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.

Innovative Solutions for Complex Problems

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. Laboratory 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, telescopes, and enabling high energy density experiments on high-powered lasers; quantum materials; and components that can function effectively in extreme environments.

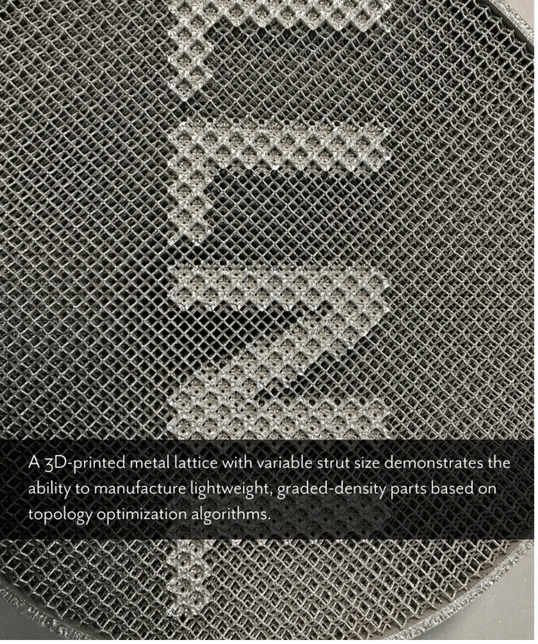
Livermore advances manufacturing technology through the development of customized feedstocks and invention of unique fabrication techniques. Diagnostic methods are developed and implemented to test components during manufacturing, which accelerates LLNL's ability to deliver timely solutions.

AMM uses an agile material development and manufacturing ecosystem to meet stakeholders' needs. The team enhances performance of materials and components, cuts manufacturing costs, minimizes supply chain vulnerabilities, recycles and reuses material, reduces waste, and accelerates 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. As shown below, AMM expertise is evident across the Laboratory:

- LLNL's high-performance computing (HPC) resources and artificial intelligence (AI) expertise accelerates multiscale, high-fidelity modeling of material synthesis and manufacturing processes critical for designing new materials and feedstocks.
- The Advanced Manufacturing Laboratory (AML) facilitates industrial and academic partnerships to address challenges across commercial and government projects.
- The Polymer Enclave enables rapid development of polymer parts for stockpile modernization programs.
- The Laboratory for Energy Applications for the Future (LEAF) fosters research that accelerates scalable structures for energy production, storage, and transmission, such as batteries, supercapacitors, desalination, and carbon capture.
- Advanced, in-situ diagnostics and non-destructive characterization tools, including quantum 3D imaging, spectroscopy, x-ray computed tomography, and high-resolution electron microscopy, let researchers assess a material's properties and identify defects.
- The Materials Characterization Center (MCC) is designed to handle a wide range of material classes from energetics to advanced radiological materials to establish process-structure-property relationships for mission-critical applications.
- The Center for Engineered Materials and Manufacturing (CEMM) develops advanced and additive manufacturing techniques, new feedstock materials, and multi-material and multiscale structures relevant to LLNL's mission-critical work.
- The Center for Design and Optimization applies computational methods to optimize systems governed by nonlinear, dynamic, multiphysics, or multi-scale phenomena.
- Organ-on-a-chip systems and 3D-printed biological cells and matrices greatly accelerate testing of medical countermeasures.
- Surfaces and interfaces are designed to mitigate corrosion and increase component lifetimes.



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.


Volumetric Additive Manufacturing (VAM) is used to print three-dimensional solid parts rapidly within resin using an "all-at-once" approach.

Accomplishments

LLNL integrates expertise in engineering, materials science, physics, chemistry, data science, modeling and simulation, and manufacturing to co-design 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 (AI) and data science to optimize designs and achieve rapid advances in materials science. Many LLNL resources contribute to these accomplishments, including:

- A 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.
- AI-driven discovery of interatomic potentials to rapidly discover new materials for applications in solid-state batteries, hydrogen storage, and CO_2 electrolysis.
- Invention of a Volumetric Additive Manufacturing (VAM) technique, which can fabricate complex 3D objects in seconds to minutes by projecting a combination of tomographic images into a photosensitive resin.
- A commercially available materials modeling platform, The Alloy Optimization Software (TAOS), that enables computational design of optimal alloys with targeted properties.
- Additively manufactured transparent glass with customized composition and structure to create a gradient index of refraction optical components.
- Customized metal alloys with thermally stable microstructures that are lightweight, corrosion-resistant, and radiation tolerant, and use of predictive models to identify age-resistant designs with applications in hypersonic vehicles, space science, high-power lasers, and nuclear reactors.
- An advanced additive manufacturing workflow to design, fabricate, characterize, and field 3D-printed fuel capsules used in ignition experiments at NIF.

The Future

The long-term vision of the AMM team involves leveraging LLNL's newest resources to expand the collaborative research space. AMM staff will explore new partnerships with industry and other research institutions, both domestically and internationally, to boost the Laboratory's ability to deliver cutting-edge solutions.

LLNL will continue to take a leadership role in Department of Energy (DOE)-sponsored research activities involving clean energy technologies such as hydrogen, including developing 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 Hub.

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 supporting the reliability of the nation's nuclear deterrent.

Lawrence Livermore National Laboratory

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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. Research is guided by multidisciplinary innovation and collaboration with academia, industry partners, and government agencies.

By combining capabilities and forging partnerships in quantitative biology, computing, engineering, and precision measurement, LLNL assesses, designs, and tests medical countermeasures against biological and chemical threats. By expanding biological models, researchers are pioneering solutions for bioenergy crop system resilience, carbon sequestration in soils, eco-friendly extraction of critical minerals, and novel biomaterials.

Integrating analytical tools, systems biology techniques, high-throughput fluidic devices, human-on-a-chip models, and high-performance computing, staff explore the mechanisms of disease, develop novel diagnostics and therapeutics, and engineer microbial communities to counter emerging threats in biosecurity, health, and the environment.

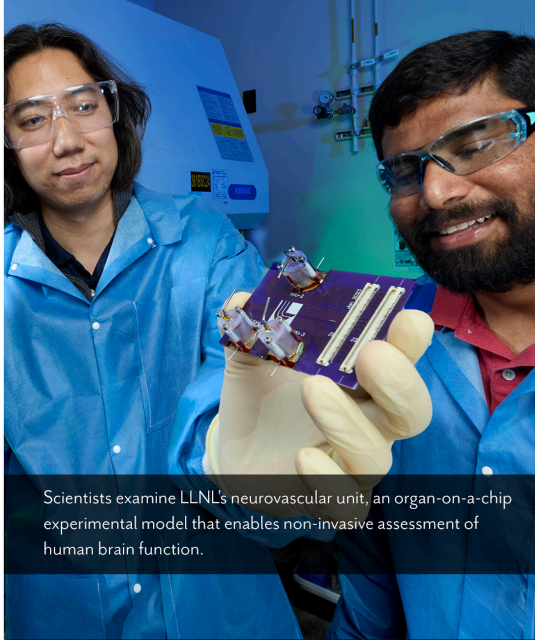
Applications

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, LLNL teams apply the design–build–test–learn cycle to tailor biological molecules and systems to achieve new functionalities. 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 only U.S. facility that offers ultra-high-sensitive isotopic analysis for biomedical researchers measuring extremely low radioisotope concentrations.
- A Biomedical Foundry within our microfabrication facility (ISO 13485 compliant) for manufacturing medical prototypes and developing human-on-a-chip models.
- A Rapid Response Laboratory (RRL) with a high-throughput automated pipeline to rapidly produce and evaluate computationally designed antibodies.
- Experimental microphysiological systems and computational platforms for biological and chemical threat analysis and therapeutic evaluation.
- Combining stable isotope probing, advanced imaging, genomic profiling, and computational modeling to study microbial communities in ecological frameworks.
- 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 High Containment Facility, an aerosol inhalation research facility (AIRLAB), and Animal Care Facility; additive manufacturing in bioprinting and biomaterials; and bio-forensic science capabilities at LLNL's Forensic Science Center.
- The Center for Predictive Bioresilience (CPB) LLNL's main hub for collaboration between computational and experimental biology. The center combines high-performance computing and experimental platforms to accelerate the design of medical countermeasures and develop advanced predictive models for early warning systems to help prevent future pandemics.


LLNL researchers are using advanced tools to show how subetadex binds and neutralizes fentanyl—a breakthrough step toward new treatments for the opioid crisis.


LLNL researchers are engineering microbes to sustainably recover rare-earth elements—critical for clean energy, electronics, and national security.


Scientists examine LLNL's neurovascular unit, an organ-on-a-chip experimental model that enables non-invasive assessment of human brain function.

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 biological and chemical threat detection, assessment, and impact predictions, accelerated development of therapeutics and countermeasures, and engineering of microbiomes for health, energy, and environmental sustainability. 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 miniaturized fieldable PCR 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.
- Creation of the Lawrence Livermore Microbial Detection Array, a pangenomic platform capable of rapid detection of over 12,000 microorganisms within a single day. This platform is now used for applications in diverse fields such as biodefense, drug and food safety, and space biology.
- Contributions to the world's first artificial retina. This invention led to high-density, microfabricated, and fully implantable neural prosthetics, and implantable/wearable interfaces now expand beyond the brain including spinal cord electrode arrays.
- Advancement of microphysiological systems, including an instrumental 3D brain model and neurovascular unit that offer insights into mitigating neurological threats.
- HPC-enabled development of the LLNL therapeutic antibody design platform. This platform is capable of designing antibodies in weeks instead of the months-to-years expected with conventional methods.
- Formulation of novel nanoparticle-based vaccine delivery methods. These formulations are undergoing animal testing to evaluate efficacy against infections caused by chlamydia and other pathogens.
- Development of sustainable biomining approaches for purifying rare-earth elements, safeguarding the domestic supply of critical minerals for U.S. energy security.
- Acceleration of drug discovery by coupling physics-based modeling with machine learning algorithms. As a result of this work, a first-in-class medication targeting cancer-related genetic mutations is now in clinical trials.

The Future

Bioresearchers integrate experimental and computational models with new capabilities to accelerate diagnostics, therapeutics, and sustainable biomanufacturing. A multifaceted approach includes early biological threat assessment, broad-target antibodies, and novel therapeutics and vaccines. LLNL is committed to bioeconomy and sustainability, driving advancement in biomanufacturing, biofuels, and ecosystem management.

Integration of big-data analytics and computational and biological modeling enhances genotype-to-phenotype predictions, improving our understanding of pathogens, host factors, and infectious disease outcomes. This involves exploring the intricate relationship between pathogen genotype, exposure conditions, and host fitness, offering revolutionary insights for disease anticipation and management. Predictive design via computational and experimental integration focuses on engineering of microbial systems and biomolecules—from proteins to small molecules—with applications in healthcare, energy, and supply chain resiliency. The Integrative Bio Resilience Laboratory (IBRL) is a planned next-generation building featuring reconfigurable BSL2 labs that blend biology, engineering, and computer science to accelerate biology-based solutions by partnering with industry and academia.

Through innovation and collaboration, the future holds proactive solutions to national security challenges.

Lawrence Livermore National Laboratory

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Earth and Atmospheric Science

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 collaborate with National Laboratories, federal and state agencies, academia, and industry to help build a safer and more resilient future.

For decades, LLNL scientists have been at the leading edge of Earth system science, improving our understanding of natural systems and supporting resilience planning for infrastructure development and national security operations. In parallel, Laboratory staff develop innovative energy technologies and waste management techniques to support energy independence.

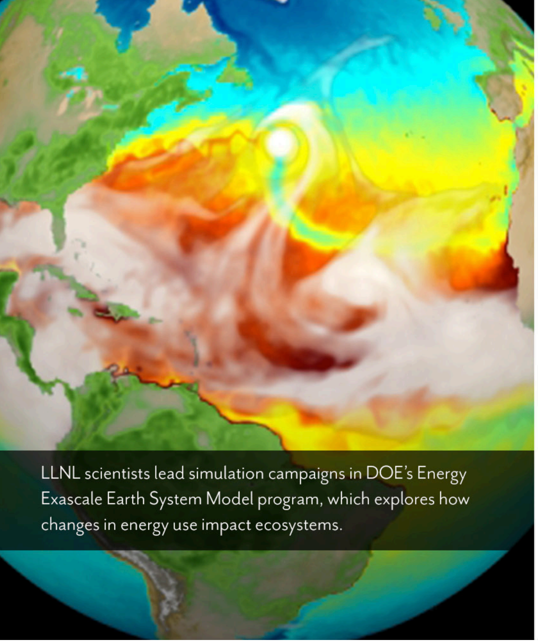
In the national security arena, Lawrence Livermore advances global-scale monitoring techniques for detecting, locating, and characterizing underground nuclear testing. LLNL's decades of innovations have strengthened response efforts for nuclear emergencies and hazardous material releases.

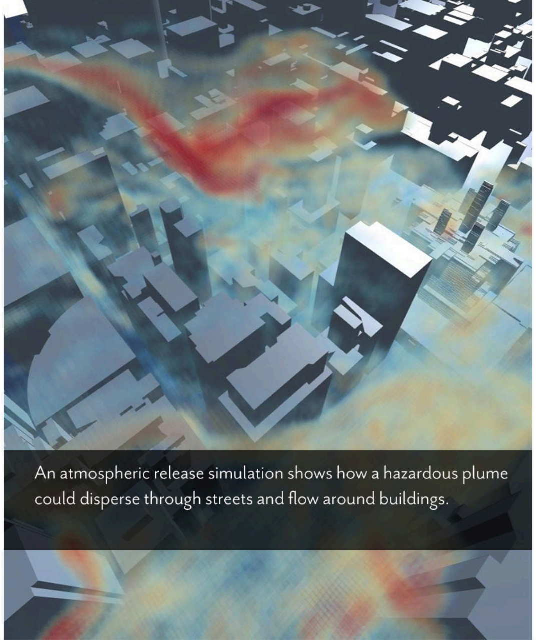
In these efforts, LLNL leverages state-of-the-art computational methods, validated with unique laboratory capabilities and large-scale field experiments.

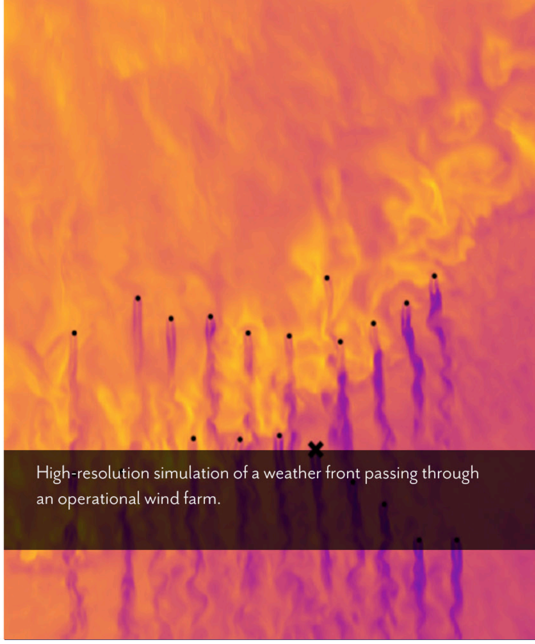
Applications

Researchers in the Earth and atmospheric sciences continually innovate to make the world safer, the environment cleaner, and our energy resources more secure. Key areas of research include seismology, geophysics, geomechanics, geochemistry, hydrology, atmospheric turbulence and dispersion, Earth system modeling and model intercomparison, environmental variability, energy systems, and geochemical cycles. The Laboratory maintains 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 leads the development of the Department of Energy's (DOE's) Energy Exascale Earth System Model (E3SM) Project. E3SM leverages capabilities at eight DOE National Laboratories and academic partners to harness the world's largest supercomputers to model and understand natural and anthropogenic impacts on our ecosystem.
- The study of Earth System Resilience includes assessing the impacts of extreme weather events on systems and operations critical to national security (e.g., the electrical grid, military installations, and supply chains), to mitigate negative impacts of energy production, and to improve Earth system simulation on spatial and temporal scales required by decision makers.
- Atmospheric researchers develop high-fidelity atmospheric fluid dynamics, turbulence, and aerosol dispersion codes. These models are used to study nuclear weapons effects, atmospheric contaminant releases, sustainable energy systems, and high-altitude flight environments.
- The Center for Accelerator Mass Spectrometry (CAMS) performs up to 25,000 ultra-sensitive isotope measurements per year, enabling nuclear forensics, environmental tracing, and validation of Earth system models used by agencies and research partners.
- LLNL's geomaterial modeling libraries capture impact and explosion physics in hard-rock environments, enabling faster, more accurate consequence assessments and resilient design for underground facilities and national security operations.
- The Laboratory leads development of GEOS, an open-source reservoir simulator for subsurface energy systems. This exascale capability, developed by a community of energy industry and academic partners, has been used in numerous studies to support reservoir management, hydraulic stimulation for oil and gas extraction, 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.


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 Earth system research since the Laboratory developed the world's first atmospheric general circulation model in the 1960s. In Earth science, LLNL scientific advancements have informed state- and federal-level policy for managing subsurface energy resources. In the national security arena, LLNL researchers enable domestic and international agency cooperation regarding treaty verification, nuclear non-proliferation, and nuclear emergency response. Key accomplishments include:

- The Gordon Bell Prize, recognizing outstanding achievements in high-performance computing, was awarded to LLNL researchers in 2023 for their work on an exascale-capable atmospheric modeling code that is paving the way towards unprecedented resolutions in Earth system simulations.
- Since 1979, the National Atmospheric Release Advisory Center (NARAC) has been on call 24/7 to support the decision-making of emergency responders 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), and assessed airborne hazards in the wake of Hurricane Katrina (2005), the Deepwater Horizon oil spill (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 3D internal images of the Earth's interior to improve seismic and nuclear event monitoring. This work has led to fundamental discoveries, such as identifying the previously unknown Southeast Indian Ocean slab.
- Livermore seismologists co-developed an EarthQuake SIMulation (EQSIM) framework, which harnesses the power of the Department of Energy's exascale supercomputers to create highly detailed, physics-based simulations of earthquakes across entire regions. With EQSIM, scientists and engineers can now generate realistic, site-specific predictions of ground motion and infrastructure risk, even in regions where little or no historical earthquake data exists.

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 novel methods that leverage machine learning and artificial intelligence, data fusion, big-data analysis, and exascale computing.
- Developing critical minerals exploration and production technologies, and new approaches for the future of mining.
- Expanding research related to emerging technologies like hydrogen storage and enhanced geothermal energy, eliminating bottlenecks on the path to large-scale deployment.
- Providing decision makers, including U.S. agencies tasked with ensuring our national security, with actionable data on natural hazards and their impact on global security. LLNL scientists are also tackling remaining challenges in using Earth system modeling data effectively for resilience planning.

Lawrence Livermore National Laboratory

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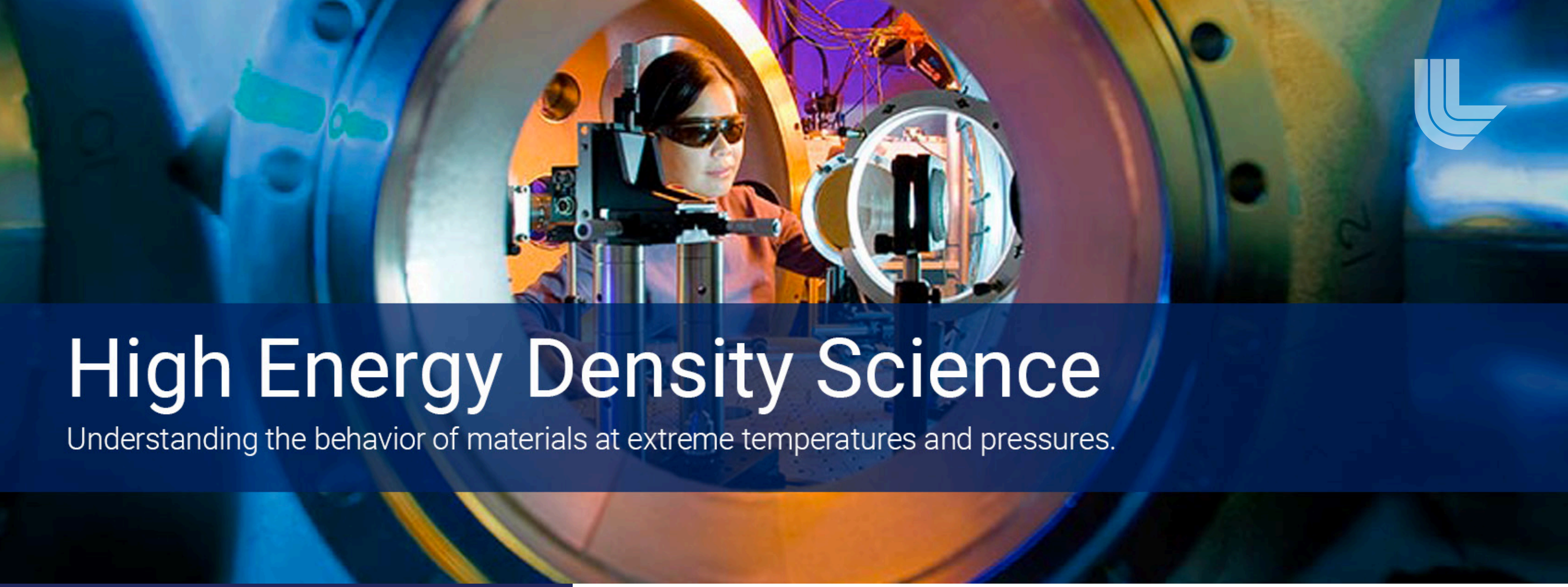


High Energy Density Science

Understanding the behavior of materials at extreme temperatures and pressures.

Exploring Matter under Extreme Conditions

High energy density (HED) science, exemplified by the National Ignition Facility (NIF), explores matter under extreme conditions. NIF concentrates energy in space and time, generating material temperatures higher than 180 million degrees Fahrenheit and pressures of more than 500 billion Earth atmospheres—conditions more extreme than the center of the sun. NIF is the only place on earth that has achieved the extreme conditions of thermonuclear ignition in a controlled laboratory setting, opening new frontiers across HED, nuclear, material, and weapon science fields.

HED experiments yield essential data for understanding nuclear weapons' conditions, validating weapon simulation codes, advancing inertial confinement fusion, and exploring related areas of national security. By replicating celestial objects' properties in the laboratory, NIF also helps researchers understand stellar evolution and other astrophysical phenomena. HED research explores unique states of matter and their applications.

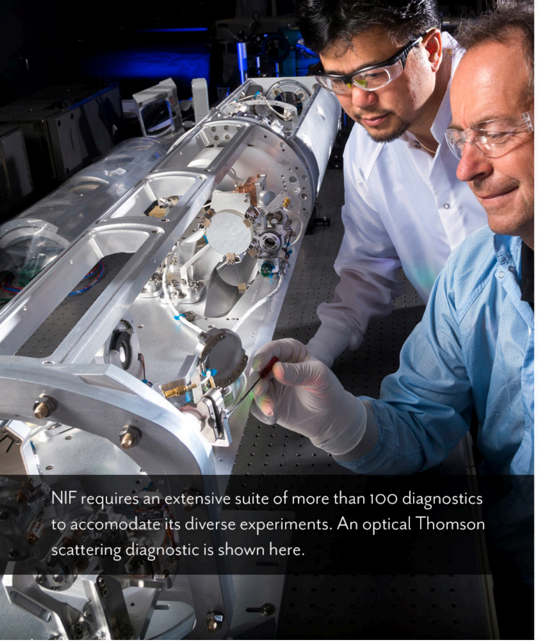
LLNL uses world-class facilities and partnerships with other research institutions with unique capabilities to explore HED science. Researchers gain new understanding of HED physics by developing cutting-edge diagnostics and platforms while applying theoretical and computational capabilities to new challenges.

Applications

The Laboratory's heritage of HED science expertise is world-renowned and crucial to the national science-based stockpile management and modernization efforts. LLNL's HED science informs annual assessments of the active stockpile, warhead modernization design decisions, and expert certification judgements about modernized warheads, all without nuclear testing.

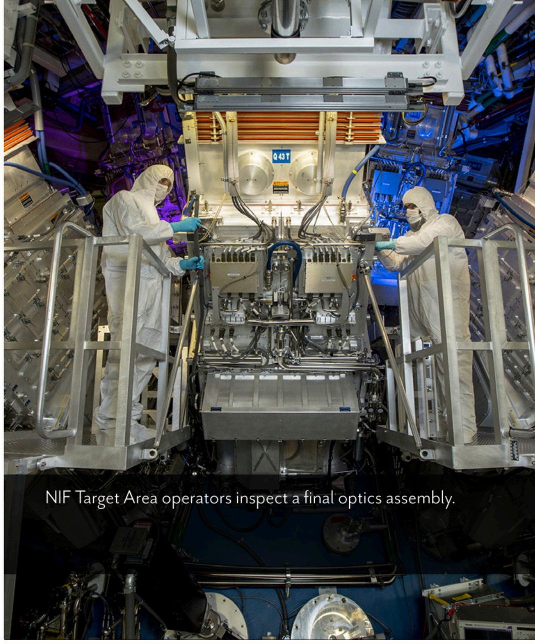
HED research also provides experimental data and important insights about the dynamic properties of materials used in nuclear weapons as they age or are subjected to the immense pressures and temperatures of a thermonuclear explosion. These experiments provide experimental design opportunities, illuminate weapons-relevant phenomena, and supply data for code validation and large-scale, high-performance computing simulations. Further applications of HED expertise at the Laboratory include:

- Setting the standard in inertial confinement fusion research, including design and analysis of igniting inertial confinement fusion experiments; design and planning for future high-yield capabilities; and understanding closely related areas of astrophysics, such as stellar structure and supernovae.
- 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.
- Generating ultra-short, intense x-ray and neutron sources, including robustly igniting plasmas, which are routinely used to understand weapons survivability conditions.
- Measuring the strength of materials at extreme temperatures and pressures on ultra-short time scales, including turbulent mixing of materials at high compression rates.
- Determining structural phase changes of materials, such as melting and recrystallization, or transitions between crystal lattice structures at temperatures and pressures inaccessible by any other method.



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

After more than 60 years, LLNL researchers achieved fusion ignition (energy produced exceeding driver energy input) in a laboratory setting for the first time. Improvements to design, target precision, and laser performance led to this historic milestone on December 5, 2022, opening new vistas of HED science. Researchers have achieved fusion ignition multiple times since that landmark experiment, resulting in higher yields and new experimental platforms to test the behavior of materials subjected to intense pulses of x-rays and neutrons. In support of HED science, LLNL has developed diagnostics to measure material properties and experimental conditions with unprecedented precision, including high-speed cameras to create "movie frames" of experiments with time resolution better than 1/10th of a nanosecond. Researchers are harnessing the emerging scientific areas of machine learning and artificial intelligence to advance HED experimental design and simulation capabilities. Other accomplishments 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 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 less than 1 billionth of a second.
- Measurements of velocities and temperatures of materials and shock fronts with advanced optical interferometers and time-resolved x-ray spectroscopy measurements in materials subjected to extreme pressures.
- Development of new platforms (like gigabar convergent geometry and the Mach wave driver) and diagnostics (like the Extended X-ray Absorption Fines Structure system).
- Quantification of energy transfer rates through materials and plasmas.
- Development of the "OPAL" radiation opacity code, which is part of the "Standard Solar Model" and provides opacity measurements for astrophysically relevant conditions at NIF.
- Development of novel machine learning algorithms for predicting the probability of achieving ignition in inertial confinement fusion experiments.

The Future

The HED field continues to advance to even higher temperatures and pressures. Addressing NIF's mid-life deferred maintenance and obsolescence issues and maximizing its full potential with the NIF Enhanced Yield Capability will expand the application suite for stockpile science and inform requirements for a future high-yield capability.

Achieving high yields will enable LLNL researchers to experimentally replicate a larger range of extreme conditions that exist during a thermonuclear detonation and to probe weapon physics phenomena in ways that have never been possible, even during the era of nuclear testing.

HED research is also opening new frontiers in science. Researchers have developed new capabilities to measure the basic properties of matter, including the equation of state and dynamic response properties of a variety of materials at the highest pressures ever achieved in a controlled laboratory experiment. LLNL researchers are also leveraging NIF's ignition platform to perform nuclear survivability experiments for materials.

Future improvements planned for the NIF laser will allow scientists to study nature in more extreme conditions, including at even higher temperatures and densities than those currently achieved.

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High-Performance Computing, Simulation, and Data Science

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

Applying Theories and Data to Mission Needs

High-performance computing (HPC), simulation, and data science at Lawrence Livermore National Laboratory (LLNL) transform theories and data that explain physical phenomena into models that can reliably predict outcomes. State-of-the-art simulations on the world's most advanced computers are foundational to the National Nuclear Security Administration's (NNSA's) science-based stockpile management and modernization mission. HPC at Livermore has a long history of success in strengthening nuclear deterrence, and LLNL is recognized as a global leader in applying HPC to advance science and technology.

LLNL embraces new opportunities in artificial intelligence (AI). The Laboratory's expanding mission benefits from data-driven and AI-augmented approaches to scientific discovery and engineering design. Applying these techniques to massive datasets and simulations lets researchers better predict the behavior of complex systems. LLNL and the Department of Energy (DOE) are tackling challenges integrating, standardizing, and interpreting highly disparate data sources, which can hinder AI model accuracy and slow analysis. Models must also be verifiable and transparent, demanding rigorous validation and clear data provenance.

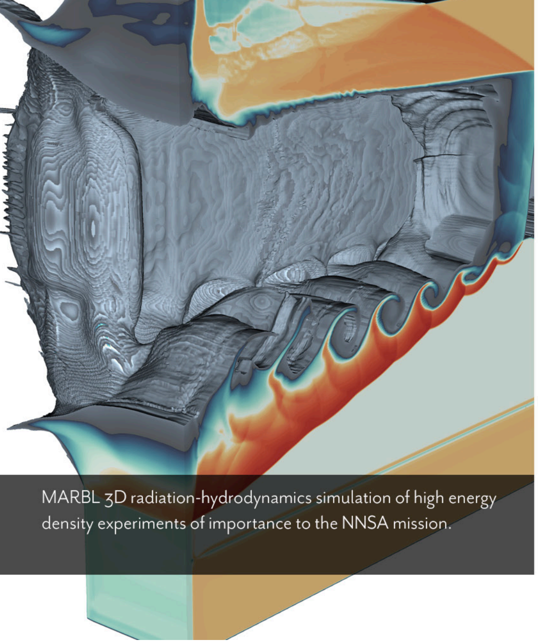
Expert uses of these newly developing tools are fundamentally reshaping scientific discovery, mission delivery, and operational efficiency. Through internal investments and partnering with industrial and academic colleagues, we aim to ensure that AI research excellence supports U.S. leadership in the global AI landscape.

Applications

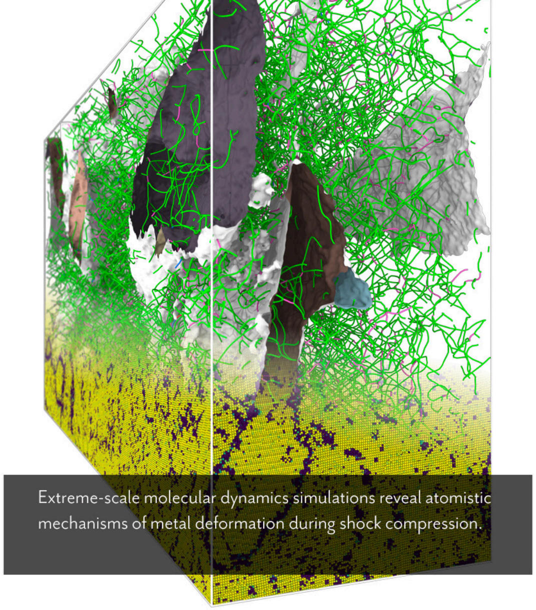
HPC is critical to stockpile management and modernization, ensuring nuclear weapons systems are reliable. LLNL uses HPC to continuously improve the scientific underpinnings of the nation's deterrent, such as studying the effects of material aging. Likewise, HPC facilitates stockpile modernization with newly designed and manufactured systems—like the W80-4 and W87-1 programs of record, as well as upcoming SLCM-N and multiple Phase 1 studies. These are redesigned systems that will enter the stockpile without underground nuclear testing—thanks to the simulations that support design, certification, and assessment.

HPC is more than big computers. Hundreds of scientists, engineers, computer scientists, data scientists, statisticians, and mathematicians are needed to develop and deploy simulations and AI tools that support nuclear deterrence, national security, and scientific research. LLNL's highly specialized codes are constantly being improved to run on advanced HPC architectures, to incorporate better numerical algorithms, and to enhance their predictive capabilities, all of which improve researcher productivity. Applications of cutting-edge capabilities include:

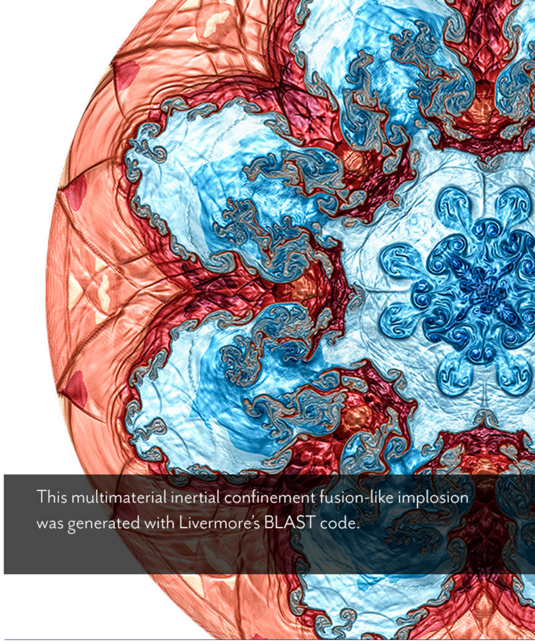
- Livermore Computing houses some of the world's most powerful computers, which use tens of thousands of processors (central and graphics processing units) working together and at the same time—known as parallel processing—to reduce the time to complete massive calculations.
- El Capitan, NNSA's first exascale computing system is capable of 2.8 billion billion (i.e., quintillion or 1018) calculations per second at peak performance. In addition to its primary role in stockpile stewardship, El Capitan provides the nation with a competitive edge in complex high-fidelity modeling and simulation as well as in the use of AI and machine learning codes applied to national security, including materials design and discovery and inertial confinement fusion. El Capitan's companion system, Tuolumne, supports open science and is being applied to energy security, earthquake simulations, and cancer drug discovery.
- Advances in HPC enable higher-fidelity 3D models with embedded (ensemble) uncertainty quantification to be used routinely in full-scale, multi-physics design optimizations, which improve the predictive capability of our codes far beyond those developed during the nuclear test era.
- Innovative HPC systems, simulation codes, and AI improve predictive understanding in complex, data-rich application areas such as advanced manufacturing, bioscience and biotechnology, nuclear science, and emerging national security threats.



MARBL 3D radiation-hydrodynamics simulation of high energy density experiments of importance to the NNSA mission.



Extreme-scale molecular dynamics simulations reveal atomistic mechanisms of metal deformation during shock compression.



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

Accomplishments

LLNL is a leader in developing and using HPC, simulation, and data science to carry out mission-driven work in strategic deterrence, national security, and basic scientific research. Incredible computational capabilities make LLNL a premier destination for HPC researchers, whether their expertise is in numerical algorithms and simulation, machine learning and AI, or parallel systems and performance. By leveraging our expertise in hardware, software, algorithms, data workflows, and physical sciences, we adopt new computing technologies to improve our understanding of complex phenomena with greater fidelity and insight. Scientists, researchers, and technicians collaborate with government, academic, and industry colleagues to tackle pressing challenges using Livermore's formidable HPC resources. Some of LLNL's recent accomplishments include:

- Developing exascale-ready simulation tools that continue to assure the safety, security, and reliability of the nation's nuclear deterrent during NNSA's annual stockpile assessment process and that allow for new designs to enter the stockpile through multiple modernization programs, both in-progress and planned.
- Integrating machine learning and other AI methods into the feedback cycle of experimentation and simulation to accelerate scientific discovery. These "cognitive simulation" tools helped LLNL scientists achieve fusion ignition, and they continue to provide new insights and more accurate predictions through the synthesis of experimental and simulation data.
- Addressing the urgent need for a rapid, agile approach for biological threat response by combining AI techniques with HPC modeling and simulation to create a novel antibody design platform informed by experimental data, structural biology, bioinformatic modeling, and molecular simulations.
- Developing new molecular discovery models that significantly outperform the state of the art for predicting synthesis routes for small molecules, with a particular emphasis on energetic molecules and their formulations. These models are being coupled with large language models to provide augmented laboratory assistance for synthetic chemists.
- 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 evolves, our computational and modeling capabilities must also advance. Our exascale—and beyond—ecosystem enables data-driven and AI methods to enhance traditional modeling and simulation, supporting national security, scientific discovery, and engineering design. Livermore is advancing the frontiers of:

- Heterogeneous HPC that derives benefit from combining a variety of hardware designs and paradigms.
- 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.
- Foundational AI and machine learning algorithms and their use to advance scientific understanding.
- The integration of HPC, cloud, and edge computing in complex workflows.
- HPC software engineering and development, including improved deployment, portability, robustness, and correctness.

Lawrence Livermore National Laboratory

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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.

Laser Expertise for Basic and Applied Science

Lawrence Livermore National Laboratory (LLNL) designs, builds, and operates a series of large and world-leading laser facilities for basic and applied science, driven by national security needs. This singular capability enables groundbreaking science, including the first-ever achievement of fusion ignition in a laboratory on December 5, 2022.

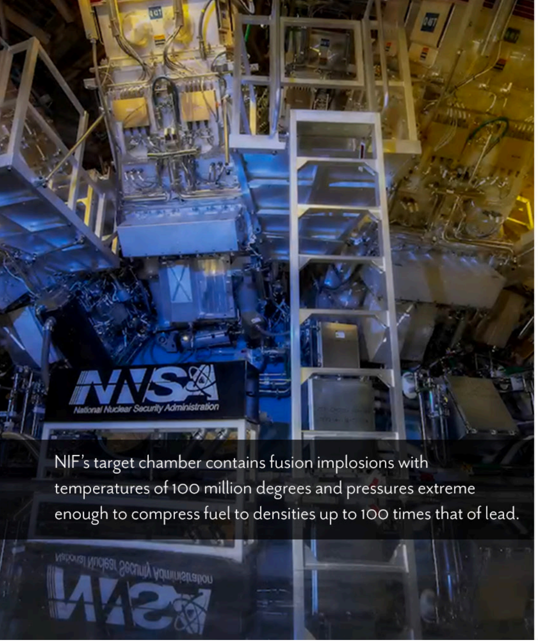
The National Ignition Facility (NIF) is a valuable tool in pursuing LLNL's core mission of safeguarding America's nuclear weapon stockpile while exploring high energy density (HED) regimes that cannot be replicated at other facilities. NIF provides key insights and data for simulation codes used in weapon performance assessments and certification. It is also an important resource for weapons effects studies and nuclear forensics analysis.

Fusion ignition was made possible by long-term investments in laser systems and optical science and technology. Future advances will help bring about a high-yield fusion facility for broader stockpile management and modernization applications while laying the groundwork for inertial fusion energy (IFE) and delivering directed energy capabilities for national security missions.

Applications

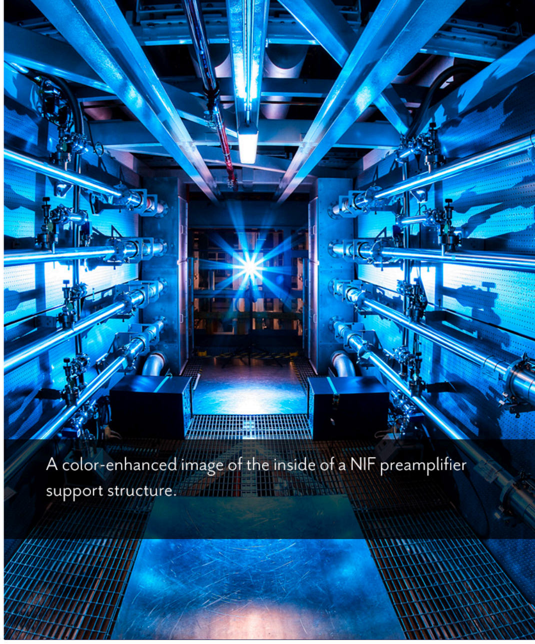
The Laboratory's leadership in lasers and optical science and technology reflects longstanding expertise in systems engineering, laser construction and operation, and collaboration with commercial partners. This is complemented by leadership in photonics, HED science, optical materials, the physics of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

- **Advanced Laser Architectures and Technologies:** LLNL develops and deploys high energy, high peak power, and high average power laser technology. LLNL is continually seeking to improve capabilities in pulse energy, wavelength, repetition rate, peak power, efficiency, beam quality, laser precision, and cost-per-delivered-energy in high energy laser systems.
- **Laser System Engineering and Performance Modeling Codes:** LLNL leverages physics-based models run on high-performance supercomputers for systems design and optimization. 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 laser-matter interactions extends beyond HED science to include optical material damage and the fundamental science of laser-based material processing.
- **Optical Diagnostics and Photonics Technologies:** This area of expertise supports LLNL experimental science platforms by delivering data to stockpile management and modernization efforts, measuring inertial confinement fusion (ICF) target performance, and measuring precision laser pulse shaping at NIF.
- **Optics and Optics Manufacturing Technologies:** LLNL researchers are developing novel designs and processes, including coatings, materials, and methods to extend the lifetime of optics.
- **Pumping Technologies: Diodes, Pulsed Power, and Energy Storage:** LLNL is advancing pump diode technologies to enable compact and efficient laser architectures. This is driving the need for energy storage and delivery technologies to power high-efficiency pump diodes, including new pulsed power technologies.
- **Adaptive Optics and Beam- and Pulse-Shaping Technologies:** The Laboratory is advancing mission-critical technologies for the precision adjustment of laser beam profiles, wavefronts, waveforms, spectra, and polarization, resulting in reliable operation of experimental facilities and optimized laser–target interactions.



NIF's target chamber contains fusion implosions with temperatures of 100 million degrees and pressures extreme enough to compress fuel to densities up to 100 times that of lead.


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.

Accomplishments

Building on decades of visionary leadership, LLNL has become a world-renowned center of excellence in the field of lasers and optical science and technology. The Laboratory's Laser Program has delivered major breakthroughs in ICF and other capabilities that support Department of Energy (DOE) and Department of Defense/War (DOD/W) missions. Recent accomplishments in the field include:

- Achieving ignition and beyond: on December 5, 2022, the NIF laser precisely delivered 2.05 megajoules (MJ) of energy to its target to produce 3.15 MJ of fusion energy, achieving the first demonstration of fusion ignition in a laboratory. This historic achievement has since been repeated at higher energy levels—a record yield of 8.6 MJ was achieved in April 2025.
- Delivering a successful Conceptual Design Review for the NIF Enhanced Yield Capability with the promise to boost NIF's laser energy up to 2.6 MJ and unlock new fusion regimes.
- Applying fusion ignition to assess weapons-grade plutonium for survivability data.
- Facilitating public-private partnerships with fusion energy companies to apply LLNL's deep knowledge of laser technology to inertial fusion energy approaches.
- Using lasers to produce muons, a subatomic particle that can pass through dense materials more easily than x-rays. These experiments have opened a range of potential imaging capabilities with national security applications.
- Standing up a DOE-funded effort to revolutionize extreme ultraviolet lithography, laying the groundwork for the next generation of semiconductors.
- Strengthening partnerships with LLNL's Jupiter Laser Facility to support LaserNetUS experiments and introduce an advanced laser pulse-shaping technology called STILETTO (Space Time Induced Linearly Encoded Transcription for Temporal Optimization).

The Future

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

Optics mitigations will continue to increase functionality, lifetime, and yield to enable improved performance of high-energy and high-power lasers; there will be special focus on even higher energy and power at NIF after facility sustainment efforts are completed and the Enhanced Yield Capability (EYC) project is delivered.

Beyond 2040, new laser architectures and design concepts will be evaluated and technology matured to address NNSA's vision for a Next Generation High Energy Density facility capable of closing the remaining stockpile management and modernization gaps in the hundreds-of-megajoules yield regime.

Improving precision and control over all laser properties, including time-dependent waveforms and spectra, beam intensity, and wavefront profiles, while tailoring polarization states to enable novel modalities for optimizing laser interactions with matter and mitigating instabilities. LLNL will continue to advance the design, development, construction, and optimization of high energy laser systems for stockpile management and modernization, IFE, user facilities, and national security applications.

Lawrence Livermore National Laboratory

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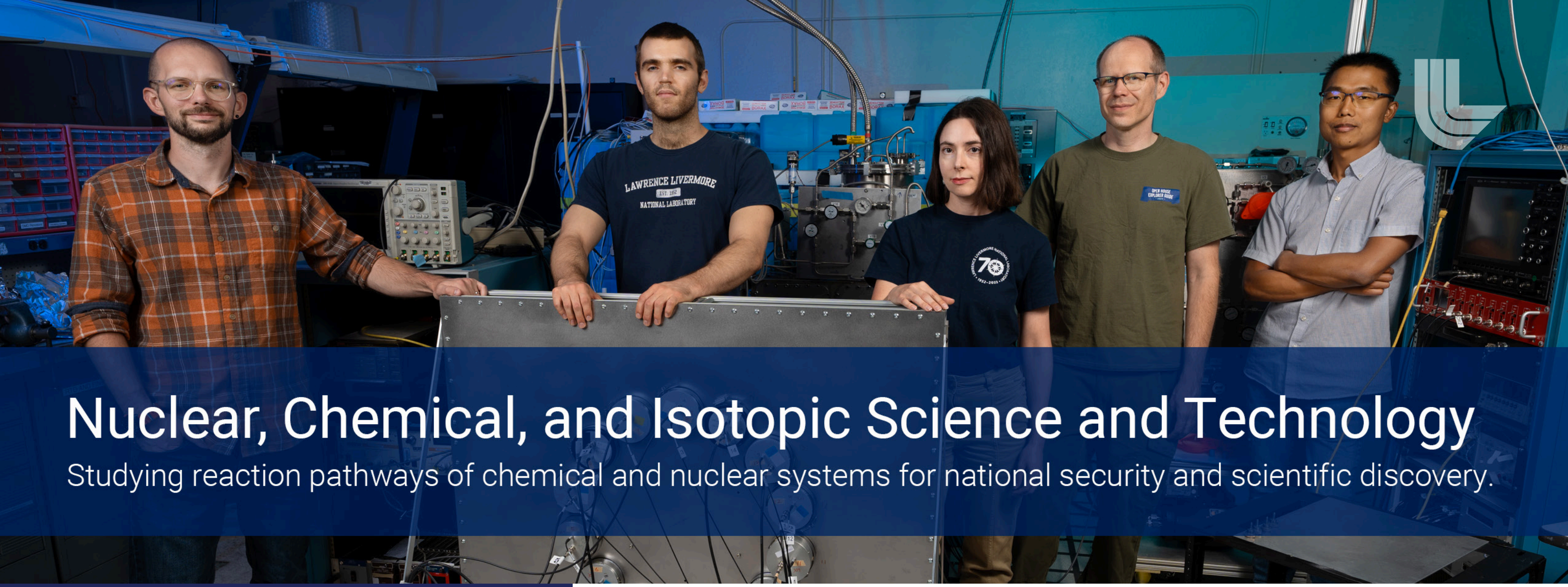


Nuclear, Chemical, and Isotopic Science and Technology

Studying reaction pathways of chemical and nuclear systems for national security and scientific discovery.

Fundamental Science and Nuclear Security

Research at Lawrence Livermore National Laboratory (LLNL) in nuclear, chemical, and isotopic science strengthens the organization's strategic deterrence and global security missions and contributes to scientific advances in nuclear and particle physics, environmental radiochemistry, cosmochemistry, high explosives research, and forensic science.

Leveraging unique experimental and computational tools, researchers study nuclear reactions, the limits of nuclear stability, actinide behavior, chemical reactions of energetic compounds, heavy-element chemistry, and emerging threats. LLNL staff also explore the evolution of our planet, solar system, and universe, from the origin of matter to the formation of the nuclei in the periodic table.

The Laboratory's scientific research efforts provide the foundation to address these challenges. The team's overarching strategy is to position LLNL at the nexus between fundamental science research and nuclear security applications. This approach supports efforts to recruit, train, and retain top-flight scientists and engineers who are key to executing the Laboratory's core nuclear security mission, while also enhancing LLNL's reputation as a world-leading scientific research center.

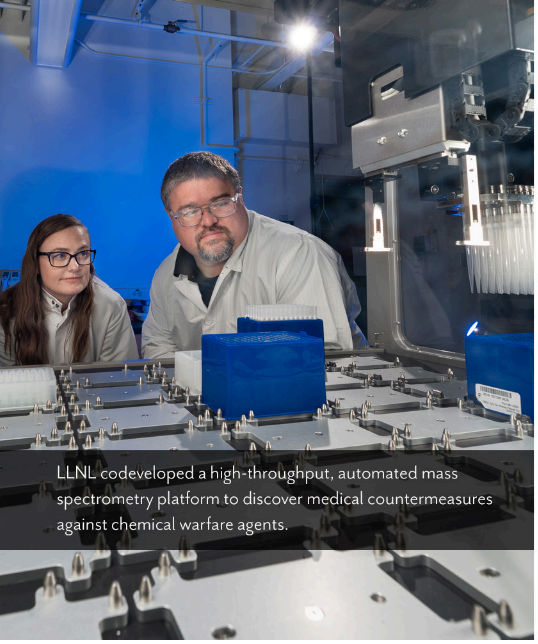
Applications

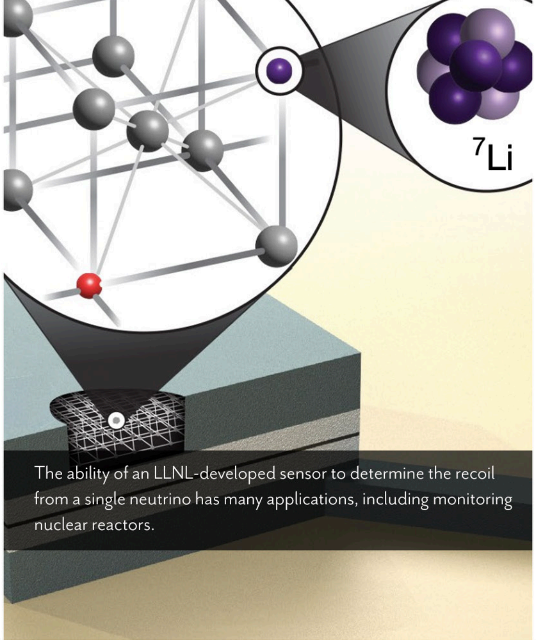
The Laboratory pursues a wide range of research that directly benefits LLNL's national security mission by improving the safety and reliability of the nuclear deterrent and enhancing detection, analysis, and assessment capabilities for materials associated with weapons of mass destruction (WMDs) and detonations. These developments also help answer far-reaching questions in fundamental science. As part of these efforts, LLNL researchers use new approaches that bring together radioactive beams, radiochemistry techniques, and artificial intelligence to improve our understanding of nucleosynthesis and reduce uncertainties in nuclear-data cross sections to support strategic deterrence and nonproliferation. Other applications of LLNL's expertise include:

- Creating novel detector systems to determine material composition and to detect threats from a distance.
- Developing a high intensity, tunable neutron source for neutron measurements that will better characterize a larger set of materials and help determine how neutrons interact with nuclei.
- Refining isotopic markers to support sustainable energy strategies and water resources.

Examples of the specialized tools and facilities used to perform this work include:

- The Nuclear Counting Facility, which supports research in stockpile stewardship, nonproliferation, and nuclear counterterrorism with a broad range of highly sensitive radiation detection systems.
- The Center for Acceleratory 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 measurements, ion beam analytical techniques, and novel isotope production methods to address a broad spectrum of scientific and mission needs.
- LLNL's microanalytical capabilities, including a one-of-a-kind imaging secondary ion mass spectrometry instrument with 10-nanometer spatial resolution. This capability can obtain trace element and isotopic information from solid samples in support of nuclear forensics, nonproliferation, cosmochemistry, and more.
- The Forensic Science Center, which supports chemical, nuclear, explosive, and biological counterterrorism efforts and provides leading-edge development and application of forensic analytical methods to WMDs.
- The Energetic Materials Center, the focal point of expertise in high explosive and energetic materials science, performs bespoke experiments at the High Explosives Application Facility and Site 300 Experimental Site for nuclear security programs.


LLNL codeveloped a high-throughput, automated mass spectrometry platform to discover medical countermeasures against chemical warfare agents.



The ability of an LLNL-developed sensor to determine the recoil from a single neutrino has many applications, including monitoring nuclear reactors.


LLNL scientists analyzed samples from the carbon-rich asteroid Bennu, illuminating the formation of asteroids and the solar system.

Accomplishments

The success of LLNL's nuclear, chemical, and isotopic research depends on the capabilities of our scientific workforce, including staff, students, and postdoctoral researchers. At LLNL, researchers are able to take advantage of a wide array of state-of-the-art equipment and capabilities, from the mass spectrometry instruments used for isotopic and chemical analysis, to novel radiation detection systems for tracking radioactive signatures, to world-class high-performance computing capabilities needed for simulations with ever-increasing precision.

These unique tools enable our scientists to be at the forefront of a wide range of topics, including nuclear and particle physics, nuclear structure and reaction data, radiochemistry, nuclear detection technology and algorithms, nuclear and chemical forensic science, cosmochemistry, and environmental isotope systems. Recent accomplishments include:

- Analyzing samples from asteroid Bennu and learning about building blocks of the solar system.
- Making new reference materials for precise dating of actinide materials and other isotopes and surrogate debris for post-detonation exercises.
- Installing a one-of-a-kind ion mass spectrometry instrument with specialized sample handling capabilities that captures images at an unprecedented resolution.
- Measuring the first cross sections using National Ignition Facility (NIF) capsules doped with radionuclides.
- Accelerating discovery of medical countermeasures for emerging chemical threats and opioid overdose.
- Developing experimental techniques to constrain the properties of the neutrino and the weak nuclear force.
- Developing predictive theory that updates scientists' understanding of fusion processes that formed heavier elements from hydrogen and helium during the Big Bang.
- Making the first measurements using the Mobile Antineutrino Demonstrator, a compact, solid-state detector used to remotely monitor nuclear reactors.
- Capturing the first nuclear structure and astrophysics results from the Facility for Rare Isotope Beams (FRIB).
- Harnessing the power of artificial intelligence to predict nuclear reactions.

The Future

Scientists working in nuclear, chemical, and isotopic science and technology will address emerging challenges:

- Applying precision chronometry to samples from the Moon and Mars to answer long-standing questions about the origin of water on planetary bodies.
- Establishing novel analysis approaches and forensic signatures for advanced nuclear fuels.
- Employing LLNL's novel microfluidic chemistry and detection system to perform the first aqueous chemistry experiments with element 112.
- Exploring the scientific underpinning for tritium production and breeding for future inertial fusion energy systems.
- Developing ultra-sensitive decay spectroscopy approaches to study samples with quantum sensors and specialized radiation detectors.
- Creating next-generation targets for production of rare isotopes for science and medical applications.
- Designing the next generation of uranium atomic vapor laser isotope separation.
- Building on initial data measurements taken at FRIB and NIF to determine nuclear reactions on short-lived isotopes previously inaccessible for experiments.
- Exploring the role of quarks and gluons in nuclei at the Large Hadron and Electron Ion Colliders.

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