LAB AT A GLANCE

LAWRENCE LIVERMORE NATIONAL LABORATORY

Science and technology on a mission is the hallmark of Lawrence Livermore National Laboratory (LLNL). In service to the Department of Energy/National Nuclear Security Administration and other federal agencies, LLNL develops and applies world-class science and technology (S&T) to ensure the safety, security, and reliability of the nation's nuclear deterrent. LLNL also applies S&T to confront dangers ranging from nuclear proliferation and terrorism to energy shortages and climate change that threaten national security and global stability.

As a national security laboratory, LLNL harnesses operational excellence and strategic partnerships to meet our mission and applies the talents of our multidisciplinary staff, premier facilities, and core competencies to the nation's pressing issues. Through strategic support of S&T, we translate innovations into national security and global stability.

FACTS

- **Location:** Livermore, California
- **Type:** Multidisciplinary national security laboratory
- **Year Founded:** 1952
- **Director:** Kimberly S. Budil
- **Contractor:** Lawrence Livermore National Security, LLC (LLNS)
- **Responsible Site Office:** Livermore Field Office
- **Website:** www.llnl.gov

CORE COMPETENCIES

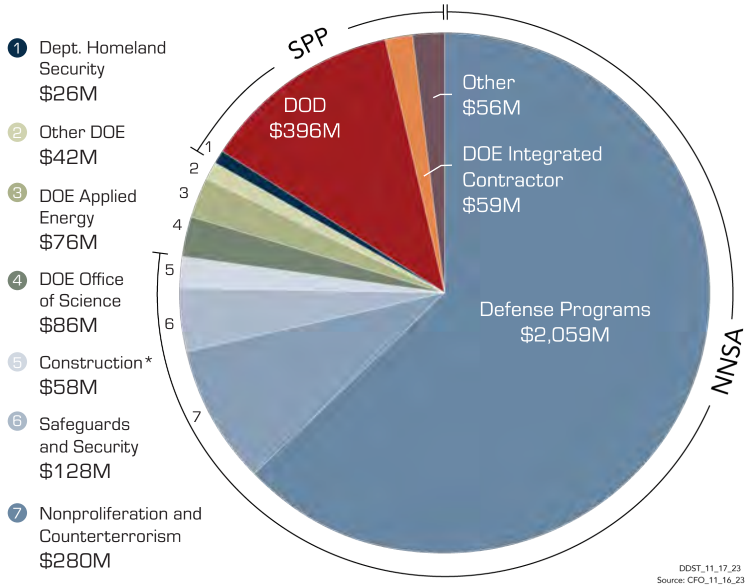
- Advanced Materials and Manufacturing
- Bioscience and Bioengineering
- Earth and Atmospheric Sciences
- High-Energy-Density Science
- High-Performance Computing, Simulation, and Data Science
- Lasers and Optical Science and Technology
- Nuclear, Chemical, and Isotopic Science and Technology

MISSION-SPECIFIC FACILITIES

- Advanced Manufacturing Laboratory
- Center for Micro-and Nanotechnology
- Center for Accelerator Mass Spectrometry
- Contained Firing Facility
- Electron Beam Ion Trap
- Forensic Science Center
- High Explosives Applications Facility
- Livermore Computing
- Polymer Enclave
- National Atmospheric Release Advisory Center
- National Ignition Facility
- Select Agent Center

FY2023 FUNDING BY SOURCE

(Total: $3,266,349,344)



*Includes one-time DOE construction funds
**SPP: Strategic Partnership Projects

FY2023 COSTS

- FY23 LLNL operating costs: $3.24 billion
- FY23 DOE/NNSA costs (include DOE/IC): $2.8 billion
- FY23 SPP costs (exclude DHS and DOE/IC): $410 million
- FY23 SPP as a % of operating costs: 12.6%
- FY23 DHS costs: $22 million

PHYSICAL ASSETS (FY23)

- 7,617 acres (owned) and 506 buildings/trailers
- 6.5 million gross square footage (GSF) in active buildings
- 58 non-operational buildings/trailers with 0.61 GSF
- 43,897 GSF leased
- Replacement plant value: $30 billion

HUMAN CAPITAL (FY23)

- 9,291 LLNS employees, including:
  - 12 joint faculty
  - 321 postdoctoral researchers
  - 144 undergraduate interns
  - 162 graduate students
- 480 contractors (non-LLNS employees)

Warheads and Strategic Deterrence

LLNL is delivering on two warhead modernization programs, sustaining the active stockpile, and partnering to modernize the nation's nuclear weapon enterprise.

Introduction

Lawrence Livermore National Laboratory (LLNL) plays a key role in the nation's strategic deterrent, acting as a nuclear weapon design laboratory responsible for the safety, security, and effectiveness of the U.S. nuclear stockpile. This core responsibility includes annual assessment of the active stockpile, culminating in a quantification of confidence that the weapon systems still meet military requirements, as well as leading the modernization of systems that are approaching the end of their useful service life. LLNL is partnering through these stockpile modernization programs to modernize the nuclear weapon enterprise, ensuring resiliency in an uncertain global future.

LLNL executes this mission through development and application of world-class scientific and engineering tools, enabling the development of modern designs that ease manufacture and the assessment and certification of systems without conducting nuclear tests. These scientific capabilities include world-class computing and experimental facilities, such as the first exascale supercomputer and the world's most powerful laser system. These capabilities inform the judgement of weapon experts, underpinning the nation's confidence in its strategic deterrent.

Applications

LLNL is the lead design agency for the nuclear explosive package in two separate programs: the W80-4 Life Extension Program (LEP) and the W87-1 Modification Program. LLNL is also responsible for assessing and sustaining three systems in the active stockpile – the W80-1, B83, and W87-0 warheads – establishing scientific confidence in the systems.

More than 5,000 LLNL team members contribute to these annual assessments and stockpile modernization programs, working closely with production agencies, NNSA, and the U.S. Air Force to design and test hardware, transfer technology, address manufacturing issues, assess material compatibility, execute vital system assessments, and ultimately deliver a deterrent the nation relies on for decades.

The W80-4 is replacing the W80-1 warhead and will be employed in the U. S. Air Force's new Long-Range Standoff (LRSO) missile. The W80-4 will be the first warhead designed for use with a new missile since nuclear testing ended in 1992.

The W87-1 Modification Program will replace the W78 warhead and will sit atop the Air Force's new Sentinel Intercontinental Ballistic Missile (ICBM). The W87-1 is the first warhead to have all components newly manufactured since testing ended, unlike prior life extension programs that relied heavily on component reuse.

These systems are based on tested nuclear designs and will not require new nuclear tests. Certification will rely on improved understanding and the highly capable toolset developed by the science-based Stockpile Stewardship Program.

In 2023, the W87-1 Mod entered the development engineering phase of the program (Phase 6.3), and the W80-4 LEP entered the production engineering phase (Phase 6.4). Both programs are working hand-in-hand with production agencies to ensure successful delivery of parts and systems that meet requirements. Simultaneously, researchers at LLNL are conducting an extensive range of full-system tests and hundreds of small-scale tests to validate computational models and the scientific basis for certifying the systems.

W87-1 Mod

W80-4 LEP

Researchers at the NIF prepare for an ignition experiment that provided data to certify modernized weapon systems and confirm they can survive hostile environments.

Engineers in the W80-4 Life Extension Program conduct environmental testing on a mock test unit to ensure systems will work when needed, but never when not needed.

A researcher produces a test component using direct-ink-write additive manufacturing. LLNL is introducing new manufacturing methods into stockpile modernization programs.

Accomplishments

LLNL has come a long way in its ability to develop, assess, and certify warheads since the end of nuclear testing in 1992. Researchers today synthesize historic nuclear test data with computational simulations and a suite of modern experiments and tests to inform their expert judgement. Scientific advancements through decades of stockpile stewardship are now enabling certification of modernized systems in both normal and abnormal environments, without new nuclear testing. Recent accomplishments include:

- Achievement of fusion ignition at NIF, and accompanying development of weapon survivability platforms to leverage ignition yields. NIF has played a key role in advancing weapon physics understanding and lends confidence to today's stockpile assessments.
- High-performance computing advances are making possible regular use of high-fidelity, 3D simulations. These advancements are being furthered by the El Capitan supercomputer, the first exascale machine in the United States dedicated to national security, and through application of machine learning and artificial intelligence.
- A next generation accelerator, Scorpius, provides the nation's first capability to capture multiple late time radiographic images of subcritical experiments. This advanced diagnostic will illuminate new insights into how special nuclear material behaves when driven by high explosives.
- LLNL is partnering to revitalize the nation's atrophied capability to produce nuclear warheads. This includes the introduction of advanced manufacturing techniques and processes, enabling the enterprise to realize efficiencies and replace materials that can no longer be used.
- Advancements in material aging and compatibility assessments are lending confidence that modernized systems will last for decades, even where new materials and processes are being introduced.

These accomplishments all have roots in the stockpile stewardship era and are being leveraged to expand the envelope of the types of systems that can be certified as safe, secure, and effective without nuclear testing. Elements of each advancement were initially developed through Laboratory Research and Development (LDRD) funding. When they showed promise, they were further matured with program funding to the point where they could make a difference for the nation's strategic deterrent.

The Future

The past decade has seen the emergence of two nuclear adversaries aggressively modernizing their nuclear capabilities. Meanwhile, the 10- to 15-year timeline to field a life-extended warhead in the U.S. highlights a significant risk to the nation's ability to respond in relevant timeframes, should a new threat arise. LLNL and its partners are revitalizing the enterprise to improve responsiveness and resilience. Key prongs to the strategy include:

- Partnering with the DOD to deliver options ensuring the long-term effectiveness of our nuclear deterrent.
- Conducting pilots focused on realizing efficiencies and prototyping aimed at accelerating maturation of technologies.
- Advancing the science, technology, and engineering required to certify novel systems with confidence.
- Development of the next generation of experts responsible for future systems.
- Modernizing the vital infrastructure that has deteriorated in the absence of new weapon development activities.

LLNL is acting in earnest on these strategies, all while delivering on the W80-4 and the W87-1.

LLNL-MI-859546
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January 23, 2024

Advanced Materials and Manufacturing

Designing unique materials and fostering innovation in advanced manufacturing to fabricate structures with the properties and performance needed to address national security missions.

Introduction

Lawrence Livermore National Laboratory (LLNL) brings a multidisciplinary approach to address our nation's need for rapid development of advanced materials and manufacturing (AMM) processes. Scientists and engineers develop innovative materials with tailored properties that can be used for energy absorption, dissipation, generation, or storage; bioinspired structures for use in drug delivery; advanced optics used in satellites and telescopes; quantum materials; and components that can function effectively in extreme environments.

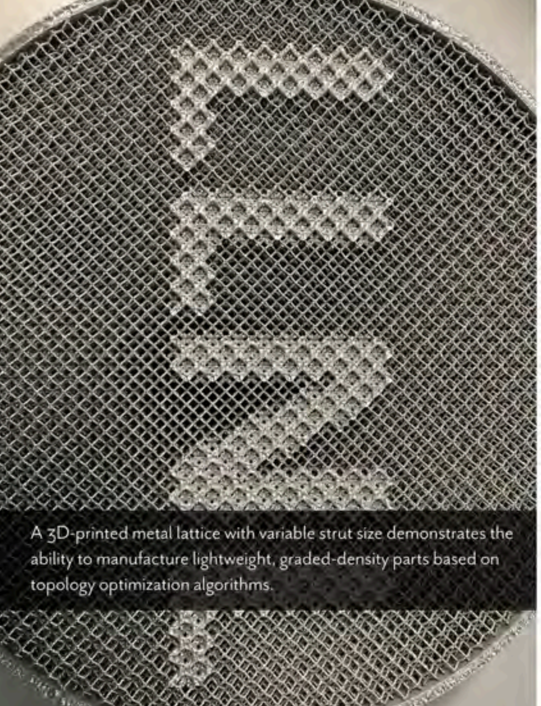
Livermore continues to advance manufacturing technology, enabling the development of customized feedstocks and inventing unique fabrication techniques. Novel diagnostic methods are developed and implemented to test and evaluate components during manufacturing, which accelerates the Laboratory's ability to deliver timely solutions.

AMM creates a more agile, responsive material development and manufacturing ecosystem to meet the needs of national security stakeholders. The team explores ways to enhance performance of materials and components, cut manufacturing costs, minimize supply chain vulnerabilities, reduce material and energy waste, and accelerate discovery, development, scalability, and deployment timelines.

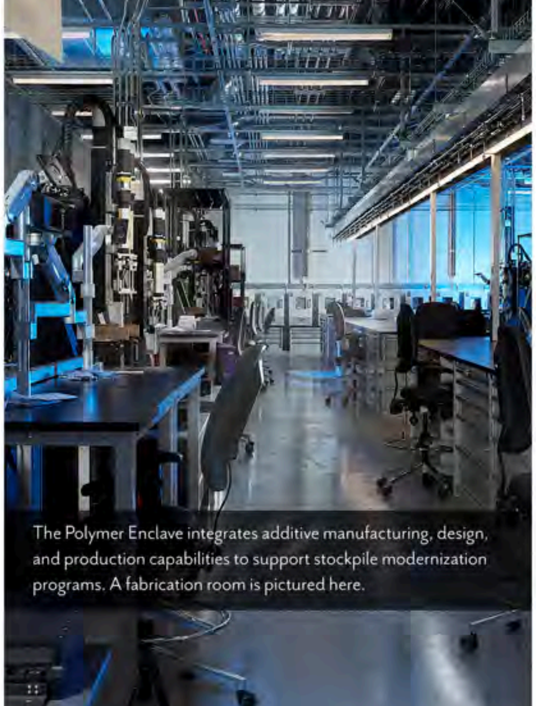
Applications

LLNL's research leverages decades of experience studying materials, manufacturing technologies, and mission-relevant applications. Livermore's expertise spans the design-development-deployment cycle, including materials that can meet emerging mission needs, capabilities to produce materials at scale, advanced manufacturing methods, and structures tailored to meet specific performance requirements. AMM expertise is evident across the Laboratory:

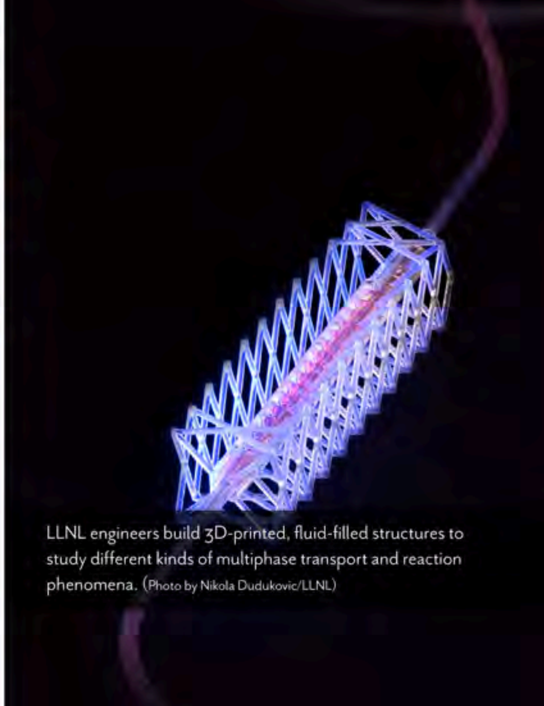
- The Advanced Manufacturing Laboratory (AML) facilitates industrial and academic partnerships to address challenges across commercial and government projects.
- The Polymer Enclave enables rapid design and development of polymer parts for stockpile modernization programs, offering a unique space where design activities and production enhancements can be rapidly tested and evaluated.
- The Laboratory for Energy Applications for the Future (LEAF) fosters cross-cutting research aimed at accelerating development of scalable, optimized structures for energy production, storage, and transmission, such as batteries, supercapacitors, hydrogen energy systems, desalination, and carbon capture and conversion.
- LLNL's high-performance computing resources and artificial intelligence expertise accelerate solutions through multiscale, high-fidelity modeling of material synthesis and manufacturing processes, enabling scientists to design new materials and feedstocks.
- A suite of advanced, in-situ diagnostics and non-destructive characterization tools, including 3D imaging, spectroscopy, x-ray computed tomography, and ultra-fast electron microscopy enable researchers to assess a material's properties and identify defects.
- Facilities designed to handle advanced radiological materials, where researchers deploy customized actinide processing techniques and deliver high-purity, actinide-based materials for mission-critical applications.
- At the Center for Engineered Materials and Manufacturing (CEMM), researchers develop new advanced and additive manufacturing techniques, new feedstock materials, multi-material and multiscale structures, fabricate materials with previously unachievable properties, and apply these advances to LLNL missions in national security and energy.
- At the Center for Design and Optimization, staff use computational methods to optimize systems governed by nonlinear, dynamic, multiphysics, or multi-scale phenomena.
- Testing of medical countermeasure is greatly accelerated by 3D printed biological cells and matrices to develop organ-on-a-chip systems.



A 3D-printed metal lattice with variable strut size demonstrates the ability to manufacture lightweight, graded-density parts based on topology optimization algorithms.



The Polymer Enclave integrates additive manufacturing, design, and production capabilities to support stockpile modernization programs. A fabrication room is pictured here.



LLNL engineers build 3D-printed, fluid-filled structures to study different kinds of multiphase transport and reaction phenomena. (Photo by Nikola Dudukovic/LLNL)

Accomplishments

LLNL integrates expertise in engineering, materials science, physics, chemistry, data science, modeling and simulation, and manufacturing to create innovative solutions. For example, material scientists study the chemical, electronic, structural, and kinetic properties of materials—including polymers, alloys, ceramics, foams, and biomimetic materials. Researchers also explore ways to enhance feedstock development, fabrication techniques, and characterization methods, while studying material aging and degradation that can impact long-term performance. Livermore experts leverage the power of artificial intelligence and data science to optimize designs and achieve rapid advances in materials science. A broad suite of LLNL resources contribute to these accomplishments, such as:

- Microcapsules containing carbon-trapping sorbents that can rapidly absorb chemicals and make them available for reuse in a range of applications, such as capturing carbon dioxide or biogas to be removed and reused or compressed and stored underground.
- A new method to 3D-print microbes in controlled patterns, expanding the potential for using engineered bacteria to recover rare-earth metals, clean wastewater, and detect actinides.
- Invention of a Volumetric Additive Manufacturing (VAM) technique, which can be used to fabricate 3D objects with complex architectures in a matter of seconds to minutes by projecting a combination of tomographic images into a photosensitive resin.
- Additively manufactured transparent glass with customized composition and structure to create a gradient index of refraction optical components.
- Customized alloys for extreme environments, with thermally stable microstructures that are lightweight, corrosion-resistant, and radiation tolerant, and use of predictive models to identify age-resistant designs—with applications such as hypersonic vehicles, space science, high-power lasers, and nuclear reactors.
- A groundbreaking method for fluid transport using 3D-printed open-cell lattice structures and capillary action phenomena. These micro-architected structures could impact many fields, including electrochemical or biological reactors used to convert carbon dioxide or methane to energy, advanced microfluidics, solar desalination, air filtration, heat transfer, transpiration cooling, and the delivery of fluids in zero-gravity environments.

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February 05, 2024

The Future

The long-term vision of the Advanced Materials and Manufacturing team involves leveraging LLNL's newest resources to expand our collaborative research space. For example, we will explore new partnerships with industry and other research institutions at the Advanced Manufacturing Lab and the Polymer Enclave, which will boost our ability to rapidly deliver solutions.

LLNL will continue to take a leadership role in DOE-sponsored research activities involving hydrogen research, including new materials to enable compact and efficient storage and delivery of hydrogen. LLNL experts will also continue participating in the DOE Energy Materials Network and the DOE Critical Materials Institute.

Additionally, the team will explore ways to adapt innovative solutions for new environments, including biosecurity, water security, space science and security, and materials for environmental remediation. LLNL will support efforts to ensure the long-term performance of our energy production and delivery infrastructure as they face risks to material used in pipelines, turbines, and nuclear power plants. At the same time, the Laboratory will continue to focus on accelerating delivery of solutions that support the reliability of our nuclear deterrent.

Bioscience and Bioengineering

Protecting the nation by countering current and future biological and environmental threats.

Health, Environment, and Energy Security

Bioscience and Bioengineering research at Lawrence Livermore National Laboratory (LLNL) delivers transformative biological solutions for national health, environment, and energy security needs. This research capitalizes on LLNL's capabilities in high performance computing, experimental biology, and automation platforms.

Our expertise in low-dose radiological effects and genomics led to a founding role in the Human Genome Project. Bioengineering advances include the invention of PCR-on-a-chip and droplet PCR. Combining capabilities and partnerships in quantitative biology, computing, and precision measurement, we excel in assessing biological threats, accelerating medical countermeasure design and testing, and innovating approaches to low-carbon material development. Researchers expanded biological models to encompass climate and ecology research and are pioneering solutions for biofuels, carbon sequestration in soils, and eco-friendly extraction of critical minerals.

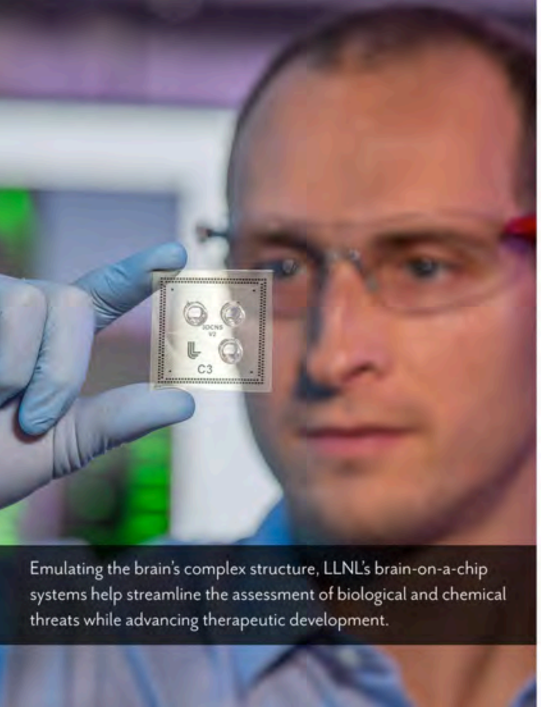
By integrating analytical tools, systems biology techniques, human models on a chip, and high performance computing, our dedicated staff dissect the underlying mechanisms of disease, develop novel diagnostics and therapeutics, and engineer microbial communities to counter biosecurity, health, and ecological threats.

Applications

Teams of scientists and engineers converge their expertise in biological science, high-performance computing, precision measurement, and engineering to understand, predict, and engineer the behaviors of complex biological systems. By coupling world-class computational resources with targeted experiments, bioscientists apply the design–build–test–learn cycle to tailor biological molecules and systems to achieve desired functionality.

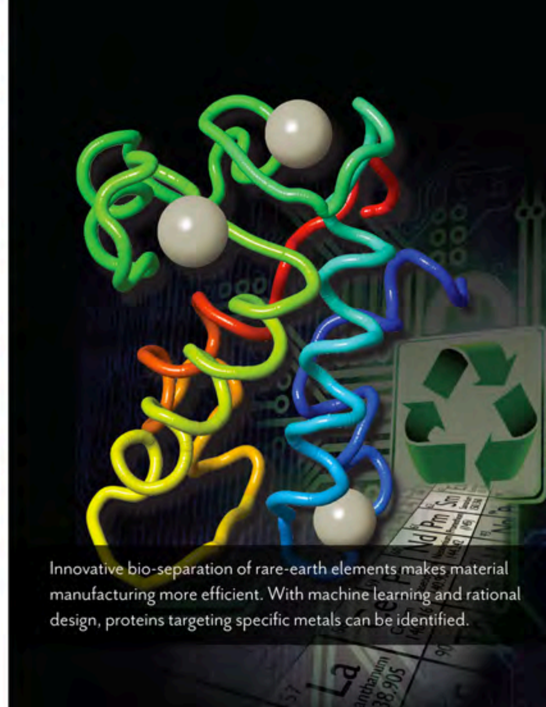
Applications of cutting-edge capabilities in bioscience and bioengineering include:

- High-performance computing to simulate biological systems across scales, including atomistic and coarse-grained molecular dynamics, quantum simulations, constraint-based genome-scale simulations, reaction–transport dynamic simulations, as well as agent-based, whole-organ, and pharmacokinetic and pharmacodynamic models.
- The National User Resource for Biological Accelerator Mass Spectrometry, the sole facility of its kind in the United States, which offers ultra-high-sensitivity quantitative isotopic analysis for biomedical researchers measuring extremely low concentrations of radioisotopes.
- A Biomedical Foundry (microfabrication facility, ISO 13485 compliant) for manufacturing medical prototypes and developing human-on-a-chip models.
- Experimental and computational platforms for the blood–brain barrier and central nervous system that can be broadly used for biological and chemical threat analysis and therapeutic development.
- A combination of stable isotope probing, advanced imaging, proteogenomic profiling, and computational modeling, which is used to investigate microbial communities within their ecological framework.
- Synthetic biology techniques and secure biosystems design for engineering safe and effective microorganisms and microbial communities for environmental applications and medical countermeasures.
- A BSL-3 Select Agent Center and Animal Care Facility; additive manufacturing with a focus on bioprinting and biomaterials; and bio-forensic science capabilities at the Laboratory's Forensic Science Center.
- Our Bio Resilience Mission Focus Area integrates biology with high-performance computing to enable innovative threat analysis and therapeutic development.



Emulating the brain's complex structure, LLNL's brain-on-a-chip systems help streamline the assessment of biological and chemical threats while advancing therapeutic development.

Research by Lawrence Livermore National Laboratory scientists suggests that immune responses could be bolstered by drugs to aid recovery from brain infections caused by emerging pathogens.



Innovative bio-separation of rare-earth elements makes material manufacturing more efficient. With machine learning and rational design, proteins targeting specific metals can be identified.

Accomplishments

LLNL brings together multidisciplinary biological expertise with world-class resources in high-performance computing and unique experimental facilities to tackle pressing national health and environmental challenges. LLNL's expanding areas of research include early bio threat analysis, assessment, and impact predictions, accelerated development of therapeutics and countermeasures, engineering of microbiomes for health, energy, and environmental sustainability, as well as the rapid detection and response to emerging novel pathogens. Furthermore, the Laboratory is at the forefront of developing innovative diagnostics and treatment approaches for cognitive impairment. Examples of LLNL bioscience and bioengineering accomplishments include:

- Development of PCR-on-a-chip and droplet PCR. These inventions have led to multiple FDA-approved commercial medical diagnostic products for detecting diseases such as tuberculosis, AIDS, and COVID-19.
- Development of the Lawrence Livermore Microbial Detection Array, a pangenomic platform capable of rapid detection of over 12,000 microorganisms within a single day. It is now used for applications in diverse fields such as biodefense, drug and food safety, and space biology.
- LLNL played a critical role in developing the world's first artificial retina. Also known as the "bionic eye," this retinal prosthesis was developed for people blinded by retinitis pigmentosa or macular degeneration. The invention led to first FDA-approved high-density, microfabricated, and fully implantable neural prosthetic ever produced.
- High-performance computing enabled the development of the LLNL therapeutic antibody design platform capable of designing antibodies in weeks compared to months-to-years using conventional methods.
- Novel nanoparticle-based vaccine delivery formulations are undergoing animal testing to evaluate efficacy against infections caused by chlamydia and other pathogens.
- Identification of microbial signatures that inform the treatment of wounds from combat-related injuries in soldiers using a combination of microbial metagenomic DNA sequencing and advanced machine learning techniques.
- Development of sustainable biomining approaches for extracting and purifying rare-earth elements to safeguard the domestic supply of critical minerals for clean energy transition.

The Future

Laboratory bioresearchers employ machine learning, omics, and unique laboratory capabilities to accelerate diagnostics, therapeutics, and sustainable biomanufacturing. Their multifaceted approach includes early biological threat assessment, broad-target antibodies, and novel therapeutics and vaccines. Additionally, there is a strong commitment to sustainability and driving advancement in biomanufacturing and ecosystem management.

Integration of big-data analytics and computational modeling enhances genotype-to-phenotype predictions, improving our understanding of pathogens, host factors, and infectious disease outcomes. This involves a meticulous dissection of the intricate relationship between pathogen genotype, exposure conditions, and host fitness, offering revolutionary insights for disease anticipation and management.

Predictive design, through computational and experimental integration, focuses on engineering of microbial systems and biomolecules, from proteins to small molecules. Its applications range from healthcare to energy, climate solutions, and supply chain resiliency. Through innovation and collaboration, the future holds proactive solutions to pressing national security challenges.

LLNL-MI-860752
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February 22, 2024

Earth and Atmospheric Sciences

Understanding the critical role Earth processes play in energy, environmental, and national security missions.

Science at a Global Scale

Earth and atmospheric sciences play a central role in Lawrence Livermore National Laboratory's (LLNL's) mission-driven work. LLNL scientists bring unique expertise and capabilities to advance engineering applications above, on, and below the Earth's surface. From refining space-based observations to analyzing seismic signals under the Earth's crust, LLNL's research teams apply their expertise to making our planet safer and more resilient.

For decades, LLNL scientists have been at the leading edge of climate science, forecasting the likely impacts of future emissions scenarios and supporting resilience planning. In parallel, Laboratory staff develop sustainable energy technologies and carbon management techniques to support a net-zero greenhouse gas future.

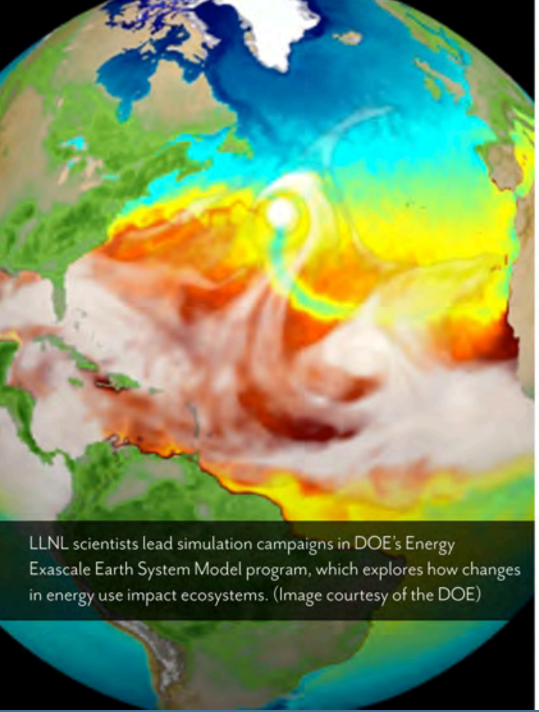
In the national security arena, LLNL advances global-scale monitoring techniques for identifying nuclear testing. The Laboratory's decades of innovations have strengthened response efforts for nuclear emergencies and hazardous material releases.

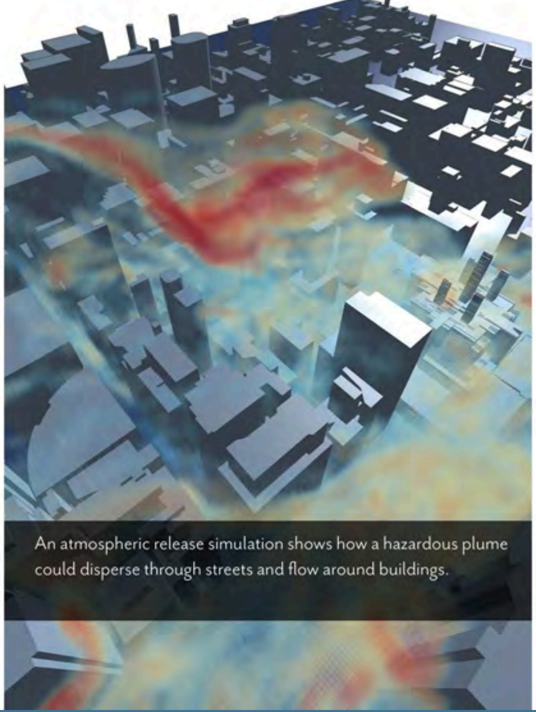
In these efforts, LLNL leverages state-of-the-art computational methods, validated with unique laboratory capabilities and large-scale field experiments.

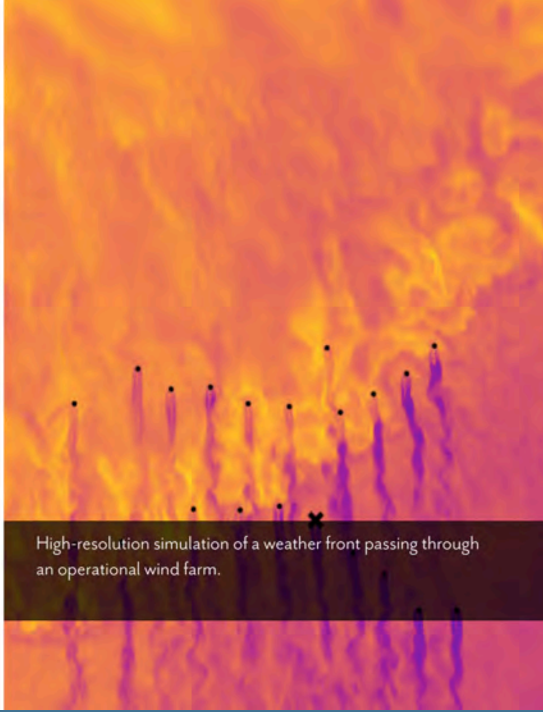
Applications

Researchers in the earth and atmospheric sciences continually innovate to make the world safer, the environment cleaner, and our energy resources more sustainable. Our key areas of research include seismology, geophysics, geomechanics, geochemistry, hydrology, atmospheric turbulence and dispersion, climate modeling and model intercomparison, climate change detection and attribution, energy systems, and carbon cycles. We maintain advanced experimental and computational capabilities to better understand the complex processes at the core of our mission applications. Select applications of LLNL's expertise in earth and atmospheric science are noted below:

- LLNL is the lead institution in the Energy Exascale Earth System Model (E3SM) Project. This capability harnesses the world's largest supercomputers to model and understand anthropogenic impacts on our ecosystem.
- Climate Resilience has been identified as a Mission Focus Area for LLNL, coupling biogeochemistry, materials, geology and climate simulation with infrastructure analysis to mitigate greenhouse gas accumulation and predict climate impacts at scale. Several Laboratory efforts apply climate models to engineering and societal challenges to better inform investments in resilient infrastructure and communities.
- Atmospheric researchers develop high-fidelity atmospheric fluid dynamics, turbulence, and aerosol dispersion codes. These models are used to study atmospheric contaminant releases, nuclear weapons effects, wind and solar energy systems, and high-altitude flight environments.
- The Center for Accelerator Mass Spectrometry (CAMS) is a signature user facility providing ultra-sensitive isotope ratio measurements and ion-beam analytical techniques. CAMS conducts up to 25,000 measurements per year to support a wide array of scientific studies.
- LLNL maintains one of the most complete geomaterial modeling libraries available for national security applications. The library incorporates complex phenomena related to impact and explosions in hard rock and similar materials.
- LLNL leads development of GEOS, an open-source reservoir simulator for subsurface energy systems. This exascale capability, developed by a community of industrial and academic partners, has been used in numerous studies to support geologic carbon storage, geothermal energy, and hydrogen storage projects.


LLNL scientists lead simulation campaigns in DOE's Energy Exascale Earth System Model program, which explores how changes in energy use impact ecosystems. (Image courtesy of the DOE)


An atmospheric release simulation shows how a hazardous plume could disperse through streets and flow around buildings.


High-resolution simulation of a weather front passing through an operational wind farm.

Accomplishments

LLNL has been leading climate science research since the Laboratory developed the world's first atmospheric general circulation model in the 1960s. In earth science, LLNL scientific advancements have secured state- and federal-level policy support for critical carbon management technologies such as geologic carbon storage and geothermal energy. In the national security arena, LLNL researchers are key enablers in national and international agency cooperation regarding nuclear non-proliferation and nuclear emergency response.

Additional accomplishments in earth and atmospheric science are noted below:

- LLNL scientists participate in assessments conducted by the Intergovernmental Panel on Climate Change, a Nobel Prize–winning institution established in 1988 to provide the scientific basis for understanding climate change.
- Since 1979, the National Atmospheric Release Advisory Center (NARAC) at LLNL has been on call 24/7 to respond to hazardous release emergencies around the world. NARAC monitored data from radiation detection sensors in Ukraine (2022), responded to nuclear power plant failures at Chernobyl (1986) and Fukushima (2011), airborne hazards in the wake of Hurricane Katrina (2005), the Deep Water Horizon oil spill fire (2010), and the spread of ruthenium across central Europe (2017).
- The Stellar Occultation Hypertemporal Imaging Payload (SOHIP) prototype telescope, recently installed on the International Space Station, uses LLNL-patented technology to detect and characterize atmospheric waves and high-altitude properties such as temperature, pressure, and density at altitudes up to 50 kilometers.
- The Geophysical Monitoring Program at LLNL generates global-scale tomographic images of the Earth's interior to improve seismic and nuclear event monitoring. This work has also led to fundamental discoveries, such as identifying the previously unknown southeast Indian Ocean slab.
- LLNL led state-wide and national studies outlining feasible strategies to achieve net-negative greenhouse gas emissions. "Roads to Removal" is a national scale analysis of carbon dioxide removal required to achieve a net-zero greenhouse gas economy in the United States by 2050. "Getting to Neutral: Options for Negative Carbon Emissions in California" assesses the technologies and tradeoffs necessary to reach the state's decarbonization goal. These reports are critical for informing state and federal policy.

The Future

Over the next few years, LLNL is prioritizing several earth and atmospheric sciences investment areas to prepare for future challenges. These include:

- Enhancing regional-to-local seismic and nuclear event characterization through investments in machine learning methods, data fusion, big-data analysis, and exascale computing.
- Expanding research on emerging technologies like hydrogen storage and direct air capture of carbon dioxide. These technologies may play a critical role in a future net-zero greenhouse gas economy, but many bottlenecks remain in large-scale deployment.
- Providing decision makers, including U.S. agencies tasked with ensuring our national security, with actionable data to foster climate resilience. LLNL scientists are tackling several remaining challenges in using climate modeling data effectively for resilience planning.

LLNL-MI-858463
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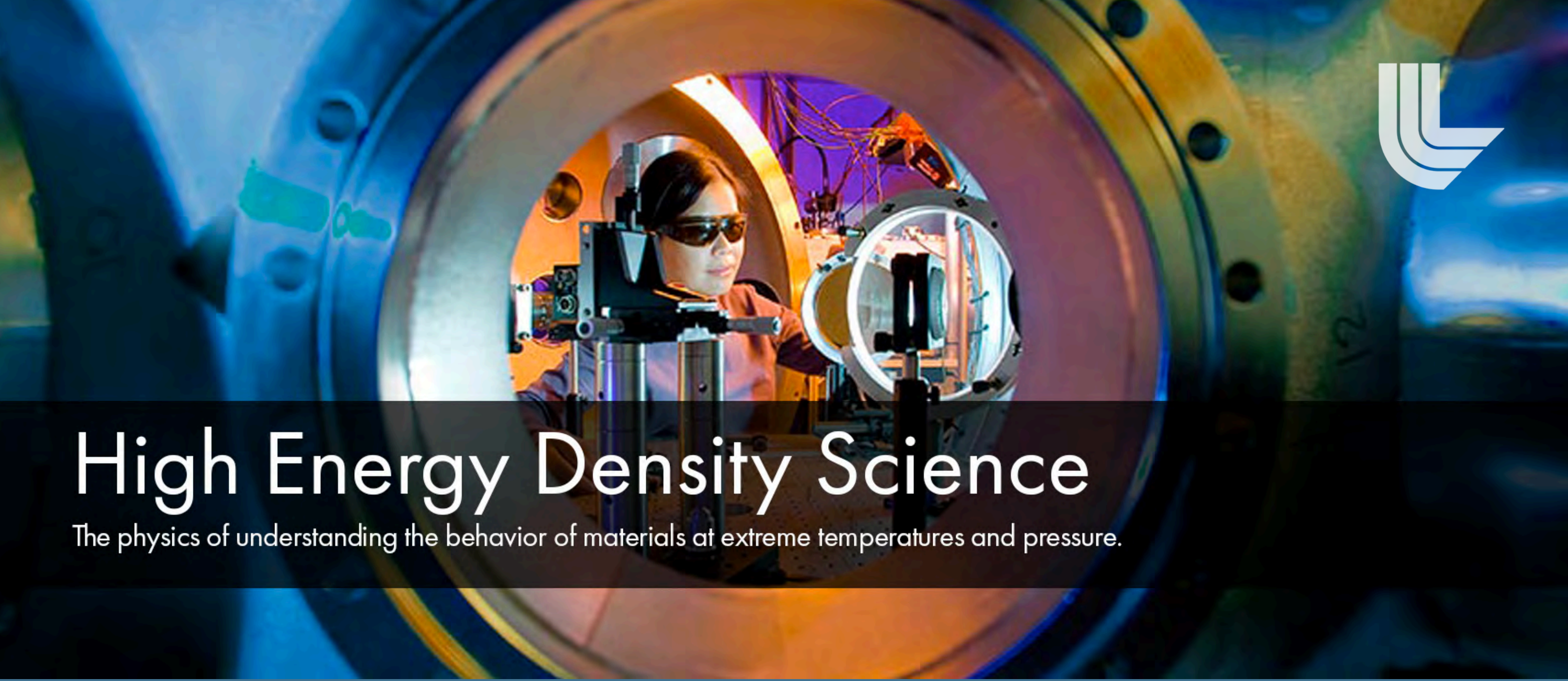
December 15, 2023



High Energy Density Science

The physics of understanding the behavior of materials at extreme temperatures and pressure.

Introduction

High Energy Density (HED) science, exemplified by the National Ignition Facility (NIF), explores matter under extreme conditions, generating temperatures higher than 180 million degrees Fahrenheit and pressures of more than 100 billion Earth atmospheres. This combination of high temperature and high pressure results in matter where energy has been concentrated in space and time.

This research reveals new frontiers in materials science by measuring properties linking the pressure, temperature, density, and structures of materials, known as the equation of state (EOS) and the transfer of radiation at unprecedented pressures and temperatures. By replicating celestial objects' properties in the lab, NIF aids in understanding stars and their energy mechanisms important to astrophysics. HED experiments yield essential data for understanding nuclear weapons' conditions, validating weapon simulation codes, advancing inertial confinement fusion, and related areas of national security.

HED research opens doors to studying unique states of matter and their applications. LLNL uses world-class facilities to advance understanding of HED physics while developing leading diagnostics, new platforms, and new theoretical and computational capabilities.

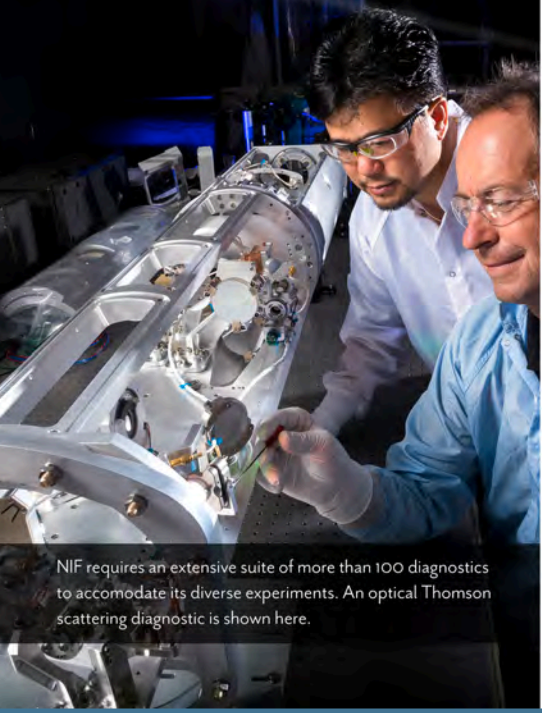
Applications

The Laboratory's heritage of expertise in HED science has led to an innovative and collaborative staff cohort, including creative and visionary laser and plasma physicists, materials scientists, chemists, computer scientists, engineers, technicians and analysts supported by health and safety experts and administrators. Their work advances inertial confinement fusion research and supports mission-critical work in nuclear deterrence and energy security.

In support of the National Nuclear Security Administration stockpile stewardship mission, HED science research provides experimental data and important insights about the materials used in nuclear weapons as they age or are subjected to the immense pressures and temperatures of a thermonuclear explosion. Data from HED experiments help inform and validate 3D weapon simulation computer codes and foster a fuller understanding of weapon physics.

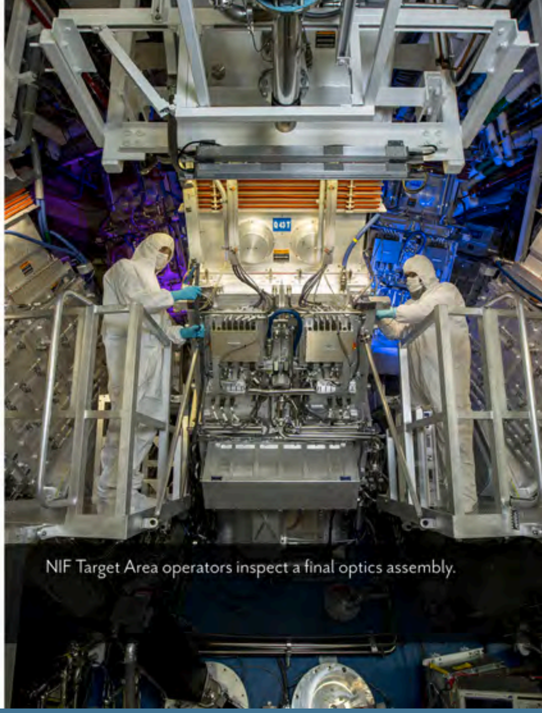
Further applications of HED expertise at the Laboratory include:

- Offering opportunities for scientists and engineers to access world-class experimental facilities and collaboratively explore matter and energy under extreme conditions at the High Energy Density Science (HEDS) Center. The HEDS Center engages a growing HED research community through outreach activities, including guest researchers, named fellowships, and HED programs at universities.
- Delivering leading-edge science and supporting the high energy density science research community with access to high-energy and high-power laser platforms at the Jupiter Laser Facility (JLF).
- Applying HED physics to the design and analysis of inertial confinement fusion experiments and closely related areas of astrophysics, such as stellar structure and supernovae.
- Generating ultra-short, intense x-ray and neutron sources.
- Measuring the strength of materials at extreme temperature and pressures on ultra-short time scales, including turbulent mixing between materials at high compression rates.
- Determining structural phase changes of materials, such as melting and recrystallization, or transitions between crystal lattice structures.



NIF requires an extensive suite of more than 100 diagnostics to accomodate its diverse experiments. An optical Thomson scattering diagnostic is shown here.

A cryogenic target used in NIF fusion experiments.



NIF Target Area operators inspect a final optics assembly.

Accomplishments

For more than 60 years, LLNL researchers and colleagues worked to achieve fusion ignition, one of science's most challenging goals. An experiment on Dec. 5, 2022, passed this historic milestone, opening new vistas of HED science and enabling access to new regimes relevant for future stockpile stewardship. In support of HED science, LLNL has developed multiple diagnostics necessary for measuring material properties on short time scales and at high densities and temperatures. LLNL researchers developed high-speed cameras to create"movie frames" of experiments with time resolution better than 1/10th of a nano-second using x-rays capable of probing ultra-dense materials. Instruments capable of measuring changes in material structures using x-ray scattering from crystals have allowed scientists to update models of solid transformations. Livermore researchers have also harnessed the emerging scientific areas of machine learning and artificial intelligence to advance HED simulation capabilities.

Further accomplishments from the HED team include:

- Experiments to understand the physics within planets, including the Earth's core, inside our solar system's gas giants, and in exoplanets.
- Experiments to explore astrophysics such as the interactions of supernova explosions with the surrounding interstellar gas.
- Study of the interaction of magnetic fields and turbulence as supernova shock waves propagate through space.
- Development of x-ray imaging diagnostics capable of resolving features 1/10th the size of a human hair in billionths of a second.
- Measurements of velocities and temperatures of materials and shock fronts.
- Time-resolved x-ray spectroscopy measurements at extremes.
- Quantification of energy transfer rates through materials and plasmas.
- Development of the "OPAL" radiation opacity code – part of the "Standard Solar Model."
- Development of novel machine learning algorithms for predicting yield of ICF ignition experiments.

The Future

HED research is opening new frontiers in materials science research. Researchers have developed new capabilities for measuring the basic properties of matter, such as the EOS at the highest pressures ever achieved in a controlled laboratory experiment.

The HED field continues to advance to even higher temperatures and pressures, and toward shorter time scales as advances in HED facilities enable more laser or electrical energy in shorter times.

Future improvements in measurement techniques will allow scientists to study nature in more extreme conditions, including more energetic astrophysical explosions and during more energetic phases of nuclear explosions.

The Materials Physics at Extremes (MPaX) group expects to transfer novel thermal diagnostics to the Nevada National Security Site within the next three years.

New capabilities over the next decade will include time-resolved x-ray diffraction measurements of solids such as lead and iron during compressions to feed back to physics models.

The repeated achievement of controlled fusion at NIF provides an intense source of neutrons, opening new fields of study on the effects of neutron energy deposition.

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Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
January 12, 2024

High-Performance Computing, Simulation, and Data Science

Addressing national security challenges through innovative computational and predictive solutions on world-class computing resources.

Introduction

The goal of high-performance computing (HPC), simulation, and data science at Lawrence Livermore National Laboratory (LLNL) is to transform theories that explain physical phenomena into models that can reliably predict outcomes.

State-of-the-art simulations running efficiently on the world's most advanced computers are the integrating element of science-based stockpile stewardship and are critical to other national security needs. Our scientists use HPC to simulate the behavior of matter under extreme conditions of temperature and pressure, which are characteristic of nuclear detonations.

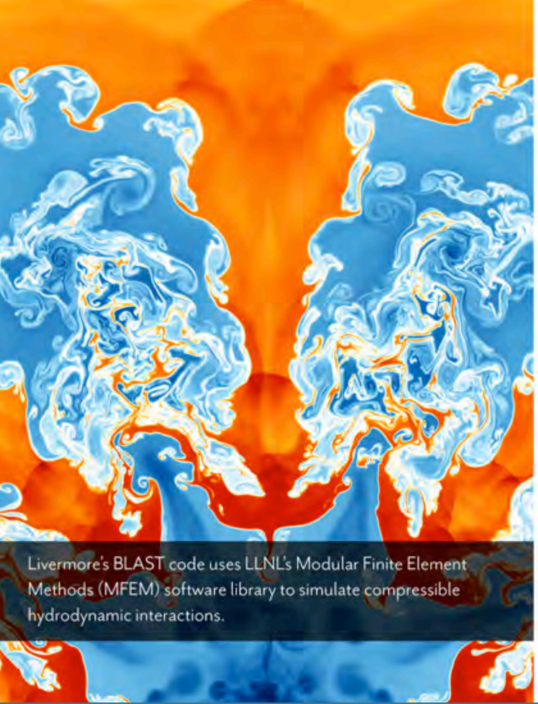
The expanding scale and complexity of the Laboratory's mission require new data-driven and artificial intelligence (AI)–augmented approaches to scientific discovery and engineering design. These techniques applied to massive data sets can help Livermore researchers better understand and predict the behavior of complex systems.

Applications

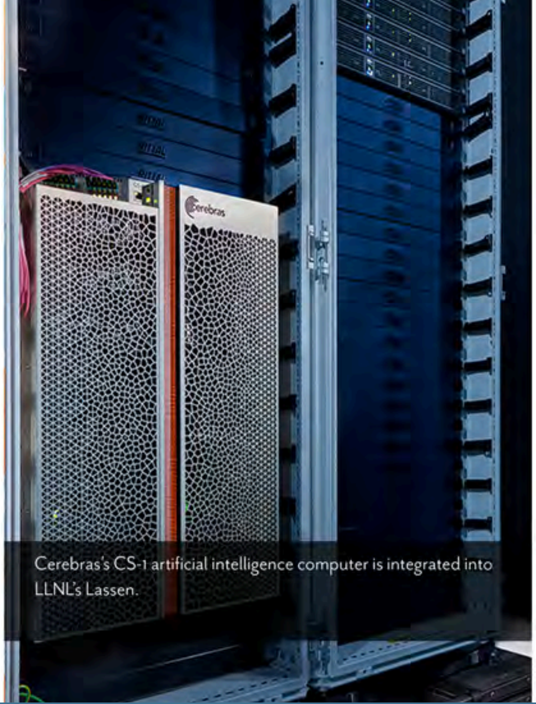
HPC at Livermore has a long history of success in close association with the Laboratory's nuclear deterrence mission. Computational scientists, computer scientists, data scientists, statisticians and mathematicians develop and use HPC to support nuclear deterrence, national security and basic scientific research. HPC capabilities remain critical to the Laboratory's science-based stockpile stewardship, ensuring the nation's existing nuclear weapons systems are safe and reliable. LLNL also uses HPC to continuously improve the scientific underpinnings of this deterrent, such as in studying the effects of material aging. Likewise, HPC facilitates stockpile modernization with newly designed and manufactured systems— like the W80-4 life extension and the W87-1 modernization programs, representing the first significantly redesigned systems to enter the stockpile since the cessation of underground nuclear testing.

LLNL's national security mission relies on simulation codes that investigate a range of physical processes. These highly specialized codes must be able to run on a variety of advanced HPC architectures, incorporate efficient solvers and numerical algorithms, and enhance researchers' predictive capabilities. Further illustrations of HPC expertise at LLNL include the following:

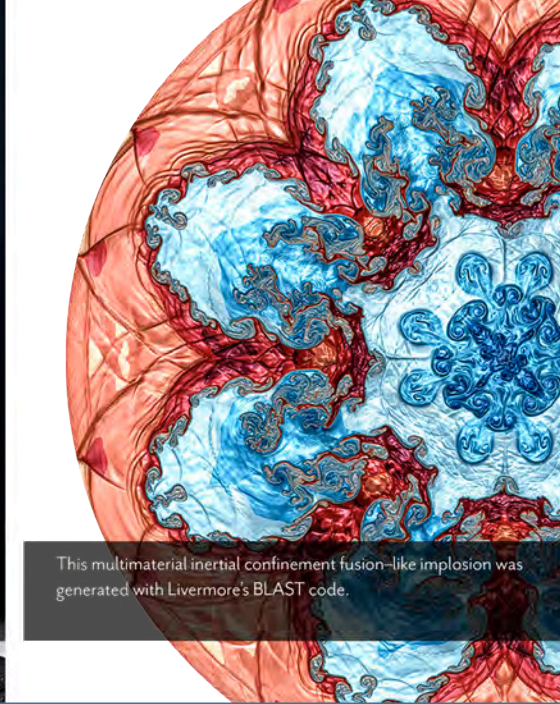
- Livermore Computing houses some of the world's most powerful computers, which use tens of thousands of processors (central and graphics processing units) running at the same time—known as parallel processing.
- El Capitan, NNSA's first exascale computing system—able to process more than a quintillion (10^{18}) calculations per second—will come online in 2024 to aid the nation's effort in a significant, time-critical weapons modernization project.
- Advances in HPC enable the use of 3D modeling in design and uncertainty quantification ensembles, which improves the accuracy of our codes instead of using outdated approximations developed during the nuclear test era.
- Innovative HPC systems and codes improve predictive understanding in complex, data-rich application areas such as advanced manufacturing, climate change, bioscience and biotechnology, energy security, nuclear science, and emerging national security threats.



Livermore's BLAST code uses LLNL's Modular Finite Element Methods (MFEM) software library to simulate compressible hydrodynamic interactions.



Cerebras's CS-1 artificial intelligence computer is integrated into LLNL's Lassen.



This multimaterial inertial confinement fusion–like implosion was generated with Livermore's BLAST code.

Accomplishments

Livermore is a leader in developing and using HPC, simulation, and data science to carry out mission-driven work in strategic deterrence, national security, and fundamental scientific research. Incredible computational capabilities make LLNL a premier destination for HPC researchers, whether their expertise is artificial intelligence, simulation or data science. LLNL scientists, researchers, and technicians often collaborate with government, academic, and industry colleagues to tackle pressing challenges using Livermore's formidable HPC resources. Some of the Laboratory's significant recent accomplishments include:

- Developing exascale-ready simulation tools that continue to both assure the safety, security, and reliability of the nation's enduring nuclear deterrent during the NNSA's annual stockpile assessment process, and also allow for new designs to enter the stockpile through multiple modernization programs in-progress and planned.
- Co-leading the Department of Energy's Exascale Computing Project and delivering algorithms, libraries, and codes that are foundational to the success of exascale-class systems.
- Integrating machine learning and other AI methods into the feedback cycle of experimentation and computer modeling to accelerate scientific discovery. These "cognitive simulation" tools helped LLNL scientists achieve fusion ignition by providing new views of inertial confinement fusion implosions as well as more accurate predictions that consider experimental parameters (e.g., laser energy, target-design specifications).
- Developing a machine learning model that can quickly and accurately predict 3D crystalline properties (e.g., density) of molecules based on their 2D chemical structures. Researchers use the model to search for new insensitive high-explosive materials.
- Using numerical simulations, powerful supercomputers, and new techniques to understand the life and death of a neutron, providing scientists a window into the subatomic world and insight into how the universe has evolved.

The Future

As LLNL's mission continues to expand in scale and complexity, so too must our computational and predictive capabilities. A computational ecosystem capable of exascale—and beyond—performance will enable new data-driven and AI-augmented approaches to scientific discovery and engineering design. We continue to build our expertise in computing hardware, software, codes, and the physical sciences to simulate these phenomena with higher fidelity and more realism.

Livermore is also pushing the frontiers of:

- Computing beyond exascale: heterogeneous, neural, and quantum architectures.
- Novel paradigms for science enabled by large-scale data analytics, machine learning, and cognitive simulation.
- New simulation technologies and algorithms, specifically in design optimization and decision support
- The interplay between HPC and cloud computing paradigms.

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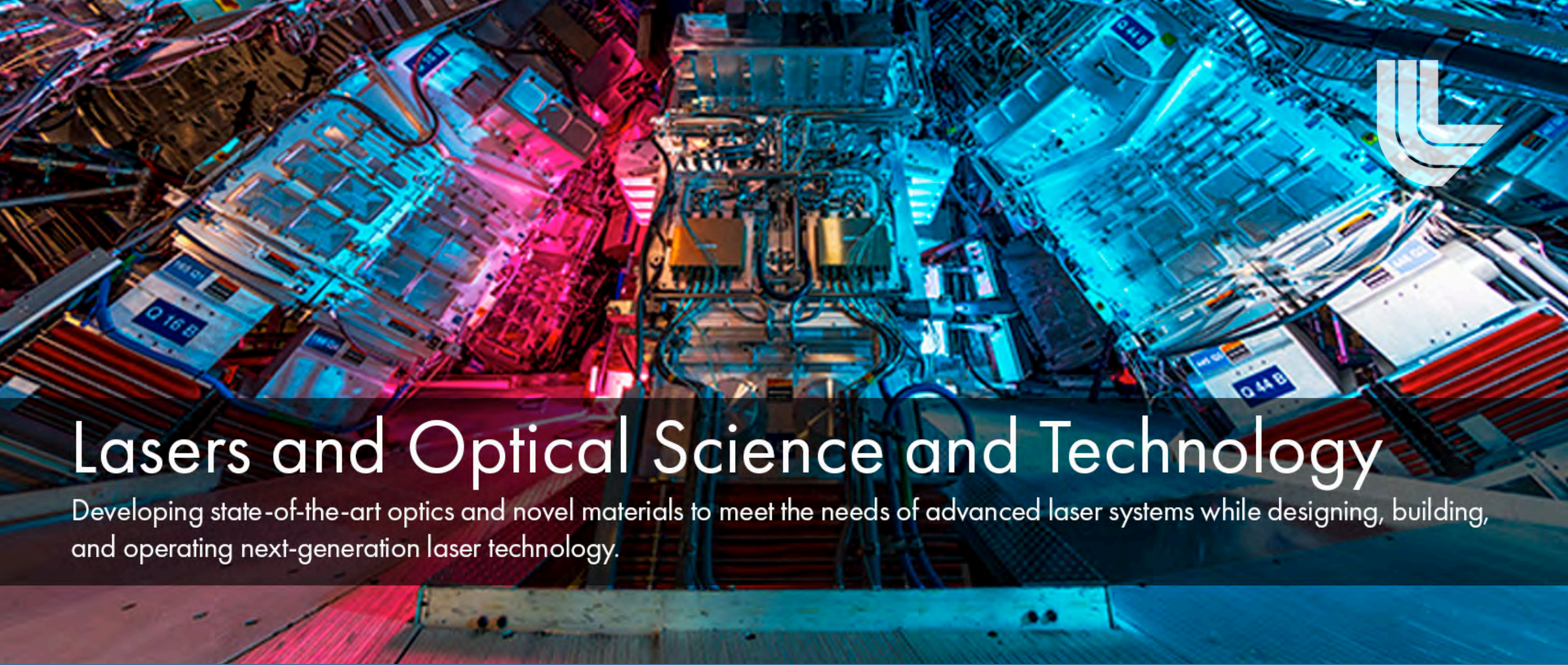
November 13, 2023



Lasers and Optical Science and Technology

Developing state-of-the-art optics and novel materials to meet the needs of advanced laser systems while designing, building, and operating next-generation laser technology.

Introduction

Lawrence Livermore National Laboratory (LLNL) designs, builds, and operates a series of large and complex laser facilities for basic and applied science driven by national security needs. These lasers have set world records in laser energy, power, and brightness. This singular capability enables world-beating science, including the first-ever achievement of fusion ignition in a laboratory on December 5, 2022.

The National Ignition Facility (NIF) – home to fusion ignition – is an invaluable tool in pursuing the lab's core mission of safeguarding America's nuclear weapon stockpile as well as exploring high energy density (HED) regimes that cannot be replicated at other facilities. NIF provides key insights and data for simulation codes used in weapon-performance assessments and certification. It is also an important resource for weapons effects studies and nuclear forensics analysis.

The Laboratory's achievement of fusion ignition has the potential to accelerate the development of next-generation laser systems and optics science and technology. Such advances can help bring about a high-yield fusion facility for stockpile stewardship and lay the groundwork for inertial fusion energy (IFE).

Applications

The Laboratory's leadership in lasers and optical science and technology reflects longstanding expertise in systems engineering, laser construction and operation, and collaboration with commercial partners. This is complemented by leadership in photonics, HED science, optical materials, the physics of laser–material interaction, and laser system modeling and simulations. The following areas of expertise exemplify LLNL's leadership:

- **Advanced Laser Architectures and Technologies:** The Laboratory is on the leading edge of high energy, high peak power, and high average power laser technology. Extending its current capability will improve metrics like pulse energy, wavelength, repetition rate, peak power, efficiency, beam quality, laser precision, and cost-per-delivered-energy in scalable high energy laser systems.
- **Laser System Engineering and Performance Modeling Codes:** LLNL science is leveraging physics models-based systems design, optimization, and the use of high-performance computers. These tools enable innovative architectures with a shorter development cycle, reduced risks and costs, and safe operations.
- **Laser–Material Interaction Science:** The Laboratory's expertise in matter–light interactions extends well beyond laser conditions typically associated with HED science. It also includes optical material damage, laser effects in directed energy weaponry, and the fundamental science of laser-based material processing.
- **Optical Diagnostics and Photonics Technologies:** This area of expertise is supporting LLNL experimental science platforms, delivering data to the Stockpile Stewardship Program, measuring inertial confinement fusion (ICF) target performance, and certifying precision laser pulse shaping on the NIF.
- **Optics and Optics Manufacturing Technologies:** LLNL researchers are developing novel designs and processes, including coatings, materials, and recycling methods.
- **Pumping Technologies: Diodes, Pulsed Power, and Energy Storage:** LLNL is advancing pump diode technologies to enable efficient laser architecture. This is driving the need for energy storage and delivery technologies to power high-efficiency pump diodes, including new pulsed power technologies.
- **Beam and Pulse Shaping Technologies:** The Laboratory is advancing mission-critical technologies for the precision adjustment of laser beam profiles, wavefronts, waveforms, and spectra. These ensure reliable operation of experimental laser facilities, optimization of laser–target interactions, and high beam quality directed energy.

NIF's target chamber captures temperatures of 100 million degrees and pressures extreme enough to compress fuel targets to densities up to 100 times that of lead. Credit: Jason Laurea

Cryogenic Systems Operator Sean Brum installs an opacity target in the NIF target positioner for a development shot for a hohlraum opacity measurement platform.

A color-enhanced image of the inside of a NIF preamplifier support structure. Credit: Damien Jemison

Accomplishments

Over the last decades, LLNL has been a world-renowned center of excellence in the field of lasers and optical science and technology. The Laser Program has delivered major breakthroughs in ICF and other capabilities that support Department of Energy (DOE) and Department of Defense (DOD) missions. Recent accomplishments include:

- On December 5, 2022, the NIF laser precisely delivered 2.05 megajoules (MJ) of energy and 440 TW of peak power to the target enabling the first demonstration of fusion ignition in a laboratory setting. This achievement, which generated 3.15 MJ of fusion energy, has since been repeated at even higher levels.
- Optical component resilience to laser damage has been increased by 4 orders of magnitude since 1997, enabling higher energy densities in laser architectures, including NIF, and more sustained and economically viable operations.
- Recent debris-induced laser damage mitigations on optics have enabled NIF to operate at 2.2 MJ (>20% above initial facility requirements) and 440 TW in FY24.
- Dramatic enhancements of multi-physics laser modeling capabilities on high performance computing platforms with an increase in fidelity of 2-5× and spatial resolution by 3 orders of magnitude.
- Modernizing NIF pulse-shaping technology has improved the precision for power balance and accuracy on target by 2-5× while future STILETTO technology demonstrated shaping with sub-picosecond resolution over nanosecond record length.
- Designing, constructing, and operating state-of-the-art high energy and/or short pulse laser systems for the National Nuclear Security Administration, DOE, DOD, and scientific user facilities.
- Collaborating with the University of California in pioneering adaptive optics to compensate atmospheric turbulence for ground-based observatories and directed-energy applications.
- Understanding failure modes of, and innovating new thermal management schemes for laser diode stacks and arrays while deploying this technology for compact and efficient pumping for high power and high energy laser systems.
- Photonic analog-to-digital and digital-to-analog conversion systems operating at GHz bandwidths have demonstrated improved dynamic range over conventional electronic counterparts by over an order of magnitude.

The Future

The next generation of laser systems will continue to expand the envelope of capability in energy, pulse width, and repetition rate.

Optics mitigations will continue to increase functionality, lifetime, and yield to enable improved performance of high energy/power lasers; there will be special focus on even higher energy and power on NIF after facility sustainment efforts are completed.

Improving precision and control over all laser properties, including time-dependent waveforms and spectra, beam intensity and wavefront profiles, while tailoring polarization states will enable novel modalities for optimizing laser interactions with matter and mitigating instabilities.

The Laboratory will continue to advance the design, development, construction, and optimization of high energy laser systems for IFE and high-yield stockpile stewardship applications. LLNL is also building the next generation of ultrashort-pulse lasers, designed for DOE-relevant HED science applications as well as strategic DOD needs.

The achievement of fusion ignition is not just a historic milestone, but a stepping stone to new possibilities in laser and optical scientific innovation.

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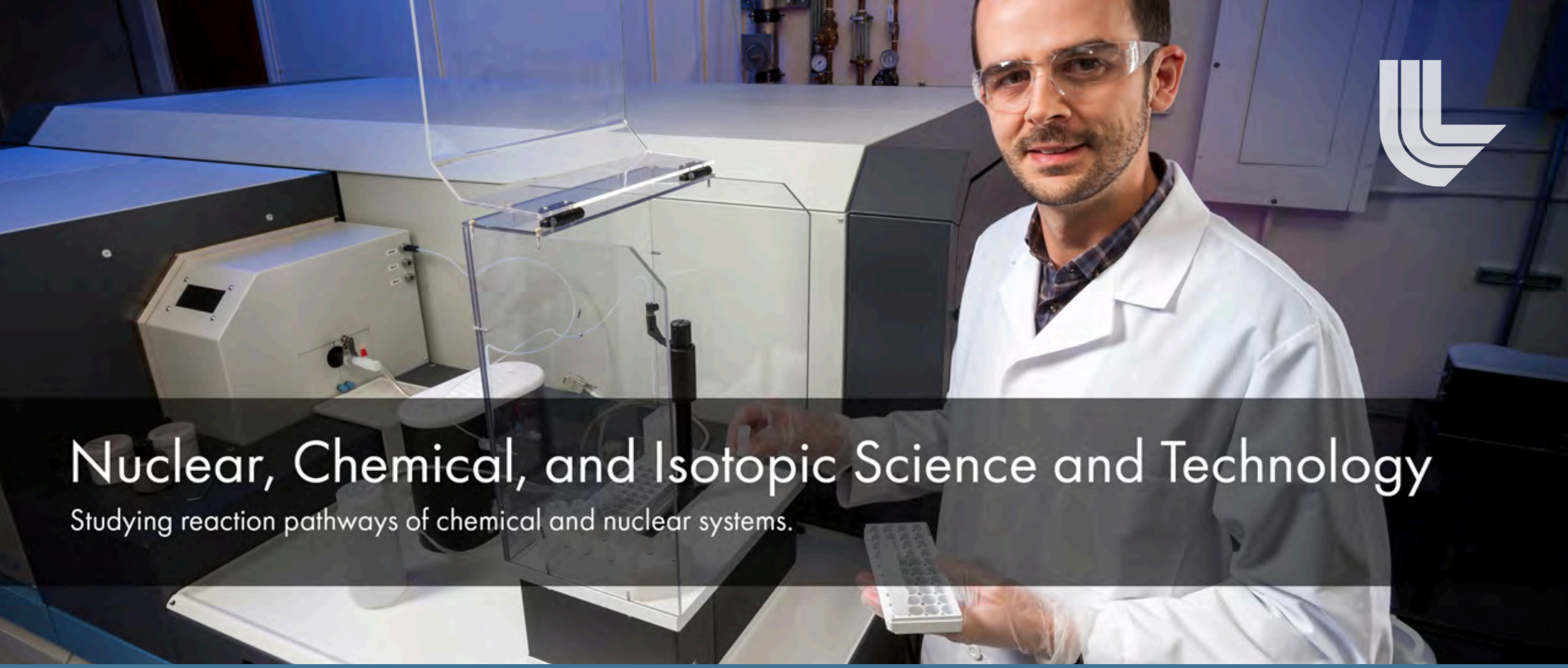
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
December 22, 2023



Nuclear, Chemical, and Isotopic Science and Technology

Studying reaction pathways of chemical and nuclear systems.

Introduction

Research at Lawrence Livermore National Laboratory (LLNL) spanning nuclei formation to planetary evolution addresses our strategic deterrence and global security missions—including threat detection and diagnostics—and contributes to scientific advances in high explosives research, nuclear and particle physics, environmental radiochemistry, cosmochemistry, and forensic science.

Leveraging unique experimental and computational tools, we study nuclear reactions, the limits of nuclear stability, actinide behavior, chemical reactions of energetic compounds, and heavy-element chemistry. We also explore the evolution of our planet, our solar system, and our universe, from the creation of matter through the formation of the nuclei that comprise the periodic table.

Our leading-edge scientific research efforts provide the foundation for addressing these challenges. Our overarching strategy is to position LLNL at the nexus between fundamental nuclear and chemical science research and nuclear security applications. This approach will support efforts to recruit, train, and retain top-flight scientists and engineers who will play a key role in executing the Laboratory's core nuclear security missions, while also enhancing LLNL's reputation as a center for innovative scientific research.

Applications

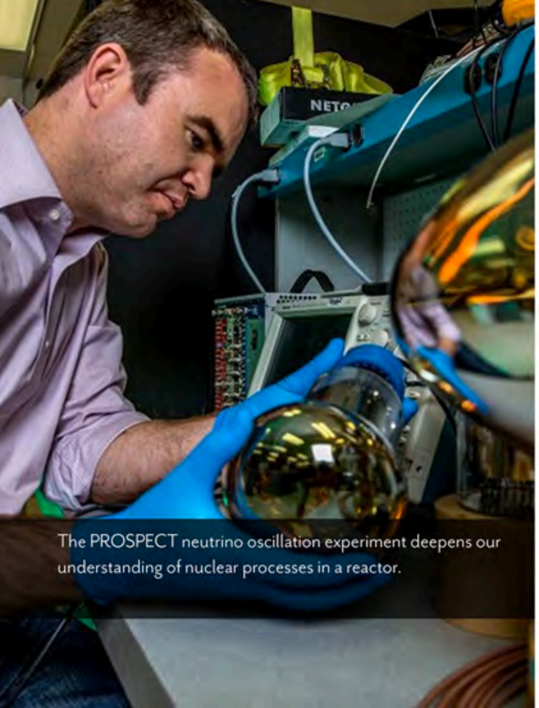
Chemical, nuclear, and isotopic science research directly benefits our national security mission by improving the safety and reliability of our strategic deterrence and enhancing our detection and attribution capabilities for special nuclear materials and nuclear detonations. Our unique isotopic analysis capabilities support LLNL's efforts to develop innovative climate change mitigation approaches.

Applications of nuclear, chemical, and isotopic expertise span the Laboratory:

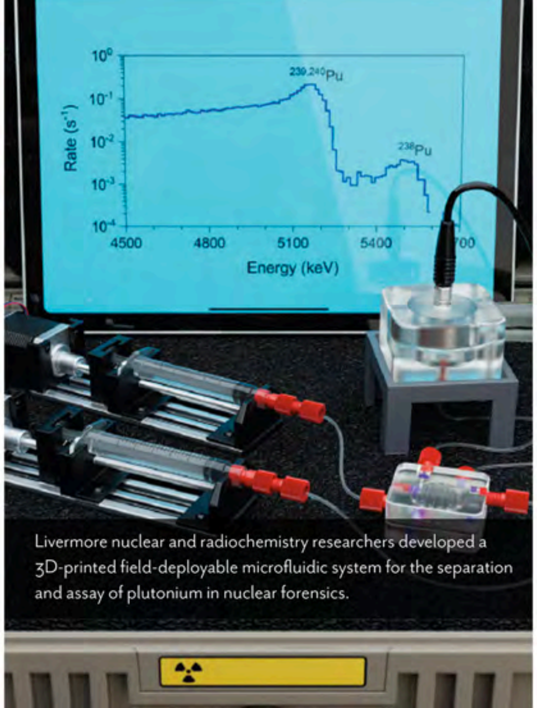
- Researchers are refining new isotopic markers to support carbon-neutral strategies and mitigate the impacts of climate change on water resources.
- Nuclear astrophysicists are developing new machine-learning tools to improve our understanding of nucleosynthesis and reduce uncertainties in nuclear data cross-sections to support strategic deterrence and nonproliferation.
- Particle physicists are launching a new effort for the Office of Science Nuclear Physics program that will unlock the mysteries of the elusive neutrino particle and help scientists better understand the evolution of our universe.
- Experts are creating novel detectors to determine material composition and to detect threats from a distance.
- Experimenters are developing a high intensity, tunable neutron source for radiography to better characterize a larger set of materials.

Examples of the specialized tools and facilities we use to perform our work include:

- The Nuclear Counting Facility, which supports research in stockpile stewardship, nonproliferation, and counter-terrorism by providing high-sensitivity radiation measurements using gamma spectrometers, solid-state detectors, alpha and beta counting systems employing ionization gas chambers, and liquid scintillation techniques.
- The Center for Accelerator Mass Spectrometry, a signature facility that uses diverse analytical techniques and state-of-the-art instrumentation to develop and apply unique, ultra-sensitive isotope ratio measurement and ion beam analytical techniques to address a broad spectrum of scientific needs.
- LLNL's suite of imaging secondary ion mass spectrometry instruments, including a one-of-a-kind instrument with 10-nanometer spatial resolution, which are used to obtain trace element and isotopic information from solid samples in support of nuclear forensics, nonproliferation, cosmochemistry, and more.



The PROSPECT neutrino oscillation experiment deepens our understanding of nuclear processes in a reactor.



Livermore nuclear and radiochemistry researchers developed a 3D-printed field-deployable microfluidic system for the separation and assay of plutonium in nuclear forensics.

Cosmochemists received a tiny sample of the asteroid Ryugu to study the isotopic composition of stardust, nanometer to micrometer sized particles.

Accomplishments

Nuclear, chemical, and isotopic research at LLNL depends first and foremost on the capabilities of our scientific workforce, including staff, students, and postdoctoral researchers. We also take advantage of a wide array of mass spectrometry instruments for isotopic analysis as well as access to world-class high-performance computing capabilities.

These unique tools enable our scientists to maintain expertise across a wide range of topics, including frontier nuclear and particle physics, nuclear structure and reaction data, radiochemistry, nuclear detection technology and algorithms, nuclear and chemical forensic science, and environmental isotope systems.

Recent accomplishments include:

- Analyzing asteroid and lunar samples in order to understand the evolution of the solar system and support future exploration of the Moon.
- Developing a novel microfluidic platform for rapid radiochemical separations and measurements in a lab or in the field.
- Leading an international effort to develop a modern toolkit for storing and using evaluated nuclear reaction data, enabling higher-fidelity nuclear physics simulations and faster adoption of new data and techniques into nuclear science applications.
- Performing precision measurements of nuclear fission cross-sections for uranium and plutonium using a time projection chamber in the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) experiment.
- In particle physics, LLNL scientists have set new limits for the axion dark matter candidate with ADMX and for sterile neutrinos with the BeEST and PROSPECT experiments.
- Using findings from Large Hadron Collider experiments to better study the interactions of quarks and gluons in conditions resembling the first microsecond after the Big Bang.
- Reducing uncertainties in the proton capture of beryllium—a new milestone in combining first-principles theory calculations with experimental measurements in a unified treatment of nuclear structure and nuclear reactions.

LLNL-MI-859327
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
January 18, 2024

The Future

Scientists working in nuclear, chemical, and isotopic science and technology are addressing the next big challenges:

- Studying the origin of matter with the nEXO experiment, the nature of the proton at the Electron Ion Collider, and the origin of the nuclear elements at the Facility for Rare Isotope Beams.
- Expanding our knowledge of nuclei by further developing predictive theory for exotic nuclei and their reactions.
- Using artificial intelligence and machine-learning techniques to improve calibration and inference with nuclear data and fundamental nuclear theories.
- Leveraging the fastest high-performance computing architectures (exascale and beyond) to predict nuclear properties and to develop expertise in quantum computing platforms.
- Harnessing the unparalleled high-energy neutron flux at the National Ignition Facility to measure stockpile-relevant nuclear reaction cross-sections and develop a firm theoretical foundation for this research.
- Employing our novel microfluidic chemistry and detection system to perform the first aqueous chemistry experiments with Element 112 at the Lawrence Berkeley National Laboratory cyclotron.

Energetic Materials

Strengthening the nuclear deterrent, conventional munitions, and homeland security with new energetic materials and applications.

Introduction

Energetic materials (EM) such as explosives, thermites, propellants, and pyrotechnics are central to Lawrence Livermore National Laboratory's (LLNL's) national security mission. EM are utilized throughout a nuclear weapon and also provide the energy source for most conventional munitions.

LLNL is a Department of Energy/ National Nuclear Security Administration Center of Excellence for the research, development, synthesis, formulation, and characterization of explosives. The primary mission of LLNL's EM Enterprise is to ensure the safety, security, and effectiveness of the U.S. nuclear deterrent.

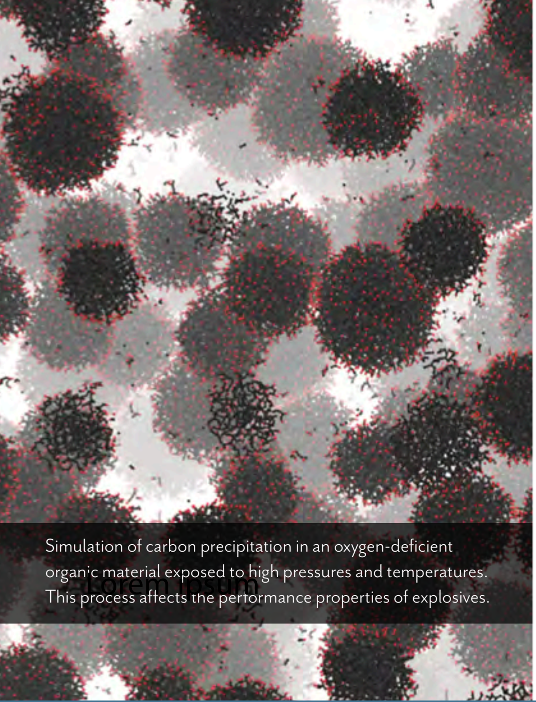
Researchers also apply their expertise to develop solutions for Department of Defense conventional weapons, explore new ways to detect and defeat home-made explosives for the Department of Homeland Security, and develop strategies to counter the threat of improvised explosive devices for nuclear counterterrorism.

Experimental facilities at Livermore's Main Site (Site 200) and remote Site 300 enable research, that, when coupled with high-fidelity modeling and simulation, help advance scientific discovery in EMs.

Applications

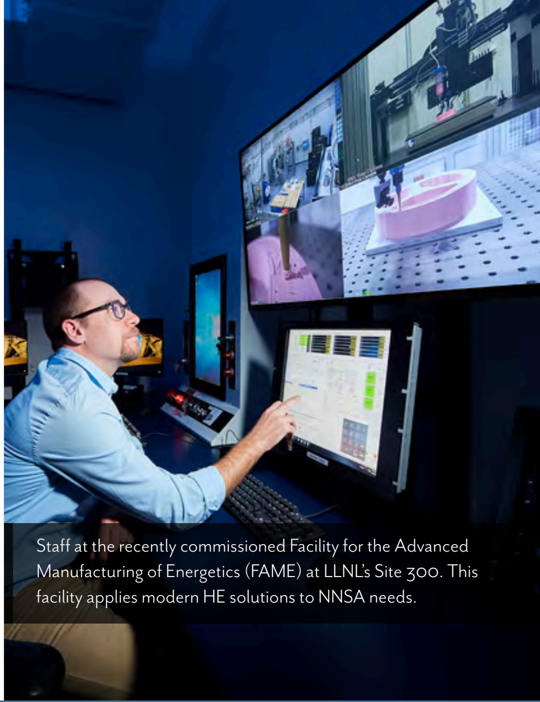
Ensuring and assessing the nation's nuclear deterrent, countering threats from adversaries, and supporting DOD conventional munitions research requires outstanding inquiry performed by exceptional scientists working at world-class facilities. EM scientists explore the energy released during energetic chemical reactions, the mechanical response, and long-term aging characteristics. Taking advantage of LLNL's family of supercomputers and advanced simulation codes, scientists continually improve EM performance and safety. Objectives for the next decade to more closely apply EM expertise across the Laboratory include:

- **Qualification Science:** Continue evolving advanced certification and qualification of explosives with next-generation theory and modeling, coupled to quantification of uncertainties and state-of-the-art experiments using advanced diagnostics.
- **Safety:** Science-informed safety basis enables rapid new explosive and process adoption.
- **Material Aging and Compatibility:** Age-aware performance models incorporating the latest data science are integrated into LLNL's code framework.
- **Manufacturing Modernization and Material Development:** Novel components and manufacturing technologies for high explosives (HE) are routinely transitioned to production in response to new requirements.
- **World-Class Facilities:**
  - High Explosives Applications Facility extension: integrates new technologies.
  - Site 300 Energetic Materials Development Enclave Campus: synthesizes, formulates, manufactures, tests, and transitions HE to production.
  - Contained Firing Facility: houses hydrodynamic experiments up to 60 kg.
  - Engineering Test Complex: ensures the lifetime of systems.
  - Forensic Science Center: supports ultratrace chemical analysis of explosive materials and decomposition products for weapon and global security programs.



Simulation of carbon precipitation in an oxygen-deficient organic material exposed to high pressures and temperatures. This process affects the performance properties of explosives.

A hemispherical pressing of the LX-21 explosive, the first addition to the nuclear stockpile since the 1990s.



Staff at the recently commissioned Facility for the Advanced Manufacturing of Energetics (FAME) at LLNL's Site 300. This facility applies modern HE solutions to NNSA needs.

Accomplishments

LLNL scientists have developed numerous new energetic materials (EMs), especially high explosives (HES), experimental techniques for their characterization, and computational models (e.g., Cheetah and ALE3D) to predict their behavior. These advancements form much of the scientific basis for the modern EM R&D community. EMs developed by LLNL are used by Livermore and Los Alamos nuclear weapon programs, and the Department of Defense (DOD) uses LLNL explosives, initiation systems, and models for their unique weapon designs. Accomplishments from the EM team include:

- LLNL invented and implemented the Mechanical Safing and Arming Device (MSAD) which prevents accidental or unintended detonation of a nuclear warhead.
- Developing LX-21 , the first new explosive to enter the stockpile without underground testing. LX-21 is based on the LLM-105 explosive molecule, invented by LLNL.
- Using pioneering additive manufacturing for complex, multi-material, explosive components resulting in three LLNL patents on the technology.
- Leading the remanufacturing of critical IHEs for W80-4 and W87-1 LEPs. LLNL researchers identified key production parameters and LLNL's Forensic Science Center developed chemical analysis protocols.
- Mitigating the risk of high-consequence subsea drilling operations (i.e. Deepwater Horizon), LLNL designed a linear shaped charge array for Shell Oil Company to sever a drill collar on-command.
- Predicting effects of material aging on explosives' performance and improving assessments of weapon service life through groundbreaking capabilities.
- Obtaining never-before-captured high-resolution data in the reaction zone of a detonating HE through research at DOE user facilities.
- Identifying new explosive threats to Homeland Security by using advanced x-ray, dual-energy, and computed tomography processing.
- Patented E.L.I.T.E.™ (Easy Livermore Inspection Test for Explosives) system for first-responders uses chemical reactions to quickly detect explosives.

The Future

Looking ahead, LLNL will continue to support Energetic Materials research and development for advanced conventional weapons, rocket and gun propellants, homeland security, demilitarization, and industrial applications of energetic materials.

In direct support of the Laboratory's mission, the program will uphold high confidence in the safety, security, reliability, and effectiveness of EMs used in our nation's nuclear deterrent.

Researchers will attain program goals, transform our enterprise, develop relevant capabilities, and advance the science, technology, and engineering of EMs.

LLNL maintains a steadfast commitment to the Laboratory's national security partners. This includes addressing the needs of the Department of Homeland Security and its Transportation Security administration while countering the threat of nuclear proliferation.

LLNL-MI-857181
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November 13, 2023

24/7 Emergency Response

Providing round-the-clock expertise and technical capabilities to support civil-emergency response and preparedness, military operations, and the intelligence community.

Scientific Expertise on Call

As a long-established Department of Energy (DOE) / National Nuclear Security Administration (NNSA) partner and member of the interagency nuclear and radiological emergency-preparedness and response community, Lawrence Livermore National Laboratory (LLNL) provides round-the-clock expertise and technical capabilities. Laboratory teams support civil-emergency scenario planning, crisis assessment and analysis of chemical, biological, radiological, nuclear, and explosive (CBRNE) threats against the U.S., and research and develop tactical tools for military operations and the intelligence community.

The Laboratory's trained, certified interdisciplinary teams of subject-matter experts possess a unique collection of skills, experience, and abilities across a range of disciplines from atmospheric modeling to weapons physics and data science and can be deployed on-site or off, within minutes, 24 hours a day, seven days a week.

LLNL's multidisciplinary teams and facilities respond to hazardous atmospheric releases, characterize and defeat nuclear threats, or, should a detonation occur, provide forensic and consequence management assistance to U.S. government officials as well as state and local authorities.

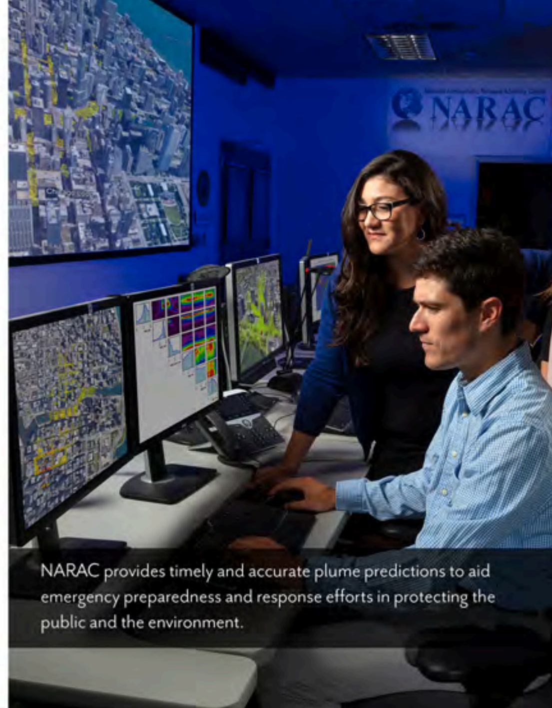
Applications

LLNL provides U.S. interagency response support against a range of nuclear, radiological, chemical, biological, explosive, and cyber threats. Various LLNL response teams provide levels of support, including 24/7 crisis assessment and forensic analysis. The Laboratory applies its response expertise in the following areas:

- LLNL is one of the three DOE laboratories that directly supports the Nuclear Emergency Support Team (NEST), NNSA's multi-mission, nuclear-emergency response capability that leverages DOE's world-class scientists and technical experts to contend with the nation's most pressing radiological and nuclear challenges. NEST is the umbrella designation that encompasses all DOE/NNSA radiological and nuclear-emergency response functions, some of which date back more than 60 years.
- NEST's National Atmospheric Release Advisory Center (NARAC) responds 24/7 to hazardous atmospheric releases anywhere in the world—predicting their evolution, exposure levels, and trajectories to protect the public and the environment. NARAC has developed an operational urban-dispersion capability and a fallout model based on first-principles physics and chemistry.
- One of two U.S. laboratories with international certification to handle chemical warfare agents, LLNL's Forensic Science Center provides sample analysis across the chemical, biological, radiological, nuclear, and explosive (CBRNE) threat space.
- LLNL and Los Alamos serve as national laboratories for the Bulk Special Nuclear Materials Analysis Program, a U.S. interagency program that ensures accurate analysis of nuclear material.
- The Counterproliferation, Analysis, and Planning System strengthens CBRNE capabilities across the Department of Defense by providing intelligence analysis and reach-back support to the intelligence community and combatant commands.
- Infrastructure protection and security experts at LLNL evaluate electrical grids, oil refineries, natural gas networks, railways, ports, and waterways for physical and cyber security. Specifically, the Rapid Impact Vulnerability AnaLysis (RIVAL) response leverages critical infrastructure expertise, intelligence information, and modeling and simulation capabilities. These resources evaluate emerging cyber threats, portray potential scenarios, reveal potential impacts, and recommend mitigation strategies.
- International Nuclear and Radiological Security teams work worldwide to secure and protect nuclear and radiological materials from theft, sabotage, and terrorism.

NEST physicist demonstrates how a portable neutron detector works as part of a training exercise.

LLNL's emergency response expertise directly benefits American warfighters abroad. Military and intelligence operations rely on decisive, authoritative information from LLNL's cohort of experts.



NARAC provides timely and accurate plume predictions to aid emergency preparedness and response efforts in protecting the public and the environment.

Accomplishments

LLNL's decades-long record of emergency preparedness and response relies on its interdisciplinary teams of subject-matter experts who possess a keen understanding of risks and threats; preparation and execution of policies, plans, and procedures; and development of innovative technologies to prevent, mitigate, and respond to threats. LLNL has provided urgent support to the U.S. Government during several recent incidents and emergencies and for emergency preparedness including:

- Ukraine (2022): NEST continuously monitors data from radiation detection sensors in Ukraine and the surrounding region to ensure real-time situational awareness of nuclear facilities. Sensor data provides early warning of an emergency at these facilities and allow DOE/NNSA scientists to provide critical technical guidance to Ukrainian partners to inform measures to protect public health and safety.
- Plutonium Finishing Plant at Hanford (2018): Assessments of potential contamination at the Plutonium Finishing Plant at the Hanford Site in Washington state were made by NARAC using a fast-running, urban-dispersion model to determine if contamination levels warranting controls might extend beyond established radiological boundaries.
- Ruthenium Detections Across Europe (2017): When a mildly radioactive plume of ruthenium-106 appeared in the atmosphere across Europe, NARAC quickly estimated probable source locations and strength using a machine-learning tool.
- Apex Gold (2016): LLNL hosted the first, minister-level exercise to identify national and international actions to address a simulated nuclear crisis and advise heads of government how to best prepare 24/7 response to a nuclear-security crisis.
- PG&E Substation Sniping (2013): After a domestic terrorism incident at an electric power station in California, LLNL conducted immediate after-action analysis, assessed security vulnerabilities, and recommended security enhancements.
- Fukushima Daiichi Nuclear Disaster (2011): LLNL deployed NEST's Radiological Assessment Program team, in conjunction with NARAC's ongoing plume modeling predictions, to analyze radiological samples to inform on public health and safety. This 24/7 effort was sustained for many weeks after the disaster.

The Future

LLNL continues to advance its technical capabilities and contribute to the nation's credible response posture by applying advances in high-performance computing and artificial intelligence as well as by rapidly gathering and interpreting intelligence and assessing credible threats.

LLNL directly supports the U.S. response infrastructure by training first responders to improve their effectiveness and reduce response times.

LLNL subject-matter experts are developing high-fidelity training materials and leveraging next-generation technologies such as augmented reality to advance first-responder training.

As LLNL researchers continue to develop informed innovative technologies, the Laboratory's 24/7 operational technical support will be further enhanced to provide increased confidence for timely and effective national emergency response.

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