2025

# INVESTMENT STRATEGY

for Science and Technology

Lawrence Livermore National Laboratory

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LLNL Deputy Director for Science and Technology

# Science and Technology on a Mission

Lawrence Livermore National Laboratory (LLNL) was founded as a "big ideas" laboratory, a place where innovative science and technological solutions to the nation's most difficult security challenges are created. Today, we continue this tradition and live by our motto, "Science and Technology on a Mission," broadening the frontier of what is or might be scientifically and technically possible.

In this time of challenges and opportunities, new technologies and increased scientific understanding are key factors in meeting global competition and assuring national security. We work in partnership with our government sponsors to build scientific expertise and technological capabilities in advance of need and stand ready to tackle the most significant issues facing our nation and the world today. Outstanding and innovative mission delivery requires talented and committed staff, state-of-the-art facilities and equipment, and robust partnerships inside the Laboratory and with colleagues at other laboratories, universities, industrial firms, nonprofits, and government organizations.

As we prepare to make investments in scientific capabilities at the Laboratory this year, our overall objective is to be purposeful and to advance the use of artificial intelligence (AI) methods and applications. Being purposeful helps ensure our investments have strategic impact and that our portfolio positions LLNL well for future contributions. And the rapid advancements in generative AI are opening new possibilities for LLNL to deploy powerful capabilities into critical research spaces and develop fundamental efforts in the broader realm of AI. These new approaches will benefit from the significant new computational capabilities at the Laboratory, notably, the El Capitan and Tuolumne computers and their supporting systems. These distinctive capabilities will strengthen LLNL and its fellow National Laboratories' ability to undertake even more challenging and impactful computational projects.

The *2025 Investment Strategy for Science and Technology* encompasses Laboratory mission and vision descriptions, updated Mission Focus Areas (MFAs) and Institutional Initiatives, along with the current Laboratory-level Objectives and Key Results (OKRs). It broadly describes the types and nature of investment decisions and the desired outcomes over a three-to-five-year time horizon that will be enabled with Laboratory Directed Research and Development (LDRD) support. Overall, the strategy describes science and technology challenges from a mission perspective and looks ahead to where pushing the boundaries of new science, technology, and innovation could lead. And, consistent with previous year's documents, the priorities for this year's LDRD program investments are described to support the 2025 call for LDRD research proposals for work to be carried out in FY26.

Thank you for taking the time to consult this document. It has been prepared to support transparency on our approach to making strategic science and technology investments. We are grateful for the ability to make strategic investments that sustain LLNL as a national resource for innovative scientific solutions to tough, important national security challenges. We are determined to use these investments to keep the Laboratory an exciting and meaningful place to work for top-flight scientists and engineers.

Pat Falcone

# Section 1: LLNL Overview

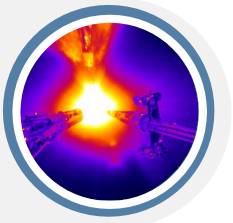
**One Mission, Many Domains.** Lawrence Livermore National Laboratory serves a wide variety of national security mission areas through the application of science and technology, and our enduring core responsibility in the area of nuclear deterrence. Established in 1952 at the height of the Cold War to advance nuclear science and technology, we recently celebrated seventy years of addressing the challenges of strategic deterrence and nonproliferation in an increasingly complex geopolitical environment. Continuing federal support for our defining responsibility has enabled the Laboratory to serve the nation with state-of-the-art facilities, world-class competencies, and a talented workforce, fostering our reputation as a global resource for questions of deterrence and stockpile stewardship.

Through the last three decades of stockpile stewardship, LLNL has made game-changing advances in our S&T capabilities and associated flagship facilities. These capabilities are necessary to safeguard the nuclear stockpile and enable innovative and transformational solutions for equally important challenges to national security and global stability.

Through that lens of national security, we've transformed many of the tools and approaches applied to our original national security mission to meet the pressing issues of our time. We apply cutting-edge S&T to achieve breakthroughs in enterprise resilience, counterterrorism, defense and intelligence, energy security and climate resilience, and research and development to produce fundamental science discoveries and faster innovation cycles. The accelerating global pace of innovation in space, cyber, and biothreats heightens the value of S&T superiority as a strategic asset. No matter the application, the Laboratory's scientific research always supports our mission.

## Section 1.1: Mission and Vision Statements

**Our Mission:** LLNL's mission is to enable U.S. security and global stability and resilience by empowering multidisciplinary teams to pursue bold and innovative science and technology.



**Our Vision:** We fearlessly and relentlessly pursue big ideas to solve the most important security challenges facing the nation and the world.

**Who We Are:** Our inclusive teams bring together exceptional scientific, technical, administrative, business, and operational experts to accomplish our important missions.

# Section 2: LLNL's Mission

LLNL's mission is to
**enable U.S. security and global stability and resilience by empowering multidisciplinary teams to pursue bold and innovative science and technology.**

For more than 70 years, Lawrence Livermore National Laboratory has applied science and technology to make the world a safer place. The Laboratory strengthens the United States' security by developing and applying world-class science, technology, and engineering that enhances the nation's defense, an increasingly complex task with two peer nuclear armed adversaries, aspiring proliferants, the militarization of space and cyber domains, and a rapidly advancing pace of change in artificial intelligence and biotechnology.

In a complex geostrategic environment, the ability to respond to scientific issues of national importance with vision, quality, integrity, and technical excellence has never been more critical. LLNL is committed to seizing this transformational opportunity by harnessing innovative S&T in bioengineering, inertial fusion energy, energy abundance, and space to address geopolitical changes and open new doors.

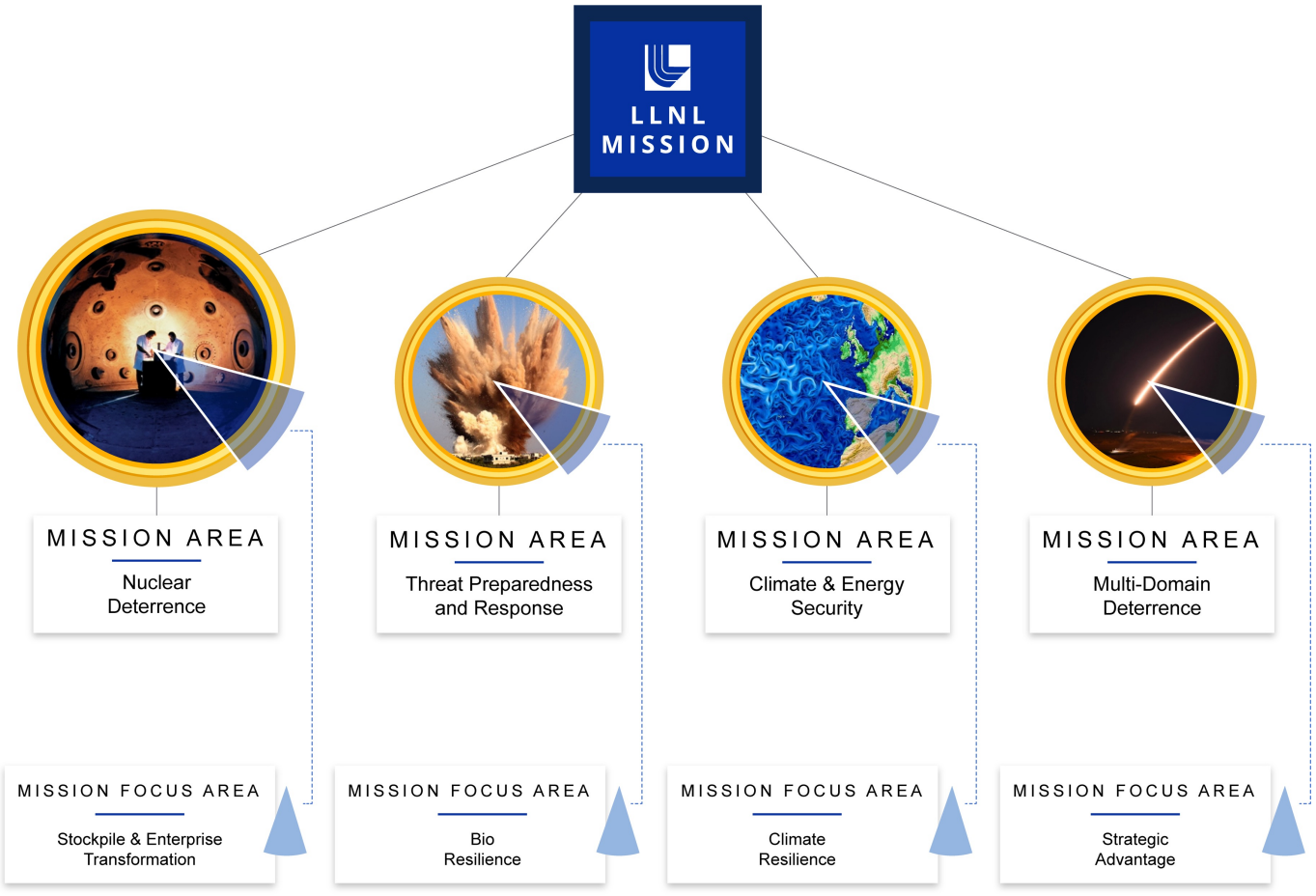
Leadership in applying transformational, mission-directed S&T to pressing national security challenges is integral to our founders' goals of multidisciplinary science, audacious ideas, and pushing the extremes of what is possible. Working at the nexus of big ideas and the frontiers of S&T has led to many LLNL successes: compact thermonuclear weapons for the Polaris program, rapid chromosome sorting that led to the Human Genome Project and biosecurity technologies, and "bleeding-edge" supercomputing and experimental capabilities that enabled science-based stockpile stewardship. This history positions us well to anticipate future challenges.

# Section 2.1: Mission Structure

Big ideas and leading-edge S&T have long been the hallmarks of LLNL. We have been fortunate to build on that legacy in areas where we bring unique and impactful insight.

LLNL is a national security laboratory with a "nuclear core." Our defining and core responsibility includes nuclear weapons, nuclear deterrence, and nuclear security. The scale, mix, and objectives of our mission programs have changed over the years. Today, we continue working to ensure the safety, security, and reliability of the U.S. nuclear stockpile, to perform the Annual Assessment, and to lead life extension and modification efforts for weapon systems.

The Laboratory counts more than 9,000 employees across the country: no matter what team, division, program, or directorate they belong to, they all contribute to our mission. By acting as good stewards of all available resources—time, effort, knowledge, and taxpayer dollars—we continue to enhance and adapt our core mission to changing national needs and priorities.




It may be useful to envision the Laboratory's central mission divided into four Mission Areas.
A subset of each Mission Area receives special management attention as a Mission Focus Area.

# Section 2.2: Mission Areas

## Mission Areas

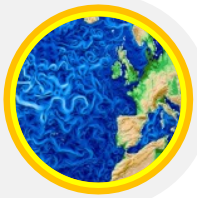
*Major domains of mission responsibility*

Our broad and evolving mission shares commonalities in four areas relevant to the current and future stability of our world. By strengthening their underlying S&T requirements, we are better able to address issues of nuclear deterrence, threat preparedness and response, climate and energy security and multi-domain deterrence. While the Mission Areas differ in size (Nuclear Deterrence is the largest Mission Area), each one includes significant work at a range of technology readiness levels, from foundational research through applied research to preliminary deployment of prototypes. Each has a history of major mission and science contributions, and each enriches and draws from LLNL's Core Competencies.

In all four Mission Areas, we count on our talented workforce to think bigger—to have bold ideas and fearlessly work at the edge of what is possible. Through their exceptional work in preeminent areas of science, LLNL's impact does not stop at our country's borders—our innovations make the world a better place to live.

**Nuclear Deterrence:** develop and apply scientific insight and engineering prowess needed to assure the safety, security, and reliability of the U.S. nuclear stockpile in an ever-changing threat environment and enable the modernization and transformation of the National Nuclear Security Administration (NNSA) production enterprise.

**Threat Preparedness and Response:** develop and deliver enduring science-based, intelligence-informed expertise and capabilities to stem the proliferation of nuclear, chemical, and biological weapons of mass destruction, understand adversary capabilities, anticipate adversarial actions, and support consequence mitigation of natural and man-made threats.



**Climate and Energy Security:** advance understanding of the global climate system, develop technologies to reduce accumulation of greenhouse gases, and pursue the domestic production and supply of affordable, clean, and increasingly carbon-free energy delivered across a secure and sustainable infrastructure.

**Multi-Domain Deterrence:** create a global strategic advantage through innovative technologies, strategies, and analyses to bolster capabilities across the full spectrum of domains, including strategic defense, conventional strike, space, cyber, and technology competition.

# Section 2.3: Mission Focus Areas

## Mission Focus Areas (MFAs)

*Focused cross-Laboratory efforts addressing targeted challenges*

As a part of the 2022 Laboratory strategy update process, Director Kim Budil solicited her Senior Leadership Team to consider a range of ongoing mission program areas and some of the most salient national and global challenges for which science and engineering, together with Laboratory program delivery approaches, might be able to render significant service. The intent was to select a small number of areas and to explore potential solutions employing more comprehensive and adaptive governance approaches.

Each of the four MFAs is based on a set of existing capabilities and program contributions, structured for maximum impact. Each MFA is overseen by a member of the Laboratory's Senior Leadership Team, ensuring the organization is prepared to tackle emerging science and technology challenges. Unique work programs have been established in each MFA that exploit existing technical expertise, take advantage of deep mission knowledge, and employ decision analyses. The four MFAs receive special management attention, but they represent just a part of the ongoing programs that constitute a Mission Area. By putting Laboratory capabilities and experts at the core of this effort, MFAs enrich LLNL's mission contributions by accelerating credible and targeted solutions for national security and global stability. MFAs and their implementation continue to evolve to meet our strategy, vision, and priorities.

Stockpile and Enterprise Transformation accelerates the advancement of the sophisticated enterprise of laboratories, facilities, and people ensuring confidence in the nation's nuclear deterrent. Bio Resilience integrates LLNL's unique computing and experimental capabilities to identify, characterize, and counter natural and man-made biological threats at dramatically reduced timescales. Climate Resilience couples biogeochemistry, materials science, geology, and climate simulation with infrastructure analysis to mitigate and adapt to greenhouse gas accumulation and predict climate impacts at scale. Strategic Advantage connects Laboratory strengths to create integrated cross-domain strategies and disruptive technology solutions.

| MISSION FOCUS AREA<br>Stockpile & Enterprise Transformation | MISSION FOCUS AREA<br>Bio Resilience | MISSION FOCUS AREA<br>Climate Resilience | MISSION FOCUS AREA<br>Strategic Advantage |
|---|---|---|---|
| Accelerate a resilient and responsive enterprise | Analyze, assess, and predict threats | Reduce greenhouse gas accumulation via advanced technology | Analyze adversary mindsets, strategies, and capabilities |
| Enhance partnerships | Develop countermeasures and therapeutics | Inform climate strategy through high-fidelity models | Recover, create, and strengthen U.S. advantages relative to competitors |
| Produce next-gen ST&E for the current and future stockpile | Establish integrated computational-experimental platforms | Assess, adapt, and mitigate national security impacts | Develop innovative analytic and technology solutions |
| Leverage world-class workforce | | | |

Each of the four Mission Focus Areas is outlined in greater detail in Section 6.

# Section 2.4: Lab-Wide Objectives and Key Results

Laboratory leadership adopted Objectives and Key Results (OKRs) as a management framework in 2022 to advance science innovation and operations excellence and enable us to fulfill mission deliverables. OKRs foster collaboration, connectivity, and help organizations reach aspirational goals. The guiding principles or "North Stars" for each of the four organizational elements will remain unchanged over the next several years, but the OKRs will be updated at a regular cadence. As OKRs are implemented across the organization, Laboratory staff will have more visibility and better understand how their work contributes to and supports LLNL's mission.

- **North Star:** Offers clear strategic direction
- **Objective:** Defines what we seek to achieve
- **Key Result:** Provides defined, measured progress

LLNL is committed to seizing this transformational opportunity with an ambitious strategy to advance on many fronts at once. We have established a strategic vision built upon four pillars: expediting mission and program delivery; driving S&T innovation; delivering operational excellence; and nurturing our people and culture. Each pillar has an associated "North Star" to set the strategic vision for that area.

# Section 3: Science and Technology Enterprise at LLNL

OKRs enable LLNL to more efficiently capture plans for continued growth. The guiding North Star for the Laboratory's science and technology OKR—**engender innovation, technical excellence, and strategic impact through multidisciplinary foundational and applied research & development**—requires processes and procedures to maximize enterprise quality and drive resource allocation decisions. As the entity charged with stewardship of the Laboratory's S&T enterprise and guided by the relevant North Star, the Office of the Deputy Director for Science and Technology (DDST) is responsible for executing the following Objective:

## Science & Technology

Objective: Align future S&T capabilities to the LLNL 2050 vision. This vital Objective comes with three Key Results:

- **Key Result 1:** Build on the historic achievement of ignition and National Ignition Facility (NIF) sustainment by submitting the CD-0 package for Enhanced Yield Capability.
- **Key Result 2:** Identify the S&T priorities supporting LLNL's 2050 vision.
- **Key Result 3:** Secure endorsement of three key investment areas to make big bets for LLNL's 2050 vision.

**Fulfillment of Key Result 1**: The CD-0 package for the Enhanced Yield Capability (EYC) project was submitted in coordination with NNSA, and unanimous approval of the CD-0 by the DOE Energy Systems Acquisition Advisory Board (ESAAB) was achieved on Sept. 27, 2024. This approval formalizes the mission need for higher fusion yields to support stockpile stewardship, with a proposed solution involving an upgrade of the NIF to 2.6 megajoules. If this proposed solution receives approval at CD-1, it will formally designate the NIF upgrade as the preferred solution, enabling unprecedented capabilities, including fusion yields in the tens of megajoules. The next milestone for the project is to achieve CD-1, where a solution to meet the mission need will be approved and a conceptual design will be completed.

**Fulfillment of Key Result 2:** During the next decades, LLNL will remain preeminent in our enduring Core Competencies of Computing and High Energy Density (HED) science. Computing will evolve and grow, as the Laboratory contemplates the nature of high-performance computing after commissioning its first exascale machine, the role of quantum and mechanical computing, and the critical importance of data engineering. HED science will remain essential for LLNL to deliver on our core nuclear deterrence mission and to broadly and effectively partner to explore fusion energy. Advanced Materials and Manufacturing will grow into a third enduring Core Competency that will underpin our nuclear deterrence, spur innovation to benefit U.S. economic competitiveness, and enable broader scientific breakthroughs. AI methods will be seamlessly integrated into every aspect of our science and technology enterprise and increase the speed and efficiency of our research and development.

**Fulfillment of Key Result 3:** To enable the science, technology, and engineering priorities of Key Result 3, LLNL will invest in three broad areas that leverage and build on today's pillar core competencies, while dramatically advancing toward capabilities required in 2050. Computing is foundational to LLNL mission delivery; new investments will drive AI to be ubiquitous in all aspects of simulation and analysis. Additional investment will ensure the safety and security of AI. Advanced materials and manufacturing have driven mission accomplishments over the last decade, and investments will accelerate the deployment of autonomous laboratories and robotics to deliver materials designs and manufacturing technologies that dramatically reduce the design-to-deployment capabilities for national security across all LLNL missions. Investments in HED science are vital to our nuclear deterrence mission and help establish capabilities and programs in laser science and fusion energy.

# Section 3.1: Science and Technology Framework

LLNL's Science and Technology enterprise has three constituent parts referred to as S&T Mobilizers: **talented staff, Core Competencies**, and **state-of-the-art facilities**. The Framework below is a broad look at the Laboratory's scientific strategic approach: we've created, nourished, and grown our three S&T Mobilizers to serve us well in delivering on our mission, as illustrated within the Vision and Strategy pillars. We also respond to emerging science challenges through the MFAs and Institutional Initiatives (explained in more detail in Section 6), which draw upon internal investments and S&T Mobilizers for a fixed amount of time. Execution involves tracking milestones and deliverables against scope, budget, and schedule—and is outside the purview of this document. The Review pillar signifies our ability to update plans, respond to changes in technology and the national security landscape, and make judicious investment decisions.

## Science and Technology Framework


By guiding internal investments and overseeing the integration of S&T expertise and resources with the Laboratory's programmatic Mission Areas, the DDST Office supports, strengthens, and enhances premier S&T across a range of disciplines.

# Section 3.2: Office of the Deputy Director for Science and Technology

On behalf of the Laboratory, the Office of the Deputy Director for Science and Technology (DDST) leads the process of investing in the Laboratory's science and technology enterprise. This approach ensures Livermore's world-renowned research excellence balances innovation with disciplined execution, and multidisciplinary teamwork with individual initiative. The combination of mission focus and scientific expertise is central to the Laboratory's strategic vision. The key functions of the DDST Office are to:

**Invest:** Coordinate internal investments to keep the Laboratory's research activities and staff at the forefront of science and technology

- Laboratory Directed Research and Development (LDRD)
  Serving as the primary resource to drive excellent science and technology for today's needs and tomorrow's challenges.
- Institutional Science Capability Portfolio (ISCP)
  Supporting multi-programmatic and cross-directorate efforts, including capability sustainment, scientific infrastructure and equipment, and sponsor engagement.
- Licensing and Royalties (L&R)
  Investing Laboratory royalties generated from successful intellectual property in the next generation of science and technology.

**Partner:** Grow relationships in service to scientific excellence and mission delivery

- Academic Engagement Office (AEO)
  Fostering collaborations and sustainment of long-term academic partnerships among LLNL researchers and the academic community. The program engages students and faculty in collaborative research, work study opportunities, and educational activities.
- Innovation and Partnerships Office (IPO)
  Serving as the engine to bring scientific breakthroughs to market by protecting and then transferring LLNL technology to the private sector through licensing and partnerships.
- Science Education
  Providing professional development instruction to teachers, as well as student enrichment opportunities ranging from field trips to virtual tours to online videos and science experiments students can try at home.
- Engagement with the Broader Science Policy Community
  Offering perspectives to policy makers and U.S. government officials while providing awareness and training to LLNL staff.
- Commitment to International Partners
  Creating and nurturing purposeful strategic science and technology partnerships with allies to bolster deterrence and build resiliency through fundamental and applied research.

More information about many of these functions can be found in Section 3.4.

# Section 3.2: Office of the Deputy Director for Science and Technology (cont.)

**Communicate:** Explaining our research approaches and outcomes to staff, sponsors, partners, and the community

- **Investment Strategy for Science and Technology**
  Outlining our strategic support of the quality, health, and sufficiency of the Laboratory's scientific and technical foundations in an annually updated document.
- **Performance Evaluation and Management Plan (PEMP)**
  Emphasizing research and development, effective partnerships, and technology transfer, the Laboratory's annual evaluation report showcases our innovative science, technology, and engineering achievements.
- **Science & Technology Review (S&TR)**
  Highlighting LLNL's significant technical accomplishments, Science & Technology Review magazine provides in-depth scientific news to general audiences.

**Enable:** Ensuring our scientists and engineers are supported with tools and programs to exercise and grow their capabilities

- **Awards and Recognitions**
  Providing awareness and support to those looking to nominate individuals and teams for our prestigious internal and external awards, and professional societies.
- **Science and Technology Institutional Assessments**
  Stewarding our External Review Committees and Board of Governors meetings to assess and provide feedback on the quality of our Core Competencies and strategic plans.
- **Postdoctoral Program Support**
  Developing the ST&E workforce pipeline of the Laboratory by furthering the career development of the postdoc through connections with the scientific community.
- **Postdoc and Mentor Career Development**
  Equipping postdocs and their advisors and mentors with the essential skills and knowledge for impactful careers in science and technology.
- **Proposal Development Support**
  Working with investigators to analyze calls for proposals, generate a compelling research plan that responds to all requirements and facilitates internal reviews that refine the project objectives.
- **Library Resources**
  Enhancing discovery, delivery, and access to scientific content by effectively organizing, describing, and preserving our scientific and cultural heritage.
- **Archive**
  Preserving LLNL's records of people, events, programs, and accomplishments for use by Laboratory staff and historians.

# Section 3.3: S&T Mobilizers

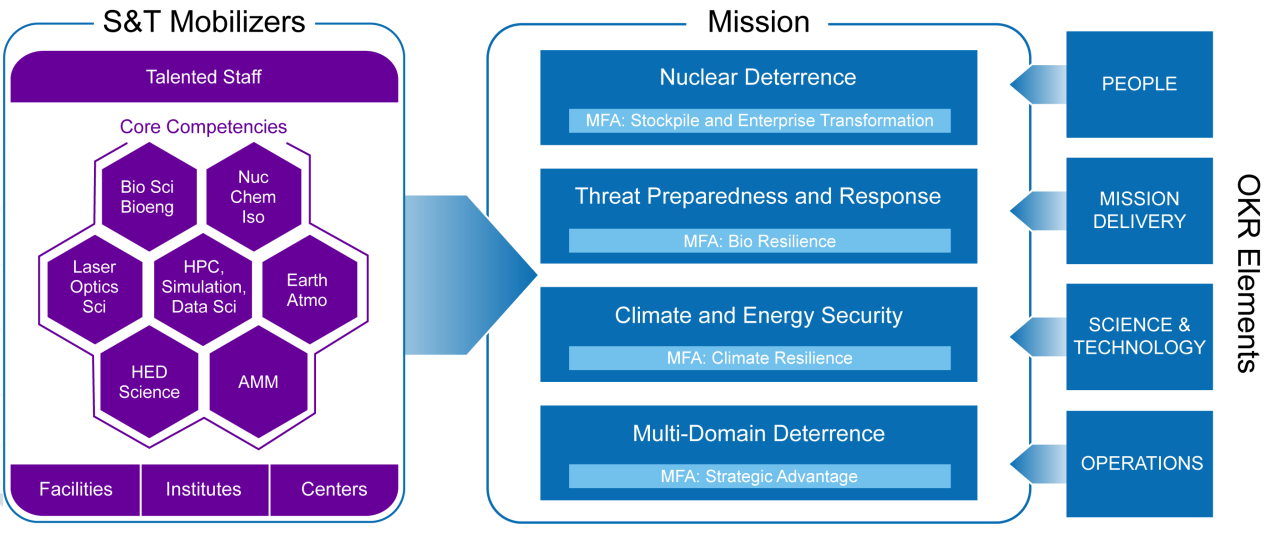
Each part of LLNL's Science and Technology enterprise is addressed in the Science and Technology Framework, and the importance of our S&T Mobilizers—**our talented staff, Core Competencies**, and **state-of-the-art facilities**—is noted throughout. This section examines the current state of each S&T Mobilizer; future-minded evolutions are outlined in Section 6.

Our workforce is at the heart of everything we do, from leveraging the experience gained from serving as an LDRD principal investigator to leading a high-consequence program to developing thought leaders by having them run a Center or Institute and form academic partnerships through collaborations based around LLNL facilities. Centers, institutes, and facilities also serve as organic recruitment pipelines, drawing motivated staff and inspiring innovative collaborations. Through thriving Core Competencies, researchers conduct impactful R&D in key areas that positions them among the world's experts in their chosen field.

S&T Mobilizers work together as a combined set of skills, tools, and resources to underpin our mission-driven work. Mission delivery requires talented and committed staff, state-of-the-art facilities and equipment, and robust partnerships with colleagues at other laboratories, universities, industry, nonprofits, and government organizations. These factors have been essential to the Laboratory's many achievements and continue to be indispensable for the Laboratory's vital missions and the advancement of science and engineering.

Discipline organizations at LLNL foster excellence and innovation in the key research disciplines needed for the Laboratory's Core Competencies. The Computing directorate advances scientific discovery through foundational and innovative research in mathematical methods; modeling and simulation; high-performance computers; operational algorithms and workflows; mission-driven data science; and software solutions. The Engineering directorate invents, designs, simulates, prototypes, builds, and deploys creative technologies including new materials, components, and systems. The Physical and Life Sciences directorate delivers multidisciplinary scientific theoretical, experimental, and computational expertise to advance knowledge and to support mission-critical research with novel insights, data, and phenomenological understanding.

As illustrated below, the OKR process and S&T Mobilizers contribute to mission success to advance scientific discovery. Note that the Laboratory's institutional Mission comprises four Mission Areas (dark blue), with a Mission Focus Area (light blue) embedded within each.



# Section 3.4: S&T Mobilizers—People

## People

*Supporting and engaging our current and future staff members*

Livermore's talented staff is its key asset. The Laboratory's many scientists and engineers bring their knowledge, expertise, and experience to address mission-critical challenges. They do so with extreme curiosity and a drive to uncover knowledge and better understand how things work with a continuously improved set of tools and approaches. Staff work individually, in multidisciplinary teams, and with partners at other laboratories, universities, and other institutions. Examples of investments that support people are listed below in two categories: investments that support individual skills and effective teaming, and those that support effective collaborations.

### Skill Development:

**Career Development:** Training, workshops, presentations, webinars, and conferences are a few of the many ways we ensure that our thousands of talented researchers, operations staff, and creative professionals advance their individual skillsets.

**Research Integrity:** The Academic Engagement Office's Research Integrity course was relaunched in 2023 as an in-person class. Research Integrity Officers from Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL) attended the class remotely and are developing similar coursework based on LLNL's efforts.

**Postdoctoral Program:** LLNL employs more than 300 postdoctoral scholars, also called postdocs, as a cohort of our research community and valuable pipeline of talent. During their tenure, postdocs conduct research publishable in peer-reviewed journals, develop scientific expertise in their field of research, present their research at national and international meetings, and learn how to be successful professional researchers. LLNL supports professional development with resources, targeted training, and events such as the annual Research SLAM! competition.

**Library:** The LLNL Research Library and its talented staff are key supporting resources for accessing the global research archive and preserving LLNL scientific and technical information. Centrally located on LLNL's campus, the library offers collaborative working space in addition to physical and digital reference collections.

**STEM Pipeline:** Laboratory initiatives and programs help attract, develop, and retain high-caliber employees. Sustaining an end-to-end workforce pipeline continues to be an important focus, from recruiting new talent and mentoring career development to recognition of career achievements.

# Section 3.4: S&T Mobilizers—People (cont.)

Partnering and Engagement:

**Academic Engagement Office (AEO):** The Academic Engagement Office fosters collaborations and partnerships between Laboratory researchers and the academic community. The team provides students and faculty at K-12 schools, community colleges, vocational schools, universities, and postdoctoral programs with research assignments, work-study opportunities, and educational activities.

**Innovation and Partnerships Office (IPO):** This team serves as a focal point for LLNL engagement with industry partners. Through research collaborations, commercialization of scientific discoveries, and empowering entrepreneurship among Laboratory researchers, IPO enables national security and economic competitiveness by transferring breakthroughs from mission-driven work back into U.S. industries.

**Science Education:** LLNL's Science Education Program offers a wide variety of experiences to students and teachers. From workshops on molecular biology and robotics to summer camps empowering women in STEM, a multitude of options exist to spark scientific discovery and leadership in students and teachers alike. The Discovery Center at LLNL provides insight into our state-of-the-art research programs for visitors of all ages.

**Science & Technology Review:** S&TR is published eight times a year to communicate our scientific accomplishments in support of national security. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

# Section 3.5: S&T Mobilizers—Core Competencies

## Core Competencies

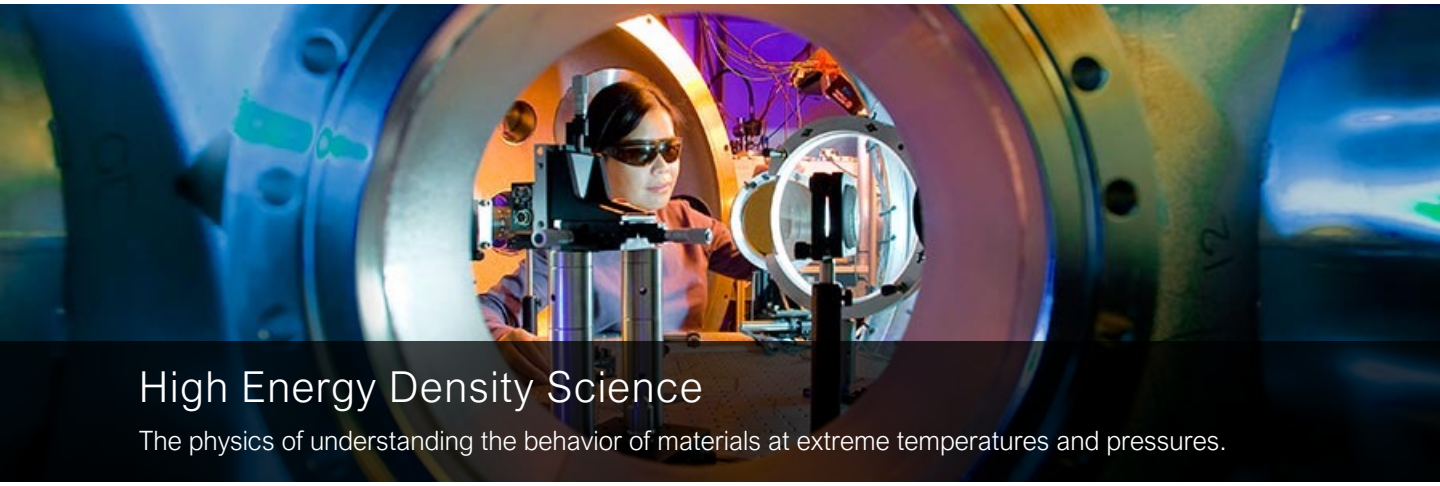
*Applying our unique capabilities to today's biggest challenges*

Core Competencies are areas of special capability or expertise in which LLNL seeks to contribute as a national—and often world—leader. From basic research to applied science and engineering, we leverage Core Competencies to understand, respond, and adapt to pressing issues. The seven Core Competencies are continually strengthened through cutting-edge research and collaborations with other laboratories, government organizations, industry, and academia.

**Mission Applications:**
Core Competencies drive the scientific and technological research—from the experimental design process to application—underpinning our mission of national security and global stability. Internal investments and externally funded activities in these areas sustain Livermore as the nation's "Big Ideas" laboratory that provides innovative solutions to the most challenging national security problems.


Each of the seven Core Competencies is described in the following pages.

# Section 3.5: S&T Mobilizers—Core Competencies



## High Energy Density Science

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

### Description:

High Energy Density (HED) science explores matter under extreme conditions—achieving temperatures higher than 180 million degrees Fahrenheit, pressures of more than 500 billion Earth atmospheres across time scales spanning from equilibrium to trillionths of a second. This research probes and discovers new scientific frontiers in the fundamental properties of matter, ranging from condensed phases to plasmas. This includes studying the pressure-volume-temperature relationship (commonly known as the equation of state [EOS]) and radiation transfer at unprecedented pressures and temperatures. LLNL researchers develop and use a variety of experimental platforms with exquisite diagnostics that are closely coordinated with advanced predictive theories and large-scale simulation and modeling conducted on world leading high-performance computing systems. HED research yields essential data for understanding nuclear weapons' conditions, delivering extreme condition physical property data for weapon simulations, validating predictive theories used in weapon simulation codes, and advancing inertial confinement fusion and related areas of national security.

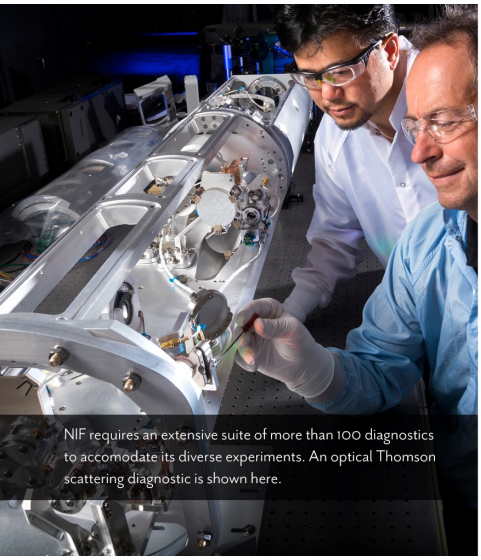
### Mission Applications:

The Laboratory's innovative and collaborative staff advance mission-critical work in nuclear deterrence and energy security while strengthening inertial confinement fusion research. In support of the National Nuclear Security Administration stockpile stewardship mission, HED science research delivers critical experimental data and predictive models used to simulate and ensure the reliable operation of nuclear weapons as they age, are subjected to the extreme conditions of a thermonuclear explosion or are refurbished as part of lifetime extension or modification programs. Advanced simulations of material dynamics and full systems on the Laboratory's world-leading high-performance computers complement experiments to fully explore and deliver predictive models of the behavior of matter in these extreme conditions.

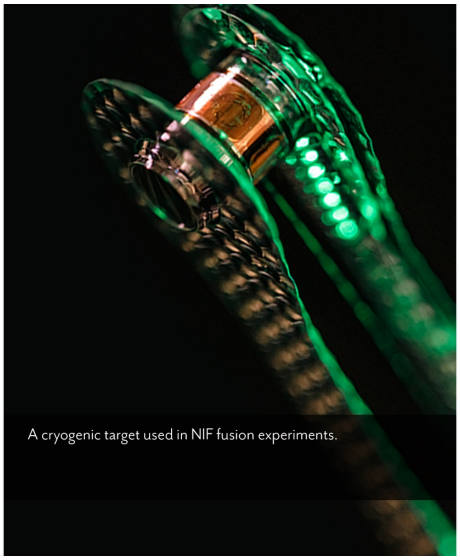
### Accomplishments:

- For more than 60 years, LLNL researchers and colleagues worked to achieve fusion ignition, one of science's most challenging goals. Ignition was achieved on Dec. 5, 2022, and has since been repeated at even higher levels of energy gain, opening new vistas of HED science and establishing a new experimental platform to test the survivability of materials.
- Within 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.

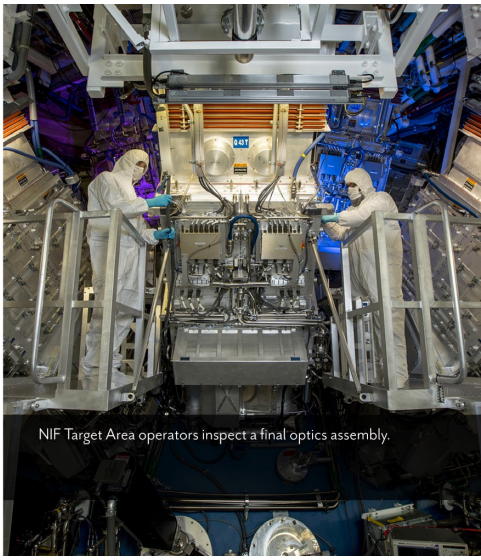
# Section 3.5: S&T Mobilizers—Core Competencies



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 (cont.):

- LLNL scientists developed the "OPAL" radiation opacity code—part of the "Standard Solar Model."
- Using high-performance computing, LLNL scientists developed novel machine learning algorithms to predict the probability of achieving ignition in inertial confinement fusion (ICF) experiments.

## 3–5-Year Vision:

Future improvements in experimental platforms, diagnostic measurement techniques, and advanced theory and modeling will enable scientists to better understand, predict, and control matter under increasingly extreme conditions—including stellar interiors, astrophysical events such as supernovae, conventional ICF reactions, magnetic fusion reactions, conventional fission reactions, and nuclear device explosions. LLNL scientists are on a path to deliver enhancements to the range of experimental platforms and the accuracy of temperature diagnostics through techniques including pyrometry at the Nevada Test Site JASPER facility and EXAFS (Extended X-ray Absorption Fines Structure) at laser drive platforms. LLNL scientists have developed a "Hazardous Materials Chamber" to enable studies of stockpile-relevant radioactive and toxic materials driven to HED conditions using penetrating hard x-rays at the premier U.S. synchroton x-ray source (Dynamic Compression Sector/Advanced Photon Source/Argonne National Laboratory). New capabilities over the next decade will include time-resolved "movies" capturing the structural and phase evolution of matter under dynamic loading conditions. In step with experimental advances, the simulations and modeling of HED experiments will also probe HED states of matter using HPC at unprecedented scales ( >100 million atom) simulations to gain microscopic insights on the properties of matter at extreme conditions. Further models of radiation transport and opacity (absorption or radiation) will continue to be refined to more accurately predict energy deposition and flow under HED conditions. The repeated achievement of controlled fusion ignition at NIF provides an intense source of neutrons, opening new fields of study on the effects of neutron energy deposition. Ignition and high gain allow us to carry out experiments that bring us much closer to nuclear weapons-relevant regimes and further improve confidence in our stewardship science codes and simulations.

# Section 3.5: S&T Mobilizers—Core Competencies

## High-Performance Computing, Simulation, and Data Science

Addressing national security challenges through innovative computational and predictive solutions.

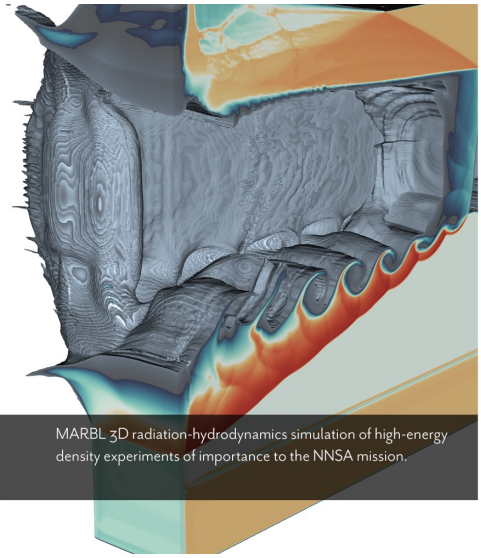
### Description:

High-performance computing (HPC), simulation, and data science transform theories that explain physical phenomena into models to 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 broadly underpin our ability to meet national security needs across our mission-driven work. For example, Livermore scientists use HPC to simulate the behavior of matter under extreme temperature and pressure conditions, which are characteristic of nuclear detonations, or other realms that are challenging to study, such as extreme conditions of radiation, corrosion chemistry, and hypervelocities. The ever-increasing capabilities of artificial intelligence/machine learning (AI/ML) are creating new ways to predictively model fundamental properties of materials from both large and sparse datasets in support of national security interests. Combining simulation and data-driven methods, the expanding scale and complexity of the Laboratory's mission require new data-driven and AI/ML–augmented approaches to scientific discovery and engineering design. These techniques applied to massive datasets are helping Livermore researchers better understand and predict the behavior of complex systems and even design new materials and systems from the ground up.

### Mission Applications:

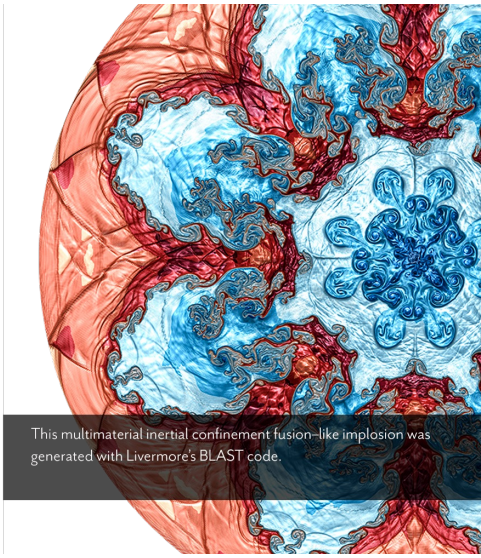
HPC at Livermore has a long history of success in close association with the Laboratory's nuclear deterrence mission. Computer scientists, software engineers, data scientists, statisticians, and mathematicians collaborate with domain scientists to develop and use simulation methodologies leveraging HPC 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. Leveraging that work rooted in deterrence, LLNL also uses HPC to continuously improve both the scientific underpinnings of this deterrent, such as studying the effects of material aging, and the broader range of today's missions, including climate modeling, quantum interactions, and more. Likewise, HPC facilitates stockpile modernization with newly designed and manufactured systems—like the W80-4 life extension and the W87-1 modification programs.

# Section 3.5: S&T Mobilizers—Core Competencies



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


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:

- LLNL has become a premier destination for HPC researchers, whether their expertise is in numerical algorithms and simulation, AI/ML, or parallel systems and performance.
- Flux—Livermore's scalable, flexible next-generation workload management framework—was extended to enable converged computing, an environment that allows scientific workflows to run faster and more efficiently by combining the power of HPC with the portability and automation of cloud computing.
- LLNL finished a three-year Strategic Initiative on Autonomous Multiscale Simulations (AMS) that is currently being transitioned into major mission codes. AMS uses a combination of software engineering, trustworthy machine learning, and advanced modeling to make multiphysics simulations faster, more accurate, and portable. Delivering continuously improving and persistent subscale models for critical use cases, such as modeling energetic materials or inertial confinement fusion promises to create a new paradigm in multiscale modeling.
- LLNL brought El Capitan, a 2.79-exaflop exascale supercomputing system, online to run mission-critical codes thanks to sophisticated portability software and diligent preparatory work with industry partners to fine-tune applications.

## 3–5-Year Vision:

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, engineering design, and timely support to critical national security missions. We will continue to build our expertise in computing hardware, software, algorithms, and the physical sciences to simulate these phenomena with higher fidelity and more realism. At the same time, we will reshape the present and the future of scientific computing by leveraging and advancing the principled and judicious use of AI to address the scientific challenges at the heart of LLNL's mission.

# Section 3.5: S&T Mobilizers—Core Competencies

## 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.

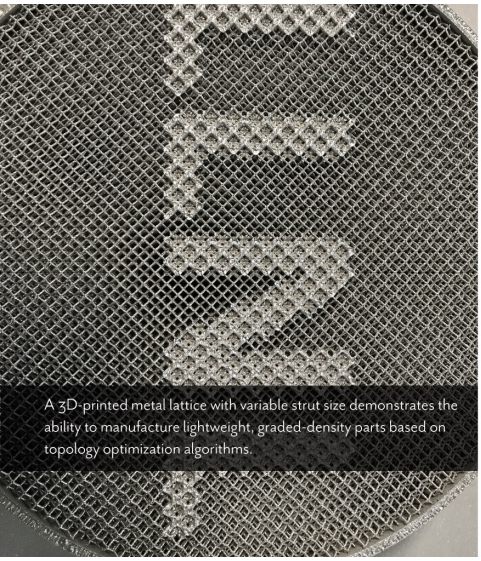
### Description:

LLNL brings a multidisciplinary approach to the rapid development of advanced materials and manufacturing (AMM) processes. Livermore continues to advance manufacturing technology, enabled by the development of customized feedstocks and unique fabrication techniques. Novel diagnostic methods are developed and used to monitor and control both legacy and emerging manufacturing methods—accelerating 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. Scientists and engineers explore ways to reduce costs, material waste, and energy consumption while enhancing functionality and accelerating discovery, development, and scalability timelines. LLNL also uses multiscale/multiphysics predictive modeling and machine learning along with experimental efforts to co-design and deploy new materials and components, as well as reduce uncertainties on how a material will perform at scale, in relevant conditions, and over its service lifetime. LLNL scientists and engineers engage in broadly collaborative efforts to achieve these goals, including strategic engagement with industry, academia, and laboratories across national and international partners.

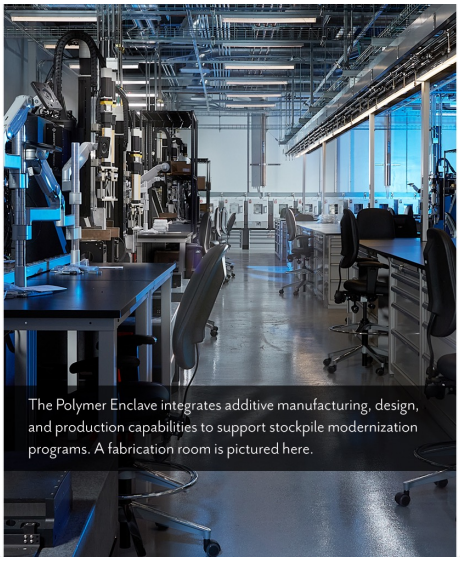
### Mission Applications:

Current research builds on decades of experience studying a spectrum of materials, manufacturing technologies, and mission-relevant applications. Livermore's expertise spans the entire 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. Scientists and engineers develop innovative materials with tailored properties that can be used for energy absorption, dissipation, generation, or storage; energetic materials; bioinspired structures for use in drug delivery; advanced optics used in satellites, telescopes, and high-power lasers; quantum materials; designer materials, metamaterials, and metasurfaces that enable novel devices across a broad electromagnetic spectrum; and components that can function effectively in extreme environments, including fusion reactors.

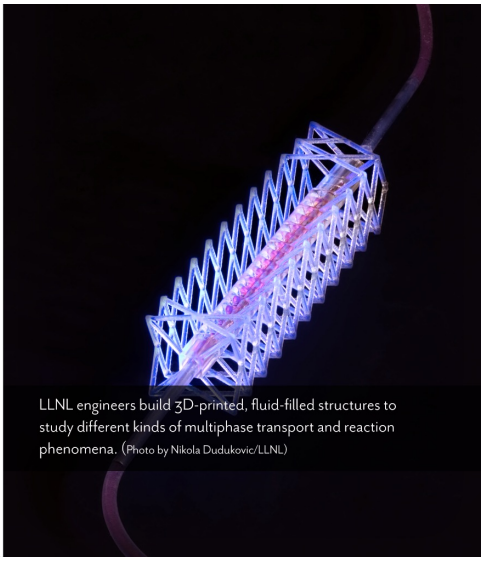
# Section 3.5: S&T Mobilizers—Core Competencies



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:

- Harnessed AI to discover interatomic potentials in new materials for applications in solid-state batteries, hydrogen storage, and CO2 electrolysis.
- Advanced additive manufacturing by constructing a workflow to design, fabricate, characterize, and field fully 3D-printed fuel capsules for use in ignition experiments at NIF.
- Developed a groundbreaking method for fluid transport using 3D printed open-cell lattice structures using capillary action could impact fields from CO2 conversion to solar desalination.
- Designed customized alloys for extreme environments with thermally stable microstructures that are lightweight and corrosion-resistant, leveraging both experiments and predictive models to identify aging-resistant materials.
- Discovered 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.

## 3–5-Year Vision:

The long-term vision for LLNL's Advanced Materials and Manufacturing Core Competency includes increased integration of automation, machine learning, and artificial intelligence to further accelerate materials discovery, design, development, and deployment. Build-out of capabilities will include collaborative spaces for materials synthesis, characterization, and testing, including flagship enclaves for energetic materials, polymers, ceramics, alloys, and rapid prototyping. Further emphasis on multi-material and graded-interface fabrications, including compatibility and aging analysis, will leverage current and future capabilities. Issues of feedstock development, availability, recycling, and reuse—in light of mineral and material criticality in the supply chain—will increasingly drive innovations. LLNL will continue to take a leadership role in DOE-sponsored research activities involving materials for a secure energy future.

# Section 3.5: S&T Mobilizers—Core Competencies

## Bioscience and Bioengineering

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

### Description:

Bioscience and bioengineering research at LLNL delivers transformative solutions to the nation's health and energy security needs. 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. This integrated approach allows us to explore underlying mechanisms of disease and engineer microbial communities, addressing biosecurity, health risks, and climate change.

### Mission Applications:

Across the Laboratory, bioscience and bioengineering research is highly collaborative to provide innovative solutions for national security challenges. Livermore scientists and engineers couple quantitative experiments with high-performance computing resources to model and understand biological systems across scales. LLNL's expanding bioscience research portfolio focuses on early biothreat detection, accelerated countermeasures, and sustainable biomanufacturing and biomaterials. Engineered experimental models and testbeds of biosystems provide physiologically and environmentally relevant data for neurovascular disease diagnosis. By combining strengths in quantitative biology, computing, and precision measurement, bioscientists and engineers apply the design–build–test–learn cycle to tailor biological molecules, microbes, and microbial communities to accelerate broad-target antibodies and sustainable biomanufacturing of low-carbon materials. Biological models are also integrated into climate and ecology research to provide innovative solutions for bioeconomy and climate change.

### Accomplishments:

- Advanced protein engineering state-of-the-art, including *Nature* publication on computational redesign of SARS-Co-V therapeutic antibody and provisional patent for redesigned AstraZeneca antibody.
- Developed sustainable biomining approaches for purifying rare-earth elements to safeguard the domestic supply of critical minerals for clean energy transition.

# Section 3.5: S&T Mobilizers—Core Competencies

LLNL's bioprinting capabilities combined with microphysiological systems streamline the assessment of biological and chemical threats while advancing therapeutic development

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.

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

## Accomplishments (cont.):

- Identified microbial signatures that predict optimal treatment of soldiers' combat-related injuries using a combination of microbial metagenomic DNA sequencing and advanced machine learning techniques.
- Advanced novel nanoparticle-based vaccine delivery formulations to new testing phase to evaluate efficacy against infections caused by chlamydia and other pathogens.
- Coupled a 3D brain-on-a-chip with a blood–brain barrier model to create a neurovascular unit that provides physiologically relevant data for disease diagnosis and treatments.
- Increased understanding of the adaptative immune response that promotes survival and blood–brain barrier integrity following Venezuelan equine encephalitis virial infection.

## 3–5-Year Vision:

Looking ahead, Laboratory teams will continue to be at the forefront of advanced diagnostics, therapeutics, and sustainable biomanufacturing through innovative, multidisciplinary research. Areas of emphasis include: 1) employing a comprehensive strategy for early biological threat assessment and developing broad-spectrum antibodies, novel therapeutics, or vaccines to counter these threats; 2) integrating big-data analytics and computational modeling to enhance genotype-to-phenotype predictions, thereby improving our understanding of our complex biological systems; biomolecules, microbes, and microbial communities to address challenges in biomanufacturing, climate change, and supply chain resilience; and 4) developing advanced instrumented experimental systems and testbeds that provide mechanistic understanding and quantitative measurements for predictive models and technology scale-up.

# Section 3.5: S&T Mobilizers—Core Competencies

## Earth and Atmospheric Science

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

### Description:

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.

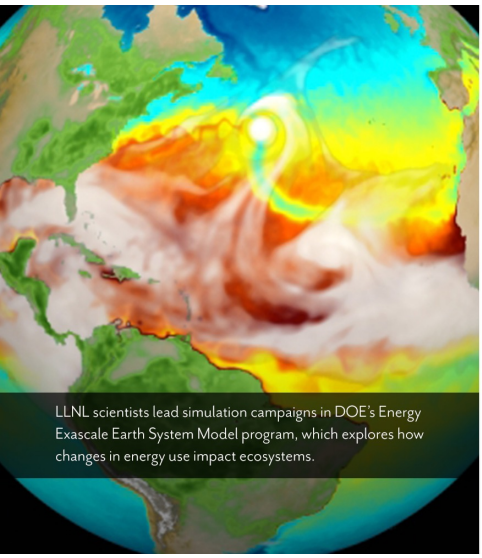
### Mission Applications:

Earth and atmospheric sciences play a central role in LLNL's mission-driven work. LLNL advances global-scale monitoring techniques for identifying clandestine nuclear testing. The Laboratory's legacy of innovation strengthens response efforts for nuclear emergencies and hazardous material releases, in addition to leveraging geoscience expertise to design and deploy next-generation weapons and intelligence gathering systems. For climate resilience, LLNL expertise in the Earth sciences, climate modeling, and energy systems provides actionable data for resilient infrastructure and to mitigate against greenhouse gas accumulation. 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.

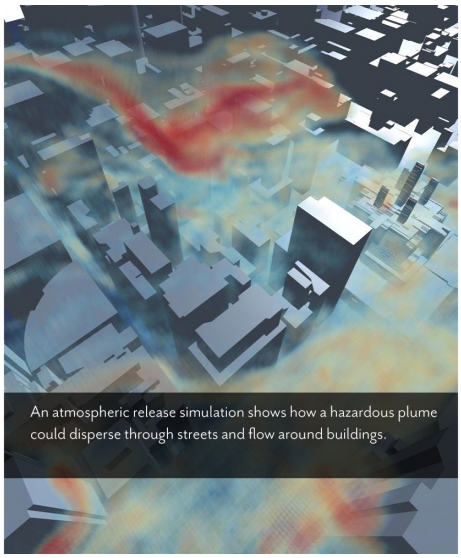
### Accomplishments:

- 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), and assessed airborne hazards in the wake of Hurricane Katrina (2005), the Deepwater Horizon oil spill fire (2010), and the spread of ruthenium across central Europe (2017).
- 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.

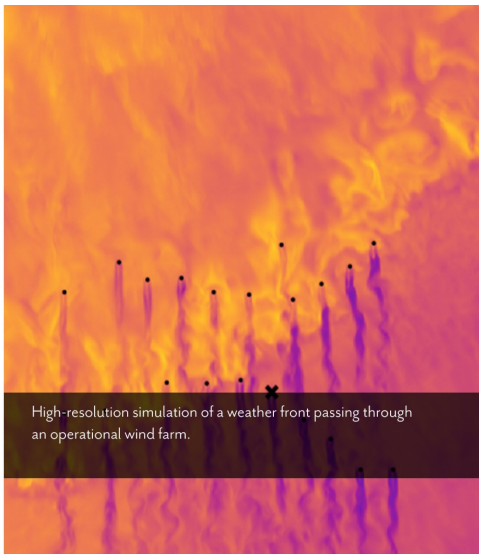
# Section 3.5: S&T Mobilizers—Core Competencies



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 (cont.):

- The inaugural Gordon Bell Prize for Climate Modeling 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 climate simulations.
- 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 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 U.S. 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 and received the 2021 Secretary of Energy Achievement Award.

## 3–5-Year Vision:

Over the next few years, LLNL will prioritize several 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; and providing decision makers, including U.S. agencies tasked with ensuring our national security, with actionable data to foster climate resilience.

# Section 3.5: S&T Mobilizers—Core Competencies

## 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.

### Description:

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. LLNL scientists have a record of high-impact innovations advancing the state-of-the-art in lasers, optical systems, imaging, and spectroscopy all in both traditional laboratory and extreme environments. This is complemented by leadership in photonics, HED science, optical materials, the physics of laser–material interaction, and laser system modeling and simulations.

### Mission Applications:

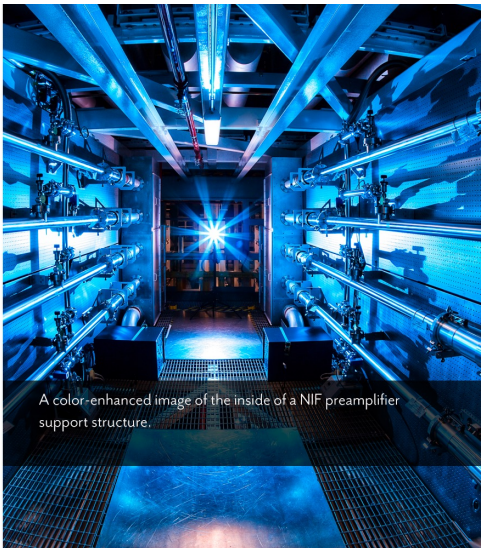
The National Ignition Facility (NIF) is a valuable tool in pursuing LLNL's core mission of safeguarding America's nuclear weapon stockpile while exploring high energy density (HED) regimes. NIF provides key insights and data for simulation codes used in weapon-performance assessments and certification and is an important resource for weapons effects studies and nuclear forensics analysis. As LLNL's scientists and engineers maintain and improve NIF, they are also developing next-generation laser and optical systems and technologies. Such advances can help bring about a high-yield fusion facility for stockpile stewardship and modernization while laying the groundwork for inertial fusion energy (IFE) and delivering directed energy capabilities for national security missions.

Space Science and Security is also a prominent area of interest for national security. LLNL research and development of adaptive optics systems has led to image quality improvements by compensating for blurring due to atmospheric turbulence in large optical telescope systems. Thin film multi-layer and interference coating modeling and fabrication capabilities at LLNL have delivered unique optical components with tailored properties needed for satellite payload systems.

# Section 3.5: S&T Mobilizers—Core Competencies

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:

- On Dec. 5, 2022, the NIF laser precisely delivered 2.05 megajoules (MJ) of energy and 440 terawatts (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, with a record high yield of 5.2 MJ achieved in 2024.
- Optical component resilience to laser damage has been increased by four orders of magnitude since 1997, enabling higher energy densities in laser architectures, including NIF, and more sustained and economically viable operations.
- Dramatic enhancements of multi-physics laser modeling capabilities on high-performance computing platforms resulted in an increase in fidelity of 2–5x and spatial resolution by three orders of magnitude.
- Collaboration continues with the University of California in pioneering adaptive optics to compensate atmospheric turbulence for ground-based observatories.

## 3–5-Year Vision:

The next generation of laser systems will continue to expand the envelope of capability in energy, pulse width, and repetition rate. Optics mitigations and new coating technologies will continue to increase functionality, lifetime, and yield of optical components to enable improved performance of high energy lasers. 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. Development of high-dynamic range metrology capabilities will enable improved detection and mitigation of defects and damage in optics exposed to ultra-high laser powers and energies.

LLNL will further advance the state of the art in lasers and optics over the next five years. Its scientists and engineers will design, develop, build, and optimize laser systems for high yield stockpile stewardship applications, IFE drivers, and directed energy. They will also introduce optical technologies that improve imaging and enable new optical systems, including space science applications.

# Section 3.5: S&T Mobilizers—Core Competencies

## Nuclear, Chemical, and Isotopic S&T

Studying reaction pathways of chemical and nuclear systems.

### Description:

Nuclear, chemical, and isotopic research will advance our scientific understanding, capabilities, and technologies in high explosives research, nuclear and particle physics, environmental radiochemistry, cosmochemistry, and forensic science to support LLNL's national security mission. 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 origin of matter to the formation of all the nuclei in the periodic table. Our 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 supports efforts to recruit, train, and retain top-flight scientists and engineers who are key to executing the Laboratory's core nuclear security missions, while also enhancing LLNL's reputation as a world-leading center for innovative scientific research.

### Mission Applications:

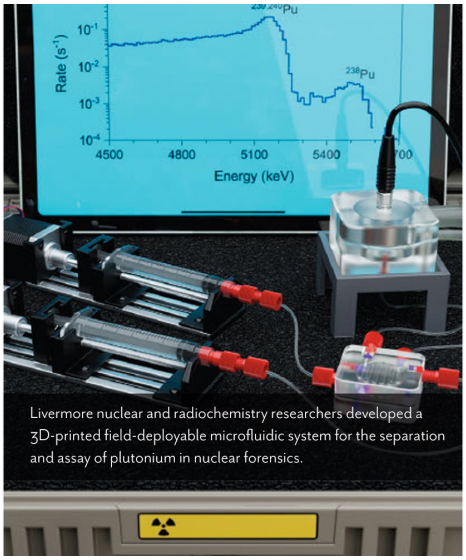
Chemical, nuclear, and isotopic science research directly benefits our national security mission by improving the safety and reliability of our strategic deterrence and enhancing our detection and attribution capabilities for nuclear materials and nuclear detonations. LLNL's unique tools enable our scientists 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. Advancement in these areas of research help answer far-reaching questions in fundamental science

### Accomplishments:

- Used 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.
- Developed novel separation extraction schemes for actinide elements using ligands and proteins that enable study of their fundamental chemical properties.

# Section 3.5: S&T Mobilizers—Core Competencies

LLNL's Secondary Ion Mass Spectrometer (SIMS) capabilities are used for characterizing and measuring the in-situ trace elemental and isotope abundances of various solid materials.




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 (cont.):

- Performed the highest precision measurements of nuclear fission properties, ranging from cross-sections to fission-product yields and decay properties, with the Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) experiment and specialized detection systems.
- Led 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.
- Set new limits for the axion dark matter candidate with ADMX and for sterile neutrinos with the BeEST and PROSPECT experiments.

## 3–5-Year Vision:

Prioritized research areas in nuclear, chemical, and isotopic science and technology include development of novel neutron sources, targets, and techniques for future nuclear data measurements for national security programs, preparation for NASA sample return missions that will use state-of-the-art new instrumentation for isotopic and spatial analysis, and investigations into the use of quantum systems for detectors and sensors as well as quantum computing for nuclear theory and data applications. LLNL scientists will also respond to long-range planning needs recently released by the Office of Science in Nuclear Physics (NP) and High Energy Physics (HEP), including the searches for neutrinoless double beta decay, sterile neutrinos, and dark matter, experimental and theoretical research on nucleosynthesis and the properties of exotic nuclei, and probing the quark and gluonic structure of nuclear matter.

# Section 3.6: S&T Mobilizers—Facilities, Centers, and Institutes

## Facilities, Centers, and Institutes

Exquisite experimental capabilities and discipline-oriented organizational units

### Description:

LLNL's facilities, centers, and institutes promote collaboration to magnify our impact on national security and global challenges. As incubators of innovation, they drive science, technology, and engineering breakthroughs by engaging staff from multiple directorates to carry out research, partner with external research communities, and build a pipeline of talented students and collaborators.

### Mission Applications:

Centers and institutes link complementary resources to continue our mission-driven work while remaining accessible to external collaborators. Some focus on the research frontiers in a particular discipline, and others are built on the shared perspectives of researchers aligned for a common application. The Laboratory's facilities house the most energetic laser in the world, powerful supercomputers, and other premier tools that support a depth and breadth of research activities.

### Key Facilities

- Advanced Manufacturing Laboratory (AML)
- Center for Micro- and Nanotechnology
- Contained Firing Facility
- Electron Beam Ion Trap
- Forensic Science Center (FSC)
- High Explosives Applications Facility (HEAF)
- Jupiter Laser Facility (JLF)
- Livermore Computing Complex
- Manufacturing Complex
- National Atmospheric Release Advisory Center (NARAC)
- National Ignition Facility (NIF)
- Optical Fabrication and Processing
- Polymer Enclave
- Rapid Response Laboratory
- Select Agent Center
- Site 300
- SKYFALL

### Discipline-Oriented Institutes and Centers

- Center for Accelerator Mass Spectrometry
- Center for Advanced Signal and Images Sciences
- Center for Applied Scientific Computing
- Center for Bioengineering
- Center for Computational Engineering
- Center for Design Optimization
- Center for Engineered Materials and Manufacturing
- Center for Global Security Research
- Center for Predictive Bioresilience
- Data Science Institute
- Energetic Materials Center
- Glenn T. Seaborg Institute
- High Energy Density Science Center
- High Performance Computing Innovation Center
- Laboratory for Energy Applications for the Future
- Livermore Center for Quantum Science
- Livermore Institute for Digital Engineering
- Nondestructive Characterization Institute
- Space Science Institute

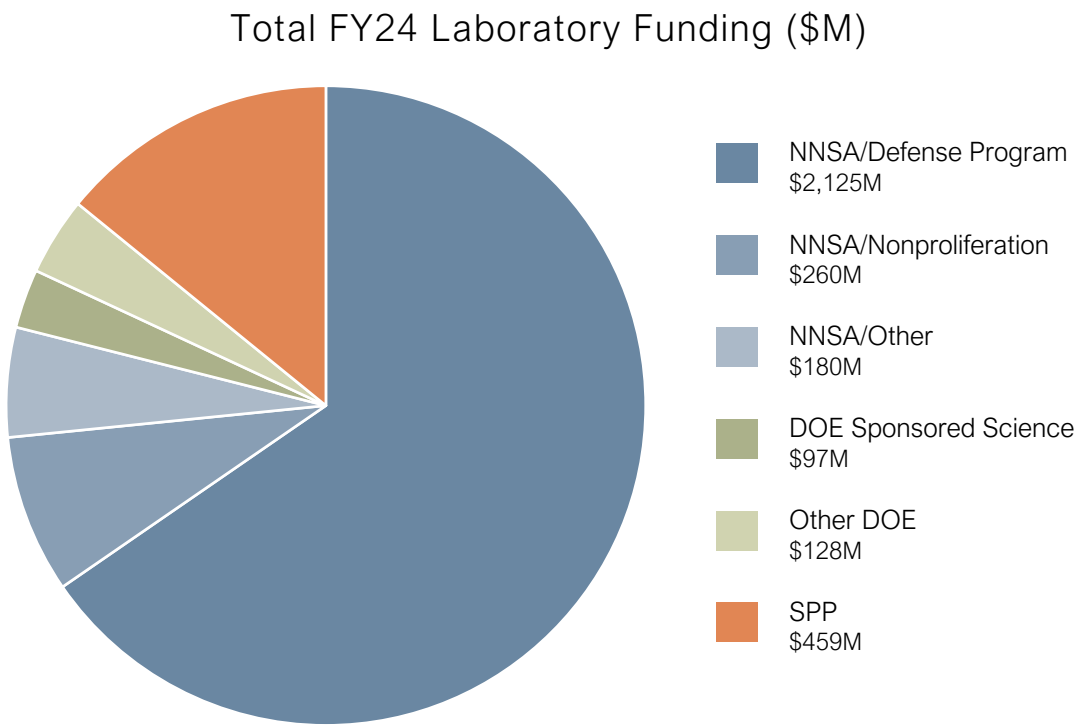
# Section 4: Support of Science and Technology

Financial support of LLNL's science and technology enterprise relies on a variety of funding sources. The largest and most important sponsor is NNSA/Defense Programs, which provides the majority of support for and enables synergy among our S&T Mobilizers. LLNL also conducts significant research and development for NNSA/Defense Nuclear Nonproliferation, DOE/Office of Science and other DOE offices. This broad and diverse portfolio allows LLNL to apply its technical competencies to the full suite of DOE missions and Departmental priorities, while providing synergy to our core NNSA mission.

Many non-NNSA mission areas benefit from the Laboratory's expertise, unique capabilities, and facilities. These Strategic Partnership Projects (SPPs), often conducted in collaboration with other organizations, serve to strengthen and broaden the science and technology expertise necessary for NNSA work. The non-NNSA DOE projects can be sponsored by other U.S. government agencies, industry, or academia, and spin back new ideas and knowledge into NNSA programs, and they attract and support outstanding researchers that contribute to a healthy, vibrant Laboratory.

In addition to externally funded work guided by sponsors, LLNL makes significant internal investments to create new capabilities, pursue leading-edge R&D, and ensure our S&T Mobilizers can address NNSA's mission and respond to emerging challenges.

Section 4 outlines sources of funding and their internal investment as detailed in the chart below:



# Section 4.1: NNSA and Sponsored Science

## NNSA Defense Program and Defense Nuclear Nonproliferation

Aided by the Laboratory's Stockpile Stewardship Program, NNSA's Defense Program (DP) has made dramatic advances in experimental and computational capabilities to gain tremendous insights into the science and engineering of operational nuclear weapons. These technical capabilities deliver tangible impacts on developing programs and are a signal to our adversaries that we are innovative and agile in response to new challenges. The mission of NNSA's Office of Defense Nuclear Nonproliferation (DNN) is to prevent the proliferation of nuclear weapons and reduce the threat of nuclear and radiological terrorism. LLNL's innovative science and technology is required to forestall nations and non-state actors from making nuclear weapons or obtaining weapons-enabling materials, knowledge, and equipment. LLNL's long-standing support of these important national priorities draws upon our Core Competencies, while an ever-evolving security environment spurs innovation and creates new technologies. LLNL currently leads multiple national efforts to advance capabilities for the nonproliferation mission, including new methods for arms control treaty verification and the use of machine learning to discover evidence of potential nuclear proliferation on a global scale. DNN funding also allows LLNL staff to develop hierarchical, multi-modal detection approaches to characterize threats and create sophisticated physics-based modeling capabilities to optimize mitigation strategies.

## DOE Office of Science

The DOE Office of Science (SC) is an enduring partner and a major source of funding for fundamental scientific research at LLNL. LLNL's SC program is formulated around a diverse portfolio of research that seeks to address major scientific challenges while contributing to the vitality of the Laboratory's Core Competencies and MFAs. LLNL's current SC portfolio includes funding from all seven program offices: Accelerator R&D and Production (ARDAP), Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), Biological and Environmental Research (BER), Fusion Energy Sciences (FES), High Energy Physics (HEP), and Nuclear Physics (NP).

## Applied Energy and Environmental Management Offices

LLNL also conducts a broad range of research activities for additional DOE Program Offices that leverage Core Competencies and provide opportunities for LLNL staff to make important contributions to national priorities. This portfolio includes funding from: Advanced Research Projects Agency-Energy (ARPA-E), the Office of Clean Energy Demonstrations (OCED), the Office of Electricity (OE), the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Environmental Management (EM), the Office of Fossil Energy and Carbon Management (FECM), the Office of Nuclear Energy (NE), and the Office of Cybersecurity, Energy Security, and Emergency Response (CESER).

## Strategic Partnership Projects (SPP)

Developing and sustaining interagency and industrial national security work enhances our capabilities. These efforts feed new technology into our mission while solving challenging national security problems for a variety of sponsors. The optimal SPP portfolio for LLNL is one that leverages and augments the Laboratory's Core Competencies, unique scientific and technical infrastructure, and integrated problem-solving skills. Approximately 75% of the SPP funding results from successful proposals to a wide variety of organizations that reside within the Department of Defense (DOD), including the Defense Advanced Research Projects Agency (DARPA) and each of the six branches of the U.S. Armed Forces. Other government agencies such as National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), and Department of Homeland Security (DHS) also provide funding for research ideas on a range of topics.

This entire portfolio of diverse research includes developing and implementing cutting-edge solutions and is a major factor in recruiting and retaining the Laboratory's talented workforce.

# Section 4.2: Internal Investments

Our internal investments—in particular, our LDRD program—support the exploration of new ideas that anticipate future needs within our national security missions. The Laboratory uses funding from LDRD, ISCP, and L&R to achieve a specific set of goals—the most important areas of attention of the Laboratory: infrastructure, research capabilities, and people.

## Laboratory Directed Research and Development

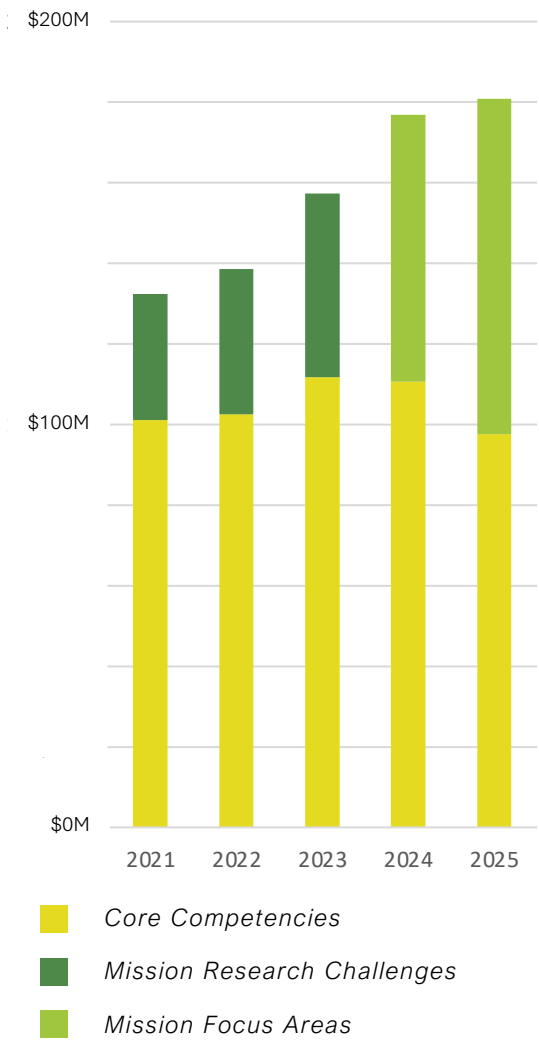
*Internally funded high-risk, potentially high-value research and development*

The LDRD program is a congressionally authorized component in the NNSA's S&T investment strategy that provides investments in cutting edge science and technology that allow the Laboratory to attract and retain the world's most talented scientists and engineers and enables them to expand the frontiers of knowledge and anticipate emerging national security challenges. Funded with approximately six percent of the Laboratory's budget, LDRD is awarded through a rigorous and highly competitive review and selection process. To meet the Laboratory's evolving mission needs, the LDRD process is designed to be flexible and allow for adjustments to achieve our national security goals.

The LDRD program is also a powerful means to hire outstanding staff, postdocs, and students; foster collaborations with other prominent scientific and technological institutions; leverage some of the world's most technologically advanced assets; and publish innovative science and technology achievements in high-impact journals and meeting proceedings.

LDRD enables LLNL to invest in high-risk, potentially high-value research and development that creates innovative technical solutions current and emerging difficult national security challenges across our Mission and Mission Focus Areas. LDRD investments into Core Capabilities ensure LLNL science, technology, and engineering stays at the cutting edge. The graphic to the right displays how LDRD funding supports Laboratory research in these categories: Mission Areas and Mission Focus Areas (MFAs), and Core Competencies.

LDRD Funding FY21 Through FY25



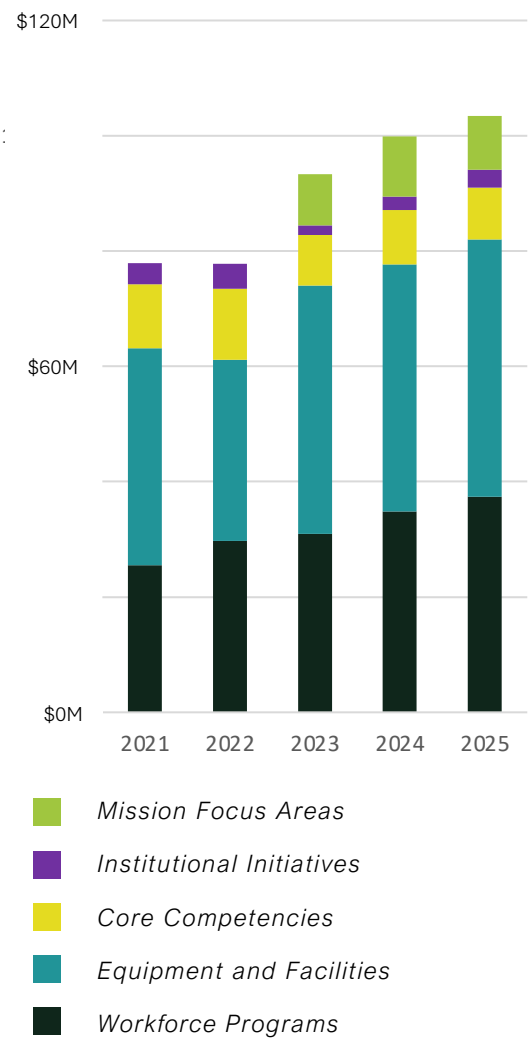
# Section 4.2: Internal Investments (cont.)

## Institutional Scientific Capability Portfolio

*Funding to maintain the Laboratory's core and mission competencies*

ISCP is an important component of LLNL's overall strategic investment program that supports capability sustainment projects, institutional equipment, multi-programmatic facilities (JFL, AML, FSC), and program development associated with supporting LLNL initiatives and priorities that have cross-directorate benefits, workforce programs, and scientific infrastructure. ISCP projects are non-R&D activities funded by indirect resources that maintain or improve the Laboratory's core competencies and must be applicable to current and future mission and S&T capabilities.

### ISCP Funding FY21 Through FY25




## Institutional Equipment

*Internally funded, multi-programmatic needs*

The Multi-Programmatic Instrumentation Committee (MPIC) collects and prioritizes requests for internally funded instrumentation purchases and enhancements.

The MPIC funding mechanism is not to be used for research and development efforts, which are typically funded internally through other programs, such as LDRD. It is instead meant to shore up core capabilities and needs that serve a broad array of programs at the Laboratory—hence the "multi-programmatic" designation. This pathway provides an excellent opportunity to upgrade or replace critical capabilities, such as decades-old instruments that no-single program/experiment can replace in a single year, or to add a new capability where there is currently a gap.

## Licensing and Royalties (L&R)

*Funding scientific collaboration*

L&R funds are generated by licensed Intellectual Property invented by Livermore researchers. Activities must meet the criteria defined by the Stevenson-Wydler Act. Recent uses of this funding include supporting LLNL's participation in the Accelerating Therapeutics for Opportunities in Medicine consortium, supporting the research of Early- and Mid-Career Award winners, and developing the Stellar Occultation Hyper-temporal Imaging Payload (SOHIP), an instrument deployed on the International Space Station in 2023.

## FY24 Institutional Equipment Purchases

| LOCATION | CAPABILITY | FY | POC | ITEM | ORG | COST $K |
|---|---|---|---|---|---|---|
| B151/RB140 | A Bruker Evo 11.7T superconducting magnet that will interface with our Avance IIIHD NMR spectrometer that serves as a user instrument. | FY24 | Derrick Kaseman | 500 MHz Magnet Upgrade | PLS | $590 |
| B361 | The Orbitrap Eclipse LC-MS provides chromatographic separation and molecular mass spectrometric analyses of biological and environmental samples. The instrument combines quadrupole, linear ion trap, and Orbitrap mass analyzers for excellent sensitivity and unparalleled resolution (>500,000 FWHM), as well as simultaneous MS and MSn analyses. The linear ion trap and orbitrap may be used in tandem, enabling collection of multidimensional data from a single run. | FY24 | David Baliu-Rodriguez | Vanquish Horizon UHPLC & Orbitrap Eclipse MS | PLS | $1280 |
| B235/R1125 | The MicroPrep PRO FEMTO is a femtosecond laser micro-machining system for the production of small samples. It will enable precision production of samples in a variety of geometries and of a wide array of materials. The system includes isolation enclosures enabling it to be safely used on hazardous and radioactive materials. | FY24 | Scott Mcbeath | MicroPrep PRO FEMTO | PLS | $819 |
| TBD | The 1130 Metro camera is an APS (active pixel sensor)-based direct electron detector manufactured by Gatan. Direct electron detection virtually eliminates all readout noise, boosting SNR compared to older generations of TEM cameras. This direct electron detection capability provides higher integrity data, for example allowing for visualization of faint peaks that have been heretofore missed at LLNL for a multitude of materials systems. | FY24 | Rohini Sankaran | 1130 Metro Counting Camera | PLS | $529 |
| B226/R1006 | The Nanochrome IV Titan Magnetron Sputtering system uses state of the art technology to produce high quality thin films. The system will be capable of producing high quality metal thin film layers by magnetron sputtering with low energy ion substrate cleaning. The system will produce single layer, multi-layer, nitride, and oxide thin films. The system provides a very high level of controlled material deposition through closed loop control system. The system will automatically deposit multilayer thin films using long throw, low pressure ion assisted magnetron sputtering and conventional sputtering in the Millitorr Pressure range. | FY24 | Bud Chesser | Nanochrome IV Titan Magnetron Sputtering System | ENG | $1339 |
| | | FY24 | Anand Gadre | AML ROCK-04 Aligner Wafer Bonder Platform | ENG | $1070 |
| B298/R141 | PhableX, based on Eulitha's proprietary Displacement Talbot Lithography (DTL) technology, offer unparalleled high-resolution printing with a low-cost photolithography system. They overcome the limitations of diffraction in conventional lithography, enabling the printing of sub-micron periodic patterns with excellent quality. The non-contact exposures protect both the mask and wafer, while the patented focus-free imaging allows uniform printing on non-flat substrates and in thick resists. The PhableX tool provides unprecedented ability to print high resolution periodic structures in a low-cost photolithography system. It is similar to a conventional mask-aligner where a photoresist coated wafer is put in proximity to a mask and exposed by a beam of UV light, but thanks to the breakthrough PHABLE exposure technology of Eulitha the resolution is no longer limited by undesired diffraction effects. Structures such as sub-micron period linear gratings and 2D patterns such as hexagonal and square lattices are printed with high uniformity and fidelity. | FY24 | Hoang Nguyen | PhableX 200 UV, Displacement Talbot Lithography System | NIF | $890 |
| B153/R1000/ Associates Space | The Blue Wave NIRIM Microwave CVD system is a diamond growth system for growing single crystal epitaxial layers of diamond. The tool will be dedicated to growing p-type (B-doped) diamond films for fabricating diamond-based microelectronic devices. | FY24 | Clint Frye | Blue Wave NIRIM Microwave CVD System | ENG | $302 |
| B179/R1000 | The imaging x-ray system is comprised of two photon-counting detectors manufactured by DECTRIS and other components (x-ray tubes, motion controllers and computer workstations) for use in conjunction with existing infrastructure in the x-ray characterization laboratory (B179/R1000). The detectors and the components substantially improve the workflow in characterization of x-ray crystal spectrometers employed on the NIF. | FY24 | Stanislav Stoupin | Photon-counting imaging x-ray system for quantitative characterization of x-ray crystal spectrometers | PLS | $371 |
| B298 | This system will provide calibrated optical imaging and reflectance data to qualify targets for dynamic compression experiments at the NIF and Omega Laser facilities, supported multiple LLNL programs. | FY24 | Marius Milot | NIF VISAR Target Qualification Station | PLS | $1000 |

# Section 5: Review and Metrics

*It is vital that we act as good stewards of all available resources*

How we allocate resources and how we evaluate programs affect how we fulfill our mission, make our research more impactful, and respond to future challenges and opportunities.

To keep our science and technology healthy and cutting-edge, we use a series of reviews and metrics to review our internal portfolio of investments. Regular portfolio review is governed by a uniform and consistent structure, so we can chart the health of our programs year-over-year. Following the guidance of Lawrence Livermore National Security's (LLNS) Parent Oversight Plan, portfolio review parameters include support of the Laboratory's mission, impact and recognition, research value, levels of collaboration, and program sustainability.

Metrics take several forms—our scientific portfolio is widely varied, and the accompanying metrics also reflect that variance. Some metrics may be applied to each entry in the portfolio, while others are tailored more specifically to each program. Current metrics include: the size and diversity of our postdoctoral cohort; the number and quality of our publications; the impact of our research, as measured by how well we transition innovations to industry and other partners; and the expertise of our staff, as recognized by awards, fellowship, and other external recognition from their peers. The Library is currently deploying SciVal to not only help our researchers better connect with their communities, but also expand the types of the metrics we consider.

The success of the Laboratory's scientific enterprise also depends on a vibrant, inclusive, and engaged workforce; state-of-the-art facilities; and meeting deliverables on time and within the budgets provided by sponsors. We are working to incorporate key performance indicators (KPIs) generated across the Laboratory and accessible via LabWatch, a data and tracking dashboard providing a source of truth for performance metrics. The underlying ethos of LabWatch is simple: "Measure to an outcome, not a number. This approach will keep us focused on metrics—and results—that matter."

We will continue to incorporate the feedback and recommendations we gain from formal review processes like the Board Of Governors (BOG), Directorate Reviews, or External Review Committees (ERCs). Portfolio review allows us to synthesize this information for our continued, collective benefit.

To keep our science and technology healthy and cutting-edge, we use reviews and metrics to assess our internal investments.

# Section 6: Emerging Opportunities

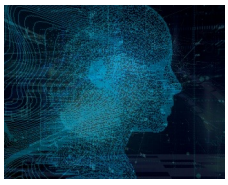
*We are striving to make the nuclear security enterprise agile, resilient, sustainable, and responsive to emerging national needs.*

This section of the *Investment Strategy for Science and Technology* outlines urgent national priorities and foundational scientific capabilities. Of particular interest this year are the rapid advancements in generative AI, opening new possibilities for LLNL to deploy powerful AI capabilities into critical mission spaces. Section 6.1 outlines areas of emerging science known as Institutional Initiatives, while 6.2 further illustrates how scientific expertise is applied to Mission Focus Areas. Sections 6.3 and 6.4 outline how our S&T Mobilizers and internal investments fulfill the Laboratory's mission-driven work in multiple ways, including through successful LDRD projects. Each element ensures the Laboratory can support new mission requirements, meet long-term mission needs, and rise to new challenges. The Laboratory's many successes are the result of our dedicated staff's efforts to strengthen national security and global stability through world-class science, technology, and engineering.

# Section 6.1: Institutional Initiatives

LLNL was established as a "Big Ideas" laboratory and generations of employees have carried forward that tradition with multidisciplinary teams and a history of taking bold—but well-considered—technical risks. The complexities of future challenges to national security demand that we build upon the Laboratory's culture of innovative thinking to achieve high-payoff advances. Innovation is part of LLNL's approach to program delivery but, more importantly, it is strongly embodied in our Institutional Initiatives.

Driven by visionaries with expertise in mission-critical fields, Institutional Initiatives evolve to reflect LLNL's "team science" approach by gathering multidisciplinary teams. By anticipating areas of increased global attention, Institutional Initiatives can "lean forward" in emerging scientific realms. The three current Institutional Initiatives are profiled below. Discussions are underway to consider a larger Institutional Initiative in AI encompassing the efforts in Cognitive Simulation and Decision Superiority and to create a new Institutional Initiative addressing aspects of advanced materials and manufacturing.



## Cognitive Simulation

The Cognitive Simulation Institutional Initiative aims to accelerate the integration of AI, high-performance computing, and empirical data for a range of scientific applications. Researchers focus on inertial confinement fusion and high energy density projects crucial to stewardship of the nation's nuclear stockpile, while additional mission-relevant applications include climate studies, AI-driven manufacturing, and biosecurity projects.

## Decision Superiority

This Institutional Initiative was created to build on mathematical advances in complex systems and AI capabilities to foster scalable, stable, and robust modeling and forecasting capabilities that can resolve decisions with limited information. Simply put, the Decision Superiority Initiative helps meet the pressing national need for decision support tools.

## Inertial Fusion Energy

The achievement of fusion ignition at the NIF demonstrates the fundamental basis of Inertial Fusion Energy (IFE) and is a pivotal first step towards a fusion energy future. The IFE Institutional Initiative is enabling the U.S. national, technical, and community leadership needed to build the foundational science and technology for IFE and support the DOE's vision for accelerating the commercialization of fusion energy.

# Section 6.1: Institutional Initiatives (cont.)

## Cognitive Simulation

*Accelerating applied science with AI*

### Description:

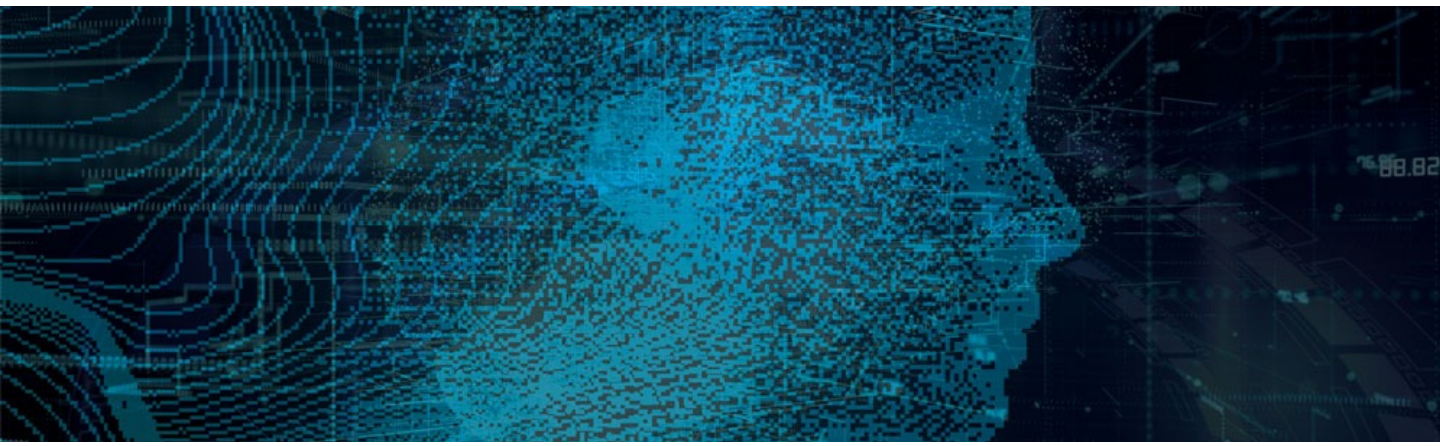
The Cognitive Simulation Institutional Initiative harnesses AI to combine LLNL's simulation capabilities with high-quality experimental datasets. These new models improve scientific predictions by coupling large ensembles of simulations with limited quantities of experimental data—a process that enables AI to incorporate, adapt to, and guide experimental observations. The improved models deliver highly detailed uncertainty quantification and quantitative measures of the value of past and future experiments.

CogSim provides solutions to key problems across LLNL's national security missions. While many techniques are pioneered entirely inside the Laboratory, several CogSim methods are expanded through public/private partnerships steered by the AI Innovation Incubator (AI3). This approach enables LLNL to share compelling interdisciplinary science challenges with AI and computing industry leaders. Demand is high for engagement with LLNL's unique CogSim research ecosystem because of the possibilities for new techniques and approaches that benefit both national security and national economic competitiveness.

### 3–5-Year Vision:

AI already plays an important role in how scientific experiments are conducted, how supercomputers run simulations, and how large datasets are analyzed to make predictions. As computing systems evolve past exascale capabilities toward zettascale and beyond, so too will AI technologies. Large language models will continue to influence scientific discovery processes including hypothesis investigation, as will models that can analyze and interpret multimodal datasets. AI-driven automation will become more routine in laboratories and experimental facilities, producing data at unprecedented rates. Advanced manufacturing techniques augmented with AI will enable adaptive design processes and smarter production operations.

As the Department of Energy considers significant large-scale AI investments, the Cognitive Simulation Institutional Initiative will ensure LLNL upholds a deliberate, focused vision for AI development and execution in addressing national security priorities. As part of this effort, AI3 will continue to coordinate multi-partner expertise focused on applications—such as through early access to proprietary commercial AI models—while nurturing the Laboratory's visibility and influence with sponsors and government partners.



# Section 6.1: Institutional Initiatives (cont.)

## Decision Superiority

*Overcoming complex planning challenges with new computational approaches*

### Description:

Decision superiority capabilities help meet the pressing national need for computational tools to create advantages in both speed and insight in international competition and warfighting. LLNL is pursuing an open research frontier in the numerical solution of integrable systems applied to mission-driven models. With advances in numerical speed and accuracy, new problem domains can be solved, including combinatorial optimization, complex systems, and a variety of physical phenomena.

Meeting the dynamic planning challenges for decision superiority requires new approaches beyond current simulation and machine learning methods, which aren't always available to make timely recommendations for rapidly changing environments. A recent breakthrough identified new ways to solve optimal control and reinforcement learning problems by casting them as components of completely integrable systems in time and space, which enables efficient solutions via parallel computations. Additional advances in probabilistic machine learning and high throughput computing methods enable solutions of decision support problems under unique national security mission constraints. Decision superiority researchers are applying these innovations by partnering with experts at LLNL and other National Laboratories in defense systems modeling and simulation.

### 3–5-Year Vision:

Based on mathematical advances in complex systems, LLNL is creating scalable, stable, and robust modeling and forecasting capabilities that can resolve complex decisions with limited information. LLNL advances could include learning how operational data can solve combinatorically difficult planning problems. Efficiently representing how operational data is embedded on conventional computing architectures is a solution that will drive evolution in computing architecture designs.

On a three-year timeline, LLNL decision superiority teams expect to demonstrate real-time planning capabilities at scale on LLNL high-performance computing systems. This will help expand modeling into social science domains, widely acknowledged as critical for managing future threats. Integrating the developing tools with humans will help build trust in the system. Within five years, evolving LLNL capabilities will enable delivery of decision support products to users across the U.S. government and will foster transfer of capabilities to a broader LLNL mission set.

# Section 6.1: Institutional Initiatives (cont.)

## *Inertial Fusion Energy*

*Igniting a clean energy future with inertial fusion*

### Description:

Fusion, the process that powers the Sun, has the potential to provide a reliable, limitless, safe, and clean energy source. On Dec. 5, 2022, a team at LLNL's National Ignition Facility (NIF) conducted the first controlled fusion experiment in history to reach ignition, also known as scientific energy breakeven, meaning it produced more energy from fusion than the laser energy used to drive it. The experiment delivered 2.05 MJ of energy to the target, resulting in 3.15 MJ of fusion energy output, demonstrating for the first time the most fundamental science basis for inertial fusion energy (IFE). This milestone validates a critical first step of laboratory-scale laser-driven IFE as a pathway to a fusion energy future.

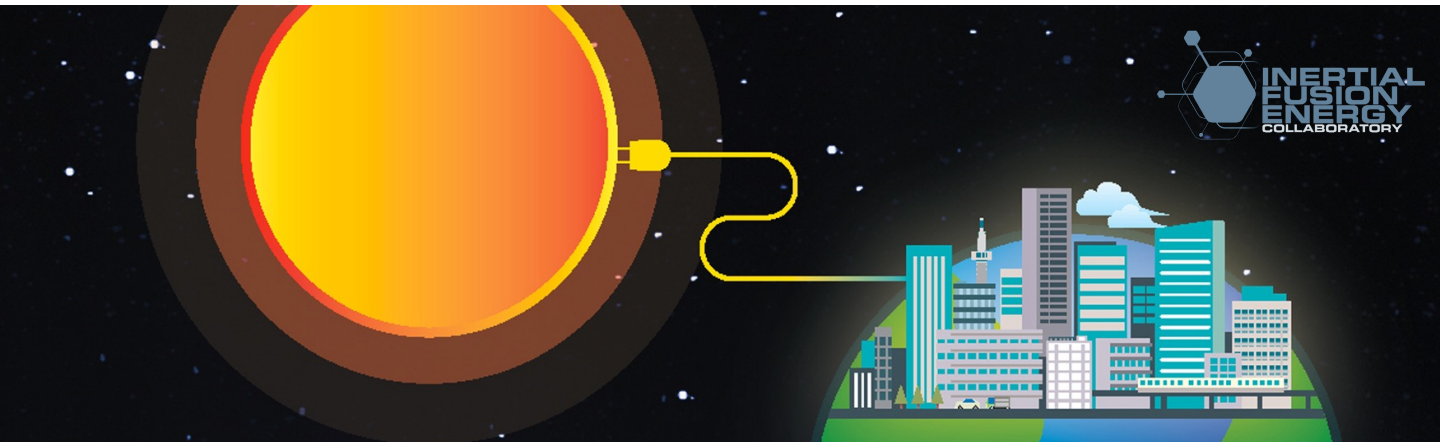
LLNL is taking a leading role in forming the national IFE program, while growing our internal program in a way that both strengthens our core mission and sets a future path for the Lab. Livermore's IFE Institutional Initiative provides inclusive leadership on the national and international stage, builds up IFE efforts within LLNL in areas synergistic with stockpile stewardship, and supports the emerging public and private IFE landscape

### 3–5-Year Vision:

In achieving ignition, the U.S. has taken the first pivotal step to inertial fusion energy. Achieving fusion energy will require sustained, long-term investments and innovations in multiple fields to enable a viable energy source.

LLNL, in partnership with the community, will continue to grow a robust and coordinated U.S. IFE program spanning the public and private sectors to build the first pilot plants, with key components including integrated plant design to drive science, technology, and engineering to close existing gaps and set requirements for fusion pilot plant concepts; a national IFE ecosystem with the necessary new facilities to advance component technologies and foundational science; access to unique, world-leading NNSA and DOE facilities to provide near-term data and reduce risk; a proactive workforce development effort spanning all levels, and inclusive public engagement about fusion.

U.S. leadership in IFE could profoundly transform long-standing energy geopolitics, strengthen energy and climate security, and bolster national security for the U.S. and allied partners. It is a worthy scientific and engineering grand challenge building on the historic achievement of fusion ignition.



# Section 6.2: Mission Focus Areas

## Stockpile and Enterprise Transformation

*Increasing the responsiveness and resilience of the Nuclear Security Enterprise*

### Description:

The Laboratory's Stockpile and Enterprise Transformation (SET) Mission Focus Area seeks to accelerate the advancement of the sophisticated enterprise of laboratories, facilities, tools, processes, and people to help realize a more modern, responsive, and resilient enterprise while maintaining confidence in the nation's nuclear deterrent.

### Mission Applications:

This MFA aligns with the Laboratory's mission-critical work to modernize the stockpile and the production complex. Advancing the experimental, design, manufacturing, and computational capabilities will add significant resilience and responsiveness to our national security efforts and enable "First Production Unit (FPU) in 5." The SET MFA further supports the Laboratory's proactive Supply Chain Risk Management and Mitigation strategy by examining every aspect of the production process using a "clean sheet" approach to determine which changes have the greatest impact.

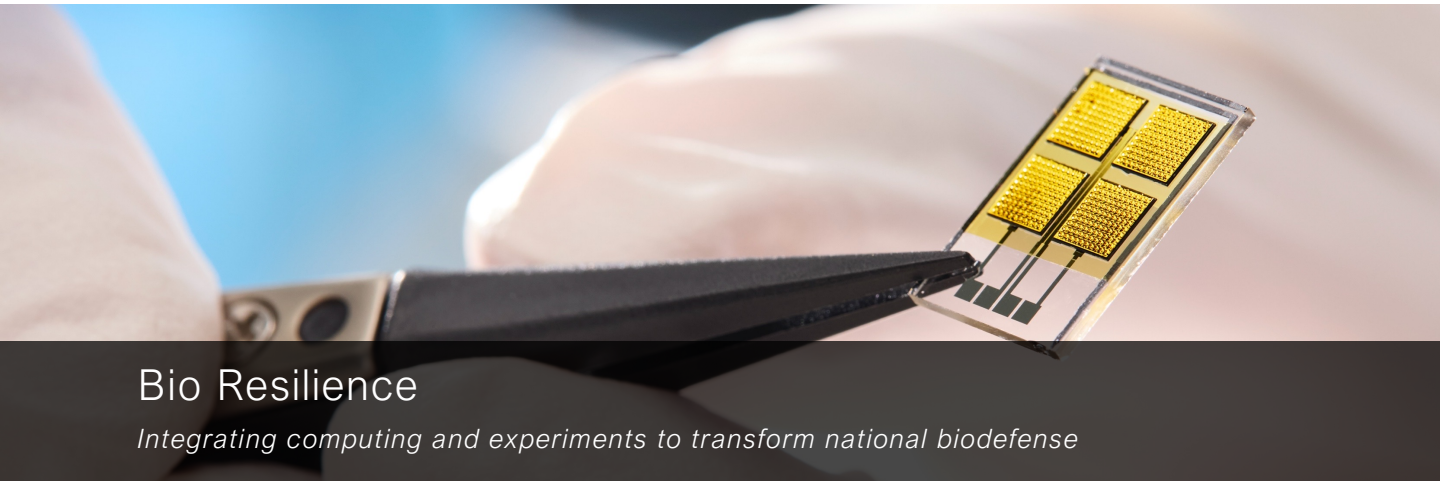
### Accomplishments:

- Polymer direct ink write on-machine inspection tools are now in use on the Kansas City National Security Complex production floor. Early benefits may be integrated into development and production processes.
- Established coordination between multiple internal efforts aimed at building critical components of a data ecosystem to understand connections, interfaces, and how each effort contribute to common goals.

### 3–5-Year Vision:

LLNL's goal of stewardship transformation aims to anticipate future deterrence needs while providing applicable solutions, champion new approaches to product realization, and modernize materials and component design and manufacturing methods, processes, and practices. This vision includes applying existing and future ST&E tools to enable responsive qualification and certification. Transformational enablers include advanced manufacturing tools—including exploring the use of automation to improve reproducibility of processes; novel non-destructive, in-situ characterization modalities to reduce inspection times; and experimental and computational tools (including AI and data sciences) to accelerate the design-produce-certify product realization process. Successfully achieving SET's goals requires building strong partnerships across the institution and the NNSA enterprise while connecting key institutional efforts to programmatic stakeholders.

# Section 6.2: Mission Focus Areas



## Bio Resilience

*Integrating computing and experiments to transform national biodefense*

### Description:

The Bio Resilience MFA aims to transform U.S. biosecurity and biodefense by integrating computing and experimentation to identify, characterize, and counter natural and man-made biological threats at dramatically reduced timescales. By building partnerships to grow our national capability for predictive biology and biodesign, we can develop biodefense, global health, and bioeconomy programs with mission-critical agencies. Objectives include providing early biological threat detection and assessment; drastically accelerating design, development, and testing of medical countermeasures; and developing integrated computational-experimental platforms for complex biosystem analysis and design.

### Mission Applications:

This MFA protects the nation by countering current and future biological and environmental threats. Biological expertise relevant to LLNL's national security mission combines AI, physics-based simulation, and targeted, automated experiments to transform biosecurity and biodefense. These efforts leverage unique LLNL capabilities in computing, AI, simulation, and experimental biology to address gaps in biosecurity and biodefense driven by the increasing risk of emerging and engineered pathogens.

### Accomplishments:

- Established an open-to-secure high-performance computing capability dedicated to biosecurity and biodefense.
- Advanced protein engineering state-of-the-art, to include *Nature* publication on computational redesign of SARS-Co-V therapeutic antibody and provisional patent for redesigned AstraZeneca antibody.
- With CRADA partner BridgeBio, LLNL developed DOE's first small molecule therapeutic to enter clinical trials.

### 3–5-Year Vision:

Researchers aim to broaden global surveillance, detection, and response to infectious agents, pathogens, and other toxins. Identification and characterization of emerging and engineered pathogens requires threat-agnostic biosurveillance and early warning capabilities that do not currently exist. The GUIDE program, one of LLNL's largest strategic partnerships with DOD, will integrate experimental and computational tools to understand, design, and optimize complex cellular systems and mechanisms for a variety of biodefense and bioeconomy applications. R&D will focus on integrated systems that use computing to steer automated experiments and the resulting data to inform new models. These active learning systems will enable a broad range of new understanding and capability to enhance our national security.

# Section 6.2: Mission Focus Areas

## Climate Resilience

*Providing scientific tools for mitigating, predicting, and adapting to climate change*

### Description:

The primary goal of the Climate Resilience MFA is to minimize and predict the impacts of climate change on national security. Our mitigation efforts focus on carbon removal methods involving carbon storage in soils, enhanced mineralization, direct air capture, etc. coupled with techno-economic analysis of removal and storage systems. This MFA aims to establish LLNL as the national resource providing the technical basis for slowing and reversing the accumulation of greenhouse gases in the atmosphere. Additionally, LLNL researchers forecast the anticipated climate response at spatial and temporal scales required for adaptation with a focus on national security and critical infrastructure.

### Mission Applications:

Climate change poses an immense risk to national security, the economy, and public health with consequences that cascade across sector boundaries. Earth System models (ESM) combine atmosphere, ocean, land, and sea-ice processes to predictive models of climate change for impact analysis. LLNL's Energy Exascale Earth System Model (E3SM) streamlines modeling workflows and assesses utility of machine learning and artificial intelligence, resulting in a seamless integration of weather predications and climate projections.

### Accomplishments:

- Symposia held at UC Merced, the University of North Carolina, and the University of Pennsylvania convened expert-led stakeholder conversations on the LLNL-authored nationwide assessment on $CO_2$ removal, Roads to Removal. Three more symposia are scheduled for FY25 in Indiana, Wyoming, and Oklahoma.
- Laboratory researchers and E3SM developers have begun organizing a cloud-resolving model data hackathon to be held in mid-May 2025 featuring international participation.

### 3–5-Year Vision:

This MFA will continue to examine how carbon removal can help minimize changes in the Earth's climate and how unpreventable changes threaten national security. Researchers will use Earth system models to address how regional and local climate impacts, such as flooding, drought, and extreme weather events, influence the electrical power grid, national security infrastructure, and critical operations. In California, a new DOE Office of Science project focused on developing a "digital twin" of Sonoma County with particular interest in understanding water availability and demand will likely require cooperation with policymakers and collaboration with other National Laboratories.

# Section 6.2: Mission Focus Areas

## Strategic Advantage

*Innovation superiority in every domain*

### Description:

The Strategic Advantage (SA) MFA addresses the national need to deter aggression against the U.S., allies, and partners, while enabling the ability to fight and win across the full spectrum of conflict to maintain and restore deterrence. This MFA integrates LLNL abilities and partnerships to support the U.S. government in developing stronger deterrence capabilities through analytics, multi-domain modeling and simulation strategies, scenario-based exercises, and technology demonstration efforts. Strategic advantage requires working across domains, the spectrum of conflict, and all instruments of U.S. national power, to reduce competitors' perceptions of the net benefit of aggression relative to restraint. Global leadership in key technology areas is also essential for ensuring U.S. strategic advantage into the future.

### Mission Applications:

Enduring U.S. strategic advantage in an era of great power competition now involves research in emerging fields like advanced weapon capabilities, conventional nuclear integration, critical infrastructure, cyber and space resilience, as well as AI and machine learning. Analysis and at-scale modeling of complex systems allows prioritizing technology development and delivery to support national strategic advantage.

### Accomplishments:

- Advances in infrastructure modeling and data exploitation enabled new capabilities to improve dual-use civilian and Department of Defense infrastructure resilience, including energy and port infrastructure.
- Inclusion of intelligence data in the LLNL Joint Conflict and Tactical Simulation kit demonstrated utility for evaluating new technical capabilities and conventional nuclear integration in a conflict.
- A 2024 workshop was held with United States Strategic Command to evaluate the deterrence implications of Electromagnetic Spectrum Operations (EMSO) during competition, resulting in LLNL software enhancements.

### 3–5-Year Vision:

The SA MFA aims to leverage and integrate LLNL's Core Competencies, all-source intelligence abilities, existing security programs and innovative research to strategically outcompete our adversaries. Central to this vision is the integration of nuclear, conventional, and non-kinetic capabilities to ensure strategic advantage across the spectrum of conflict. Upcoming MFA efforts will include a single end-to-end deterrence scenario focused on assessing capability gaps and exploring technological solutions.

# Section 6.3: Future State of S&T Mobilizers

The future of innovative science at LLNL depends on the S&T Mobilizers: our people, infrastructure, and Core Competencies. Our workforce is at the heart of everything we do, from training postdocs to be principal investigators through our LDRD program, to developing thought leaders by having them run a Center or Institute and advance Core Competencies. It is vital that the Laboratory continues investing in what allows our workforce—no matter their role—to be productive, innovative, and successful.

## People

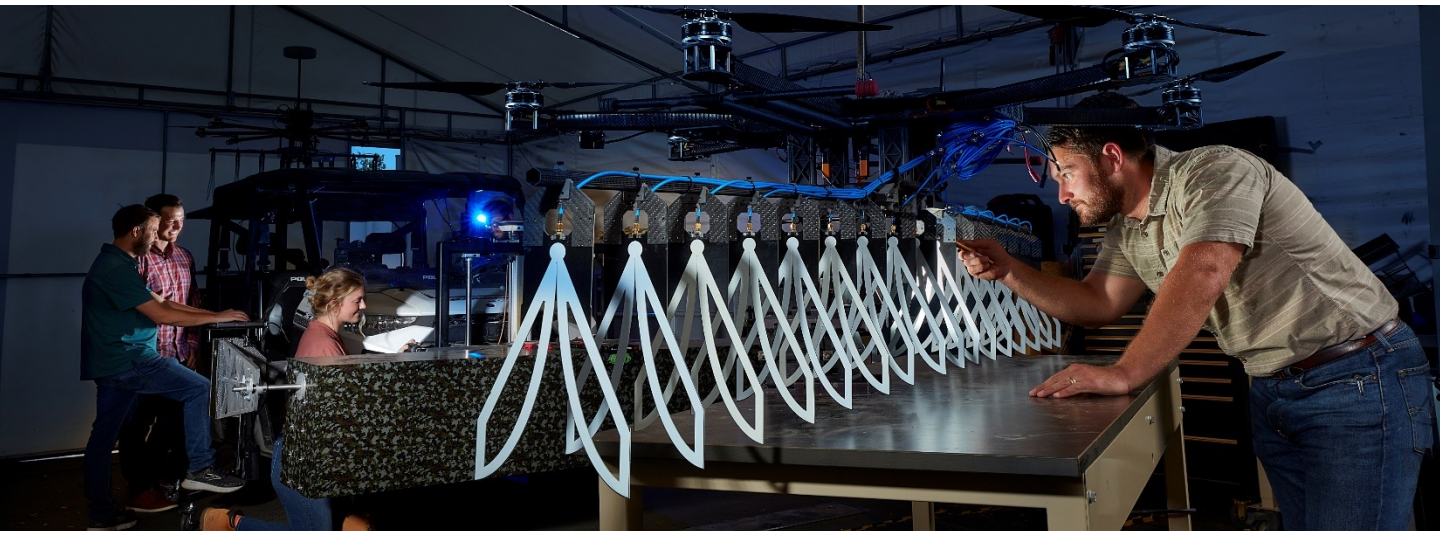
Across the Lab, effective team science is enabled through a healthy research culture of respect, openness, interdisciplinary teaming, workforce diversity, and collaborative approaches. Each year, we participate in hundreds of recruiting and conference events as we continue to develop talent pipelines for succession planning to meet the Laboratory's future needs. Our Faculty Mini-Sabbatical Program brings top academic talent from colleges and universities across the U.S. to exchange knowledge and build partnerships. Faculty experience Laboratory resources and capabilities, share best practices, and advance their skills. Whether it's sparking scientific interest in K-12 students or recruiting the next generation of nuclear physicists, developing our workforce pipeline continues to be a strategic priority.

## Facilities, Centers, and Institutes

2023 included a systematic review of internally-funded Centers and Institutes to ensure they are aligned with Laboratory priorities, support MFAs and OKRs, and are resourced appropriately. This portfolio review strengthened the community of such entities and offered an opportunity to share best practices. LLNL will continue to provide essential support to facilities and capabilities to enable impactful basic and applied research and development and to support mission- and sponsor-driven work.

## Core Competencies

The Laboratory continually works to enhance the quality, relevance, and vitality of all seven Core Competencies. We will actively pursue efforts to assess these competencies, including the support provided by our LDRD program and our institutional funding, and validate quality via external reviews, honors awarded to LLNL staff, and the success of external partnerships. Our visibility in the external research community, and our ability to shape and respond to our sponsors' vision and strategic plans, will also serve to demonstrate our expertise.

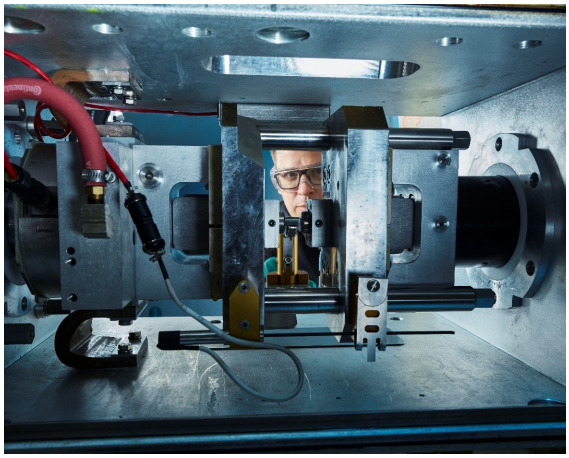


# Section 6.4: LDRD Highlights

Several examples of successful mission-driven work dependent on the S&T Mobilizers can be seen within the LDRD program:

## Advanced Materials and Manufacturing

LLNL's national security mission requires the rapid development of materials with unique properties and the advanced manufacturing capabilities to deliver real-world solutions. LDRD investments have been instrumental in the development of a wide range of materials design and manufacturing processes that strengthen our ability to deliver timely, mission-relevant solutions.

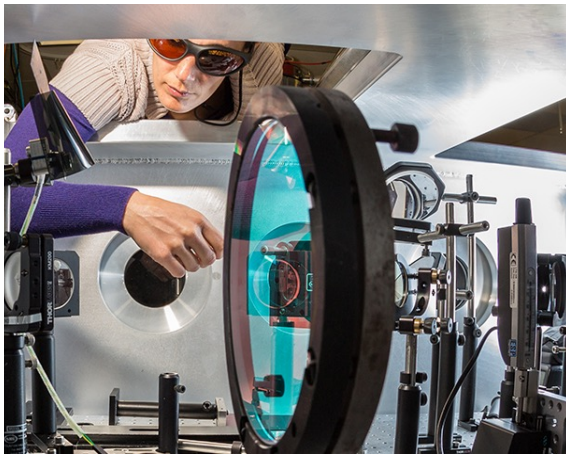


Livermore engineers, materials scientists, and additive manufacturing experts develop nanotechnology, novel feedstocks, and biomimetic, quantum, and energetic materials.

Extreme environments push materials to their limits, creating an enormous demand for new materials with improved performance under extreme conditions. While this demand is broadly recognized, the design-to-deployment timescale for new alloys is decades. Responsive frameworks that accelerate the timescale for materials discovery, design, and deployment are needed.

LDRD investments are using artificial intelligence and machine learning to accelerate the development and validation of tailored alloys that meet the demands of leading-edge technologies for national-security requirements. Our work targets high entropy alloys, metals that demonstrate extraordinary material properties under extreme conditions, including high strength at high temperatures and long life in corrosive environments.

LLNL's materials-design capabilities are transformative, providing solutions for new materials to fast-track the technological loop to address emerging challenges.



LLNL researcher Felicie Albert prepares the Callisto laser system and setup for betatron x-ray experiments at the Jupiter Laser Facility.

## High Energy Density (HED) Science

LLNL is a world leader in HED science, developing unique experimental platforms and detailed diagnostics to better understand the fundamental properties of matter. For over 25 years, LDRD investments in HED science have pushed the frontiers of science exploring matter at extreme conditions and at conditions required for understanding weapon physics and inertial confinement fusion.

Today, LDRD projects leverage artificial intelligence and machine learning with high-repetition-rate lasers to revolutionize the analysis of plasma x-ray spectra. This approach rapidly deduces plasma properties such as temperature and density while accounting for temporal evolution and spatial gradients. By integrating multi-modal experimental and simulation data through machine learning, we aim to reduce analysis timescales from months or years to days or weeks, providing a scalable framework for timely answers to key HED physics questions.

# Section 6.5: Future State of Strategic Investments

We take seriously the responsibility to steward funding and make strategic investments in science and technology that keep the Laboratory relevant, vibrant, and ready to respond to complex enduring and emerging national security challenges.

## Future State of Funding

NNSA—principally Defense Programs and other offices—will continue providing significant funding and support for the people, facilities, and Core Competencies that are the foundation for our science and technology enterprise. Sponsored science from the DOE Office of Science and other government agencies like NASA, NIH, and DARPA will enhance our S&T Mobilizers and help attract and retain the next generation of science leaders. There will continue to be strong demand for internal resources, and thoughtful prioritization will be critical as we consider recapitalization of important facilities, enhancing experimental facilities, and supporting our talented staff.

## Future State of Review and Metrics

Assessing the effectiveness and impact of internal investments, the quality of the research we conduct, and the engagement, expertise, and contributions of our staff is essential for the Laboratory's continued success. Over the next years, we anticipate adding to our existing suite of metrics and performing more benchmarking from a pool of similar organizations including as many DOE Labs as possible, DOD FFRDCs, and other government-funded R&D organizations. A long-term objective will be using LabWatch as the permanent repository for all science-related metrics and associated data. LabWatch ensures that all users are relying on the same verified data to understand our successes and opportunities for improvement.

External reviews performed by trusted and independent experts provide valuable insight into the health and direction of our foundational science and technology enterprise, how well it aligns to near- and long-term mission drivers and vibrancy of our workforce. We will examine how best to use the well-established review processes, including Directorate Reviews, External Review Committees, and the Science and Technology Committee of the LLNS Board of Governors. Reviews work best when they are held at the right frequency and produce a mix of actionable recommendations and observations about how LLNL fits into the broader national security and basic science landscapes. We will continue to adjust the charges given to the committees to best match what the nation asks us to do while responding to internal priorities. Over the next few years, we anticipate creating new tools to integrate publications, honors, awards, and intellectual property successes to assess the achievements of our people, Core Competencies, and MFAs.

# Section 6.5: Future State of Strategic Investments (cont.)

## Future State of Partnerships

### Academic Engagement Office

The Laboratory's Academic Engagement Office has a long history of fostering collaborations and partnerships between Laboratory researchers and the academic community. The team provides students and faculty at K-12 schools, community colleges, vocational schools, universities, and post-doctoral programs with collaborative LLNL research assignments, work study opportunities, and educational activities that support the Laboratory's mission. Moving forward, an effort will be made to define and nurture a set of strategic academic relationships to enhance engagement with particular student cohorts. By continuing to connect with students at all stages of learning, the team develops the Laboratory's future workforce while enhancing our community's awareness and understanding of science.

### Open Innovation

A more mobile, open Laboratory helps us respond rapidly to the security challenges of a deeply connected world. The Laboratory's partnership and open innovation initiatives are purposefully oriented to ensure excellence and to understand the use and implications of critical and emerging technologies. These connections with industry, government agencies, universities, and international counterparts cultivate entrepreneurship, help the nation grow, and meet national and global security challenges.

### Livermore Valley Open Campus

The Livermore Valley Open Campus (LVOC) was created to foster collaboration among LLNL, Sandia National Laboratories, private industry, and academic institutions. Earlier investments in LVOC collaboration spaces, such as the Advanced Manufacturing Laboratory and the adjacent office building space have resulted in productive collaborations. Celebrating its first full year of operations at LVOC in FY23, the University of California Livermore Collaboration Center (UCLCC) reflects a growing dimension of parent company support and expertise and manifests a vision of enhanced university/laboratory collaboration. UCLCC serves as a multi-campus hub to expand collaborations and partnerships through outreach and education. New facilities at LVOC—the Integrated Bio Resilience Laboratory and the Prototyping Enclave—are being planned. These two experimental facilities will address critical areas of emerging research.

Driven by premier science and technology, LLNL's internal investments support a talented workforce, world-class competencies, state-of-the-art facilities, and our mission-driven work.

# Acronym List

AEO: Academic Engagement Office

AI: artificial intelligence

AI3: AI Innovation Incubator

AMM: advanced materials and manufacturing

BOG: Board of Governors

DARPA: Defense Advanced Research Projects Agency

DDST: Deputy Director for Science and Technology

DHS: Department of Homeland Security

DOD: Department of Defense

DOE: Department of Energy

DNN: Office of Defense Nuclear Nonproliferation

EOS: equation of state

ERC: external review committee

FFRDC: Federally Funded Research and Development Center

FY: fiscal year

FSC: Forensic Science Center

HEAF: High Explosives Applications Facility

HED: high energy density

HPC: high-performance computing

ICF: inertial confinement fusion

IFE: inertial fusion energy

IPO: Innovation and Partnerships Office

ISCP: Institutional Scientific Capability Portfolio

JLF: Jupiter Laser Facility

KPI: key performance indicator

LDRD: Laboratory Directed Research and Development

LLNL: Lawrence Livermore National Laboratory

LLNS: Lawrence Livermore National Security

L&R: licensing and royalties

LVOC: Livermore Valley Open Campus

OKR: objectives and key result

NASA: National Aeronautics and Space Administration

NARAC: National Atmospheric Release Advisory Center

NIF: National Ignition Facility

NIH: National Institutes of Health

NNSA: National Nuclear Security Administration

MFA: Mission Focus Area

MJ: megajoule

ML: machine learning

R&D: research and development

SC: Office of Science

SOHIP: Stellar Occultation Hyper-temporal Imaging Payload

SPP: Strategic Partnership Project

SSP: Stockpile Stewardship Program

S&T: science and technology

ST&E: science, technology, and engineering

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**Cover image:** The aim of LDRD SI project *Invisible Organ: The Next Level of Human Health and Resilience,* was to develop capabilities that leverage the human microbiome (all the microbes associated with the human body) to improve human health. One thrust within this effort was to develop an intestinal microbiome-on-chip system, allowing LLNL to test the health impacts of different microbiome conditions.

To accomplish this, LLNL researchers needed to recreate the environment of the human intestine, which has a complex 3D structure, including "finger-like" projections called villi. This image shows our bioprinted villi (pillars extending up toward the viewer), which are implanted with human intestinal epithelial cells. I sometimes describe the image as a "bug's eye view", as this is what it would look like if you were a bacterium floating through the human intestine, looking down at the intestine landscape below you.

Photo Source: Claire Roberson, William (Rick) Hynes, and Nicholas Be