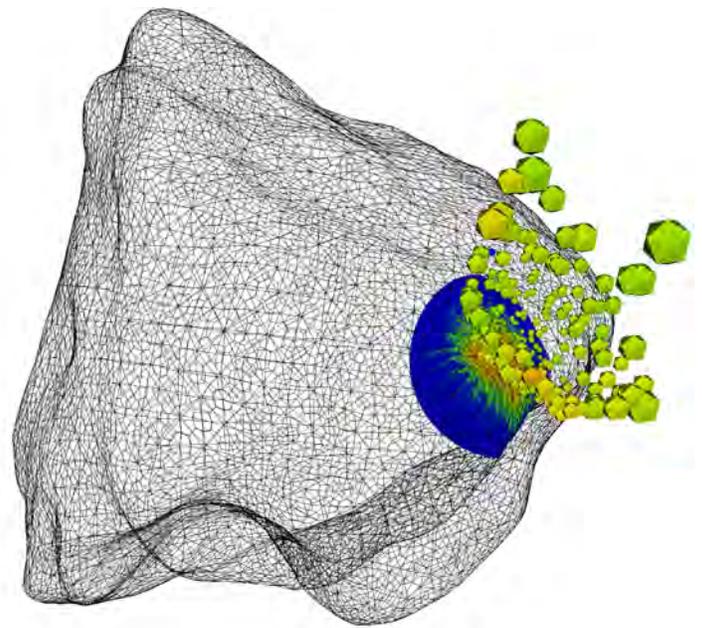
What began in 2011 as a project funded by the Laboratory Directed Research and Development Program has grown into ongoing activity that includes modeling various asteroid deflection methods. Now, Lawrence Livermore is collaborating with NASA and the Johns Hopkins University Applied Physics Laboratory (APL) to support a NASA mission known as the



Double Asteroid Redirection Test (DART)—a proposed full-scale asteroid deflection test tentatively scheduled to launch in 2020.

Harnessing Kinetic Energy

Deflection has become a significant area of focus in planetary defense research. Livermore-directed simulations of deflection by means of nuclear explosions have yielded valuable understanding of scenarios in which a large asteroid bears down on Earth with little warning. (See *S&TR*, December 2009, pp. 12–14.) Additional Laboratory research includes predictive modeling using energy and density inputs based on actual NEAs observed in the solar system. (See *S&TR*, December 2013, pp. 12–15.) The Laboratory’s planetary defense team builds on these efforts by modeling a nonnuclear deflection method known as kinetic impact.



Laboratory researchers are using Spheral, an adaptive smoothed particle hydrodynamics code, to model the asteroid Golevka as it is impacted by a 10,000-kilogram mass traveling at 10 kilometers per second. Ejected pieces breaking away from the asteroid add to the total momentum imparted to the body, helping further nudge it away from its Earthbound course.

The kinetic impact method involves ramming an impactor—an uncrewed spacecraft—against an asteroid to transfer momentum that pushes the asteroid away from its Earthbound trajectory. If undertaken sufficiently far in advance, the most effective direction in which to move an asteroid is along the direction of its orbit. Over time, as the asteroid continues along its path, deflection away from the point where the craft nudged it will accumulate. The objective is to permanently alter the asteroid’s orbit so that the distance between it and Earth is large enough to assure safety.

Rockets can transport only a limited amount of mass to an asteroid, thus kinetic impact is most feasible against NEAs less than a few hundred meters across, as well as those with warning times of at least a decade before their orbits intersect Earth’s. Even within these parameters, the variables associated with the kinetic impact method are numerous. The research requires experts from many fields working together to build models incorporating realistic asteroid properties and to run simulations on large computer clusters. Bruck Syal states, “The Laboratory is the perfect place to attack a problem like this.”

The Livermore team uses Spheral, an open-source code, for many of its kinetic impact simulations. Bruck Syal notes, “To model an asteroid’s response to deflection, we need a very good shock physics code and very capable computing resources.” Run on Livermore’s RZ-Zeus and RZ-Merl supercomputers, Spheral is an adaptive smoothed particle hydrodynamics code

that allows researchers to perform meshless simulations. With this approach, they can focus on local effects of the spacecraft and its target asteroid without the computational burden of “meshing” variables from the surrounding space. In this way, the team can also understand what happens to the pieces, known as ejecta, that break off at the point of impact. As Spherical developer Owen elaborates, “The code lets us model the physics of failure and fracture with a great deal of accuracy.”

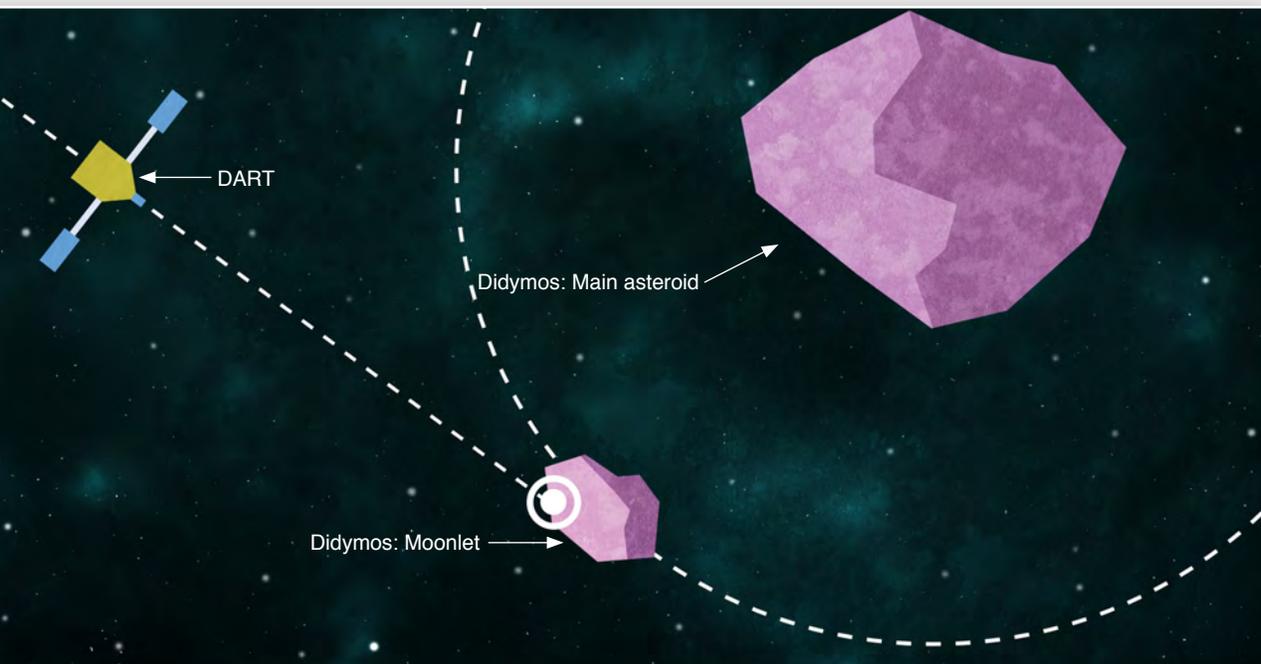
Model Behavior

In addition to size, predictive modeling must take into consideration a host of other variables, such as the asteroid’s composition, porosity, shape, rotation, and mass; the impactor’s velocity and angle of impact; and velocity of the resulting ejecta. These factors and their myriad combinations underscore just how challenging modeling is in kinetic impact investigations. Bruck Syal points out, “Simulations require considerable time to separate out the effects of all these variables.” For the purpose of investigating the effects of different asteroid properties, the team assumed a 1,000-kilogram aluminum sphere as a simplified spacecraft model and NEAs composed of silicon dioxide, a material frequently used in planetary impact modeling.

One critical variable the team studied is asteroid porosity. They found that an asteroid’s porosity and density are more significant than its composition in determining the effects of kinetic impact. Porosity in the asteroid absorbs energy as compaction occurs, resulting in less ejecta being thrown off at the impact site. However, because a highly porous asteroid has less mass for a given size, the impactor would need to impart less momentum to deflect the body.

Momentum is the quantity of most concern in kinetic impact simulations, but it is not only the momentum imparted by the impactor that interests researchers. Because asteroids have little gravitational pull, ejecta escaping away provide additional or “bonus” momentum to the asteroid. Without this help from the ejecta, the momentum delivered to the asteroid would come from the impactor alone, as in a lump of clay hitting a solid object. A key objective of the team’s work is to estimate the amount of bonus momentum generated by a kinetic impact.

How fast the impactor needs to travel and where it needs to hit also depend on the asteroid’s size and shape. “Accounting for realistic shapes makes kinetic impact much harder to model,” says Owen. An ideal scenario, in which the impactor hits a perfectly smooth, round asteroid dead on, is unlikely. Local shape effects—the influence of specific nooks and crannies at the site of impact—could cause ejecta to move



The proposed Double Asteroid Redirection Test (DART) will provide the first test of the deflection of an actual asteroid using kinetic impact. Earth-based telescopes will observe the binary asteroid system Didymos as the DART spacecraft impacts the smaller of the two asteroid bodies, which is only 150 meters across.

in different directions away from the impact crater, redirecting thrust and thereby reducing the bonus momentum. Using the dimensions and irregularities of a real asteroid named Golevka, the team modeled 10,000-kilogram impactors colliding at 10 kilometers per second and varied the site of impact. Results indicated that topography, such as a sloped or concave surface, may dampen the effectiveness of the kinetic impact method. However, accounting for such irregularities—that is, solving for the bonus momentum in simulations—would inform impactor specifications in a real deflection event.

Full-Scale Opportunity

The Laboratory's simulations highlight the importance of continued research in planetary defense and illuminate the field's uncertainties, all of which will come under scrutiny ahead of the DART test. DART will target Didymos, a binary asteroid composed of a main asteroid (approximately 700 meters across) around which orbits a smaller moonlet (approximately 150 meters across). As Earth-based telescopes carefully observe and characterize the system, DART will impact the moonlet at 6 kilometers per second—more than 13,000 miles per hour, or more than 25 times an airliner's cruising speed. The impact is expected to reduce the moonlet's velocity by approximately 1 millimeter per second—a decrease that will be quantifiable from Earth. "DART provides a rare opportunity to test the kinetic impact technology at full scale," notes Bruck Syal.

In preparation for DART, the Lawrence Livermore team will continue investigating various impact scenarios, including benchmarking and simulations of Didymos's variables. When DART hits the Didymos moonlet, the impact will alter the object's orbit around the larger asteroid. "This will be the first such test of deflection for planetary defense purposes," explains project lead Miller. Ground-based telescopes will monitor changes to the moonlet's orbital period, providing an indication of how much deflection occurred and, therefore, how much bonus momentum was imparted. DART, if approved



In this simulation for the DART mission, a 400-kilogram impactor has hit Didymos's moonlet at 6 kilometers per second. Sphera's meshless numerical method allows the Livermore team to evaluate the evolving ejecta velocity field. Here, the innermost 13 meters of ejecta from the impact point are modeled, with the grayscale cutout indicating accumulated strain inside the asteroid (below escape speed) and colors denoting velocities exceeding the 5-centimeter-per-second escape speed.

to go forward, will test the efficacy of the kinetic impact method, further strengthening the foundation of NEA deflection as a viable planetary defense strategy against a potentially catastrophic threat.

– Holly Auten

Key Words: asteroid, deflection, Didymos, Double Asteroid Redirection Test (DART), Johns Hopkins University Applied Physics Laboratory (APL), kinetic impact method, Laboratory Directed Research and Development Program, moonlet, near-Earth asteroid (NEA), planetary defense, predictive modeling, Sphera.

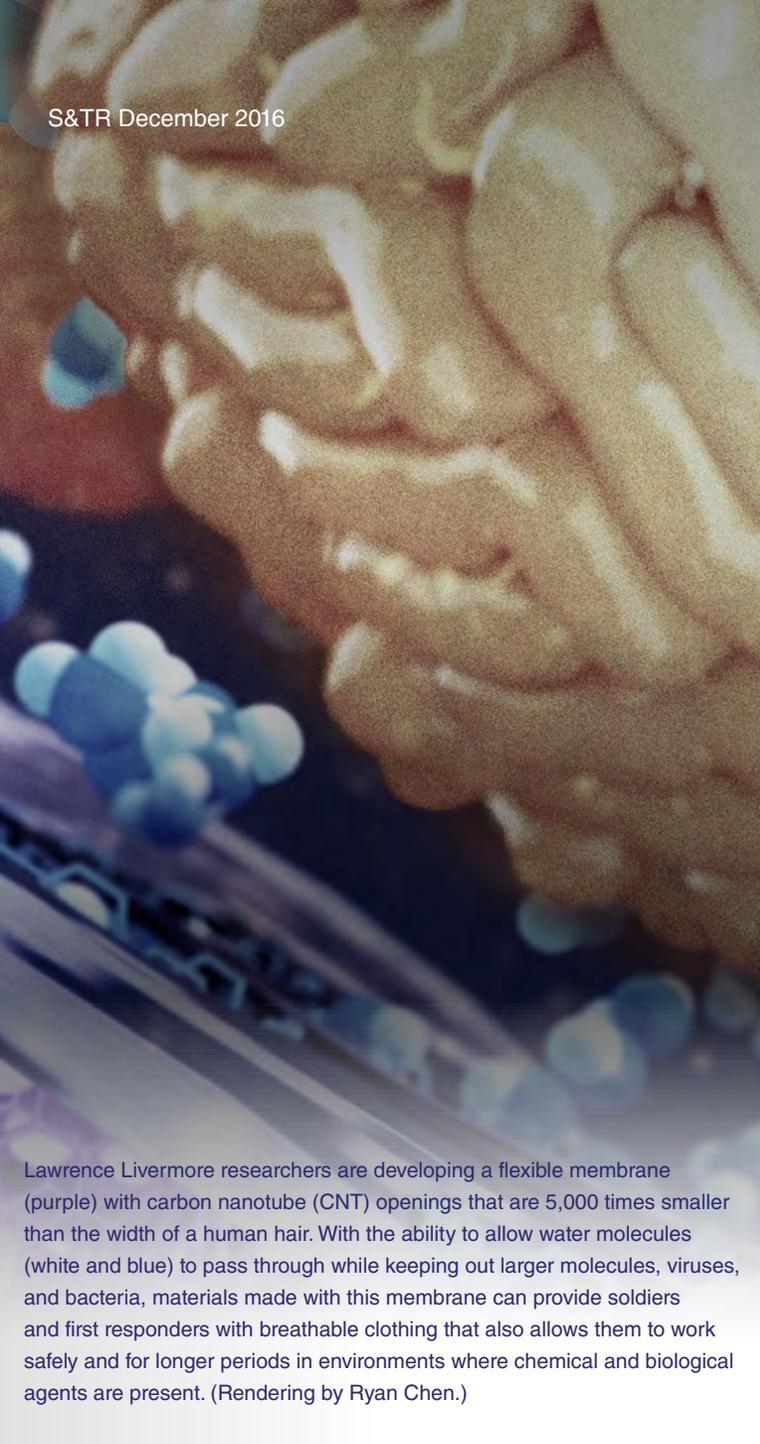
For more information contact Megan Bruck Syal (925) 423-0435 (syal1@llnl.gov).

TINY BUILDING BLOCKS OFFER OUTSIZED PROTECTION AND BREATHABILITY

SOLDIERS need uniforms that provide camouflage, comfort, and the best possible protection against various forms of attack. With support from the national laboratories, the U.S. military has made strides in recent years in enhancing the protection that helmets and body armor provide against conventional weapons such as explosive devices. (See *S&TR*, April/May 2012, pp. 14–16; and March 2010, pp. 14–17.) However, soldiers also need defense against unconventional weapons such as biological or chemical agents, as evidenced by the use of sarin and chlorine in the current Syrian conflict. However, uniform fabrics currently available require wearers to forfeit either protection against biological and chemical hazards or a significant level of comfort. Breathable materials—those that allow

efficient transmission of water vapor (sweat) away from the skin—tend to be effective against only a narrow spectrum of threats, while materials that offer increased protection limit the amount of time an individual can work in a potentially contaminated environment without suffering heat stress.

This tradeoff may soon be a thing of the past. Lawrence Livermore researchers Francesco Fornasiero, Ngoc Bui, Eric Meshot, Chiatai Chen, José Peña, and Kuang Jen Wu are pioneering the use of carbon nanotubes (CNTs) to create a base layer material that simultaneously provides biological threat protection and permeability to water vapor and which can be paired with a “smart” surface layer that guards against chemical agents. The team, with support from

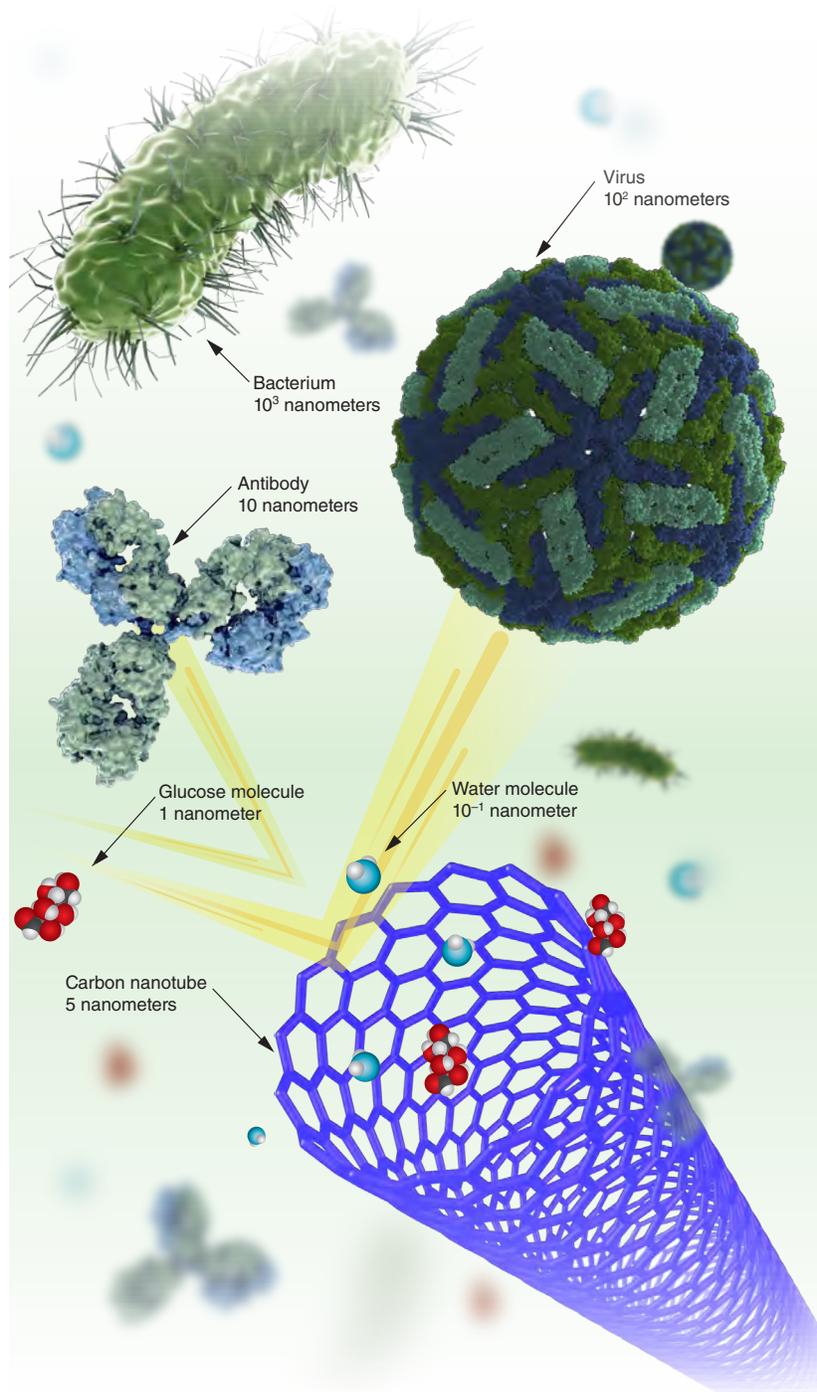


Lawrence Livermore researchers are developing a flexible membrane (purple) with carbon nanotube (CNT) openings that are 5,000 times smaller than the width of a human hair. With the ability to allow water molecules (white and blue) to pass through while keeping out larger molecules, viruses, and bacteria, materials made with this membrane can provide soldiers and first responders with breathable clothing that also allows them to work safely and for longer periods in environments where chemical and biological agents are present. (Rendering by Ryan Chen.)

the Defense Threat Reduction Agency and the Laboratory Directed Research and Development Program, has already attained a crucial milestone in developing this next-generation protective garment by demonstrating that the proposed base layer is highly protective yet remarkably breathable.

A Forest of Tiny Tubes

CNTs are strong, hollow graphite cylinders that typically measure tens of micrometers long and 50 nanometers or less in diameter. The extremely smooth interior walls of CNTs enable gases and liquids to flow through rapidly. (See *S&TR*, October/November 2010, pp. 12–13; and January/February 2007, pp. 19–20.) Thanks to their



The size of the membrane's CNT openings is significantly narrower than bacteria and viruses, whose passage is therefore blocked. Moisture—that is, water molecules—can pass through, ensuring breathability for the wearer of the material.

narrow dimensions, the tubes also block the passage of other, larger molecules. The CNTs used by the team have diameters of less than 5 nanometers—5,000 times narrower than a human hair, and much smaller than bacteria or viruses.

Fornasiero, the project's lead, explains the team's material synthesis process. "We start from vertically aligned nanotube 'forests,' which are tightly packed arrays of tubes 20 to 30 micrometers tall. Having a high density of nanotubes is crucial for maximum breathability. Then we infiltrate the gaps between the tubes with a vapor-deposited polymer. The deposition from the vapor phase allows the tubes to maintain a vertical orientation when forming the composite material," he says. CNTs span the thickness of this material, creating many tiny transport channels, while the polymer fill—parlylene, an impermeable material often used as a moisture barrier—blocks the passage of molecules in the gaps between the tubes. Mechanical testing has confirmed that the CNT-polymer membrane is quite sturdy, which is important for a material intended to be worn. Bui notes, "We envision that a protective suit could eventually be made entirely of this material or be comprised of panels of this material."

Smooth Moves

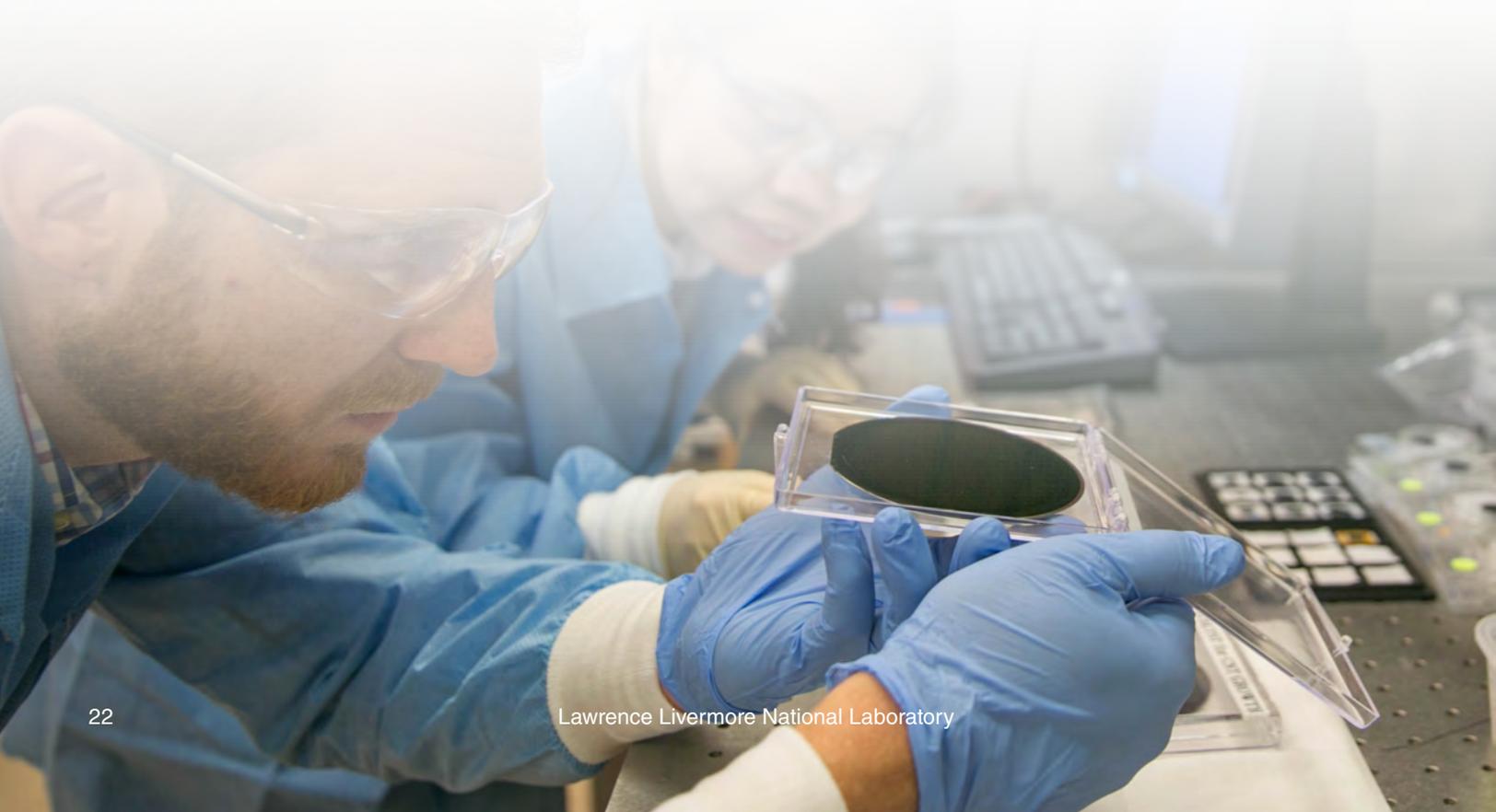
CNT openings account for roughly 5 percent of the Livermore membrane's surface area, a higher percentage than has been achieved by most other CNT membrane synthesis projects. This density of passages, as the team has demonstrated, permits exceptionally high perspiration rates through the material. To quantify the membrane's breathability, the researchers exposed the two sides of the membrane to different concentrations of water vapor. They then measured the rate at which the moisture traveled from the more humid to the less

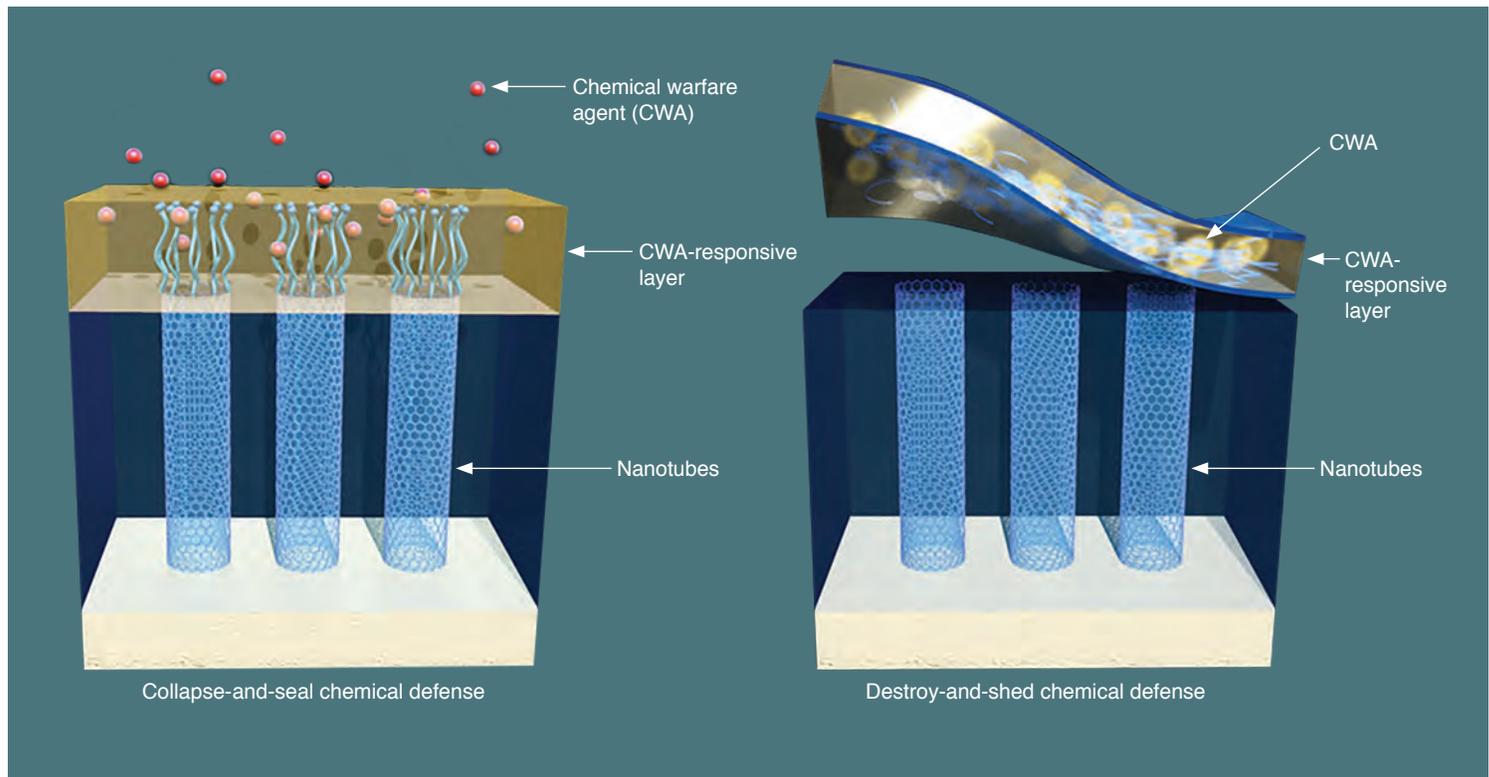
humid side. To allow efficient evaporative cooling of the wearer's body through perspiration, protective gear must provide a moisture vapor transfer rate (MVTR) greater than 2 kilograms per square meter per day. Livermore's CNT membranes provided an MVTR some four times greater than this breathability baseline, beating out popular, commercially available breathable materials. The gas-transport rates sustained by the CNTs even exceeded those predicted by gas diffusion theories by more than an order of magnitude.

Fornasiero and his colleagues also tested the material's protective properties by assessing how well the membrane blocked the passage of different molecules. Potassium ferricyanide ions are only a nanometer in diameter, which is smaller than the CNT openings, so the team expected that these ions would travel through the membrane. However, because these ions and the CNT openings share a negative charge, only about half were let in. Negatively charged dye particles 3 nanometers wide were blocked entirely, most likely because of a combination of size exclusion and charge exclusion, while 5-nanometer-wide nanoparticles of gold coated with polyethylene glycol were too large for the openings and were therefore fully excluded, as well.

As anticipated, Dengue virus suspended in solution could not penetrate the material, either. Although on the small side for a virus, Dengue is, at 40 to 60 nanometers, far larger than the CNT openings. In contrast, the virus freely penetrated the base membrane of a

Livermore researchers Eric Meshot (left) and Ngoc Bui evaluate the uniformity of a CNT array on a 4-inch wafer. Gaps between the CNTs are filled with a vapor-deposited polymer to block the passage of any organism or substance excluded by the CNTs.





commercially available breathable material, which has much larger pores for water vapor transfer. This test result indicates that such commercial materials offer little to no protection from dangerous viruses.

Smart Skin

After confirming that their new membrane combines superior breathability and biological threat protection, the researchers moved on to the next scientific challenge—integrating chemical protection in the same tiny package. Chemical agents are too small for CNTs to block through simple size exclusion, but the membrane can be equipped with a dynamic, protective top layer that performs the task. Colleagues at the Massachusetts Institute of Technology and the University of Massachusetts at Amherst are exploring two alternatives, both of which rely on the concept of a sensor molecule built into the material to identify chemical threats. In one concept, the surface layer reacts to a chemical agent by destroying the threat and then shedding the affected regions. The other concept envisions a surface layer that shrinks or collapses in response to the threat to reversibly seal the CNT openings, temporarily sacrificing breathability for enhanced safety.

“These responsive membranes can effectively mitigate the wearer’s physiological burden by locally switching to a less breathable but more protective state when needed,” notes Fornasiero. The collaboration is currently focused on making this transition from

illustrations show two possible approaches for a responsive surface layer that could be applied over the CNT material to provide protection against smaller chemical-agent molecules. (left) Embedded “sensors” (threadlike structures) identify a chemical threat, upon which they collapse to close the CNT pores and blocks passage of the agent. (right) A sensor material detects and destroys a chemical agent, upon which the entire exposed section of the surface layer sloughs off.

breathable to protective state as effective as possible. If all goes well, U.S. troops could be wearing this “smart second skin” in less than a decade. The suit will likely also find ready adoption among civilian first responders and infectious disease caregivers. Meshot says, “The Laboratory’s mission is national security, and so our team’s goal is to push science capabilities forward to provide solutions that keep people safe, whether in a military or civilian setting.” This remarkable material could protect wearers in a truly diverse range of situations.

—Rose Hansen

Key Words: biological agent, breathability, carbon nanotube (CNT), chemical agent, chlorine gas, first responder, membrane, moisture vapor transfer rate (MVTR), sarin, second skin, soldier, unconventional weapon, uniform.

For further information contact Francesco Fornasiero (925) 422-0089 (fornasiero1@llnl.gov).

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-digit number in the search box at the U.S. Patent and Trademark Office's website (<http://www.uspto.gov>).

Patents

Ablation Layers to Prevent Pitting in Laser Peening

Lloyd A. Hackel

U.S. Patent 9,409,254 B2

August 9, 2016

Methods, Compounds and Systems for Detecting a Microorganism in a Sample

Bill W. Colston, Jr., J. Patrick Fitch, Shea N. Gardner, Peter L. Williams, Mark C. Wagner

U.S. Patent 9,434,997 B2

September 6, 2016

Tethered Float Liquid Level Sensor

William Dean Daily, III

U.S. Patent 9,435,679 B2

September 6, 2016

Apparatus and Method for Enabling Quantum-defect-limited Conversion Efficiency in Cladding-pumped Raman Fiber Lasers

John E. Heebner, Arun K. Sridharan, Jay Walter Dawson, Michael J. Messerly, Paul H. Pax

U.S. Patent 9,450,373 B2

September 20, 2016

Awards

Matt Edwards, a longtime Laboratory employee and lieutenant colonel in the California Army National Guard, was recently honored with the prestigious **Legion of Merit (LOM)**, the sixth highest military award, from the **U.S. Armed Forces**. He received the LOM for his “exceptionally meritorious service as the Regional Defense Counsel, Pacific Region, Army National Guard Trial Defense Service from February 1, 2011, to December 31, 2013. As the inaugural Regional Defense Counsel representing military personnel charged with misconduct, Edwards built the Pacific Region into a singular powerhouse of defense advocacy and litigation . . . and created the first and only Army Reserve National Guard Defense Appellate Division in the nation.”

Seven Lawrence Livermore employees—**Chris Krenn, Errett Hobbs, James Stölken, Linda Stuart, Mehul Patel, Ashley Bahney, and Rebecca Nikolic**—have received **National Security Affairs (NSA) certificates** from the **Bush School of Government and Public Administration** at Texas A&M University. The employees completed the yearlong program, which includes a five-week intensive residence course in College Station, Texas. The NSA certificate program is administered by the Bush School in cooperation with the Laboratory's Office of University Relations and Science Education. Sixty Livermore employees have graduated from the program since its inception in 2008.

Livermore physicist **Tammy Ma** has won the **American Physical Society's 2016 Thomas H. Stix Award** for Outstanding Early Career Contributions to Plasma Physics Research. Ma was recognized for “innovation and leadership in quantifying hydrodynamic instability mix in inertial confinement fusion implosions on the National Ignition Facility and for key contributions to experiments demonstrating fusion fuel gains exceeding unity.” The award, established in 2013, annually honors an individual who has made outstanding theoretical, experimental, computational, or technical contributions in plasma physics early in his or her career. Ma was also recently awarded the Presidential Early Career Award for Science and Engineering, the highest honor

bestowed by the U.S. government on science and engineering professionals in the early stages of their independent research careers.

Lawrence Fellow **Aurora Pribram-Jones** is one of two recipients of the **Howes Scholar** award presented by the **Department of Energy (DOE) Computational Science Graduate Fellowship Program**. The award honors Fredrick Anthony Howes, who managed the DOE Applied Mathematical Science Program in the 1990s. Each year, a recent graduate of the DOE program is selected for the award based on demonstrated scientific achievement, leadership, and service. Pribram-Jones uses mathematics to computationally predict the properties of matter, with an emphasis on potential functional theory, linear response for thermal ensembles, and mathematical conditions on finite-temperature exchange-correlation functionals.

Laboratory employee **Craig Wuest** has received the **Office of the Secretary of Defense Medal for Exceptional Public Service**, one of the top civilian awards presented by the **Department of Defense (DOD)**. The award cites Wuest's work to strengthen DOD's nuclear survivability posture and his role as executive secretary for the Defense Science Board Task Force on Deterring, Preventing, and Responding to the Threat or Use of Weapons of Mass Destruction. Wuest worked for three and a half years as a senior scientific adviser to DOD's assistant secretary of defense for nuclear, chemical, and biological defense programs.

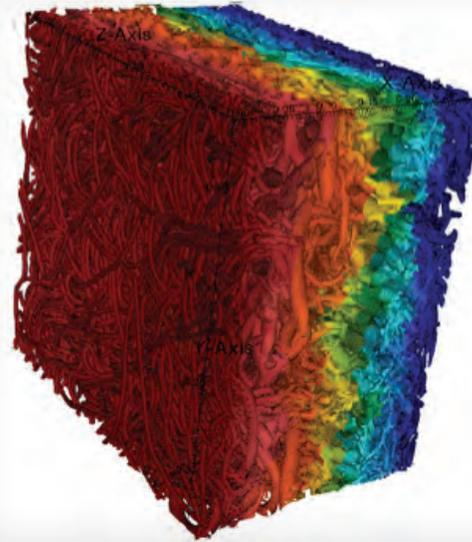
The Laboratory received a 2016 **Environmental Stewardship Award** in the Sustainable Communications category from DOE's **National Nuclear Security Administration (NNSA)**. Four initiatives by Livermore's Sustainability Performance Program—the Green Hotline and Environmental Safety and Health Newsletter, compost and recycling program in the cafeterias, employee electric vehicle program, and Bike to Work Day—received the award, which recognizes successful and innovative communication and marketing strategies that promote sustainability goals and best practices.

Laser Experiments Illuminate the Cosmos

Lawrence Livermore's 192-beam National Ignition Facility (NIF), the world's largest and most energetic laser, allows scientists to test materials in high-energy-density (HED) regimes not accessible by any other means—temperatures and pressures found only in stars, giant planet cores, and detonating nuclear weapons. Fundamental HED experiments at NIF are conducted as part of the Discovery Science Program, which provides academic users access to NIF's HED regimes and enhances collaborations between Livermore scientists and academia. The HED experiments fall broadly into three categories: equation of state—the relationship between pressure, temperature, and density; strength, namely the speed and extent of the deformation of a solid under stress; and phase changes—the rearrangement of atoms from a solid to a liquid, for instance. In addition, a number of experiments focus on laboratory astrophysics, plasma nuclear physics, hydrodynamic instabilities, and turbulence. Discovery Science experiments probe such mysteries as the source of ultrahigh-energy cosmic rays, collisionless astrophysical shock formation and evolution, nuclear reactions in HED plasmas, how stars form in molecular hydrogen clouds, how elements form in the interiors of stars, and the likely composition of the cores of exoplanets—planets outside our solar system. The experiments help train a new generation of HED researchers and attract outstanding young scientists to Livermore's research staff.

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Supercomputers Help Solve U.S. Manufacturing Challenges



Through the Laboratory's High Performance Computing for Manufacturing Program, U.S. manufacturers partner with national laboratories to accelerate innovation and increase energy efficiencies.

Also in January/February

In R&D Magazine's annual competition for the top industrial inventions, Laboratory researchers won awards for the following:

- GLO transparent ceramic scintillator
- Polyelectrolyte-Enabled Ltoff technology
- Carbon Capture Simulation Initiative Toolset

Livermore researchers use a new on-site laboratory for resonance ionization mass spectrometry to identify nuclear materials and determine their origins.

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