LAWRENCE LIVERMORE NATIONAL LABORATORY

SCIENCE AND TECHNOLOGY ON A MISSION

FY 2016 Annual Report

ABOUT THE LABORATORY

Lawrence Livermore National Laboratory (LLNL) was founded in 1952 to enhance the security of the United States by advancing nuclear weapons science and technology and ensuring a safe, secure, and effective nuclear deterrent. With a talented and dedicated workforce and world-class research capabilities, the Laboratory strengthens national security with a tradition of science and technology innovation—anticipating, developing, and delivering solutions for the nation's most challenging problems.

The Laboratory is managed by Lawrence Livermore National Security, LLC (LLNS), for the National Nuclear Security Administration (NNSA), a semi-autonomous agency within the U.S. Department of Energy (DOE). LLNS is a limited liability company managed by Bechtel National, Inc.; the University of California; BWXT Government Group, Inc.; and the URS Division of AECOM. Battelle Memorial Institute also participates in LLNS as a teaming subcontractor. Cutting-edge science is enhanced through the expertise of the University of California and its 10 campuses and LLNS' affiliation with the Texas A&M University system.

ABOUT THE COVER

(right) The cover features maintenance work that contributed to efficient operations at LLNL's National Ignition Facility, where more than 400 system shots were fired during fiscal year (FY) 2016. (left) On the back cover, a sample is prepared for chemical analysis at the Forensic Science Center, which develops and provides leading-edge capabilities to support many LLNL mission areas, including chemical, nuclear, radiological, and biological counterterrorism.

Lawrence Livermore National Laboratory

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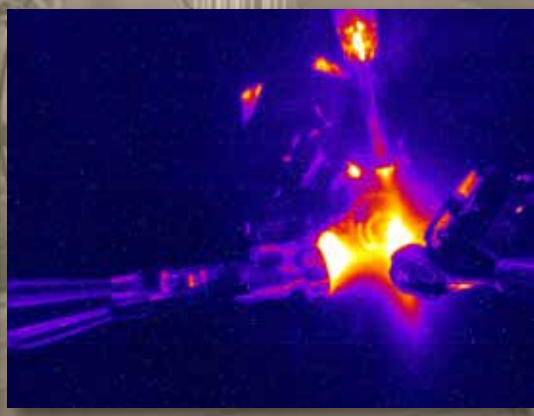
U.S. Government Printing Office: 2015/670-187-52044
UCRL-AR-211126-16

Researchers at LLNL are developing a "human-on-a-chip," a miniature external replication of key organs in the human body that integrates biology and engineering and combines microfluidics with multielectrode arrays. Their goal is to provide a noninvasive testing platform that will predict human exposure to drugs and toxins more accurately than animal studies.

INSIDE FY 2016

SCIENCE AND TECHNOLOGY ON A MISSION



LAWRENCE Livermore National Laboratory's (LLNL's) enduring mission for the Department of Energy and its National Nuclear Security Administration is helping to make the nation—and the world—safer and more secure through world-class science, technology, and engineering. This annual report is a snapshot of notable progress made in FY 2016 that advanced the frontiers of science and technology in service to national and international security.

During FY 2016, Laboratory researchers applied the unique tools of the Stockpile Stewardship Program to fulfill our core nuclear security mission of assessing and certifying the aging nuclear weapons systems in our care. We also mapped out options to extend the life of the W80-4 warhead for the U.S. Air Force's Long-Range Standoff missile. For example, we demonstrated that new, 3D printing techniques can produce parts with optimized material and engineering properties at lower cost and with much faster production times.

Weapons system certification relies heavily on physics models validated by experiments, many of which are performed at the National Ignition Facility (NIF). Researchers at NIF study the physics of a functioning nuclear weapon at extreme temperatures and pressures, expanding scientific knowledge on many fronts.

Leading-edge high-performance computing (HPC) is required for stockpile stewardship and other national security needs. Livermore HPC scientists are preparing for the arrival of Sierra, a next-generation supercomputer much more capable than today's most powerful machines. In addition, national security sponsors are leveraging LLNL expertise in "big data" to extract meaning from enormous amounts of information. This expertise is central to a partnership we have formed with the National Cancer Institute to fight cancer.

This annual report also highlights experiments aimed at improving capabilities to detect low-yield nuclear events and to better prevent and respond to weapons-of-mass-destruction terrorism. LLNL and an industrial partner made a forensics breakthrough: biological identification based on information encoded in human hair proteins. Three new elements, discovered by Laboratory scientists and collaborators, were added to the periodic table. And, to help mitigate climate change, researchers combined biology and 3D printing to convert methane to methanol.

These successes would not have been possible without an outstanding workforce with access to one-of-a-kind research facilities—people who bring new ideas, work with integrity and zeal, and thrive in an inclusive work environment. We are honored that LLNL was named to the *Forbes* 2016 list of America's Best Employers—and to be the only national laboratory on the list.

We are also strengthening safety and security, investing in infrastructure to enhance workplace quality, and taking innovative approaches to modernize the nation's nuclear weapons enterprise.

Enhancing national security in a rapidly changing world requires vigilance, innovative thinking about emerging threats, productive partnerships with industry and government, and continuing to leverage Livermore's enormous scientific, technological, and engineering expertise and resources. Lawrence Livermore is moving on all fronts to carry out its critical mission.

NUCLEAR DETERRENCE

Ensuring the safety, security, reliability, and effectiveness of the enduring stockpile

LLNL's foremost responsibility is to ensure the performance of the nation's nuclear arsenal. The knowledge gained through experiments, theory, and simulations is applied to assess the condition of stockpile weapons and to develop and certify needed modifications with confidence in the absence of nuclear explosive testing.

The successful flight test of a Minuteman III intercontinental ballistic missile in September concluded with the splash down of an instrumented mock W87 warhead in the waters of the Kwajalein Atoll in the Marshall Islands. LLNL is the lead design agency for the W87 nuclear explosive package.

Machinists Wesley Scoggins (left) and Ronald Cabeceiras examine a steel sheet before pressing it into a test part with the Laboratory's new hydroform. The 31-ton, state-of-the-art hydraulic press, needed for W80-4 work, was acquired with support from NNSA's Capabilities Based Investment Program.

Annual Stockpile Assessment

In FY 2016, Livermore completed Cycle 21 of the annual stockpile assessment. The process included comprehensive peer review by the nuclear design laboratories (LLNL and Los Alamos National Laboratory) of each other's weapons systems. LLNL scientists continue to improve the baseline weapons-physics simulation codes that support the annual assessments and certification of weapons. A wide range of stockpile surveillance activities and flight tests also provided critically needed data. For example, in September 2016, a joint DOE–Department of Defense flight test was conducted out of Vandenberg Air Force Base. The Minuteman III intercontinental ballistic missile carried an instrumented mock W87 warhead developed by LLNL.

Life-Extension Program Activities

LLNL is partnered with Sandia National Laboratories as the design agencies to develop and certify a warhead, the W80-4, for the bomber-delivered Long-Range Standoff missile. The Phase 6.2 study, now underway, to extend the stockpile lifetime of the W80 will result in a mature set of requirements and refined, cost-conscious design options. The Laboratory made excellent progress in the life-extension program (LEP)—implementing effective project management and control tools, developing design options, making necessary supportive infrastructure upgrades, and maturing component technologies. One critical need is to qualify and remanufacture additional insensitive high explosives to be used in the refurbished W80-4 warheads. Investments being made to upgrade aging high explosives facilities and infrastructure at Site 300 will support this work and a wide range of national security activities.

The design and certification process will require innovations and proficient use of NNSA's exceptional computational and experimental resources. An area of significant innovation at LLNL is additive manufacturing (AM) to improve the quality and reduce the cost of materials and parts for weapons undergoing LEPs. Major achievements include producing parts for assembly testing (with a first-ever specific part) and developing refined capabilities to control the microstructure and physical properties of AM-produced parts. Two major hydrodynamic tests conducted in FY 2016 provided important validation data in support of the design option for the W80-4 that used the latest AM technology.

Preparing for Sierra and Beyond

In September 2016, LLNL received two Sierra "early delivery" systems, which researchers will use to explore the systems' capabilities and test software. Sierra, a next-generation supercomputer built by IBM to be delivered in 2018, is expected to provide more than 120 petaflops

LLNL researchers examine on a powerwall the results of a simulation tailored to run efficiently on next-generation supercomputers.

(10^{15} floating-point operations per second) peak performance. Its procurement is part of the DOE-sponsored CORAL (Collaboration of Oak Ridge, Argonne, and Lawrence Livermore national laboratories) program to accelerate the development of high-performance computing (HPC) to meet mission needs. The collaboration is providing a strong basis for NNSA and the DOE Office of Science to pursue its Exascale Computing Project, which includes funding from DOE's FastForward initiative for leading HPC companies to develop exascale (10^{18} flops) computing technologies. Livermore has led procurement activities for CORAL, FastForward, and the acquisition of next-generation capacity computing machines for the NNSA laboratories.

To prepare for the arrival of the Sierra machine, code specialists are implementing significant changes to nuclear-weapons simulations to take advantage of performance improvements made possible by the presence of graphics processing units (GPUs)—a prominent feature of the Sierra machine. Employing tools developed at LLNL, the production team for one large code, ARES, was able to speed up performance by a factor of 11 with the NVIDIA GPU (used in Sierra) as compared to that on a single core of a traditional central processing unit.

Materials scientist Zachary Seeley holds up a gadolinium–lutetium–oxide (GLO) transparent ceramic scintillator. It dramatically improves high-energy radiography capabilities. Developed for stockpile stewardship, the technology won an R&D 100 Award in FY 2016 for its many other potential applications.

Stockpile Stewardship Experiments

Livermore successfully executed its work in the FY 2016 National Hydrodynamic Test Plan, including carrying out an integrated weapons experiment using an advanced optical technique to continually measure implosion symmetry of a mock weapon pit. This test was one of two major hydrodynamics experiments conducted to mature technologies with potential use in LEPs and improve predictive capabilities that underpin all facets of stockpile stewardship. Other tests supported the nuclear counterterrorism program and studied details about high-explosives performance. Laboratory scientists, engineers, and technicians are also engaged in design, development, and fabrication activities for subcritical experiments performed at the Nevada National Security Site.

Experiments at the Joint Actinide Shock Physics Experimental Research (JASPER) Facility and the National Ignition Facility (NIF) provide essential data about plutonium. Eleven experiments were conducted at JASPER and researchers fielded five plutonium experiments at NIF, including the first test measuring the material's strength at extreme conditions. (Additional NIF experiments in support of stockpile stewardship are described on pp. 6–7.) The experimental work is complemented by leading-edge efforts to model the complex properties of plutonium. For example, Livermore scientists developed a first-principles model that shows good agreement with recently measured magnetic properties of plutonium, a feature of the element first predicted by LLNL scientists.

Broadly Supporting the NNSA Complex

Laboratory personnel engaged in many activities to assist other sites in the Nuclear Security Enterprise. These efforts have enhanced technical capabilities at Pantex to nondestructively examine weapons pits (a technological development that won an R&D 100 Award in 2016), production methods (including AM) at the Kansas City National Security Campus, and safety processes broadly across the enterprise. In addition, LLNL has partnered with NNSA to develop the methodologies, templates, and tools for NNSA to establish an enterprise-wide infrastructure strategic plan (see p. 18).

NATIONAL IGNITION FACILITY

Supporting stockpile stewardship through a wide range of nonignition experiments and pursuit of laser fusion ignition, and operating as a national user facility for high-energy-density science

In FY 2016, a total of 417 system shots were fired at the National Ignition Facility (NIF)—exceeding the year's goal through continued improvements in efficiency. This number includes a recording-setting 17 shots during the last week of March. The total exceeded the figure for FY 2015 and more than doubled the 191 shots completed in FY 2014.

Experiments Supporting Mission Goals

NIF is serving as a highly productive cornerstone of stockpile stewardship. In FY 2016, 165 shots explored pertinent high-energy-density (HED) science and 146 advanced the prospect of demonstrating inertial confinement fusion (ICF) and energy gain, which is needed to develop an experimental platform for stockpile stewardship that provides thermonuclear burn. In addition, 33 system shots supported diverse national security applications, 38 focused on discovery science, and 35 were dedicated to developing new experimental capabilities.

Shown while being constructed in NIF's target bay, the Advanced Radiographic Capability (ARC) is currently undergoing demonstration testing. It is designed to produce radiographic "movies" of NIF experiments.

A shot-time image captures an experiment simulating stellar nucleosynthesis.

Stockpile Stewardship HED Science Experiments

HED science experiments at NIF explored wide-ranging physical phenomena central to stockpile stewardship. The shots gathered information about the properties of high-*Z* (high-atomic-number) materials at extreme conditions, radiation hydrodynamics and transport, and material mixing. These issues are critical to understanding nuclear weapons performance and improving the predictability and results of fusion ignition experiments. Researchers conducted the first material dynamics experiments examining the strength of plutonium at extreme conditions, and they continued a series of high-*Z* diffraction shots to study plutonium's equation-of-state at extreme pressures. Shots with tantalum foils tested both high-*Z* material strength models and new experimental platforms that provide greater capabilities. Tantalum becomes even stronger at the pressure of 3.5 and 5.0 million atmospheres (megabars)—at least two times stronger than strength model predictions.

Progress in Studying Fusion Ignition

Achieving fusion ignition and energy gain at NIF is a grand scientific challenge, and scientists are making progress on several fronts. Adjustments to the laser pulses (called "adiabat shaping") are reducing hydrodynamic instabilities, and changes to the hohlraum (the case enclosing the fuel capsule) are helping control the overall symmetry of implosions. In addition, the R&D 100 Award–winning polyelectrolyte enabled liftoff (PEEL) technology offers an approach

Designer Scott Vonhof and target design manager Carolyn Vargas review the design of an enlarged-diameter NIF hohlraum. An experimental campaign tested the use of larger hohlraums without gas fill as an approach to improving the symmetry of the hot spot in imploded fusion targets.

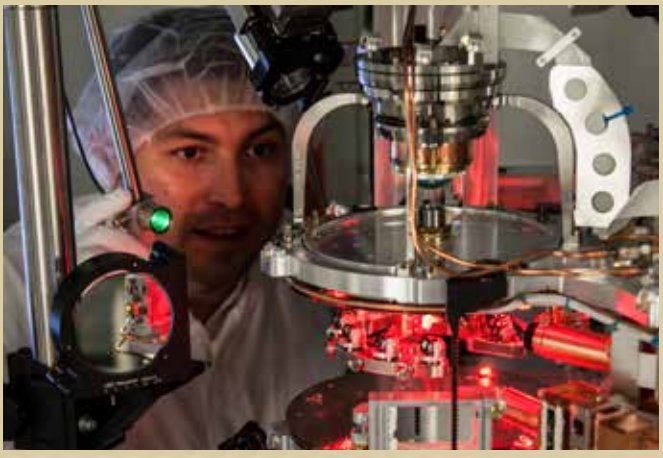
The new Target and Diagnostic Manipulator (TANDM) will further enhance the efficiency of NIF operations.

to reduce the implosion asymmetries caused by the "tent"—an ultrathin membrane that supports the target capsule within the hohlraum. ICF and many facets of HED research will further benefit from the newly commissioned Advanced Radiographic Capability (ARC). In FY 2016, the diagnostic was used for radiography experiments. ARC undergoes continuing testing to create a radiographic "movie" of the critical phases of an ICF implosion.

A new "wetted-foam" target design, first tested at NIF in FY 2016, will open up opportunities to study the target's central hot spot and its surrounding region. Developed by a team of researchers from LLNL, Los Alamos, and General Atomics, these target capsules are lined with a polymer foam that is saturated with liquid deuterium–tritium fuel. ICF shots in FY 2016 also included "shock/shear" experiments, led by scientists from Los Alamos. The tests were designed to further understand turbulent mix models. The target used in the experiment—a miniaturized shock-tube that includes a thin metal foil—is sheared by shock waves passing in opposite directions on opposing sides of the foil.

Discovery Science at NIF

In early August, the NIF team devoted a full week of experimental time to Discovery Science, providing five user groups with access to the unique HED conditions that NIF can create. One team continued a campaign to create collisionless shocks, which occur at astrophysical scale in supernova remnants, gamma-ray bursts, and cosmic ray acceleration. Another team studied Rayleigh–Taylor instability growth, and two others investigated the properties of warm dense plasmas that are created in ICF experiments and may be found in the core of large planets. In addition, the first three Turbulent Dynamo campaign experiments took place. The goal of these experiments, led by a team from Oxford University, is to study how the kinds of turbulent plasma conditions that exist throughout the cosmos amplify small "seed" magnetic fields into the fields that fill galaxies such as the Milky Way.



Target Alignment System Calibration Laboratory Manager Edwin Casco uses collimated light from an eye-safe lamp to verify alignment and clearances inside the new target alignment system. The red light is from light-emitting diodes used to illuminate NIF targets during alignment.

Another new series of Discovery Science experiments is exploring nucleosynthesis, the process by which stars make heavier elements from hydrogen and helium. Researchers can create conditions in a NIF experiment that are very similar in density and temperature to the interior of a star. The first three experiments focused on the chain of nuclear reactions that convert hydrogen into helium and turn a small amount of matter into energy. The multi-institutional team of researchers is measuring the reaction rates—data to be used to inform and improve models of nuclei production in stellar interiors. Two more rounds of experiments are scheduled.

Technologies to Improve Operations and Capabilities

In addition to many procedures that have increased operational efficiency, new technologies and equipment are also improving NIF's shot rate. In FY 2016, the NIF team installed the first of two new Target and Diagnostic Manipulators (TANDMs). They also installed the Advanced Tracking Laser Alignment System (ATLAS) and a new Target Alignment Sensor (TAS) that work together to provide NIF a wholly integrated alignment system. ATLAS speeds up the exacting process of aligning diagnostics inside the target chamber. This tracking system is more flexible and offers greater capability than the two systems previously used to align the diagnostic instrument manipulators (DIMs). ATLAS also eliminates the need to install additional target alignment systems as new capabilities such as TANDMs are commissioned. Each TANDM is a combination DIM and positioner for warm targets. Operations with the newly deployed TANDM together with the current target positioner (TarPos) are more efficient. They allow NIF's third target positioner (Cryo TarPos) to be dedicated to growing cryogenically cooled target layers while the others service experiments.

GLOBAL SECURITY

Reducing the threat from terrorism and weapons of mass destruction and enhancing global stability

LLNL develops innovative advanced technologies to help the government anticipate, identify, and address global security threats. By applying scientific and engineering expertise in chemical, biological, radiological, nuclear, and explosive weapons, our experts support threat preparedness, prevention, protection, and response and recovery. Innovations in space situational awareness and cyber defense help strengthen national security in an interconnected world.

Used for training purposes, the Spectroscopic Injection Pulser (SIP) mimics radiation sources by injecting high-fidelity signals of any isotope or mixtures of isotopes into the amplifiers of radiation detectors.

LLNL engineer Justin Jones inspects the interface at the top of the high-explosives canister in preparation for the Source Physics Experiment-6.

Tools to Search for Special Nuclear Materials

Law enforcement or homeland security agencies search for radiological or nuclear threats before many special events or when credible evidence exists that a device has been implanted. LLNL is leading a multilaboratory team that completed prototype development of the Optimization Planning Tool for Urban Search (OPTUS). The software program, which uses detailed physical descriptions of urban areas and sophisticated optimization algorithms, helps teams conduct more thorough searches in less time. Search teams and planners are now testing and refining OPTUS.

Livermore researchers also designed a device, called the Spectroscopic Injection Pulser (SIP), for training first responders to deal with the consequences of any nuclear incident. Training exercises on the use of radiation detectors typically employ relatively harmless, but less realistic, isotopes as surrogates for special nuclear materials. SIP adds realism by injecting into a radiation detector signals that would be detected if actual radioactive materials were present, taking into account the detector's location relative to the supposed radiation sources. The technology, which was supported by Laboratory Directed Research and Development funding, has been demonstrated to representatives from U.S. federal agencies, the International Atomic Energy Agency (IAEA), and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization.

Tests to Better Detect Low-Yield Nuclear Explosions

LLNL researchers played a leading role in planning and conducting the final two Source Physics Experiments (SPEs) in the Phase I series. Phase I consisted of six underground high-explosive detonations in hard rock, designed to improve the United States' ability to detect and identify low-yield nuclear explosions amid the clutter of conventional explosions and small earthquakes. SPE-5 was the highest yield test in the series, a 5-ton (TNT-equivalent yield) underground chemical explosion. Fired in April 2016, the test provided important information about how explosions generate shear waves, which are used to monitor nuclear tests. The jolt measured 2.0 on the Richter scale and was detected at several hundred seismic stations, including some at distances of more than 400 kilometers. SPE-6 was conducted in October 2016 and was the shallowest of the series. By comparing SPE-6 to the previous deeper high-explosives SPE tests and nearby historic underground nuclear tests, researchers are gaining a better understanding of the effects of depth and size on explosion-generated seismic signals.

Apex Gold was the first minister-level gathering to identify national and international actions in the event of a nuclear crisis.

Biosecurity Preparedness in the Subway

Researchers used DNATrax, developed at LLNL, to study how a biological agent, such as anthrax, released by accident or as a result of a terrorist attack might disperse throughout the nation's largest rapid transit systems. An LLNL field team supervised the release of DNATrax, a harmless aerosol, at New York City's Grand Central Terminal and two other major subway hubs. The team then helped collect environmental samples of the particles at more than 50 subway stations. The Department of Homeland Security sponsored the multiagency test, led by the MIT Lincoln Laboratory, to gather information to help local authorities and emergency management personnel in preparedness planning. This was the first comprehensive study of its kind performed on a major subway system during normal operating hours.

Human-on-a-Chip Monitors Live Neurons

Livermore researchers are working to predict the effects of potentially harmful chemicals, viruses, or drugs on humans without resorting to animal-based tests. They are testing an innovative "human-on-a-chip," a miniature external replication of human-body organs that integrates biology and engineering with a combination of microfluidics and multielectrode arrays. Called the iCHIP (in-vitro Chip-based Human Investigational Platform), the device is the first platform to demonstrate that long-term culture and chemical interrogation of primary human brain neurons on microelectrode arrays is possible. Microelectrodes noninvasively monitor how live neurons seeded and grown on the chip interact and react to chemical stimuli ranging from caffeine to real chemical agents.

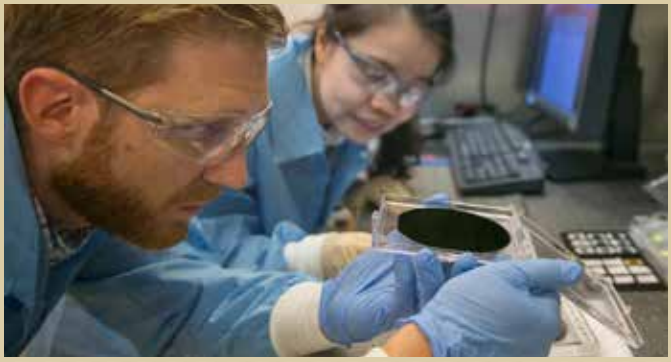
Researchers use a nontoxic aerosol tracker developed at LLNL to study how airborne biological agents might disperse through the New York City subway system.

Apex Gold

Apex Gold was the first minister-level gathering to identify potential national and international actions in the event of a nuclear crisis. Held at LLNL, the two-day exercise in January 2016 was hosted by the U.S. Department of Energy and the Netherlands Ministry of Foreign Affairs. Ministers and other delegates from 37 nations attended as did representatives from the IAEA, INTERPOL, the European Union, and the United Nations. Presented with a hypothetical nuclear terrorism scenario, attendees worked together to determine response options. Livermore international security experts helped develop the scenario and hosted Laboratory tours and equipment demonstrations that provided context for the exercise. Apex Gold laid the groundwork for the Nuclear Security Summit, hosted by President Barack Obama, March 30–April 1, 2016. LLNL's National Atmospheric Release and Advisory Center (NARAC) provided simulations to the Nuclear Security Summit. The White House recognized the valuable support that NARAC provided.

A "Smart Skin" to Protect Soldiers

Laboratory scientists are applying nanotechnology to create military-grade clothing for protecting U.S. soldiers from chemical and biological attacks. The research, conducted for the Defense Threat Reduction Agency, aims to provide soldiers with breathable and lightweight protective suits within 10 years. The "smart skin" features flexible polymeric membranes with aligned carbon nanotube channels that are 5,000 times smaller than the width of a human hair. Sweat and air move easily through the nanotubes, and tests have shown that bacteria and viruses are too large to pass. LLNL scientists and collaborators are now examining two options to sense, react, and block smaller-diameter chemical agents from entering the nanotubes.



In work that aims to protect soldiers from biological and chemical threats, a team of Laboratory scientists has created a highly breathable material that protects against biological agents.

ENERGY AND ENVIRONMENT

Using science and technology to improve national energy security and surety, protect the environment, and understand and mitigate climate change

Laboratory researchers apply leading-edge capabilities to develop efficient, environmentally benign energy technologies and to investigate the processes behind climate change.

One HPC4Mfg project aims to improve efficiency in the smelting process and help reduce steel manufacturer's reliance on coke—a coal-based fuel with high carbon content.

Livermore engineers (from left) Guillaume Petitpas and Salvador Aceves examine a liquid-hydrogen fuel tank at the Laboratory's Cryogenic Hydrogen Test Facility.

Computational Innovation to Boost U.S. Industry

The High Performance Computing for Manufacturing (HPC4Mfg) Program currently provides $11.4 million to support 28 projects involving 23 U.S. companies and Lawrence Livermore, Lawrence Berkeley, and Oak Ridge national laboratories. Established at LLNL by DOE's Office of Energy Efficiency and Renewable Energy (EERE) in 2015, the program funds experts at DOE's national laboratories to work directly with manufacturing industry partners. HPC4Mfg helps companies use HPC to better understand manufacturing processes so that they can increase energy efficiency, reduce environmental impacts, and advance clean-energy technologies. The program is growing, with the second round of proposal solicitations for the year launched in September 2016.

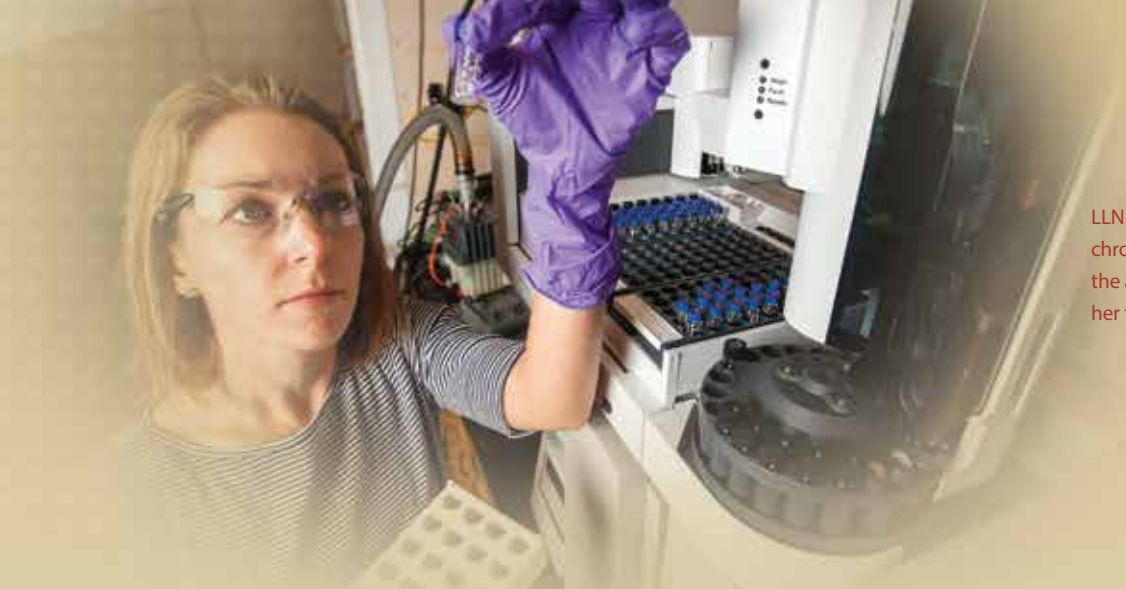
As part of the program, LLNL is working with Purdue University and a steel manufacturing consortium to simulate and optimize the smelting process and reduce reliance on coke—a coal-based fuel with high carbon content. Other projects aim to improve paper manufacturing, enhance predictability in additive-manufacturing processes, and increase the efficiency and component life of aircraft engines through design optimization.

Innovations for Hydrogen-Powered Vehicles

Supported by DOE's EERE, researchers are using the Laboratory's new Cryogenic Hydrogen Test Facility to improve hydrogen storage and delivery for vehicles. For nearly two decades, LLNL scientists have been at the forefront of researching hydrogen as a viable pollution-free transportation fuel. The test facility includes a stainless steel containment unit to test the safety of full-scale vehicular hydrogen vessels. Livermore, in partnership with Spencer Composites and BMW, has designed and built several innovative prototypes. The pumping station at the test facility uses a new high-density liquid-hydrogen pumping process that fuels vehicles more quickly with less costly, smaller, and more energy-efficient equipment than current hydrogen fueling stations.

Conversion of Methane to Methanol

Laboratory scientists have combined biology and 3D printing to create the first reactor that can continuously produce methanol from methane at ambient temperature and pressure. Methane is a greenhouse gas, and emissions from oil and gas extraction pose



LLNL chemist Sarah Baker holds a gas chromatography vial used to measure the amount of methanol produced by her team's enzyme-embedded polymer.

a potential for net global warming. By converting methane to methanol, it can be used for fuels, solvents, and antifreeze. The team removed enzymes from methanotrophs, methane-eating bacteria, and mixed them with polymers that they can print (or mold) into innovative chemical reactors. The printed enzyme-embedded polymer is a highly flexible and efficient reactor, which should be useful in a wide range of applications.

Secrets about Soil Carbon Revealed

A Livermore-led research team is probing the fundamental mechanisms that regulate decomposition rates of soil organic matter (SOM) at the level of individual microbial cells and mineral particles. Two-thirds of the carbon in the terrestrial biosphere is stored underground as SOM, a complex mixture of decaying plant and microbial cell material. The amount of carbon that is retained within SOM, rather than released as atmospheric carbon dioxide (CO_2), is an important factor affecting climate change. The team is combining the capabilities of two advanced, high-resolution imaging technologies: the nanometer-scale secondary ion mass spectrometer (NanoSIMS) at Livermore and scanning transmission x-ray microscopy (STXM) at Lawrence Berkeley. One discovery is that the organic compounds released by plant roots can act directly on soil minerals, break chemical bonds, and release long-stored carbon. As climate change increases plant growth, the release of CO_2 into the atmosphere by this mechanism will accelerate.

Livermore researchers Peter Weber and Jennifer Pett-Ridge prepare a sample for testing in the nanometer-scale secondary ion mass spectrometer (NanoSIMS), one of only a few such instruments in the world dedicated to isotope imaging in microbial biology and soils research.

Oceans, Clouds, and Global Climate Change

Three studies by LLNL scientists and colleagues further substantiate growing concerns about climate change. One study, published in *Nature Climate Change*, found that half of the increase in global ocean heat content since 1865 has occurred over the last two decades. Changes in ocean heat storage are important because the ocean absorbs more than 90 percent of the Earth's excess heat increase associated with climate change. In another study, published in *Nature*, scientists found that changes in cloud patterns during the last three decades match those predicted by climate model simulations. These cloud changes are likely to have a warming effect on the planet. Much of the uncertainty in how much the planet will warm in response to greenhouse gas emissions is due to uncertainty in how clouds will respond. A third paper, published in *Science*, concluded that today's climate models are making clouds too bright and overly reflective as the planet warms. This high reflectivity may be causing models to underestimate how much global warming will occur as a result of increased atmospheric CO_2.

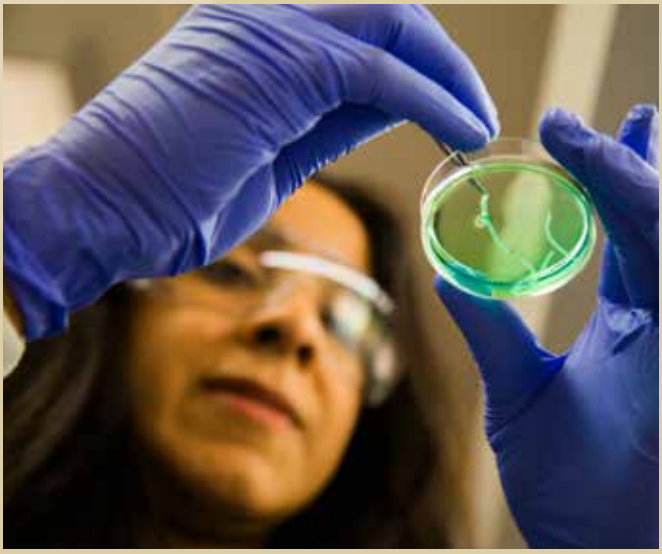
Enhancing Power Grid Cyber Security

Cyber security experts from Lawrence Livermore and Lawrence Berkeley national laboratories are leading a new program to develop new data analysis methods for better protecting the nation's power grid from advanced cyber threats. The team is collecting data from various sources and evaluating them using advanced analytics to identify threats and improve response methods. The group is partnering with the Electric Power Board and the National Rural Electric Cooperative Association, which will provide data and collaborate in technology transfer to the power industry. The effort is a component of DOE's Grid Modernization Initiative, announced by Secretary Ernie Moniz in January 2016. Altogether, LLNL researchers are working on 14 new grid research projects through this $220-million, three-year initiative.

SCIENCE AND TECHNOLOGY

Expanding the boundaries of scientific knowledge and advancing the technological state of the art to solve problems of national and global importance

Research applying Livermore's multidisciplinary approach to problem solving and world-class experimental and computational resources leads to exciting discoveries and innovative advances that support mission needs.



Using a 3D printer and a bio-ink made of materials compatible with the human body, engineer Monica Moya (shown) and her team have successfully printed a vascularized network of cell tissue.

A pair of meteorites are destined to be vaporized by high-powered lasers, and the data they provide for asteroid deflection research could one day save the planet.

Key Advances in Additive Manufacturing

New materials created at Livermore in FY 2016 by additive manufacturing (AM) are serving as fundamental building blocks of innovation. For example, researchers printed "living" blood vessels using a 3D printer and a bio-ink made of biocompatible materials. The printed cells and other biomaterials form tubes that deliver nutrients to a surrounding environment of printed cell tissue, and self-assembled capillaries deliver nutrients to the tissue. The printing process allows more effective reproduction of cell physiology for ex vivo human health research, such as LLNL's human-on-a-chip project (see p. 9).

Livermore researchers also 3D-printed parts out of reactive materials, enabling them to exercise more control over the energy release rate of reactive composites, such as thermite nanoparticles. This development promises new reactive materials for applications that need bursts of energy, automotive air bags for example. In addition, researchers built multiple layers of lattices, ranging from nanometer- to centimeter-scale, to produce ultralightweight 3D flexible materials. With properties not found in nature, these materials could find use in applications like aircraft parts, flexible armor, and batteries. Other materials reported over the year include those that can fold and unfold over time (adding a fourth dimension to 3D materials) and ultralight supercapacitors for energy storage.

Laboratory researchers are also delving into the complex physics of 3D printing techniques to optimize material design for meeting functional needs and improving quality control, which is important for product certification. For example, through research in micro-scale interactions and material dynamics, they have discovered phenomena that better explain the causes of porosity in metal parts produced by the laser powder-bed fusion process, paving the way toward improvements in AM part performance.

A Focus on Asteroids

Astronomical objects, such as asteroids, provide insight into the origins of our solar system and are of keen interest to Laboratory scientists. However, they also threaten life on Earth. NASA has identified more than 14,000 asteroids crossing the vicinity of Earth's orbit. Planetary defense researchers at Livermore have modeled the physics of deflecting an asteroid on a collision course with Earth through a high-energy impact. Research published in the past year used computer simulations to examine how asteroid shape, density, porosity, and rotation affect the strategy of deflection by kinetic

Physicist Manyalibo (Ibo) Matthews uses a unique in situ diagnostics test bench to study how defects or deformations occur in metals during the 3D-printing process.

impact and has provided options on how to design such missions. Livermore's planetary defense team is also studying meteorites scavenged from Antarctica. These samples are vaporized by strong laser pulses in the Laboratory's Jupiter Laser Facility to collect data about physical properties that are needed to design a high-impact deflection mission.

Researchers from LLNL and the Johns Hopkins University Applied Physics Laboratory are on the team selected to participate in one of two NASA Discovery Program missions to explore the early solar system. They are developing GeMini Plus, a new high-purity germanium-based detector that would fly on the 16 Psyche mission, designed to visit the asteroid of the same name that follows Jupiter's orbit. The asteroid is thought to present an opportunity for studying a body resembling a planetary core. The mission is targeted to launch in October 2023. This team earlier developed the original GeMini gamma-ray spectroscopy instrument, which flew on the highly successful MESSENGER mission to Mercury.

Forensic Analyses Using Human Hair Proteins

Livermore researchers and a Utah startup company have developed the first-ever biological identification method that exploits the information encoded in proteins of human hair. This groundbreaking technique, in addition to DNA profiling, can provide a science-based, statistically validated way to identify people and link individuals to evidence. DNA profiling is ineffective when too much time has passed. The new protein identification method has been able to detect protein in human hair more than 250 years old. It offers another tool to law enforcement authorities for crime scene investigations and to archaeologists for studying historical remains.

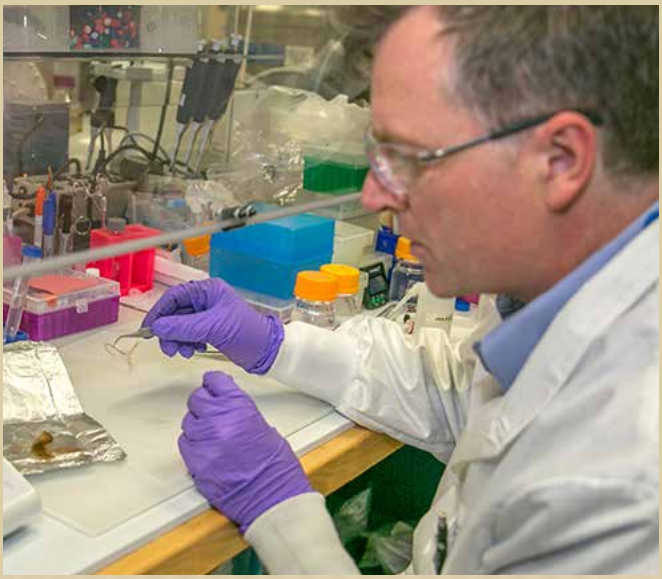
Once the method is optimized, researchers believe they will be able to use a set of 90 to 100 protein markers from a small number of human hairs, possibly as few as one, to distinguish an individual from the rest of the world's population. Although hair is sometimes used as forensic evidence, the current subjective methods of hair comparison are frequently inaccurate. Developing protein markers as an identification tool establishes a quantitative, scientific foundation for using hair in forensic science.

New Elements Named and New Nuclei Discovered

The International Union of Pure and Applied Chemistry officially added to the periodic table two new elements (115 and 118) co-discovered by LLNL and the Joint Institute of Nuclear Research (JINR), in Dubna, Russia, and a third new element (117) co-discovered by Livermore, JINR, Oak Ridge National Laboratory (ORNL), Vanderbilt University, and the University of Nevada at Las Vegas. Element 118, now called Oganesson, is named for Yuri Oganessian, the leader of the Russian research team at Dubna credited for discovering six elements. Tennessine, element 117, honors the state where ORNL is located. The new element 115 is named Moscovium, after the Moscow Region. These elements join others previously co-discovered by LLNL and JINR including Livermorium (116), and Flerovium (114). The fruitful, longstanding Livermore–Russian research collaboration dates back to 1989. The Livermore team responsible for the new elements, working with international collaborators, also discovered five new atomic nuclei to be added to the chart of nuclides. These exotic new nuclei were created as the collaborative team explored new methods for synthesizing super heavy elements.

Partnership Advances Cancer Research

Livermore has a crucial role in a DOE–National Cancer Institute (NCI) partnership in which the DOE national laboratories are



Biochemist Glendon Parker examines a 250-year-old hair sample that has been analyzed for human identification. Researchers from LLNL and a Utah startup company have developed the first-ever biological identification method that exploits the information encoded in proteins of human hair.

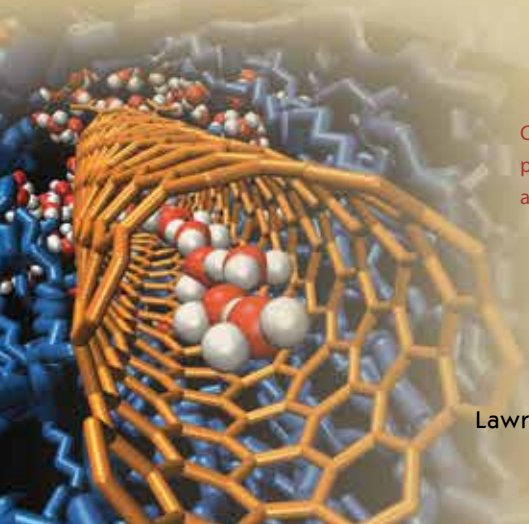
applying high-performance computing (HPC) to develop cancer treatments, tools for biosecurity, and cures for infectious diseases. LLNL is contributing to each of three pilot programs. The DOE–NCI partnership is a key element of the Cancer Moonshot Initiative, which seeks to double the rate of progress in the understanding, prevention, diagnosis, and treatment of cancer.

HPC enables biomedical researchers to perform data analytics on large sets of patient, drug, and other types of data for establishing patterns in data sets that are too large for the human brain alone to process. HPC-based simulation is also useful for testing drug and treatment options, saving time and effort by identifying the best ones early in the development process and pre-screening candidates prior to synthesis. A simulation of drug-membrane permeability developed by Livermore exemplifies this approach. Using HPC, Laboratory researchers tested the ability of large numbers of candidate drug molecules to treat nerve agents by simulating their efficacy at penetrating cell membranes and reversing the effects of these chemical weapons. Their new approach, which involves simultaneously simulating many candidates passing through the membrane, reduced compute time substantially.

Advancing Nanotechnology for New Applications

For the first time, LLNL researchers have shown protons can be transported an order of magnitude faster through carbon nanotubes as small as eight-tenths of a nanometer in diameter than through bulk water. Carbon nanotube porins, tube-like nanostructures developed at Livermore, are more than 20,000 times smaller in diameter than a human hair. They can function as one-dimensional water wires, moving protons in a line of water molecules faster than biological channels and/or human-made proton conductors. Practical applications include proton exchange membranes, proton-based signaling in biological systems, and the emerging field of proton bioelectronics (protonics).

Livermore's scientists also developed a library of nanoporous gold structures on a single chip. Using laser microprocessing to control the size and shapes of structures in gold, they generated a set of 81 samples with different morphologies for use in research areas such as advanced batteries, neural technology, biosensors, and living cell–material interaction. This work exemplifies how Livermore is helping develop the building blocks and basic knowledge necessary to exploit nanoscale phenomena in useful technologies.



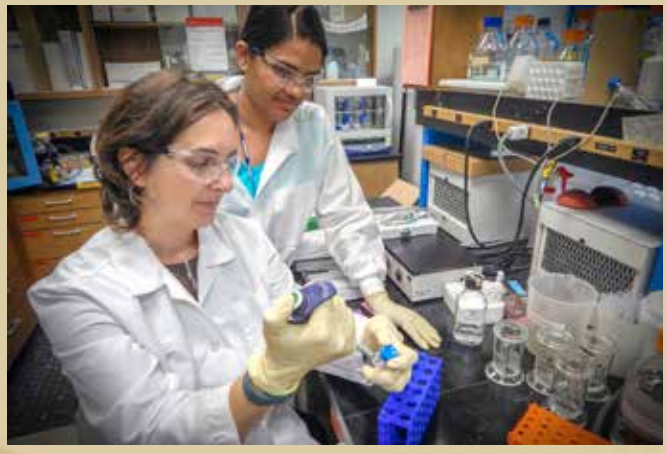
Carbon nanotubes can transport protons much faster than other available mechanisms.

Biomedical Scientists Seek Cures for Medical Conditions

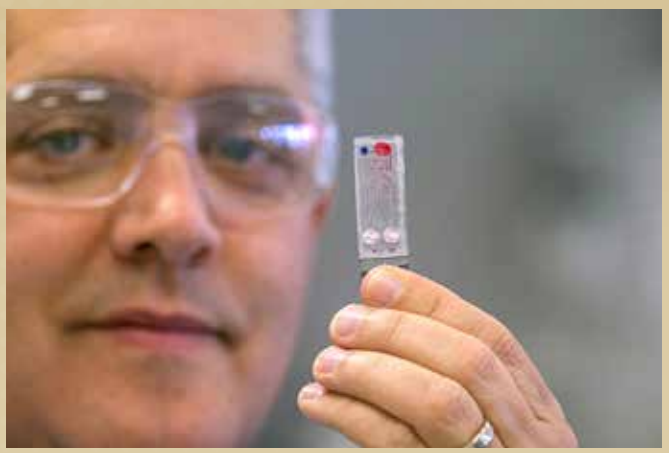
In FY 2016, Livermore addressed a range of ailments from bone formation to brain trauma to respiratory infection. Biomedical scientists found that a deficiency in the secreted bone protein sclerostin (SOST) allows prostate cancer cells to metastasize to the bone because the presence of SOST may have an inhibitory effect. A separate finding by Livermore scientists suggests the SOST gene may respond to loading stresses on the bone, signaling it to turn on or off as the bone loads and unloads. When the SOST gene is off, bone formation proceeds normally. This result could help scientists develop ways of preventing bone loss in astronauts living in space. The researchers also found for the first time that SOST is also deeply involved with fracture healing, potentially leading to future treatments that harness the cells generating SOST to heal injuries elsewhere in the body.

Blast-induced traumatic brain injury afflicts soldiers in combat. Livermore physicists and colleagues have simulated the effect of this type of trauma using HPC to better understand how blasts affect the brain. The shock wave from these blasts induces shear forces in the cranium, producing bubbles within brain cells that damage cell walls. As these bubbles collapse, they generate enough force to induce pore formation in cell membranes. The pores open up membranes to unregulated ion exchanges with external fluids. This eventually leads to a cascade of events including the death of neurons—brain cells. The work is aimed at finding ways to reduce the effects of brain trauma.

Laboratory researchers also study infectious threats to our health. This year, they sequenced the genome of the deadly Middle East Respiratory Syndrome to improve understanding of how it was transmitted through mutations from animals to humans. Such work initiates the process of developing more effective treatments and slowing the disease's spread during outbreaks. Livermore's biosecurity mission motivates these studies.



LLNL scientists Gaby Loots (left) and Aimy Sebastian count and prepare live cells for visualization. They have discovered a specific secreted protein that inhibits prostate cancer metastasis to bone.



Radiobiologist Matthew Coleman displays a passive flow lateral device for biodosimetry. This single-use protein detection assay is similar to the medical diagnostic instrument Coleman helped develop for NASA to use for deep-space missions.

A stainless steel ball is supported by a thin sheet of plastic about 200 atoms thick. The plastic sheet was produced using an R&D 100 Award–winning technology known as polyelectrolyte enabled liftoff, which was developed by LLNL researchers and General Atomics.

Medical Diagnostics to Assist NASA

Livermore's expertise in medical diagnostics technology, developed for biosecurity applications, will help NASA safeguard the health of astronauts. Livermore and its research partners, including NASA Ames Research Center, developed a comprehensive in-flight medical diagnostic system weighing less than one pound for human deep-space missions, such as a flight to Mars. The team was recognized with an award from NASA for their work. The device will use biomarkers from breath, saliva, and blood to measure the health and radiation exposure of astronauts.

Scientists at Livermore partnering with three NASA research centers will use a second device, the Lawrence Livermore Microbial Detection Array (LLMDA), to study microbes inside the closed environment aboard the International Space Station. LLMDA will help the astronauts evaluate the microbes that might pose threats to their health. Instead of culturing bacteria, which takes days, LLMDA sequences the genes of bacteria, and scientists compare the results to a library of sequenced species genomes, generating results in 24 hours. LLMDA has proven itself in studies of injured soldiers' combat wounds. The NASA project will focus on microbes and virulent or antibiotic-resistant genes found aboard the station.

Expanding Industrial Partnerships

LLNL is benefiting the U.S. economy with innovative technology and scientific advances. In FY 2016, LLNL obtained 97 new patents, asserted 93 new copyrights, and licensed 20 new technologies. Licensing income for the year totaled approximately $8.4 million. In addition to serving as a focal point for technology transfer, LLNL's Industrial Partnerships Office (IPO) trains Laboratory staff in the fundamentals of business, entrepreneurship, and technology commercialization. For example, IPO helped develop and, with Sandia National Laboratories, hosts the National Labs Entrepreneurship Academy, taught by the University of California at Davis Graduate School of Management. To date, four three-day-long courses have trained a total of 130 LLNL and Sandia scientists and engineers. IPO also regularly works with Silicon Valley entrepreneurship and angel investment groups. Monthly webinars presenting technology to the entrepreneurial community are held to highlight technology that has commercial potential.

Three R&D 100 Award Winners

This year, Livermore won three R&D 100 awards, bringing the total to 158 such honors since 1978. These awards recognize the year's 100 best technological innovations. Two of the winners directly support stockpile stewardship (see pp. 5–6). The gadolinium–lutetium–oxide (GLO) transparent ceramic scintillator sharpens the quality of 3D x-ray images by substantially reducing data acquisition time and enhancing the spatial resolution of x-ray computerized tomography images. With this capability, scientists and engineers can improve the assessment and quality control of high-density parts, such those used in power plant turbines and jet engines. The polyelectrolyte enabled liftoff (PEEL) technology is a robust, scalable method of fabricating stronger and thinner freestanding polymer films that are larger in area than conventional methods can produce. Livermore uses PEEL at its National Ignition Facility to fabricate membranes as thin as 30 nanometers that serve as compliant, load-bearing elements for laser targets. Because the process is easily scalable in size and manufacturing quantity, it could eventually be applied to sensing, catalysis, filtration, and wound-healing applications.

Livermore shared its third award with five universities and three other national laboratories. The team developed the Carbon Capture Simulation Initiative toolset, which includes a suite of computational tools and models to accelerate the development of carbon-capture technology for manufacturers and businesses.

SAFE, SECURE, AND SUSTAINABLE OPERATIONS

Conducting safe, secure, environmentally sound operations and modernizing the Laboratory's infrastructure to meet evolving mission needs

Committed to the highest level of operational performance, LLNL implements best practices in environment, safety, and health (ES&H), and security. Management systems support continuous improvement in work practices. Prudent risk management coupled with active measures to prevent accidents ensures the safety of employees and the public. Investments are targeted at modernizing the Laboratory's infrastructure.

Cyber security analysts Patrick Stevens (left) and Darren Lynch discuss the use of SafeWeb—a tool to protect LLNL computers from malicious websites.

Administrator Shirley Davis discusses physical security as part of a security awareness campaign in December 2016 that included a traveling exhibit of interactive displays and information handouts.

Award-Winning ES&H

The Laboratory's injury and illness rates remain near historic lows. FY 2016's total recordable case (TRC) rate of 1.40 continues recent excellent performance, and the days away, restricted, or transferred (DART) rate, which is a measure of severity of injuries, is 0.57. Both figures are down by more than 40 percent since the contract transition in 2008. LLNL received two National Safety Council awards for its low rate of lost workday incidents. Continual improvement is a key facet of LLNL's Integrated Safety Management System, which is certified with Occupational Health and Safety Assessment Series (OHSAS) 18001 accreditation. In addition to its ergonomics program, Livermore launched new initiatives to reduce slips, trips, and falls—the most common injuries. With nearly 1,000 people participating in the Wellness Program's annual Get Active Campaign, LLNL won the distinction as this year's *Fittest DOE Lab in the Nation*.

Effective Operations

In FY 2016, operations at LLNL were effectively and efficiently managed, with notable successes in many areas. In ES&H, the Laboratory maintained ISO 14001 and OHSAS 18001 certification and external auditors identified 34 noteworthy practices. Nuclear Operations implemented improvements in facility-level nuclear safety, provided effective assessments, and supported Laboratory programs and other DOE sites in the areas of Nuclear Criticality Safety and Safety Basis. The Laboratory's Emergency Management program completed all deliverables according to its Emergency Readiness Assurance Plan, including a full-participation exercise and two functional exercises at facilities with potentially hazardous operations. In addition, the Cyber Security Program provided a stable and responsive operating environment in support of successful mission execution. Laboratory-wide efforts are under way to heighten security awareness and improve overall performance.

In addition, LLNL had many successes delivering efficient and effective business operations, systems, and information technology. Of particular note, Director Bill Goldstein received DOE's Director of the Year award for encouraging and promoting collaborations with small businesses. In the prior year, nearly 63 percent of the $350 million spent for services in support of LLNL's missions were awarded to small businesses. DOE's goal is 52 percent.

Safety in work practices is paramount, especially in facilities such as the High Explosives Applications Facility, which houses high-explosives firing tanks, energetic-material synthesis laboratories, and a two-stage gun (shown with technician Paul Dealmeida) for shock-physics experiments.

Improvements to Work Planning

LLNL worked an ambitious schedule in FY 2016 to complete the infrastructure necessary for Laboratory-wide implementation of the revamped work planning and control (WP&C) process. This major undertaking will change how mission, site-wide service, and facility and infrastructure work is planned, scheduled, and released. The goal is to create and implement a single WP&C process across the Laboratory that is more robust and efficient and provides value-adding work control documents and processes.

Overall, the Laboratory is on track with phased implementation of the WP&C process, which for mission-directed work affects more than 3,500 employees operating under more than 1,150 existing work control documents. Accordingly, changes are being pursued deliberately and cautiously. The Laboratory began early implementation of the new process at Site 300 in early April. Implementation has also begun in selected program areas at the main site. A Functional Management Review completed in September 2016 concluded "the WP&C process has significant potential and, once realized, can serve as a template for the DOE Complex."

Progress Toward Site Sustainability Goals

LLNL's Environmental Management System, which has International Organization for Standardization (ISO) 14001 accreditation, ensures environmentally responsible work practices. These practices provide a systematic approach to identifying and reducing the environmental impact of Laboratory activities. The 2015 *Site Annual Environmental Report* (issued in October 2016) records LLNL's compliance with environmental standards, describes environmental protection and remediation programs, and presents the results of environmental monitoring.

LLNL also met its sustainability goals in FY 2016. The Laboratory has already achieved its FY 2020 greenhouse-gas reduction goal of 28 percent. In addition, Livermore has maintained vigilance in its water-savings program. The Laboratory is meeting California Governor Jerry Brown's mandatory potable water irrigation-reduction requirements and has reduced irrigation usage by more than 50 percent since FY 2013. However, the demand for cooling tower water (e.g., used for high-performance computing facilities) remains substantial. Operations began in February 2016 at a 10-acre 3.3-megawatt solar farm located in LLNL's northwest buffer zone. The solar farm is generating about 500 megawatt-hours per month to help meet goals for renewable energy use.

(above) The Emergency Operations Center provides centralized coordination of response activities. In an actual emergency, the center would be assisted by trained employee volunteers, who periodically practice in drills and exercises. (below right) LLNL's 3.3-megawatt solar farm is operational.

Maintaining the Infrastructure

LLNL invested nearly $18 million from the site support budget to improve the workplace environment. This work included roof repairs, heating, ventilation and air conditioning replacement, utility upgrades, and facility improvements, and achieved, for the first time since the contract transition, the annual investment goal of 2 percent of Replacement Plant Value. The investment also increased funding and staffing for infrastructure and maintenance at LLNL's remote experimental complex, Site 300. With $11 million direct funding, LLNL replaced 11 pieces of foundational but obsolete equipment required for the weapons program. Examples include commissioning of a hydroform pressing machine (see p. 4) and high-speed digital framing cameras used in hydrodynamic experiments. These improvements strengthened Livermore's overall infrastructure and enhance work effectiveness and safety as activities ramp up for the W80-4 life extension program. Efforts also began to migrate applied materials engineering capabilities out of a 60-year-old substandard building into a modernized complex with a smaller, more efficient footprint.

MANAGING FOR THE FUTURE

Positioning the Laboratory for continuing science and technology excellence directed at important national missions

In FY 2016, LLNL focused on engaging with sponsors and stakeholders, strategic planning, and building for future successes.

Acting Computation Associate Director Kim Cupps gives a tour of the new high-performance computing facility, home to some of LLNL's newest unclassified machines. The facility supports academic alliances and important initiatives such as the DOE-wide exascale computing project.

LLNL ranks among the 500 companies on the *Forbes* 2016 list of America's Best Employers.

Strategic Engagements and Planning

Director Bill Goldstein and his management team participated in discussions about national security and the evolving strategic landscape with wide-ranging audiences. Events in Washington, D.C., early in the fiscal year included National Security Lab Day on Capitol Hill, NNSA's 20th Anniversary of Stockpile Stewardship event, and the Strategic Weapons in the 21st Century Conference, co-hosted by LLNL and LANL. Livermore also participated in DOE's Big Ideas Summits, organized and hosted the U.S. Air Force Nuclear Enterprise Meeting in January 2016, provided the venue for Apex Gold (see p. 9), and staged workshops on cross-domain deterrence. These engagements helped provide a foundation for strategic planning activities.

The strategic planning effort provided a fresh re-examination of the Laboratory's programmatic, workforce, and infrastructure directions. Working groups drawn from across the Laboratory focused on four programmatic directions—modern deterrence, cyber security, biosecurity, resource security, and two cross-cutting issues—workforce and infrastructure. Key mission research challenges were identified, which together with the Laboratory's set of core competencies, will provide direction for internal investment priorities in science, technology, and engineering (ST&E). Initiatives are under way to ensure continued workforce excellence and to modernize the Laboratory's facilities and infrastructure (F&I).

Investing in Facilities and Infrastructure

Officials from NNSA and other government representatives visited in June to dedicate a new supercomputing facility at the Laboratory. The $9.8 million sustainable facility provides flexibility to accommodate future advances in computer technology and meet a rapidly growing demand for unclassified high-performance computing. The facility is now home to a Sierra "early delivery" system and the first of NNSA's next-generation-capacity computing machines (see p. 4).

Additional construction is under way supported by increased direct funding from NNSA. LLNL will be executing nearly $100 million of construction projects in FY 2017–2018. A new line item–funded project—the first since 2009—will expand the Laboratory's electrical utility distribution system. Other projects range from upgrades to radiochemistry laboratories to new safety systems at Site 300.

Future F&I plans were reviewed at NNSA's first Master Asset Plan "Deep Dive" meeting, held at LLNL. Livermore is working as an innovative partner with NNSA to develop methodologies, templates, and tools for the enterprise-wide Master Asset Plan. The objective is to

LLNL Director Bill Goldstein converses with participants at National Security Day on Capitol Hill.

achieve prioritized, long-term enterprise planning that reduces risk and aligns infrastructure investments with mission goals. Three LLNL teams received NNSA Office of Safety, Infrastructure, and Operations Excellence Awards for their F&I efforts. One team is implementing BUILDER, a knowledge-based condition assessment infrastructure modeling system, and another is refining the Mission Dependency Index, a tool for assessing the mission consequences of F&I failure. The third team manages legacy facilities at the lowest cost while mitigating risks to workers and the public.

NNSA also selected LLNL as the lead for the complex-wide Cooling and Heating Asset Management Program (CHAMP) partnership. Based on a unique groundbreaking approach to supply chain management pioneered at Livermore, CHAMP is NNSA's first-ever building system-based program for strategically managing inherently complex heating and cooling infrastructure.

Sustaining Workforce Excellence

An outstanding workforce is the Laboratory's principal strength. Staff members bring to their jobs impactful new ideas, work with integrity and zeal, and thrive in an inclusive work environment. LLNL was named to the *Forbes* 2016 list of America's Best Employers, ranking No. 102 out of the 500 employers chosen. It was the only national laboratory on the list and ranks among the top 10 employers in the San Francisco Bay Area. Accomplishments and initiatives highlight staff quality and the importance of recruiting and nurturing future technical and programmatic leaders. Notably, 19 Laboratory employees received DOE Secretary's Honor Awards this year and another was given the Office of Secretary of Defense Medal for Exceptional Public Service (see pp. 22–23).

Laboratory postdoctoral researchers and Livermore graduate scholars presented their research to colleagues at the 9th annual Institutional Postdoctoral Poster Symposium.

Livermore's educational outreach programs range from activities designed to interest young students in scientific careers (see pp. 20–21) to those that bring prospective future scientists and engineers to LLNL. In FY 2016, the Laboratory welcomed more than 900 students—a new record—with many coming as interns during the summer academic break. In addition, LLNL continues to expand the hiring of postdoctoral fellows. About 220 fellows are onsite and the conversion rate from postdoctoral fellow to staff member is about 65 percent. LLNL is also establishing strategic partnerships with strong research universities to keep at the cutting-edge of ST&E. Furthermore, the Laboratory is pursuing initiatives to meet mission needs for engineering support, including a machinist apprentice program and a veterans training program.

LLNS Board of Governors Activities

The LLNS Board of Governors and its committees provided oversight to the Laboratory. The committees delved into issues crucial to mission and mission-support activities. Board members participated in external review committees (ERCs)—panels of independent experts—to critically assess the quality of LLNL's technical workforce and the effectiveness of research efforts in meeting mission goals and anticipating future national needs. The ERCs held six meetings in FY 2016. Their reports, which provided DOE/NNSA with an independent validation of work quality, consistently affirmed the mission relevance and high impact of Laboratory research. The Board also charters Functional Management Reviews (FMRs) to examine issues on an as-needed basis. Six FMRs were completed in FY 2016 in topical areas ranging from banking and payment processing to work planning and control. Recommendations provided by Board committees, ERCs, and FMRs have led to substantive responsive actions.

LLNL machinist Brandon Pratt is one of the latest graduates from the Machinist Apprentice Program, a four-year on-the-job training for entry-level machinists.

COMMUNITY CONNECTIONS

Supporting local communities through science education and charitable giving

Each year the Laboratory engages in a wide range of community activities. Many are directed at enhancing science, technology, engineering, and mathematics (STEM) education. Other prominent community outreach efforts include volunteer work supporting local service agencies and charitable giving. In addition, LLNS conducts an annual grant program that provides a direct investment in community education, arts, and services.

Each year, the Laboratory hosts more than 100 instructors from high schools and community colleges at its Teacher Research Academy, providing state-of-the-art lessons in science and technology to educators.

Laboratory employees participate in the Run for HOME (Helping Others More Effectively). This event, held in late October, kicks off LLNL's annual charitable-giving campaign.

Learning That's Fun-damental

More than 12,500 children at the fourth- and fifth-grade levels, along with their chaperones, were introduced to scientific concepts through hands-on experiments at Fun With Science events. Presented by Laboratory employees and retirees, the popular program provides an entertaining introduction to scientific phenomena and helps prepare young minds as they embark on their science education. In addition to shows held at LLNL's Discovery Center, Fun With Science is presented at street fairs, science festivals, and other special events.

Partnerships in Education

Each summer, educators look to LLNL's Teacher Research Academy to gain key skills they need to bring state-of-the-art science into their classrooms—from biotechnology and high-performance computing to 3D printing and astrophysics. In FY 2016, the Laboratory hosted more than 110 teachers from all over California—and more than 500 students across the nation—for internships and educational training.

The Laboratory remains committed to introducing practical science and technological curricula to the classroom with support provided by the LLNS Community Gift Program (see p. 21). In addition, senior leaders from the Laboratory, including the director and deputy director, met with members of the Livermore Joint Unified School District and science curriculum educators to discuss common goals and opportunities for future collaboration.

Science Fare at the Fair

Livermore continues to promote science through various fairs and festivals. In November, the Laboratory participated in the Bay Area Science Festival, which attracted more than 30,000 young scientists and their families to AT&T Park in San Francisco, California. In addition to participating in presentations of Fun With Science, attendees were also challenged to show off their scientific know-how and use their pedal power to make lights glow and small household appliances hum.

Closer to home, the Laboratory continued to sponsor the annual Alameda County Science and Engineering Fair (ACSEF), held in March. Approximately 680 middle- and high-school students and more than 175 teachers from 18 school districts participated in the fair. More than 170 awards and scholarships were distributed for first, second, and third place, and 60 special awards were given by national and local government and industry sponsors. The ACSEF is affiliated with the Intel International Science and Engineering Fair and the California State Science Fair, the state's most elite science competition for middle- and high-school students.

LLNL's popular Fun With Science program, an interactive "show and tell" of scientific concepts, prepares young minds as they embark on their science education. Although geared toward grade-schoolers, the show is popular with all ages.

LLNL also sponsored Expanding Your Horizons, held several times a year throughout the San Francisco Bay Area, to introduce STEM careers to middle- and high-school girls. The free events pair women scientists and engineers with students to conduct hands-on demonstrations of science and discuss career paths.

Saturday is Science Day

LLNL's Science on Saturday (SOS) lecture series for middle- and high-school students plays to sold-out crowds every year. More than 5,000 people attended this season's 12 lectures held in the cities of Livermore and Tracy, and plans are underway to expand the program to Oakland. Each topic highlights cutting-edge science and technology at the Laboratory. This season, SOS presented themed discussions on women in STEM—pairing Laboratory researchers with local science educators to discuss topics such as searching for new elements, placing human physiology on a microchip, harnessing fusion energy, and understanding the world through statistics. As always, the presentations are free of charge and recorded for the University of California's TV website and YouTube.

The Laboratory takes a look at Hollywood's perspective on science and technology through the Science on Screen lecture series for students ranging from middle-school to college level. It combines popular feature-length movies with prominent researchers from the Laboratory, who discuss the scientific viability of what's depicted in these classic, cult, science fiction, and documentary films. This year's series of three lectures, again playing to sold-out audiences, looked at the study of earthquakes, re-creating the power of the sun through fusion energy, and miniaturizing human physiology.

The Laboratory also partners with Las Positas College for an annual Science and Engineering Seminar Series. LLNL researchers present "behind the scenes" perspectives of how multidisciplinary science really works. The seminars, targeted for science majors and faculty, help connect students to potential career paths.

HOME Campaign and Community Gifts

Employees and LLNS raised more than $3.8 million in the 2016 HOME (Helping Others More Effectively) campaign, an annual charitable drive that benefits community and nonprofit agencies in the Tri-Valley, San Joaquin Valley, and greater San Francisco Bay Area. Employees pledged almost $2.8 million, while LLNS contributed $1 million in matching funds.

At an October ceremony at the LLNS office in the city of Livermore, Director Bill Goldstein presented checks totaling $100,000 to the recipients of the 2016 LLNS Community Gift Program. LLNS received 81 applications totaling almost $700,000 in requests. Thirty-four applications were selected for awards through a committee review process. The majority of these awards serve children in the Tri-Valley and San Joaquin County, and focus on science, mathematics, education, and cultural arts.

The Laboratory's hands-on displays and scientific challenges have become a mainstay of the annual Bay Area Science Festival, held at AT&T Park in San Francisco, California, in November. The festival attracts more than 30,000 aspiring scientists and their families.

What began as a simple lecture series for middle- and high-school students has turned into a highly anticipated annual gathering. Science on Saturday, featuring LLNL scientists and engineers speaking about their research, plays to standing-room-only crowds in Livermore, and Tracy.

WORKFORCE RECOGNITION

Acknowledging exceptional performance and expertise

Stakeholders and the broader scientific community recognize the achievements and high-quality work of Livermore's talented and innovative workforce. These awards are indicative of the value of LLNL's research.

Prestigious PECASE Honor

Physicist Tammy Ma received a Presidential Early Career Award for Science and Engineering (PECASE), the highest honor bestowed by the U.S. government on researchers in the early stages of their careers, for her innovation and leadership studying inertial confinement fusion implosions at the National Ignition Facility (NIF).

DOE Secretary's Honor Awards

Nineteen LLNL employees received 2015 Secretary's Honor Awards from DOE Secretary Ernest Moniz. Those honored for their work on the Iran implementation effort include Director Bill Goldstein, George Anzelon, Chris Carson, Kyle Chand, Roger Miller, Jennifer Vandersall, Amy Gaffney, and Audrey Williams. Brad Hart, Armando Alcaraz, Patrick Grant, Annie Kersting, Carolyn Koester, Kenton Moody, Philip Pagoria, and John Reynolds were recognized for work performed in studying a radiological waste release at the Waste Isolation Pilot Project. Julio Friedman and A.J. Simon were honored for their part in preparing the DOE's Quadrennial Technology Review. Clifford Shang, was recognized for his contributions to the Laboratory Operations Board General Purpose Infrastructure Crosscut Committee.

Department of Defense Civilian Honor

Craig Wuest received the Office of the Secretary of Defense Medal for Exceptional Public Service. The award honors Wuest's work to strengthen the nation's nuclear survivability posture and his service 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.

High-Performance Computing Recognized

HPCWire has Recognized the Collaboration of Oak Ridge, Argonne, and Lawrence Livermore (CORAL), which will bring the Sierra supercomputer to the Laboratory in 2018, with an Editor's Choice Award for "Best High-Performance Computing Collaboration between Government and Industry."

APS Fellows

The American Physical Society (APS) named seven LLNL scientists as fellows: (from top) Fred Streitz, Damian Swift, Pierre Michel, Stavros Demos, Yuan Ping, Lee Bernstein, and Vladimir Smalyuk.

AMS Fellow

Climate scientist David Bader has been elected a fellow of the American Meteorological Society (AMS). Election to the grade of AMS fellow recognizes outstanding contributions to advance atmospheric and related sciences, technologies, applications, and services for the benefit of society.

AAAS Fellow

The American Association for the Advancement of Science (AAAS) named Kenneth Turteltaub a fellow for his development of ultraprecise accelerator mass spectrometry methods for biomedicine and his work on carcinogenesis, the formation of macromolecules, and low-dose pharmacokinetics.

National Academies of Sciences Panel

Bioinformatics scientist Jonathan Allen has been selected to serve on a U.S. National Academies of Sciences, Engineering, and Medicine panel that will study microbiomes (microbial communities of organisms growing in the environment) found in buildings.

Laboratory Astrophysics Prize
The Laboratory Astrophysics Division of the American Astronomical Society selected Peter Beiersdorfer as the recipient of the 2016 Laboratory Astrophysics Prize. Beiersdorfer was cited for his numerous contributions to the study of astronomical environments at extreme-ultraviolet and x-ray wavelengths.

NNSA Defense Program Awards of Excellence
Ten teams of Livermore researchers and engineers and one individual were presented with the NNSA Defense Programs Awards of Excellence. Brigadier General Stephen L. Davis, acting deputy administrator for Defense Programs, presented the awards.

NNSA Excellence Awards
Eighteen teams, including seventeen Laboratory employees, received Excellence Awards presented by James J. McConnell, associate administrator, NASA's Office of Safety, Infrastructure, and Operations. Recipients were honored for demonstrating extraordinary achievements on key intralaboratory projects.

Patriot Awards
Employer Support of the Guard and Reserve (ESGR), an office of the Department of Defense, recognized Roger Rocha and Mark Zagar with Patriot Awards. The ESGR Patriot Award recognizes supervisors for contributing to national security and protecting liberty and freedom by supporting employees participating in America's National Guard and Reserve force.

SPIE Harold E. Edgerton Award
Christopher Barty, the chief technology officer for the Laboratory's National Ignition Facility and Photon Science Principal Directorate, won the SPIE Harold E. Edgerton Award for his work on ultrafast lasers and laser-based x-ray and gamma-ray science.

Fast Company Top 100
Chemist Dawn Shaughnessy has been named No. 9 on the *Fast Company* Top 100 Most Creative People in Business for 2016.

DOE Technology Transfer Awards
Two Livermore engineers received from DOE's Technology Commercialization Fund grants to help their promising energy technologies move to the marketplace. Brian Guidry received a $432,000 grant for his cryo-compressed hydrogen tank technology. Material scientist Jeff Haslam and his team received $150,000 for their fire- and water-resistant pre-filter.

Neill Griffiths Award
At the International Symposium on Ballistics, a team of Livermore researchers received the Neill Griffiths Award, recognizing the most significant contribution to shaped-charge technology. Their work helped solve the problem of how to sever the connection between an offshore drilling rig with the seabed in case of an emergency.

Thomas H. Stix Award
Physicist Tammy Ma has won the APS' Thomas H. Stix Award for Outstanding Early Career Contributions to Plasma Physics Research for her leadership and key contributions to inertial confinement fusion experiments at NIF.

Howes Scholar Award
Lawrence Fellow Aurora Pribram-Jones received the Howes Scholar Award presented by the DOE Computational Science Graduate Fellowship Program for demonstrated scientific achievement, leadership, and service.

Diablo Magazine "Forty Under Forty"
Diablo Magazine featured three LLNL researchers in their "Forty Under Forty" issue. The annual list recognizes young professionals in the San Francisco East Bay who are leaders in their fields. Experimental physicist Tammy Ma was No. 3 for her fusion research. NIF Applications Division Leader Lisa Belk, No. 15, heads a team of more than 80 people providing computation support to NIF. Research engineer Monica Moya, No. 37, is the principal investigator for a project that uses 3D printing to create tubes made from human cells and biomaterials.

Meteoritical Society Awards
The Meteoritical Society honored Lawrence Livermore researchers present and past. Carolyn Crow won the Gordon A. McKay Award for her presentation "U-Xe Degassing Ages of Terrestrial and Lunar Impact Zircons." Greg Brennecka, a former researcher, earned the Nier Prize for his work on isotopic variations in meteorites and the chronology of the solar system.

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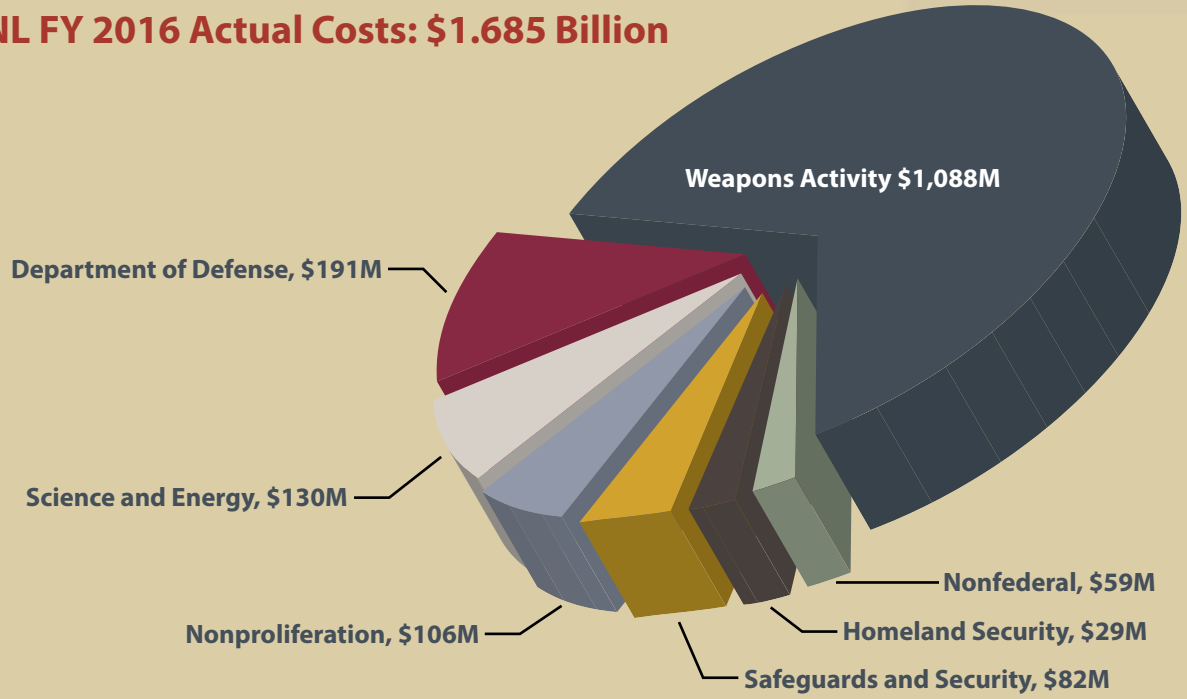
Laboratory Director William Goldstein (left) joins LLNS Board of Governors Vice Chairman Barbara Rusinko and Chairman Norman Pattiz at a joint meeting of the LLNS and Los Alamos National Security, LLC, boards. The two boards work to better integrate activities and make both laboratories and the NNSA enterprise more effective and efficient.

General Welch Honored with Foster Medal

Retired U.S. Air Force General Larry D. Welch is the second recipient of the John S. Foster Jr. Medal. Welch has been dedicated to serving the nation since 1951, earning a reputation as an inspirational leader, team builder and innovator. His distinguished career is highlighted by service as the Chief of Staff of the U.S. Air Force and a member of the Joint Chiefs of Staff from 1986 to 1990. Welch also served as Commander in Chief of the Strategic Air Command from 1985–86, responsible for operational planning for all U.S. strategic nuclear systems. Welch continues to serve the nation as a senior fellow of the Institute for Defense Analyses. He led the institute as president and chief executive officer from 1991 to 2003 and again from 2006 to 2009.

The John S. Foster Jr. Medal is administered by LLNS to commemorate Foster's exceptional and inspirational career. Each year, the medal is bestowed on an individual who has demonstrated exceptional leadership in science, technology, and engineering or policy formulation in support of U.S. nuclear security.

LLNL FY 2016 Actual Costs: $1.685 Billion



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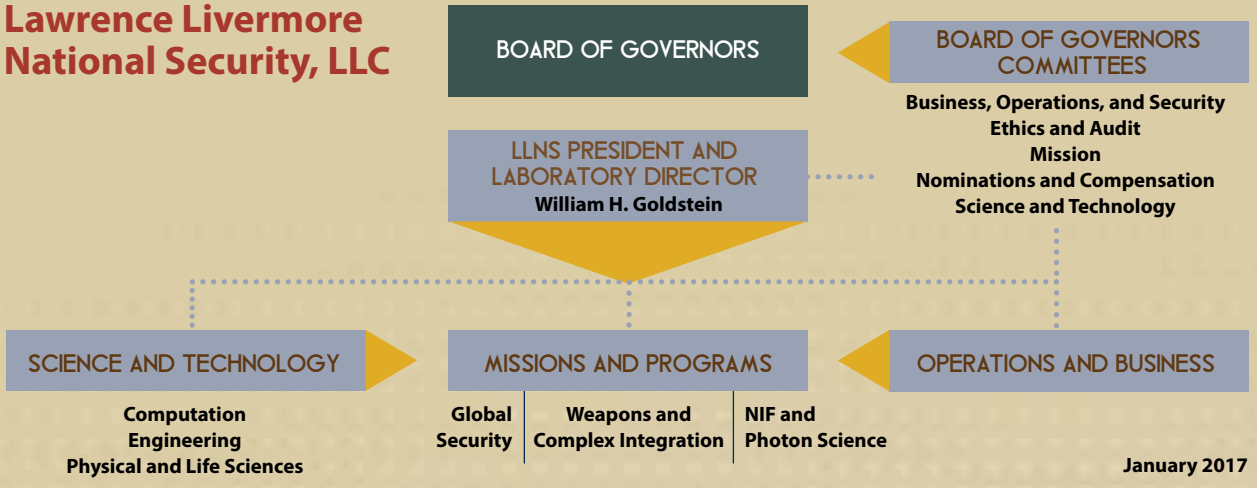

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