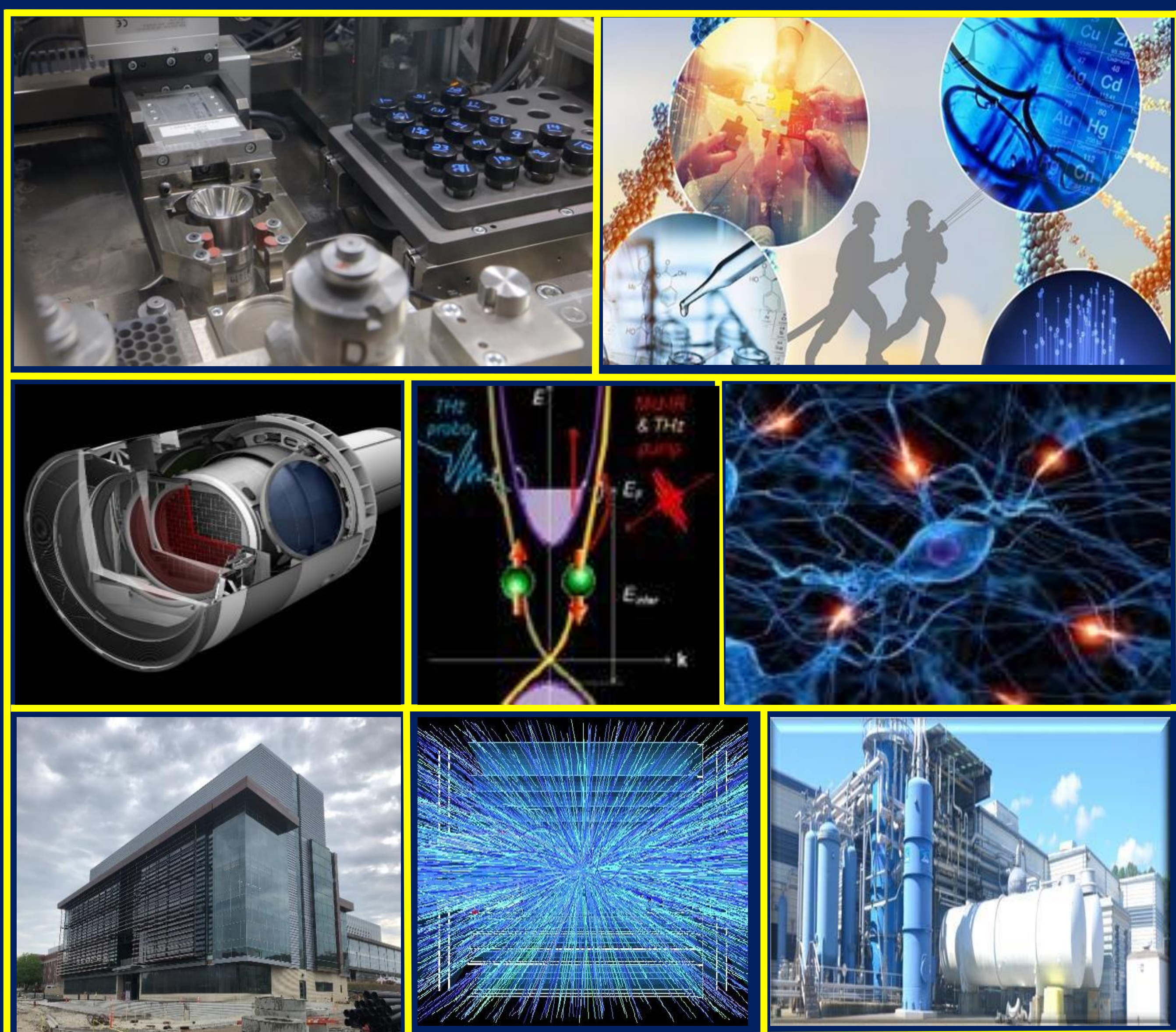
U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy's Ten-Year-Plans for the Office of Science National Laboratories FY 2019



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INTRODUCTION

The Department of Energy (DOE) is responsible for the effective stewardship of 17 national laboratories, of those ten are stewarded by the Office of Science and focus on discovery science. The DOE national laboratories were created as a means to an end: victory in World War II and national security in the face of the new atomic age. Since then, they have consistently responded to national priorities: first for national defense, but also in the space race and more recently in the search for new sources of energy, new energy-efficient materials, new methods for countering terrorism domestically and abroad, and addressing important critical national needs.

Today, the national laboratories comprise the most comprehensive research system of their kind in the world. In supporting DOE's mission and strategic goals, the SC national laboratories perform a pivotal function in the nation's research and development (R&D) efforts: increasingly the most interesting and important scientific questions fall at the intersections of scientific disciplines—chemistry, biology, physics, astronomy, mathematics—rather than within individual disciplines. The SC national laboratories are specifically designed and structured to pursue research at these intersections. Their history is replete with examples of multi-and inter-disciplinary research with far-reaching consequences. This kind of synergy, and the ability to transfer technology from one scientific field to another on a grand scale, is a unique feature of SC national laboratories that is not well-suited to university or private sector research facilities because of its scope, infrastructure needs or multidisciplinary nature.

As they have pursued solutions to our nation's technological challenges, the national laboratories have also shaped, and in many cases led, whole fields of science—high energy physics, solid state physics and materials science, nanotechnology, plasma science, nuclear medicine and radiobiology, and large-scale scientific computing, to name a few. This wide-ranging impact on the nation's scientific and technological achievement is due in large part to the fact that since their inception the DOE national laboratories have been home to many of the world's largest, most sophisticated research facilities. From the "atom smashers" which allow us to see back to the earliest moments of the Universe, to fusion containers that enable experiments on how to harness the power of the sun for commercial purposes, to nanoscience research facilities and scientific computing networks that support thousands of researchers, the national laboratories are the stewards of our country's "big science." As such, the national laboratories remain the best means the Laboratory knows of to foster multi-disciplinary, large-facility science to national ends.

In addition to serving as lynchpins for major laboratory research initiatives that support DOE missions, the scientific facilities at the SC national laboratories are also operated as a resource for the broader national research community. Collectively, the laboratories served over 37,000 facility users and more than 8,000 visiting scientists in Fiscal Year (FY) 2018, significant portions of which are from universities, other Federal agencies, and private companies.

DOE's challenge is to ensure that these institutions are oriented to focus, individually and collectively, on achieving the DOE mission, that Government resources and support are allocated to ensure their long-term scientific and technical excellence, and that a proper balance exists among them between competition and collaboration.

This year, DOE engaged its laboratories in a strategic planning activity that asked the laboratory leadership teams to define an exciting, yet realistic, long-range vision for their respective institutions based on agreed-upon core capabilities assigned to each.[1] This information provided the starting point for discussions between the DOE leadership and the laboratories about the laboratories' current strengths and weaknesses, future directions, immediate and long-range challenges, and resource needs, and for the development of a DOE plan for each laboratory. This document presents strategic plans for ten national laboratories for the period FY 2019-2029.

[1] A table depicting the distribution of core capabilities across the science and energy laboratories is provided in Appendix 1, along with the definitions for each core capability category.

AMES LABORATORY

Lab-at-a-Glance

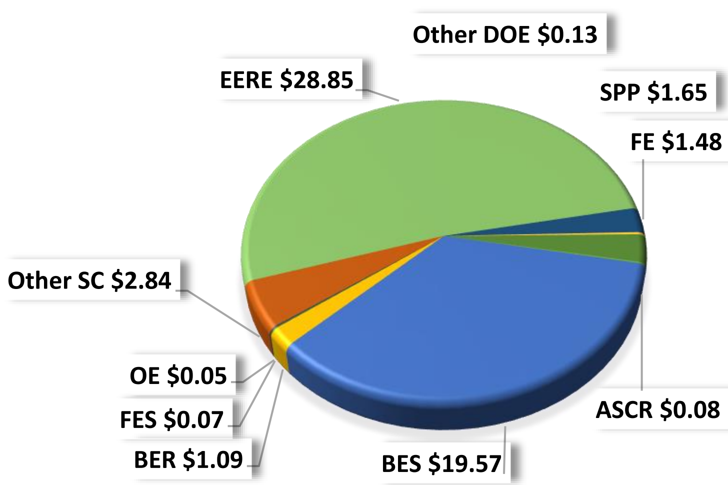
Location: Ames, IA
Type: Single-program Laboratory
Contractor: Iowa State University of Science and Technology
Site Office: Ames Site Office
Website: www.ameslab.gov

- **FY 2018 Lab Operating Costs:** $55.8 million
- **FY 2018 DOE/NNSA Costs:** $54.2 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $1.7 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 3.0%
- **FY 2018 DHS Costs:** $0 million

Physical Assets:
- 10 acres and 13 buildings
- 341k GSF in buildings
- Replacement Plant Value: $96.6 M
- 0 GSF in 0 Excess Facilities
- 0 GSF in 0 Leased Facilities

Human Capital:
- 307 Full Time Equivalent Employees (FTEs)
- 45 Joint Faculty
- 44 Postdoctoral Researchers
- 99 Graduate Student
- 81 Undergraduate Students
- 0 Facility Users
- 120 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

Ames Laboratory is a world-class institution dedicated to creating materials, inspiring minds to solve problems, and addressing global challenges. For more than 70 years, Ames Laboratory has successfully partnered with Iowa State University to lead in the discovery, synthesis, analysis, and use of new materials, novel chemistries, and transformational analytical tools. Our focus and expertise in the science of synthesis, science of quantum materials, science with rare earths, and science of interfaces positions the Laboratory as a materials research powerhouse that:

- Invents materials with new physical and chemical functionalities, especially those that harness the potential of rare-earth elements, through creative and innovative synthesis techniques;
- Determines novel physics and chemistry of materials and molecules using instrumentation developed at Ames Laboratory as well as instrumentation at the Nation's scientific user facilities;
- Shares these materials and knowledge with partners and collaborates nationwide and worldwide to advance fundamental knowledge in physics, chemistry, and materials science; and
- Promotes the applications of these materials for economic and national security through in-house activities and external collaborations

Ames Laboratory has a proven track record of transitioning basic energy science through early-stage research to licensed technologies and commercialization through Strategic Partnership Projects. Ames Laboratory advances our national and economic competitiveness while reducing technical barriers for U.S. industry. Complementing our leadership in materials discovery and materials understanding, we lead research in advancing catalytic processes, novel electronic, photonic, and magnetic materials, and rare-earth science. Ames Laboratory is addressing the global challenge of critical materials by leading DOE's Critical Materials Institute (CMI); tackling the 100-year-old technology of compressed vapor refrigeration to improve efficiency and reliability through discovery of new caloric materials and systems; and developing tools and models to address key barriers to metal additive manufacturing. Building on our core capabilities, our vision is to lead the U.S. in the synthesis and exploration of materials for next generation information and energy technologies and enhance our world-leading capabilities by advancing chemical processes in synthesis, characterization, and multi-scale theory.

Core Capabilities

The strengths of Ames Laboratory's core capabilities are key to achieving our mission to create materials, inspire minds to solve problems, and address global challenges. Ames Laboratory research is focused on transformational breakthroughs in the fundamental understanding of the chemistry and physics of materials using innovative approaches that arise from the core capabilities and our foundational strengths of science of synthesis, science of quantum materials, science with rare earths, and science of interfaces. New fundamental discoveries in the core areas of Chemical and Molecular Science and Condensed Matter Physics and Materials Science enable successes in Applied Materials Science and Engineering. Each of the three core capabilities identified by DOE's Office of Science involves interdisciplinary teams of world-leading researchers that utilize unique expertise and capabilities to address areas of national need and deliver on DOE's mission.

Ames Laboratory's core capabilities support DOE's strategic objectives, and those of DOE's Office of Science, in particular, to:

- Deliver scientific discoveries, capabilities, and major scientific tools that transform the understanding of nature;
- Strengthen the connection between advances in fundamental science and technology innovation;
- Support a more economically competitive, secure, and resilient U.S. energy infrastructure; and
- Accelerate scientific breakthroughs and develop new innovations for more sustainable U.S. energy production, conversion, and usage.

Applied Materials Science and Engineering

The application of knowledge derived from fundamental experimental, computational, and theoretical chemistry and physics research to design, discovery, and synthesize advanced materials with specific energy-, information-, and environment-relevant functionalities is a well-known strength of the Laboratory. Ames Laboratory develops, demonstrates, qualifies, and deploys materials that accelerate technological advancements in a wide range of fields—from materials that keep things cool in the European Space Agency's Planck satellite, to a lead-free solder used in virtually all electronics, to analytical techniques that can detect harmful chemicals at parts-per-trillion concentrations, to new materials for efficient electrical transmission.

Based on more than 70 years of rare-earth element research, this core capability is further strengthened by the highly successful Critical Materials Institute (CMI), a DOE Energy Innovation Hub, led by Ames Laboratory. The mission of the CMI is to assure supply chains of materials critical to clean energy technologies—enabling innovation in U.S. manufacturing and enhancing U.S. energy security. Rare-earth elements are the most prominent of the critical materials today. CMI's efforts aim to assure economically viable processing techniques for improved availability of these materials for clean-energy technologies, develop new techniques to recover materials from waste and scrap, and find acceptable alternatives to critical materials for use in devices such as generators, motors, lighting, and magnets. CMI-funded researchers have filed 115 invention disclosures, filed 55 patent applications, had eight patents issued, and licensed eight technologies.

Advances in fundamental science through BES-funded research in chemical and molecular sciences and condensed matter physics and materials has motivated expansion into applied areas, such as new catalysts for biofuel production, magnets, alloys for extreme environments, and sensors or cooling technologies with caloric materials, which are thermodynamically responsive but need better response and control. Caloric materials research is accelerating innovation by designing, discovering, and deploying materials in which reversible, thermal (caloric) response is triggered by magnetic, stress, and electric fields, or any combination of these fields. Demonstrating our ability to exploit phenomena discovered during their basic research phase of development, in less than three years of operations this research has produced 12 disclosures, five patent applications and one patent issued. We have deployed a one-of-a-kind device, CaloriSMART®, to benchmark caloric compounds.

Ames Laboratory's world-leading advanced powder processing capabilities are advancing rapid and low-loss additive manufacturing of metal and metal oxides. This is being achieved through improved process yield, powder surface quality and passivation, and particle size/shape uniformity and yield to tailor feedstock for advanced manufacturing processing by gas atomization. Working with sister laboratories, Ames Laboratory is developing tools and models to address key barriers to metal additive manufacturing. Ames Laboratory also developed an additive powder feed testbed to enable rapid process development and informed qualification of the additive manufacturing components and processes.

With our applied research in decision sciences, we work to integrate models, information, and other artifacts related to a product or process. We challenge the notion that one cannot integrate analysis into decision making on-the-fly. In partnership with the National Energy Technology Laboratory, Ames Laboratory is working to build the middleware tools needed to integrate the concepts of cyber-physical systems and digital twins into the energy system and materials development process of research and development, design, and deployment. This will create a "discovery-application feedback loop" in which newly conceived ideas can be rapidly tested and sorted, and challenges can be overcome more effectively, thus reducing the development process from decades to years.

Major Sources of Funding: Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, Office of Advanced Research Projects Agency-Energy, and Strategic Partnership Projects.

Chemical and Molecular Science

This core capability recognizes Ames Laboratory's world-leading competence in developing and applying theoretical, computational, and experimental methods to study structure and reactivity of chemical and biological materials, with emphasis of interfacial interactions relevant to catalysis and separations. These efforts support the DOE mission of addressing energy-related materials and processes, as well as environmental challenges.

Ames Laboratory improves the fundamental understanding of molecular design and chemical processes for energy needs by developing and utilizing both electronic structure theory and non-equilibrium statistical mechanical and multiscale modeling. The primary focus is on methods that enable the study of condensed-phase chemistry and surface reaction phenomena, including at liquid-solid interfaces in heterogeneous catalysis. Theory developments include fragment molecular orbital, effective fragment molecular orbital, and effective fragment potential approaches that can be applied to systems comprising large numbers of atoms. An integral component of these efforts is the advancement of computational chemistry codes, especially GAMESS and NWChemEX, and the development of interoperability between these two computational chemistry codes. Our unique competencies in theory include the development of highly scalable computational chemistry codes to take advantage of exascale computers.

We are also globally acknowledged for our research focused on bringing together homogeneous and heterogeneous catalysis by developing 3D interfacial catalysts that combine the best characteristics of both to mediate efficient reductive transformations under less forcing reaction conditions. Our core capabilities include synthetic techniques, rigorous spectroscopic characterization, and mechanistic studies. The focus is upon reduction of functional groups that are abundant in biorenewable compounds and energy-relevant molecules, whose conversion suffers from a lack of selective and energy efficient catalytic processes. An entirely new approach that further advances our core capabilities in interfacial chemistry aims to create a new generation of cooperative catalysts that enable chemical upcycling of energy-rich macromolecules and thereby help to effectively utilize hydrocarbon polymer waste. This Ames Laboratory-led team project is developing new catalytic methods for upcycling hydrocarbon-based polymers and establish principles of cooperativity in catalytic materials that are specifically designed to interact with macromolecules on multiple length scales.

Central to the success of our chemical sciences programs are advances in the development, implementation, and applications of world-leading characterization tools. Atomic-scale characterization of catalysts, energy storage materials and other solids is available through state-of-the-art solid-state nuclear magnetic resonance (NMR) technologies, including ultrafast magic-angle spinning and dynamic nuclear polarization (DNP) NMR. These methods are being advanced in our Laboratory to reach groundbreaking sensitivity and resolution levels. We have also developed and applied in situ Raman imaging to measure the distribution of biomolecules important for energy capture within the plant tissue and continue to develop other chemical analysis tools that enable us to measure biological function in live plants and study spatial and chemical inhomogeneities in separation media with unprecedented spatial resolution.

Looking forward, we will further expand our synthesis methods, analytical tools and theory. By combining advances in exascale computing, quantum chemistry, data driven science, catalysis, separation science, and world-class characterization tools we will ensure that Ames Laboratory continually strengthens its research programs and guides the scientific discourse in chemical and molecular science.

Primary Source of Funding: Office of Science.

Condensed Matter Physics and Materials Science

Ames Laboratory is a leader of condensed matter physics and materials science within the national scientific enterprise. Specifically, Ames Laboratory has been at the forefront of research in rare-earth science and novel electronic and magnetic materials since the Laboratory was started, seven decades ago. Ames Laboratory provides the Nation with the highest quality materials for conducting fundamental research, invents new materials, and provides key insights into the fundamental physics and chemistry of these materials. We do this by working collaboratively both within the Laboratory and with external collaborators. It is the deep understanding that Ames Laboratory has in precision and demanding synthesis of the highest quality materials that allows the science community to disentangle the truly novel physics and chemistry from inherent impurity-caused materials issues that so frequently impact the scientific enterprise’s understanding of the nature of materials.

Ames Laboratory continues to improve and bolster its core capability in Condensed Matter Physics and Materials Science by carrying out leading experimental and theoretical research in the science of synthesis, science of quantum materials, science with rare earths, and the science of interfaces.

Synthesis: We are continuing to develop our in situ and in operando capabilities, guided by theory, to enable direct observations of nucleation, growth of many metals, intermetallics and self-assembly of nanoparticles using advanced TEM techniques at the SIF. We have established a new materials system for tunable quantum materials with strong spin orbital coupling and non-centrosymmetric symmetry, key structural features in materials exhibiting topologically protected states and 3D heterostructures.

Quantum materials: Ames' new Energy Frontier Research Center for the Advancement of Topological Semimetals (CATS) will underpin our effort to understand and discover new quantum phenomena and functionality in topological materials. A new FWP in 'Light-Matter Quantum Control: Coherence and Dynamics' is using ultra-short mid-infrared and terahertz pulses to isolate and control the surface properties of photovoltaic materials. These methods are also proving invaluable in understanding quantum coherence in 3D topological insulators and superconductors. Our experimental efforts are underpinned by new theory tools to understand and control emerging 2D phenomena with special emphasis on magnetic spin states.

Rare earths: Rare earth research remains a strong focus in the area of materials design and prediction, from unique magnetic and quantum phenomena to developing the understanding on how to manipulate their phase transitions for energy harvesting. Our theoretical efforts in first principles methods development are advancing our understanding of strongly correlated systems and guiding materials discovery and synthesis in this area.

Interfaces: Understanding and controlling interfaces spans a wide range of phenomena that includes control over the propagation of light with matter, guiding self-assembly and engineering interfaces that control phase transformations, both in growth of solids from the liquid and solid-state transformations. We continue to develop unique methods coupled to advanced theory to expand dynamic nuclear polarization NMR to a wide range of materials challenges. We are advancing theory for predicting self-assembly and solid-state phase transitions.

Accelerating materials discovery is a key motivation in developing computational methods for the scientific community. This is accomplished by developing methods to better understand functional materials using quantum Monte Carlo simulations, self-consistent electronic structure calculations incorporating total energies, spin excitations spectra, and classical and quantum molecular-dynamics simulations. Understanding synthesis far-from- equilibrium requires new algorithms to predict the structure and properties of complex materials. Pioneering theoretical methods with innovative numerical algorithms are being created to enable computational discovery of new materials and to fashion materials by design using DOE's significant leadership computing resources. These methods serve to guide experiments and reduce the time needed to develop advanced materials to serve the Nation's energy needs. These capabilities in theory and discovery bolster Ames Laboratory's capabilities in Material Science and enable the DOE to maintain world leadership.

While Ames Laboratory has developed science and capabilities to utilize the full palette of the periodic table to achieve its mission, it continues to develop the fundamental science and synthesis methods of rare-earth materials. From its unique facilities to produce, process, manipulate, and characterize rare-earth materials to the highly visible BES projects and applied programs such as the Critical Materials Institute (CMI) and caloric materials research and systems, all have benefited from and contributed to sustaining this key core capability. Basic research on rare earths at Ames Laboratory is distinguished by its strong tradition of inspiring and enabling novel energy technologies such as magnetostrictive actuators and magnetic refrigeration. The applications of rare earths have evolved rapidly over the years. While intuition, serendipity, and trial-and-error have been successful strategies in the past, modern demands for precise tuning and control require a clear theoretical basis and the mining of huge physicochemical datasets.

Primary Source of Funding: Office of Science

Science Strategy for the Future

Ames Laboratory's science strategy builds on our foundational pillars – science of synthesis, science of quantum materials, science with rare earths, and science of interfaces – to enable impactful advances in chemical and molecular sciences, condensed matter physics and materials, and applied materials science that will transform science and lead to technological breakthroughs. We have designed two strategic initiatives to bolster our foundational strengths and further integrate our science amongst the pillars and core capabilities. The chemical sciences and synthesis, and exploitation of novel states and emergent phenomena initiatives leverage the Laboratory's scientific capabilities, focus on our highest priority research directions, and position Ames Laboratory to continue to make impactful scientific advances.

The scientific strategy of the 2019 Ames Laboratory Annual Laboratory Plan is based on our recent Strategic Plan, which describes important directions and targets of opportunity in materials discovery that are needed to address key scientific challenges for upcycling of polymers, quantum information and sensing, next generation computing technologies, quantum states and materials, and energy conversion and harvesting technologies. Wherever possible, we will cultivate these advances for applications to benefit U.S. economic, energy, and national security interests.

Infrastructure

Overview of Site Facilities and Infrastructure

Ames Laboratory is located in Ames, Iowa on the campus of Iowa State University (ISU). The Laboratory occupies 10 acres of land leased from ISU with 13 DOE-owned buildings. There are four research buildings, an administrative building, and eight support buildings on the campus. The Ames Laboratory campus consists of 340,968 gross square feet (GSF) with a replacement plant value (RPV) of $96.6M. At the end of FY 2018, our workforce included 307 full-time equivalent (FTE) employees, or 473 people in the Laboratory workforce.

The four research buildings are for general use and support research for all three of our core capabilities: (1) applied materials science and engineering, (2) chemical and molecular science, and (3) condensed matter physics and materials science. The three older research buildings (Harley Wilhelm Hall, Spedding Hall, and Metals Development) on the main campus range from 58 to 70 years old. The buildings have good structural integrity, but they were designed for research needs of the mid-1900s. These three buildings were rated "Substandard" in the 2014 DOE Laboratory Operations Board (LOB) infrastructure survey (68.6% of the GSF). The remaining DOE-owned buildings were rated as "Adequate" (31.4% of the GSF).

Ames Laboratory has no utility generating plants; the Laboratory receives its utilities from the City of Ames, Iowa State University, and Alliant Energy. Electricity is purchased through the local municipality (City of Ames). Water, steam, chilled water, and natural gas are purchased through ISU. Natural gas for the support buildings is purchased from Alliant Energy. ISU has updated utility systems that support Laboratory operations. Since 2015, ISU has upgraded its distribution systems for electricity and chilled water, and also converted some of its boilers from coal to natural gas. Future plans include updates to the storm and sanitary sewers, power, and the conversion to natural gas for more boilers. ISU's $74M investment in infrastructure improvements that have made a positive impact on Ames Laboratory operations.

Harley Wilhelm Hall
(1949)

Spedding Hall
(1953)

Metals Development Building
(1961)

Technical & Administrative Services Facility (1995)

Sensitive Instrument Facility (SIF)
(2015)

Shop Buildings and Warehouse
(1964-1991)

Campus Strategy

Ames Laboratory relies on unique laboratory and midscale scientific infrastructure, as well as national user facilities, to meet its mission. Judicious investment in Ames Laboratory facilities and infrastructure has expanded the potential of our highly skilled staff and motivated new opportunities to impact the scientific community. As we continually advance such facilities and capabilities, we also continuously improve upon the collaborative Ames Laboratory scientific competencies.

The Sensitive Instrument Facility (SIF) provides Ames Laboratory with an advanced platform to continue the pursuit of science-driven development and operation of state-of-the-art analytical tools, as well as specialized laboratory environments that enable rapid onsite analysis of materials to expedite discovery. It is the instrumentation and computational resources (atomic to macroscale capability) of our midscale scientific infrastructure within Ames Laboratory that provide the Laboratory with a competitive advantage to deliver high impact science and achieve scientific breakthroughs.

Goal two in our Strategic Plan, Mission-enabling Infrastructure and Facilities, prioritizes investments for success of the Laboratory's strategy. Given the general purpose of our facilities, each project supports our core competencies of 1) Applied Science and Engineering, 2) Chemical and Molecular Science, and 3) Condensed Matter Physics and Materials Science.

Current Gaps

The Laboratory utilizes the Mission Readiness process to review existing facility improvement requests and identify new ones for consideration. Then we use the Capital Asset Management Process (CAMP) and management review to develop a prioritized set of project requests. In the Lab Plan investment table, the Laboratory identified $49.5M in facility needs (GPP investments). The facility needs consist of 12 large projects, some of which are broken into phases, to modernize the oldest buildings at the Laboratory. More than 95% of the facility needs identified are for the three older research buildings ($47.5M).

To address the facility needs of its aging facilities, the Laboratory recommends that $4M of capital funding be invested each year for the next 12 years. This sustained level of capital funding represents a volume of work that the Laboratory can effectively manage and helps with staff capacity planning. The buildings must remain operational during major renovations and infrastructure upgrades, and utilities interruptions must be limited in order to avoid negative impacts to our research mission. The Laboratory is limited to the amount of space it can free up for a project because it does not have alternate space available to temporarily move activities. This additional coordination extends the duration for a majority of the improvement projects.

In our mission readiness review, several recurring gaps were identified for all three of our older research buildings.

Fire Alarm and Emergency Notification Systems: These systems have come to the end of their useful life across the complex. Corrective maintenance efforts and costs continue to increase as the Laboratory tries to maintain the aging systems and correct increasing frequency of malfunctions. A complete replacement of the fire alarm system, including the installation of control panels, detection devices, fire alarm devices, mass notification LED signage, and new wiring is needed. The upgrade of the fire alarm and emergency notification systems across the Ames Laboratory complex will provide assurance the systems are working accurately, while also improving the Laboratory's capabilities to effectively communicate fire, severe weather situations, and any other safety notifications.

Building Envelopes: Building envelopes include roofs, exterior walls, windows, and other exterior building systems. All three general use research buildings are in need of upgrades or repairs to the building envelopes. When investments lead to improvements, GPP funds are used. When investments are focused on repairs, overhead funds are used. The next project being planned will strip off the roofs to the three primary research buildings in order to add insulation to improve energy efficiency and to improve each building's ability to protect people and equipment. New roofing will be a white roof system that will add to energy efficiency and eliminate the need for damaging ballast. The improvement will add at least 25 years to the life of the buildings.

Backup-Emergency Power & UPS Systems: The two existing diesel generators used for backup/emergency power on the main campus are past their useful life and do not have the capacity to add additional backup/emergency loads for new equipment. They can only handle 25% of the total electrical demand of the Laboratory; enough for life/safety systems only. Currently, critical research equipment, information technology equipment, and operational equipment are protected by many decentralized UPS systems (most at point of use). These systems require various forms of maintenance, upkeep, and upgrades, which demands a great deal of effort and coordination. A centralized UPS system for each mission critical building would benefit the Laboratory by improving uptime and providing facility-wide protection for sensitive electronics. These larger UPS systems are also capable to ensure critical systems will keep running during power disturbances such as blackouts, brownouts, sags, surges, or noise interference.

Plumbing: Most of the water supply piping and sewer drain piping are original to their respective buildings. These systems were evaluated as deficient during the 2014 LOB Infrastructure Assessment. The number of water leaks, complaints of sewer smells, and clogged drains has increased dramatically over the last couple of years in the three older research buildings. The Laboratory inspected the sewer lines below the concrete floors utilizing cameras in FY 2016 and conducted surveys of pipe chases in FY 2018. The original sewer lines under the concrete floors and in the vertical pipe chases are deteriorating. Major cracks were also found and repaired in several sewer drains behind vertical chase enclosures in FY 2017 and FY 2018.

Condition of Research Laboratories: Another critical gap is the condition of the research laboratories. The 2014 LOB infrastructure survey identified 101,000 square feet of space as being in poor or fair condition. Many of these laboratory spaces have original fixtures, rusted cabinets that are hard to operate, pocked work surfaces from chemical exposure, asbestos containing materials, and inadequate lighting. In FY 2017, the Laboratory renovated 6,600 square feet of laboratory space in poor and fair condition and renovated another 6,100 square feet of lab space in FY 2018. Overall, the Laboratory has renovated 21,000 square feet of space since the 2014 LOB survey, improving about 20% of spaces. Our capacity to renovate space is approximately 4,000 to 6,000 square feet per year. With 80,000 square feet of lab space remaining in poor or fair condition, it would take the Laboratory approximately 15 to 20 years to bring these spaces to adequate condition.

Helium Recovery: The low-temperature laboratory (LTL) needs several important upgrades to support the Ames Laboratory mission. Having in-house helium liquefaction and recovery services has several advantages. First, it enables short-term planning. During normal operation of the LTL, research efforts can obtain liquid helium essentially on demand (about one day compared to a week or more for commercial suppliers). Second, despite costs associated with support of LTL operation included into cost of liquid helium for research groups in Ames Laboratory, in-house liquefaction provides notably cheaper liquid (current rate is $7/liter) than the cheapest market options (the cost of liquid helium ranges in the U.S. between $8 to $20 per liter). Third, in-house production makes delivery independent of varying Midwest weather conditions, which can impact delivery. Supply of liquid helium in quantities necessary for complete laboratory operation (currently it is about 5,000 liters per month) is not feasible with local providers. Finally, the global advantage of saving helium gas helps to address the challenge of a limited worldwide supply of helium.

Telecommunications Infrastructure: The Laboratory lacks the physical telecommunications infrastructure needed for current and future computing needs. Physical cabling, conduit, raceway, and telecommunications closets were not a consideration when the three research buildings were built. The majority of emerging technologies require the fast and efficient transmission of data from sensors and devices and greater bandwidth than is currently available.

Electronic Access Control: Electronic access control is another gap. Starting under the American Recovery and Reinvestment Act (ARRA), the Laboratory began converting its door access from physical keys to electronic proximity card readers. Once the ARRA funds were exhausted, the Laboratory allocated GPP funds to continue to make progress in the conversion. The exterior doors, the property protection areas for the site, and the interior doors for two buildings were completed. This electronic system provides the staff a greater amount of control for access situations and helps to provide better safety, security, and accountability for room use. For instance, the exterior doors of the Laboratory are open throughout the day. With the electronic access control system, it would only take one command to lock down all Laboratory exterior and interior doors in the case of a significant security or safety incident. However, most of the interior doors in Spedding Hall and Metals Development are still physical key access only and require conversion to electronic card access.

Building Maintenance & Repair: The maintenance program, funded from overhead dollars, consists of activities necessary to keep the existing inventory of facilities in good working order and extend their service lives. It includes regularly scheduled maintenance, corrective repairs, and periodic replacement of components over the service life of the facility. It also includes facility management, engineering, documentation, and oversight required to carry out these functions. The condition of the research buildings has been maintained even as they age beyond normal service life. The Laboratory anticipates it will need to continue to operate in the older buildings over the 10-year window of this plan. Historically, the Laboratory has invested approximately 2% of Replacement Plant Value (RPV) per year into maintenance and repair activities. This level of resources has been able to control deferred maintenance in the buildings. However, the combination of limited capital improvements and aging facilities has placed a greater demand on maintenance resources. Just maintaining the condition of the facilities does not ensure they will continue to meet the needs of research activities. Maintenance and repair expenditures were increased to approximately 2.8% of RPV in FY 2016, and 2.4% of RPV in FY 2017 and FY 2018 to aid in replacing aging components and keeping up with deferred maintenance.

Investment Summary

The Laboratory made significant progress in FY 2018 with the electrical upgrades in Metals Development and Wilhelm Hall, the window replacement in Spedding Hall, and the design for the new air handlers in Metals Development. Through continued investment, we plan to fulfill our Strategic Plan objectives and goals to provide facilities to support scientific objectives, to provide infrastructure that supports mission readiness, and to pursue opportunities for future scientific capabilities. The Laboratory received additional SLI-GPP funding ($3,492K) in June 2018 to support Mission Enabling Space Renovations at the Laboratory. This funding is being used to renovate approximately 10,000 square feet of research and office space. Design is currently underway for Phase 1 of this project – renovating 5,000 square feet of space on the 3rd floor of Spedding Hall for DNP expansion and NMR consolidation. This investment by DOE will allow the Laboratory to accelerate its investment planning and accelerate the positive impact on our mission.

To address the gaps in our facilities and infrastructure, the Laboratory is requesting to sustain the funding level of BES-GPP at $1,000K per year. The Laboratory is also requesting sustained SLI-GPP funding of $3,000K per year for FY 2020 and beyond. Ames Laboratory plans to fund maintenance and repair activities through overhead at over 2.0% of RPV for the duration of this plan. Deferred Maintenance (DM) is projected to drop from $1,200K to $550K over the next 12 years. Support of this investment strategy will result in the three older research buildings moving from “Sub-Standard” to “Adequate” for their Overall Asset Condition.

We have aligned planned infrastructure activities with our Strategic Plan objectives, as follows:

Objective 1: Provide facilities that support our scientific objectives. Research equipment was installed in the three new research bays at the SIF. The Laboratory received SLI-GPP funding in June 2018 to support our Mission Enabling Space Renovations project ($3,492K total). The Laboratory will update and modernize approximately 10,000 square feet in Spedding Hall. Phase 1 of the project is currently in design and will renovate approximately 5,000 square feet in Spedding Hall for Dynamic Nuclear Polarization (DNP) research expansion, and Nuclear Magnetic Resonance (NMR) research consolidation.

Objective 2: Provide infrastructure that supports mission readiness. The Laboratory significantly improved its infrastructure in FY 2018. Construction for the Upgrade of Electrical Systems in Mission Critical Buildings ($2,000K) and Upgrade of Spedding Hall Windows ($1,300K) was started in FY 2018 and will be finished in FY 2019.

Design for the Upgrade Fire Alarm and Emergency Notifications Systems project will start in FY 2019 utilizing BES-GPP funding. The Laboratory is requesting $4,000K in GPP funding for FY 2020 to deal with critical infrastructure issues including: Upgrade Emergency-Backup Power Systems and Upgrade Building Envelopes on Mission Critical Buildings. The Laboratory is requesting S3,000K in Safeguards and Security (S&S) funding in FY 2020 for access control upgrades. We are requesting sustained funding of $1,000K per year (BES-GPP), and $3,000K per year (SLI-GPP) from FY 2020 to FY 2031. The focus during the next 12 years will be on these projects: Upgrade Plumbing Systems in Mission Critical Buildings, SLI Mission Readiness Renovations, BES Mission Readiness Renovations, Improvements for Helium Recovery Operations, Building UPS Systems, Upgrade Network Cabling and IT Rooms, and Upgrade Network to 100GB.

Objective 3: Pursue opportunities for future scientific capabilities. Discussions during Strategic Planning and Mission Readiness have guided the Laboratory to consider repurposing several areas across the campus to support future research activities. New research initiatives will be defined with supporting facilities and infrastructure projects. The Paint & Air Conditioning Shop, the Records Storage Building, and some spaces in Metals Development are being considered for supporting new activities.

Site Sustainability Plan Summary

Ames Laboratory's commitment to meet the DOE sustainability goals through projects, tasks, and activities begins with the integration of the Environmental Management System (EMS) into the Integrated Safety Management System (ISMS) to ensure the implementation of safety and environmental management in all aspects of Laboratory work, from planning to completion.

Ames Laboratory uses its Environmental Management System (EMS) and the associated Steering Committee (EMSSC) as a vehicle to provide awareness of the objectives and targets to Laboratory employees. The EMSSC has adopted the Site Sustainability Plan objectives and targets and proposes initiatives to assist in the achievement of these goals.

The age of facilities makes it very challenging to achieve energy efficiency and sustainability. However, Ames Laboratory continues to make progress, and our success in purchasing renewable energy in the form of wind power has been praised by DOE's Sustainability Performance Office. In FY 2016, NREL screened Ames Laboratory for cost-effective renewable energy opportunities that would lower the site's 25-year lifecycle cost of energy. This screening found that while there is an incentive for Photovoltaic (PV) use, the low cost of utility electricity and average solar resource makes it difficult for PV to be cost-competitive.

Ames Laboratory met the fleet reduction goal of 35%, and 75% of the remaining fleet vehicles are Alternative Fuel Vehicles (AFV). Ames Laboratory increased its usage of AFV by 1,488% from FY 2005 to FY 2017 and met the overall goal of 10% annual increase between 2005 and 2015.

Ames Laboratory completed installation of required advanced electric meters in FY 2010 and is in the process of identifying and prioritizing sub-metering to better track progress toward sustainability goals.

Ames Laboratory achieved compliance with the High Performance and Sustainable Buildings (HPSB) guiding principles, but with the addition of the SIF, the compliance fell to 12.5%, short of the 15% goal. The SIF meets the requirements for LEED Certified, but did not achieve the required energy efficiency of 30% below the current ASHRAE 90.1 standard, only meeting 19 of the 20 required metrics for 2016 HPSB guiding principles. We continue to implement the guiding principles in all of the major buildings where it is economically justified to ensure 17% of existing buildings are compliant by 2025.

ARGONNE NATIONAL LABORATORY

Lab-at-a-Glance

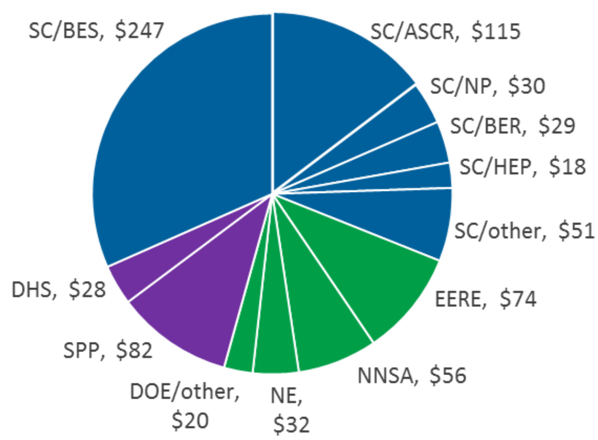
Location: Lemont, Illinois
Type: Multi-program Laboratory
Contractor: UChicago Argonne, LLC
Site Office: Argonne Site Office
Website: www.anl.gov

- **FY 2018 Lab Operating Costs:** $782 million
- **FY 2018 DOE/NNSA Costs:** $672 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $82 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 14%
- **FY 2018 DHS Costs:** $28 million

Physical Assets:
- 1,517 acres and 154 buildings
- 5.0 million GSF in buildings
- Replacement Plant Value: $3.8B
- 0.02 million GSF in 16 Excess Facilities
- 0.3 million GSF in Leased Facilities

Human Capital:
- 3,237 Full Time Equivalent Employees (FTEs)
- 343 Joint Faculty
- 260 Postdoctoral Researchers
- 270 Graduate Student
- 325 Undergraduate Students
- 7,921 Facility Users
- 790 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

Argonne National Laboratory accelerates science and technology to drive US prosperity and security. Based in the Chicago suburbs since 1946, Argonne is managed for the US Department of Energy (DOE) by the University of Chicago (UChicago) through UChicago Argonne, LLC.

The Laboratory conducts research that spans the spectrum from basic science to engineering solutions that change the world for the better. Argonne's scientists and engineers are recognized nationally and internationally for leadership in:

- Creating new knowledge through pivotal discoveries in chemistry; materials; nuclear and particle physics; and life, climate, and earth system sciences
- Driving advances in computation and analysis to solve the most challenging problems
- Shaping the nation's future through engineering of advanced technological systems

We build on our discoveries and innovations to improve energy production, storage, and distribution; protect critical infrastructure; and strengthen national security.

The powerful capabilities of our Advanced Photon Source (APS) and Argonne Leadership Computing Facility (ALCF) propel breakthroughs across our broad research portfolio. We are upgrading both of these flagship user facilities, which also serve external researchers: the ALCF will deploy the nation's first exascale computer in 2021 and the APS will be the world's leading hard x-ray microscope by 2025. Three additional major facilities accelerate scientific progress by Argonne and external researchers: the Argonne Tandem Linear Accelerator System, Atmospheric Radiation Measurement Climate Research Facility's Southern Great Plains Site, and Center for Nanoscale Materials. Together, these five facilities serve one of the largest scientific user communities in the DOE complex.

A diverse network of partnerships enriches Argonne's work and enhances the value we deliver to America. Those partnerships include research collaborations with UChicago, other leading universities, and other national laboratories as well as technology transfer collaborations with industry. We support the Chicago region and the nation through community outreach and educational opportunities for the next generation of researchers.

Argonne is committed to extending our proud legacy of unlocking science and technological frontiers to secure America's energy future and deliver economic growth.

Core Capabilities

Argonne's broad base of expertise in science and engineering, which comprises 18 of the 24 core capabilities defined by DOE for its laboratories, is a powerful asset to meet key national needs for scientific and technological leadership. We use these capabilities to advance the missions of our sponsors as we accelerate science and technology to drive US prosperity and security.

Our multifaceted R&D portfolio enables our scientists and engineers to deliver groundbreaking discovery science and innovative solutions to critical challenges in energy, security, and infrastructure. Our collaborations with UChicago, other universities, other DOE laboratories, and industry enrich our contributions to the nation.

Partnerships with UChicago are integral to our research programs. These partnerships include long-standing collaborations between individual researchers as well as enterprise-level collaborations. Examples of the latter include the Center for Molecular Engineering (CME), an Argonne-based partner to UChicago's Pritzker School of Molecular Engineering, and the Chicago Quantum Exchange (CQE), based in that School. The CQE, an intellectual hub for advancing quantum information science (QIS), is anchored by UChicago, Argonne, Fermilab, and the University of Illinois at Urbana-Champaign. It also includes the University of Wisconsin at Madison, Northwestern University, and six corporate partners.

Another example of an enterprise-level collaboration between Argonne and UChicago is the Joint Task Force Initiative (JTFI), launched in 2018, in which Fermilab also participates. The JTFI includes investments by UChicago in the two laboratories, with the goal of driving development of high-impact research programs that draw on the combined strengths of the three organizations.

Our core capabilities, listed below and summarized on the following pages, lie in basic research, early stage applied R&D, and major facilities. The expertise of our scientists and engineers both supports, and is supported by, our suite of large-scale experimental facilities that also serve thousands of researchers from outside Argonne. Those foundational facilities include four on our Illinois site and one in Oklahoma:

- Advanced Photon Source (APS)
- Argonne Leadership Computing Facility (ALCF)
- Argonne Tandem-Linac Accelerator System (ATLAS)
- Atmospheric Radiation Measurement Climate Research Facility's Southern Great Plains (ARM-SGP)

- Center for Nanoscale Materials (CNM)

Accelerator science and technology	Condensed matter physics and materials science
Advanced computer science, visualization, and data	Cyber and information sciences
Applied materials science and engineering	Decision science and analysis
Applied mathematics	Large-scale user facilities and advanced instrumentation
Biological and bioprocess engineering	Nuclear and radio chemistry
Chemical and molecular science	Nuclear engineering
Chemical engineering	Nuclear physics
Climate change sciences and atmospheric science	Particle physics
Computational science	Systems engineering and integration

Table: Argonne National Laboratory core capabilities

Accelerator science and technology

Capability

Argonne's accelerator science and technology capabilities center around the APS, ATLAS, and the Argonne Wakefield Accelerator (AWA) and range from electron storage rings and linear accelerators operated as x-ray sources to hadron linear accelerators and advanced accelerator technology. This portfolio of expertise is the foundation for our successful operation of a suite of facilities that support a broad range of scientific research; it also forms the basis for developing enabling technologies for future research and facilities at Argonne and other institutions. Activities among facilities are coordinated and communicated via the Argonne Accelerator Institute.

The nearly 200 Argonne scientists and engineers who work in this field are recognized internationally for their expertise in six areas:

- *Modeling, design, and operation of photon sources, electron accelerators and storage rings, X-ray free electron laser seeding and oscillators, and insertion devices, particularly superconducting undulators.* We have complementary expertise in beam diagnostics, stability and feedback systems, and vacuum system engineering. All of these capabilities underlie the APS Upgrade (APS-U) project as well as future X-ray sources at Argonne and elsewhere in the DOE complex
- *Generation, acceleration, and reliable delivery of stable- and rare-isotope ion beams* serving nuclear physics research at ATLAS. We support several DOE and worldwide accelerator initiatives using expertise gained at ATLAS over the past 40 years in linear accelerator design and modeling and in the design and development of state-of-the-art superconducting radio-frequency cavity systems for ion accelerators. We are leveraging our unique expertise and infrastructure for superconducting cavity production, testing, cleaning, and processing to support five major efforts. Those efforts are the APS-U bunch-lengthening system, cryomodule production for the SLAC National Accelerator Laboratory's Linac Coherent Light Source II, the Proton Improvement Plan II project at Fermilab, the Facility for Rare Isotope Beams at Michigan State University, and R&D for a future electron ion collider
- *Advancements in high-gradient, two-beam acceleration using dielectrically loaded structures,* in support of high-energy physics research. This work is centered at the AWA, a unique facility combining the world's highest electron bunch charge produced by a photocathode gun with a state-of-the-art linear accelerator and beam instrumentation. Using the AWA, we are currently

working to evaluate emittance manipulation techniques in support of future capabilities in photon science. The AWA also is open to the user community for general accelerator R&D in structure and plasma wakefield acceleration, radiation generation, and electron source development.

- *Areas vital to future accelerators and colliders,* including high-power radio frequency sources, generation and preservation of high-brightness beams, photo-injectors, collective beam instabilities, and two-beam acceleration with high transformer ratios. This research is synergistic with our work to improve the performance of light sources and colliders and address national security applications.
- *State-of-the-art accelerator modeling and controls:* our advanced accelerator modeling codes *elegant* and TRACK are used worldwide and we develop EPICS software tools and applications for distributed control systems for accelerators.
- *Support for accelerator outreach, training, and education* via the US Particle Accelerator School based at Fermilab, the summer undergraduate Lee Teng Fellowship in collaboration with Fermilab, and the DOE-funded graduate accelerator education program led by Michigan State University.

Mission relevance and funding

This capability supports the broad DOE/SC mission to enhance the capabilities of its current accelerator-based scientific user facilities while driving development of next-generation user facilities. Current sponsors include DOE/SC-BES, -HEP, and -NP and DOE/NNSA.

Advanced computer science, visualization, and data

Capability

Argonne is a leader in computer science, visualization, and data. We are recognized for our innovation in extreme-scale systems software, scientific software productivity, and high-performance computing tools for data-intensive science. This leadership is critical to achieving DOE's exascale computing objectives.

We will continue to enhance and promote this capability and will build new capacity in these areas:

- Foundational computing software and algorithms Foundational computing software and algorithms for quantum and neuromorphic computing, with a focus on software and methods for science
- Automation of scientific discovery through machine learning, cloud computing, and high-performance computing; this includes platforms to support the basic and applied sciences
- New concepts and strategies that capitalize on our work in data visualization, analysis, and management for the capture, transport, reduction, transformation, storage, and understanding of data in DOE applications
- New systems architectures for end-to-end computing to enable progress from today's sensing-analysis-simulation-reasoning-control approach to tomorrow's fully automated science, leveraging our expertise in system software, distributed computing, and high-performance computing
- New fundamental concepts and techniques to support and enhance scientific simulations and data analytics reliability and correctness through advanced resilience, data reduction, and error analysis

Examples of ways in which Argonne's computer science enhances multiple disciplines include the following:

- The SciDAC-4 Rapids Institute for Computer Science and Data is enhancing data analysis capabilities in four strategic research areas:
    - In hard x-ray science: data transfer from APS to ALCF, real-time analysis, and parallel algorithms
    - In materials and chemistry: integrated modeling, analysis, and ultrafast imaging of nanocrystals
    - In physics: high-performance computing analysis of cosmological and accelerator physics models and experiments
    - In applied materials: novel active learning for additive manufacturing
- Development of novel wireless sensor networks for science: the Waggle project is enabling a new breed of reliable sensors for smart-city applications and sensor-driven environmental science, and the Array of Things project is deploying them in Chicago
- Development of DLHub for materials and chemistry research: This self-service platform for publishing, applying, and creating new machine learning and deep learning models makes it easier for researchers to benefit from advances in those technologies
- Acceleration of data transfer and sharing speeds among DOE laboratories and partners: Advanced data-analysis-informed enhancements to the Globus data management service that increased performance across ESNet 100-gigabit/second links, in some cases by 50%
- 2018 DOE Early Career Research Program award for research into scalable data-efficient learning for scientific domains
- Two 2018 R&D 100 awards: one for Darshan, a software package for investigating and tuning input-output behavior of high-performance computing applications, and one for Swift/T, a software package for running large workflows on parallel computers

Argonne-developed software is also tested and deployed at the National Energy Research Scientific Computing Center at Lawrence Berkeley National Laboratory and at the Oak Ridge Leadership Computing Facility. Argonne and Fermilab are exploring the future of data storage and networking by leveraging unique Illinois networking infrastructure. Production supercomputer systems worldwide use Argonne's research software tools, and, in exascale computer science, we are highly regarded for our development of operating system and runtime software. We are also involved in managing and executing DOE's research plan for exascale computing, and we maintain partnerships with researchers in Japan and Europe.

Mission relevance and funding

This capability supports the DOE/SC-ASCR mission to develop and deploy high-performance and leadership computing resources for scientific discovery. Additional current sponsors include DOE/ECP; DOE/SC-BER and -BES; NIH; NIST; DOD, and NSF. Much of this additional funding supports co-design activities, basic and applied research, and interdisciplinary research partnerships with scientists in various application areas.

Applied materials science and engineering

Capability

Argonne applies internationally recognized expertise in materials development, synthesis, processing, and scale-up to drive advances in clean energy technologies. Applied and basic science teams from across the Laboratory do this work using a unique suite of resources. Those resources include materials characterization at the APS and CNM; computational science using the ALCF; one-of-a-kind facilities for materials synthesis and for fabrication and testing of components and devices; CME expertise; and process R&D and scale up of materials in our DOE/EERE-funded Materials Engineering Research Facility (MERF).

The capabilities in the MERF enable scientists and engineers to bridge the gap between bench-scale science and industrial implementation. Researchers develop scalable processes and advanced manufacturing techniques to produce innovative materials in sufficient quantities to enable industrial testing and accurate cost modeling.

Argonne is a leader in creating innovative materials and applying those materials to real-world challenges. For example, we develop thin films and nanostructured materials, using both atomic layer deposition and enhanced vapor deposition, and extend those technologies to a variety of high-performance applications, including fuel cell catalysts, solid-state lighting, radio-frequency energy harvesting, and advanced communication devices. In other work, we develop ultracapacitor materials for transportation applications and membrane materials and systems for gas- and liquid-phase separation, for uses such as hydrogen production, biofuels processing, lithium metal manufacture, and water treatment and reuse. An expanding focus is the recovery and reconstruction/upcycling of specialized materials, with the establishment of the DOE/EERE-funded ReCell Center focused on recycling of lithium-ion batteries.

Our applied materials science and engineering has produced more-efficient batteries, new solar panel designs, high-performance sponges for oil adsorption, nanofiber magnets, high-performance lubricants, and improved nuclear energy fuels and materials. Ongoing work has shown promise for more-efficient nuclear fuel reprocessing, lighter-weight transportation alloys, advanced energy storage devices, and higher-performance superconducting materials for use in detectors, accelerators, and energy transmission.

We are expanding the MERF to provide additional laboratory and collaborative space to enable additional materials manufacturing, synthesis, and processing capabilities for varied application domains.

Argonne's nuclear materials work focuses on verifying the safety of current light-water reactors and developing new materials to improve the economics and enhance the safety of advanced reactors. This research builds on our capability to design and develop materials for extreme conditions and our nuclear engineering capability.

The Argonne Collaborative Center for Energy Storage Science (ACCESS) is facilitating maturation of novel battery materials and their deployment to industry. We also partner with industry through innovative manufacturing institutes, including PowerAmerica, Digital Manufacturing Design and Innovation Institute, and Reducing Embodied-energy and Decreasing Emissions (REMADE).

Mission relevance and funding

This capability supports the missions of DOE and other federal and private-sector organizations in the areas of nuclear energy, energy efficiency, renewable energy, energy storage, and environmental stewardship. It builds on discoveries in our core capability in condensed matter physics and materials science, with an ultimate goal of moving those discoveries to market. It is aligned with the goals of the DOE Energy Materials Network (EMN) and supports many of the consortia, including the Chemical Catalysis for Bioenergy (ChemCatBio) and Lightweight Materials (LightMat) consortia.

Current sponsors include ARPA-E, DOE/EERE, DOE/NE, DOE/NNSA, DOE/SC-BES, DARPA, NRC, and a wide and growing range of industrial partners who produce critical materials to enhance American competitiveness and strengthen national security.

Applied mathematics

Capability

Argonne is recognized for broad-ranging foundational research in mathematical modeling, analysis, and algorithm development, implemented in scalable software for the world's largest computing systems. We excel in the scalable solution of partial differential equations (PDEs) and provide best-in-class expertise in automatic and algorithmic differentiation (AD). We also are a recognized leader in mathematical optimization algorithms, modeling, software, and theory. Our strategy for the future emphasizes:

- Creating time- and energy-efficient PDE and optimization solvers for the exascale era and beyond
- Extending and combining AD, data assimilation, optimization, and PDE capabilities to support efficient solution of design, decision, and control problems while accounting for error estimates and uncertainty
- Applying expertise in optimization, statistics, and AD as building blocks for machine learning for scientific applications
- Expanding our capabilities in machine learning, statistics, quantum algorithms, and other strategic areas
- Combining approaches – machine learning, statistics, and optimization – to solve inverse and analysis problems associated with simulation, observation, and experimental data

Important recent advances in Argonne's applied mathematics capabilities include the following:

- New scalable computational frameworks for modeling and solving large-scale-optimization-under-uncertainty problems by using high-performance computing for the planning, design, and control of networked systems such as electrical, gas, transportation, and water networks
- New multimodal machine learning, statistical modeling, and algorithmic approaches to analyzing experimental, observational, and simulation data, including APS data and environmental observations
- Automated machine learning, multi-objective optimization, and differentiation algorithms deployed for applications such as urban data analytics, supercomputing performance, and oceanographic modeling and also applied to post-Moore architectural concepts

Argonne's advances in applied mathematics are captured in state-of-the-art software, including:

- The Nek5000 and NekCEM software packages, which employ the spectral element method to efficiently solve large problems in computational fluid dynamics and computational electromagnetics
- PETSc, used by hundreds of scientific applications, which provides scalable linear solvers, nonlinear solvers, and time integration methods for solving discretized PDEs
- The ADIC, OpenAD/F, Rapsodia, and SWIG-PyADOLC AD tools for C, Fortran, Python, and R
- DSP and MINOTAUR, which solve optimization problems with both discrete and continuous variables
- Scalable solvers, such as TAO and PIPS, for optimization problems with billions of variables and constraints

This software ecosystem, designed to run on the most powerful supercomputers in the world, makes it possible to answer a broad range of science and engineering questions, including how to operate and upgrade the power grid, how mantle convection affects the earth's geological evolution, and how to cool nuclear reactors efficiently. These capabilities have been recognized by multiple R&D 100 Awards and the naming of staff members as Fellows of the Society for Industrial and Applied Mathematics.

Mission relevance and funding

This capability supports the DOE/SC-ASCR mission to develop and deploy high-performance and leadership computing resources for scientific discovery. Other current sponsors include DOE/ECP; DOE/EERE; DOE/NE; DOE/OE; DOE/SC-BER, -FES, -HEP, and -NP; DARPA; DHS; and NSF: much of this funding entails interdisciplinary research partnerships leveraging applied mathematics expertise.

Biological and bioprocess engineering

Capability

Argonne's bioprocess research determines the fundamental engineering mechanisms for biological energy capture and conversion, from the molecular to the unit-operation scale, and uses the results to pioneer first-principles bioengineering approaches. Our new approaches to biological and bioprocess engineering combine synthetic biology and synthetic chemistry to create biomaterials with tuned functionalities.

This capability draws on the CNM, the APS, and Argonne's computational expertise and resources. CNM's tools for imaging and manipulating biomolecules, cells, and processes over multiple scales are used extensively for bioprocessing. We use multiple APS beamlines – including one dedicated to the DOE/SC-BER-funded Structural Biology Center – to determine the crystallographic structure of biological macromolecules and to characterize catalysts in thermochemical conversion processes: associated capabilities include bionanoprobe and micro-diffraction tools. Our Advanced Protein Characterization Facility can produce and characterize tens of thousands of unique proteins each year, including their biophysical and biochemical properties. Our computational expertise and resources have enabled us to be leaders in developing bioinformatic tools for the larger research community.

Current research directions and investments focus on:

- Synthetic biology for biosystems design. We annotate and model microbial and microbiome systems (KBase) to enable discovery of enzyme function, predictive design of strains and communities, and ecological understanding. We integrate this capability with our experimental expertise in protein characterization, structure-based design of proteins, engineering of microbial genomes, and use of biohybrid materials to visualize biological functions in cells and the environment. We are advancing this capability through internal investments, university collaborations, and strategic partnership projects.
- Bioprocesses and biomanufacturing. Our work to improve bioprocesses emphasizes directed molecular evolution for natural and artificial photosynthetic systems, catalyst separation and reuse, bioreactor design and operation from bench to pilot scale, and extraction and separation of biofuel candidates from bioreactors without disruption of bioprocesses. Sustainable plastic design combines efforts across Argonne in data science, environmental science, biology, and soft-matter chemistry. As the lead lab for the DOE/EERE-BETO Bioprocessing Separations Consortium, we have applied ion-adsorbent wafers to directly capture organic salts produced during fermentation and developed and applied nanomaterials that can be used in situ in fermentations to selectively bind toxins or inhibitors and be reused more than 100 times.

Through recent advances in biological and bioprocess engineering, we have demonstrated the ability to predictively engineer microbes from the environment, microbes for biotechnology, energy-converting proteins with radically altered function, and enzymes to transform biomass. This creates a synthetic biology capability to develop designer microbes and communities for fundamental understanding of biological functions, biomanufacturing, and energy-water research, and for linking with biohybrid research by our chemists and material scientists. We couple computational and experimental approaches to facilitate analysis, predictive modeling, and design of microorganisms and environmental microbiomes across scales.

Through the DOE-SC/BER KBase project, we integrate modeling and computational analysis − including metabolic modeling, cheminformatics, omics, and meta-omics − to support bioengineering efforts for microbes, plants, and microbial communities. We also contribute to the development of biomanufacturing technologies as part of the DOE/EERE-BETO Agile Biofoundry project, and are a member of the Feedstock Conversion Interface Consortium initiated by that office. In addition, we are a leader in lifecycle and techno-economic analyses of bioenergy-related processes and analyses of the impacts of bioenergy system deployment on soil carbon, water footprint, water quality, and landscape design.

Mission relevance and funding

This capability supports the missions of DOE and other entities that seek to better understand plants and microbes to engineer them for bioenergy, carbon storage, bioremediation, and environmental quality. Current sponsors include DOE/EERE, DOE/SC-BER and -BES, national security agencies, industry, and local government entities.

Chemical and molecular science

Capability

Chemical and molecular science is central to many of Argonne's research programs. World-leading strengths include chemical characterization of matter, computational and theoretical chemistry, electrochemistry, functional chemistry, interfacial chemistry, mechanistic chemistry, molecular control of chemical transport and chemical reactivity, molecular design and synthesis, and light-matter interactions. Our work explores trends in chemistries across the entire periodic table, and includes expertise in gas phase, liquid phase, and solid-state chemistries. In support of the DOE/SC mission, we have used these strengths to deliver scientific advances relevant to DOE mission needs in catalysis, combustion, electricity production from chemical energy, energy storage, geochemistry, heavy element separations, and solar and photosynthetic processes.

We have unique competencies in ultrafast characterization of reactions, thermochemical analysis, organometallic chemistry combined with heterogeneous catalysis, synthesis of unique physical and chemical environments, characterization of interfaces and interphases, metal ion separations, nuclear coordinate and electronic structure modeling, and cascading gas phase reactions.

The computational resources and characterization tools available through ALCF, APS, and CNM are integral to this capability. Other facilities central to our work include our unique High-Throughput Research Laboratory, atomic layer deposition laboratories, existing and under-construction radiological facilities, and Advanced Electron Paramagnetic Resonance Facility.

The advancement of this capability is enhanced by our engagement with UChicago, particularly through the CME, and with Northwestern University through the Northwestern University – Argonne National Laboratory Institute for Science and Engineering. With both institutions, we recently stood up the Energy Frontier Research Center on Advanced Materials for Energy-Water Systems (AMEWS), which is focused on the science of water/solid interfaces, with an emphasis on molecular separations.

In addition, our core capability in condensed matter physics and materials science complements these strengths through materials design and synthesis and functional material development. We advance our DOE/SC-BES discoveries in chemical and molecular science through collaborations with industry and in conjunction with expertise embodied in our core capabilities in chemical engineering and applied materials science.

Argonne's strategy advances an integrated, systems approach to the chemical and molecular sciences in concert with our chemical engineering and applied materials science and engineering core capabilities. We seek to unify the understanding of the periodic table, taking advantage of our expertise in the chemistry of the light elements, through the transition metals and on to the heavy elements. We seek to understand transient processes within molecules through our ultrafast chemistry and ion and electron transport expertise. Additionally, competing reactions are at the core of our strategy, which seeks to understand the interactions of these competing processes, including the role of rare events and spectator species. Efforts in understanding dynamics, structure, and transport of complex environments will impact areas such as separations, catalysis, geochemistry, and photochemical processes. Finally, understanding interfaces in dimensions of x, y, z, and time is vital to our work within this core capability.

Looking forward, we are expanding our capabilities in polymer science and advancing investigations on how to predict and control the flow of electrons, ions, and molecules at interfaces relevant to geochemistry, separations, catalysis, electrocatalytic and electrochemical processes, and light-induced processes relevant to solar energy conversion. To address the challenges and opportunities of predictive chemistries, we will further integrate Argonne's expertise in computational, theoretical, and data sciences into experimental chemistry research, based on output from our JTFI work in artificial intelligence for science. Precision synthesis for controlled chemical conversions will continue to be at the fore in addition to the necessary characterization of atoms and molecules spanning length scales from atomic to microns and time scales from ultrafast to seconds under in situ and operando conditions.

During FY20, our DOE/SC-BES heavy elements chemistry and separations science programs will move to the Materials Design Laboratory, which will advance our systems approach by fostering new interdisciplinary science within a state-of-the-art research complex.

Mission relevance and funding

This capability supports the missions of DOE/SC-BES and other DOE/SC programs. Additional current sponsors include DOD.

Chemical engineering

Capability

Chemical engineering research at Argonne addresses the nation's energy and security challenges by building on and informing basic energy research while developing transformational technologies for electrochemical energy storage, biomass conversion, chemical and light energy conversion, and water cleanup. This capability integrates chemical engineering expertise with our core capabilities in chemical and molecular science, condensed matter physics and materials science, and biological and bioprocess engineering.

Our success in applying our foundational knowledge in electro-, photo- and thermo- chemistry and catalysis, and in interfacial sciences, has led to global recognition for our lithium-ion (Li-ion) battery, solar conversion, combustion chemistry, and fuel cell research. We are now advancing the next generation of Li-ion batteries, looking beyond Li-ion batteries, developing solid-state batteries and solutions for stationary storage, and advancing methods to recycle Li-ion batteries through our new ReCell Center. Our multidisciplinary efforts are developing advanced membranes, electrodes, and electrocatalysts that reduce the cost and improve the durability of fuel cells based on both solid-oxide and polymer-electrolyte membrane technologies. Our high-temperature gas phase chemistry and chemical and material scale-up expertise are leading to new engine designs and pathways for translating DOE/SC discoveries and DOE/EERE-VTO foundational research to meet industry and consumer needs.

In addition, we are accelerating the development of catalysts that do not use platinum-group metals for fuel cells, through the use of high-throughput materials synthesis, characterization, and performance evaluation of equipment and methodologies. This activity is a cornerstone of DOE's ElectroCat research consortium, which we co-lead with Los Alamos National Laboratory. Other efforts are intended to reduce the costs to produce renewable liquid transportation fuels through advances in catalysis and improved approaches to radioisotope processing.

Argonne operates a unique suite of facilities for energy storage and conversion R&D, a suite that is integrated with our process and systems modeling capabilities. Our modeling capabilities include process unit modeling, performance vs cost modeling, and techno-economic and life cycle analysis. Facilities include:

- Cell Analysis, Modeling and Prototyping (CAMP) facility. Cells manufactured in this facility enable realistic, consistent, and timely evaluation of candidate battery-cell chemistries in a close-to-realistic industrial format.
- Electrochemical Analysis and Diagnostics Laboratory (EADL). This laboratory provides battery developers with performance evaluation of cells, modules, and battery packs, allowing diagnostic analysis of battery components after use to identify mechanisms that limit battery life.
- Post-Test Facility. This facility is designed to understand failure modes in batteries with air-sensitive materials, such as those from lithium-based or sodium-based battery technologies.
- High-Throughput Research (HTR) Laboratory. This laboratory provides robotic tools and reactor systems for rapid, automated, and parallel approaches to chemical synthesis and materials development, thereby accelerating discovery and optimization of materials for catalysis, energy storage, fuel cells, solar energy, and nanoscale chemistry.
- Materials Engineering Research Facility (MERF). This facility allows researchers to explore the scale up of materials and chemical processes as we work with industry to move national laboratory discoveries and industry innovations to the marketplace. It is described in more detail under our applied materials science and engineering capability.
- Low Energy Accelerator Facility (LEAF). This facility is used for radioisotope processing.

To meet increased needs, we recently updated LEAF and completed a three-fold expansion of CAMP; we currently are expanding MERF. DOE/EERE provides the majority of funding for CAMP, EADL, MERF, Post-Test Facility, and the HTR Laboratory. DOE/NE supports LEAF.

Mission relevance and funding

This capability supports the missions of DOE and other agencies to advance energy storage and fuel cell science and engineering. Current sponsors include DOE/EERE, DOE/NE, DOD, and industry.

Climate change sciences and atmospheric science

Capability

Through research in climate change and atmospheric sciences, Argonne improves understanding of the earth's atmospheric and environmental systems and advances efforts to address climate-related energy, water, and security challenges. The Laboratory makes leading contributions in three areas: atmospheric measurement and analysis, earth science simulations, and soil and biogeochemical science. We are investing in integrating these three areas to develop a predictive understanding of the role of heterogeneity in mediating water, energy, and carbon exchanges in earth systems. This investment leverages a number of Argonne strengths described below.

Argonne's strengths in atmospheric science are grounded in our ability to make sophisticated atmospheric measurements at an unprecedented scale and under challenging circumstances. Today we oversee operational activities across all the ARM sites supported by DOE/SC-BER. In addition, we operate the ARM Southern Great Plains site, which is the world's largest and most extensive research facility for in situ and remote sensing of cloud, aerosol, and atmospheric processes. We also provide the global scientific community with unique expertise and software for atmospheric instrument operation and measurements. Our Py-ART software for radar data is recognized internationally.

We apply our aerosol/cloud science and instrument expertise, along with ARM data, to better understand terrestrial-atmospheric coupling and the role of cloud processes in the hydrologic cycle and to define the impact of surface- and boundary-layer coupling on low-level clouds. We have made fundamental contributions to the physics of low-level clouds using ARM data and developed novel methods for retrieving atmospheric thermodynamic and cloud properties from data collected by suites of remote sensing instruments.

Argonne's efforts to advance earth science simulation emphasize the application of high-performance computing to develop robust predictive capabilities. We support the computational objectives of DOE's flagship Energy Exascale Earth System Model (E3SM) in addition to the data and analytical needs of other DOE R&D areas related to climate and atmospheric science.

We are developing models that we use in combination with field observations to understand the influence of aerosols and aerosol life cycle on low-level clouds and the earth's radiation budget. For example, we have used this approach to gain valuable insights into the life cycle of aerosols from biomass combustion in Africa, and we continue to incorporate aerosol and dust science into E3SM.

Argonne is an international leader in downscaling earth system modeling results to project possible future local climate conditions. We recently used our 12-km-resolution climate projections for North America to support quantitative analysis of risks to industrial infrastructure from future extreme weather. By combining our projections with regional atmospheric and hydrological models, we estimated the future probability of high winds, heavy precipitation, flooding, and coastal storm surge in the Southeast.

We have collaborated with DOE/EERE-WETO and NOAA to improve the accuracy of numerical weather prediction models over complex terrain, in support of wind-energy production. In this project, Argonne scientists analyzed wintertime cold pool events and boundary layer wind jets and provided three heavily instrumented wind sites and two physics sites that gathered latent and sensible heat flux data.

Using the APS, Argonne pioneered the application of synchrotron technology to perform chemical and physical analyses of atmospheric dust, aerosols, and soils. The APS Upgrade will vastly expand the capabilities of this technology for environmental science.

More broadly, our soil and biogeochemical scientists are developing a deep predictive understanding of soil responses to environmental change and perturbation, from the molecular to the regional scale. We apply microbial ecology to advance knowledge of soil processes, develop novel technologies to characterize soil properties, and use geospatial analytics to extend field measurements.

We have produced spatially explicit estimates of carbon stocks of permafrost-affected soils in the far northern hemisphere, using our pioneering rapid mid-infrared spectroscopy technique to assess the degradation state of organic matter in those soils. This information is vital to predicting future carbon emissions from soils in this vulnerable region. We are also developing novel sensor technology to monitor soil moisture, a critical variable in both soil and atmospheric processes.

Mission relevance and funding

This core capability supports the missions of DOE/SC-BER and other federal entities with climate and atmospheric science initiatives. Additional sponsors include DOE/EERE-WETO, NSF, DOD, NASA, and NSF.

Computational science

Capability

Computational science, a cornerstone of Argonne's R&D enterprise, advances the solution of critical problems in many scientific disciplines. Our Laboratory-wide computational activities involve more than

350 scientists and engineers working in interdisciplinary project teams that include applied mathematicians and computer scientists. Argonne's computational science effort is strongly supported by the capabilities of the ALCF, Joint Laboratory for System Evaluation, and Laboratory Computing Resource Center.

We will continue to enhance and promote our computational science capabilities, in the following ways:

- Leverage our computational science division and data science and learning division to build strong collaborative projects with scientists and engineers across Argonne in modeling, simulation, and machine learning. We are facilitating crosscutting Laboratory-wide engagement in computing and fostering multidisciplinary teams for conducting leading-edge computational science.
- Through our computing divisions, provide computational scientists and engineers with ready access to broad and deep expertise in traditional and emerging scientific computing methods and tools. These methods include modeling and simulation, data science, machine and deep learning, software development and optimization, and next-generation technologies such as quantum and neuromorphic computing.
- Use a matrix model to integrate domain expertise with methodological expertise in computational science, data science, and machine learning.
- Take advantage of the co-location of hardware and staff expertise to strengthen proposals of both internal and external computational science groups as they apply for DOE's Innovative and Novel Computational Impact on Theory and Experiment and ASCR Leadership Computing Challenge awards.

Some examples of the impact and leadership of Argonne's computational science capability follow:

- We performed some of the world's largest high-resolution cosmological simulations with Argonne's HACC code, modeling the universe over billions of years. HACC plays an important role in benchmarks for future DOE computing systems and is a significant part of two major efforts within DOE's Exascale Computing Project (ECP).
- We developed and implemented algorithms and toolkits for analysis of large datasets from Argonne's APS, the Large Hadron Collider in Switzerland, and the Large Synoptic Survey Telescope.
- Our peers have recognized the computational science enabled by our PETSc library with multiple Gordon Bell prizes and the joint prize in Computational Science and Engineering awarded by the Society for Industrial and Applied Mathematics and the Association for Computing Machinery.
- Our NekCEM/NEK5000 code has been used in applications spanning fluid flow, thermal convection, combustion and magnetohydrodynamics. It won an R&D 100 award in 2016 and is used in two application projects within the ECP.
- Argonne staff engage in development of community codes such as NAMD and QMCPACK.
- We participate in 10 SciDAC application partnerships spanning environmental science, fusion, high-energy physics, nuclear physics, and nuclear engineering.
- We developed and contributed to a spectrum of applications: these include elegant (accelerator simulation), TomoPy (x-ray tomographic analysis), and Green's Function Monte Carlo (properties of nuclei). The latter revealed new details of the carbon-12 nucleus structure and is enabling research that will improve understanding of subatomic particles.

Mission relevance and funding

This capability supports missions across all of DOE and other entities that fund R&D. Current sponsors include ARPA-E; DOE/EERE; DOE/OE; DOE/SC-ASCR, -BER, -BES, -FES, -HEP, and -NP; NIH; NASA; NSF; and industry.

Condensed matter physics and materials science

Capability

Argonne's internationally recognized condensed matter physics and materials science research predicts, designs, and creates new materials and advances understanding of their behavior. Our leadership in this field relies on the breadth and depth of our expertise in materials chemistry and physics, scattering and imaging, theoretical and computational science, and the integration of APS, CNM, and ALCF capabilities into our work.

Our strategy emphasizes the role of defects and interfaces across three areas: quantum and spin coherent matter, soft matter and hybrid materials, and electrochemical phenomena. We give crosscutting emphases to precision synthesis, in situ and operando studies coupled to modeling and simulation, and nascent AI and data science approaches. We study magnetic, superconducting, and catalytic materials; quantum metamaterials; ferroelectrics; correlated oxides; polymers; topological materials; and electrochemical oxides. The CME is an important element of our strategy; its staff members bring expertise in soft matter and in semiconductor- and superconductor-based QIS platforms.

Our capabilities and tools uniquely position us to deliver scientific breakthroughs. Key assets include materials discovery using high-pressure floating-zone crystal growth and thin-film growth of topological matter and refractory transition metal elements as well as oxychalcogenides, diamond, and aluminum nitride as platforms for discovery in quantum information science. We are innovating in situ characterization approaches, including coherent diffraction, three-dimensional pair-distribution analysis of diffuse x-ray and neutron scattering, terahertz dynamics, and Lorentz microscopy for imaging vector magnetization.

Argonne leads the Midwest Integrated Center for Computational Materials, which is a collaboration with UChicago and four additional universities, and plays a key role in the Center for Predictive Simulation of Functional Materials at Oak Ridge National Laboratory. We also are a leader in simulating vortex dynamics of superconductors, of importance to multiple programs supported by DOE/SC.

Our core materials science reinforces the work of the Argonne-led Joint Center for Energy Storage Research, through our Electrochemical Design Laboratory, and plays a principal role in materials-focused Energy Research Frontier Centers. Those centers include two led by Argonne [Advanced Materials for Energy Water Systems (AMEWS) Center and the Center for Electrochemical Energy Science] and four led by other institutions. UChicago and Northwestern University are partners in the AMEWS Center. We will leverage the ultrafast electron microscope at CNM to explore phenomena such as transient behavior in ferroic nanostructures, structural phase transitions, and phonon interactions.

Our work has had recent impact at frontier areas of science including (1) topological superconductivity in strontium-doped bismuth selenide, (2) critical slowing-of charge order explained through a combination of ultrafast optical and x-ray experiments and dynamical mean field theory, and (3) simultaneous measurement of strain and stacking faults in gallium nitride nanowires using coherent x-ray ptychography. Additional recent impact areas include (1) phonons as a prime candidate mechanism for superconductivity in twisted bilayer graphene, (2) nanomagnetic arrays to encode quantum information into electron beams, (3) novel core-shell iridium oxide structures to understand oxygen reduction reactions, and (4) neutron diffuse scattering as a means to isolate competing interactions in relaxor ferroelectrics.

Looking forward, we will address research and technique-development in coherent x-ray scattering that will help to shape the scientific mission of the upgraded APS, for instance through expanded in situ and operando studies of ionic motion in solids and liquids, accelerated by combining coherent x-ray probes with machine learning.

We will propose new fundamental research to advance materials for the QIS, AI, and data science revolutions. In QIS, we will explore quantum magnonics and structured electron beams and develop new qubit platforms via atomic layer deposition and molecular beam epitaxy approaches to defect creation and control. We also will propose first-principles, simulation-based approaches for predicting synthetic pathways for inorganic solid-state materials. Preparing for Argonne's Aurora exascale computer, we will propose data science approaches built on collaborations among condensed matter physicists, materials scientists, and experts in AI and data science.

During FY20, we will occupy the Materials Design Laboratory, which will provide state-of-the-art infrastructure for quantum, magnetic, superconducting and scattering science programs. Looking ahead, we will develop scientific programs and expertise to shape the planned Sensing and Imaging at Argonne building.

Mission relevance and funding

This core capability supports the missions of DOE/SC-BES and other DOE/SC programs. Additional sponsors include DOE/EERE, DOE/NNSA, DOD, and industry.

Cyber and information sciences

Capability

Through our cyber and information sciences programs, we protect, analyze, and disseminate information from computer systems and other electronic sources to defend our nation from cyber attacks. This work supports the overall cybersecurity of national infrastructure, including the electric grid, water systems, transportation assets, and supply chains.

We take a collaborative cross-disciplinary approach to address emerging problems in this arena and deliver results of global impact. Internally, our cyber and information sciences activities leverage Argonne's advanced computing and engineering capabilities, including the APS, ALCF, and Laboratory Computing Resource Center. Our external partners include researchers from universities, other national laboratories, and the private sector.

We help protect the nation as a trusted partner to government agencies, through our research into the resiliency of critical cyber assets, the security of cyber-physical systems, and the collection and dissemination of intelligence needed to defend against cyber threats. Through our cyber and information sciences strategy, we:

- Conduct proactive cybersecurity research in critical infrastructure risk and resilience, moving target defense, autonomous vehicle security, machine learning for intrusion detection, and other technologies to improve national security
- Share cyber threat information using real-time, machine-to-machine methods in support of the DOE enterprise, the energy sector, and other federal entities using the Cyber Fed Model, which Argonne runs as DOE's primary system for sharing cyber threat information relative to the Cybersecurity Information Sharing Act of 2015
- Develop capabilities to leverage machine-to-machine information sharing to help cyber defenders hunt for active threats in their networks, collaborate on analysis, and orchestrate their defenses
- Design tools for evaluating the resiliency, dependencies, and defenses of computer systems that operate critical infrastructure, as well as the consequences of attacks on those systems
- Inform government and private-sector entities of potential cyber vulnerabilities through the DHS Regional Resiliency Assessment Program

- Apply cutting-edge research and development to design systems supporting power grid operations that are resilient to the cybersecurity threats of the future, in support of the DOE/CESER Cybersecurity for Energy Delivery Systems program
- Conduct short- and long-term assessments of cyber threats, vulnerabilities, consequences, and dependencies, including trend analyses
- Partner with DOE/CESER to develop and host its annual collegiate CyberForce Competition™, which uses scenarios focused on energy-critical infrastructure to develop the nation's next generation of cyber workforce by increasing students' understanding of cyber-physical threats, vulnerabilities, and consequences
- License Argonne's patented MORE Moving Target Defense technology, recipient of an R&D 100 Award, which enhances cybersecurity through a rotation of multiple operating systems that can be deployed in a production information technology environment
- Deploy advanced algorithms and tools that monitor the physics of the power grid to detect and mitigate attacks on cyber-physical systems

Facilities that support this capability include enterprise data centers that host a multi-agency secure private cloud and state-of-the-art facilities for analyzing vehicle cybersecurity. We currently are investing resources to integrate high-performance computing and dependency modeling as it applies to the cybersecurity mission space.

Mission relevance and funding

This capability supports the missions of DOE, DHS, DOD, and industry. Current DOE sponsors include DOE/CESER, DOE/EERE, DOE/EPSA, DOE/IN, DOE/NE, DOE/NNSA, and DOE/OCIO. Current DHS sponsors include the Federal Emergency Management Agency, Office of Intelligence and Analysis, and Cybersecurity and Infrastructure Security Agency.

Decision science and analysis

Capability

Argonne is recognized for addressing pressing national challenges in decision science and analysis through development and application of novel modeling approaches. These approaches include agent-based modeling, complex adaptive system modeling, system dynamics, and complex network analysis. We have attained international leadership in the development of high-performance computing software tools (Repast, EMEWS, and PLASMO) and their use in extreme-scale agent-based modeling applications. This capability, linked with our cyber, information science, and systems engineering capabilities, positions us to deliver effective solutions to complex problems that require multidisciplinary solutions.

We approach problems as dynamic and interrelated systems in order to address uncertainty, rapidly changing environments, and imperfect/incomplete data. Combining these models with traditional deterministic methods better informs key decision makers.

Facilities that support this work include an immersive data visualization STudio for Augmented Collaboration (STAC) and the ALCF. We have applied leadership computing capabilities to the analysis of social and behavioral systems, including predictive modeling of the spread of infectious disease and information in urban areas and the effectiveness of interventions to mitigate disease spread. Looking to the future, we expect to make increasing use of advanced computing approaches and architectures, including exascale systems, machine learning, and artificial intelligence.

Staff members across multiple Argonne divisions are dedicated to a decision science and analysis strategy in which we:

- Analyze infrastructure assets and systems, with particular emphasis on lifeline sectors and the electric grid, to inform government and private-sector decisions regarding risk mitigation, resilience enhancement, restoration, and recovery in an all-hazards environment. Our infrastructure work also draws on our capabilities in systems engineering and integration. For example, we use predicted hurricane paths in the East Coast and Gulf regions to forecast likely power outages, to facilitate restoration of service
- Extend decision science capabilities beyond our traditional energy infrastructure assessments to address emerging problems in energy-water interdependence and urban sciences
- Develop and deploy models and associated web applications to analyze supply chains, to inform state-wide decision-making by emergency managers in response to expected and unexpected impacts to various systems
- Develop models and conduct analyses of global supply chains to inform decisions affecting the national stockpile of critical materials that support national security and advanced energy technology
- Assess the complex interactions (cascading and escalating) of infrastructure dependencies in local, regional, national, and international systems to inform resilience-enhancement decisions
- Analyze the social dynamics of energy and national security issues to inform decisions pre-, trans-, and post-event for a variety of scenarios
- Apply our expanded Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) life-cycle-analysis model to inform decisions about new technologies and concepts within initiatives such as the DOE/EERE-FCTO H2@Scale program
- Use agent-based modeling to model the propagation outcomes of gene editing and gene drive technology through populations over generations

In addition, we are addressing how best to meet future DOE needs for earth system prediction. A scientific challenge is to capture the reverse feedback from human behavior on the environment. Supporting research focuses on model coupling, ensemble modeling, and uncertainty propagation, with the goal of providing model-generated information to decision makers, and on understanding the social dynamics of how information, and misinformation, spreads through social networks. We are collaborating with UChicago researchers in this area.

Mission relevance and funding

This capability supports the missions of DOE, DHS, DOD, and industry. Current DOE sponsors include DOE/CESER, DOE/EERE, DOE/IN, DOE/NE, DOE/NNSA, DOE/OCIO, DOE/OE, and DOE/OP. Current DHS sponsors include the Federal Emergency Management Agency, Cybersecurity and Infrastructure Security Agency, and Office of Intelligence and Analysis.

Large-scale user facilities/advanced instrumentation

Capability

Advanced Photon Source (APS)

Funded primarily by DOE/SC-BES, the APS is an internationally leading source of high-energy x-rays for scattering, spectroscopy, and imaging studies. Grounded in Argonne's unique blend of expertise in high-energy x-ray science, instrumentation, optics, and accelerator physics, the APS provides unmatched capabilities for studies over a wide range of length and time scales. Capabilities include in situ and operando sample environments; macromolecular crystallography; high-pressure environments and shock physics; x-ray interrogation of electron and lattice excitations; and real-time studies of evolving systems. We have initiated the APS Upgrade project, to create the world's brightest hard x-ray storage-ring light source.

Argonne Leadership Computing Facility (ALCF)

Funded by DOE/SC-ASCR, the ALCF operates two open-science supercomputers, an IBM Blue Gene/Q system (ALCF-2, named Mira) and an Intel/Cray XC40 system (ALCF-Lithium, named Theta), that rank among the 25 fastest machines in the world. The ALCF provides petascale-computing capabilities and support services that enable the computational science and engineering community to run the largest and most complex calculations. ALCF also hosts the Joint Laboratory for System Evaluation, which gives our staff and collaborators access to the latest production and prototype computing resources, and operates a Cray Xeon cluster (named Cooley) used for data analysis. In 2021, the ALCF will deploy DOE's first exascale system, an Intel/Cray machine (ALCF-3, named Aurora).

Argonne Tandem Linear Accelerator System (ATLAS)

Funded by DOE/SC-NP, ATLAS is a superconducting linear accelerator and the only DOE user facility for low-energy nuclear research. It provides high-intensity heavy-ion beams in the energy domain best suited to study the properties of the nucleus. At ATLAS, the Californium Rare Ion Breeder Upgrade (CARIBU) has the unique capability to provide both stopped and reaccelerated beams of radioactive neutron-rich nuclei. ATLAS offers its users an array of unique experimental systems to take full advantage of the accelerator capabilities.

Atmospheric Radiation Measurement
Southern Great Plains (ARM-SGP) site

Funded by DOE/SC-BER, the ARM-SGP site is the world's largest and most extensive field site for climate research. Its instruments are arrayed across 9,000 square miles, with a heavily instrumented central facility on 160 acres near Lamont, Oklahoma. In addition to operating the ARM-SGP site, Argonne oversees operations and instrumentation and provides instrument and measurement expertise to all ARM sites. Scientists from Argonne and other institutions use ARM data to advance scientific understanding of cloud, aerosol, and atmospheric processes, which supports improvements in models of the earth's climate.

Center for Nanoscale Materials (CNM)

Funded by DOE/SC-BES, the CNM supports interdisciplinary nanoscience research, with an emphasis on quantum materials, manipulation of nanoscale interactions, and nanoscale dynamics. Its unique capabilities include near-field optical measurements at the extremes of space and time resolution, scanning tunneling microscopy, ultrafast electron microscopy, extreme nanofabrication, and the first generation of user tools for QIS. Collaborations with APS include a hard x-ray nanoprobe and a synchrotron x-ray scanning tunneling microscope. Significant upgrades in CNM research tools will be needed to enable the Center's users to continue making groundbreaking discoveries over the next decade. Argonne is committed to working with DOE to continue upgrading CNM instrumentation through internal investment, the CNM operating budget, and other opportunities. A recent multi-laboratory Major Items of Equipment proposal to DOE/SC-BES, for Nanoscale Science Research Centers Recapitalization, identifies opportunities to greatly strengthen our user-facility core capability.

Mission relevance and funding

This capability supports the DOE-SC mission to operate scientific user facilities that provide the highly advanced research tools needed to address the world's greatest challenges in science and technology. Our facilities are sponsored by DOE/SC-ASCR, -BER, -BES, and -NP. Support for specific capabilities also is provided by DOE/NNSA, DOE/OE, NIH, NSF, and industry.

Nuclear and radio chemistry

Capability

Argonne executes pioneering work in nuclear chemical engineering, chemical separations, and the materials and chemical science of actinides, radioisotopes, and the nuclear fuel cycle. Our strategy to maintain and build on this capability includes gaining new understanding of the:

- Materials chemistry and thermophysical properties of actinides in extreme environments, such as the high-temperature and molten salts encountered in future nuclear energy systems
- Production and chemical separation of radioisotopes essential to groundbreaking medical and national security technologies
- Structure-property relationships foundational to actinide chemistry and solvent extraction across a broad spectrum of energy-related areas, from nuclear fuel and material separations to radioisotope production
- Critical ion-ion correlations that underpin effective syntheses of transuranic materials and drive actinide/fission-product separations
- Technical basis for next-generation separations and safeguards technologies for future nuclear energy systems

A distinctive portfolio of research capabilities and facilities enables this work, including:

- APS, ATLAS, and ALCF
- Electron microscopy tools including the Intermediate Voltage Electron Microscope
- Two co-located, purpose-built radiological facilities: a low-energy electron linear accelerator (LINAC) and a chemical separations system for radioisotope production and isolation
- Radiological laboratories that enable development and testing of advanced electrochemical and aqueous processes, to support development of innovative nuclear fuel cycle and safeguards technologies

We apply these capabilities to actinide science that produces novel approaches to the synthesis, characterization, and modeling of transuranic complexes. Our work uses purpose-built radiological facilities to extend understanding of the pure and applied chemistry of these artificially made elements. We target predictive bonding and energetics models, within the context of separations relevant to nuclear energy, by using Argonne computational facilities to interpret x-ray analytical characterization at the APS. We are applying the insights from these studies to develop efficient separations processes and associated safeguards technologies that promise to reduce nuclear waste generation in a secure, efficient, and cost-effective manner.

Within the context of minimizing the world's reliance on weapons-usable nuclear material in reactor applications, we are a leader in the production of molybdenum-99/technetium-99m, which is currently the most important and in demand medical isotope for diagnostic nuclear medicine. In collaboration with industrial sponsors, we have developed and demonstrated new accelerator-based production channels and chemical purification methods to facilitate domestic molybdenum -99 production without the use of weapons-usable materials.

In parallel, we are leveraging our radiochemistry expertise to develop our electron LINAC – one of the most powerful electron accelerators across the DOE complex – and radioisotope separations capability into a production facility for theranostic medical isotopes. We are poised to become a supplier of copper-67 to the DOE National Isotope Development Center (NIDC) and have ongoing radiochemistry R&D applied to other cancer-fighting medical isotopes, including scandium-47 and high-priority actinium-225. Capable of diagnosing and treating tumors such as prostate and bone cancer with targeted radiation, these radioisotopes provide a game changing approach to cancer diagnosis and treatment.

We also conduct sensor and detector research for national programs in border, cargo, and transportation security, as well as chemical, biological, radiological, and nuclear incident mitigation; our focus includes millimeter wave technologies for remote detection and sensors, as well as forensics to identify sources of nuclear and biological materials.

Mission relevance and funding

This capability supports the missions of DOE and other organizations that seek to advance understanding of actinide chemistry, radioisotopes, and technologies for future nuclear energy systems. Current sponsors include DOE/NE, DOE/NNSA, DOE/SC-BES and -NP, and overseas research organizations.

Nuclear engineering

Capability

Argonne pioneered nuclear energy systems and continues to be a world leader in advancing nuclear energy science and technology. We are recognized for ground-breaking research in both advanced nuclear energy technology and nuclear materials security. Our nuclear engineering capability supports significant national goals in nuclear power safety, nuclear energy development, nuclear nonproliferation, isotope research and production, and protection of critical infrastructure. Our nuclear engineering staff draws on unique Argonne capabilities in nuclear and neutron physics, thermal-hydraulics, materials science, nuclear and radio chemistry, x-ray imaging, and computational science.

Key facilities that support this work include APS, ALCF, ATLAS, and our Intermediate Voltage Electron Microscopy-Tandem Facility, which has unique capabilities to image changes in materials during irradiation. Using ALCF, Argonne has made groundbreaking advances in exploiting high-performance computing for multiphysics analysis of nuclear-reactor behavior. Nuclear engineering research also employs our specialized engineering development laboratories for detailed studies of nuclear reactor materials and components under prototypic conditions through the engineering scale. Throughout our history, we have enhanced the efficiency and benefits from our research through national and international collaboration with research and industrial partners.

Argonne has long invested significant effort in maintaining and expanding core capabilities in neutron physics and advanced reactor design and safety analysis. We are viewed as the world leader in designing and analyzing fast-neutron-spectrum systems and understanding the performance and safety behavior of fuels and materials in nuclear reactors. Our contributions to the design of passively safe reactor systems and our understanding of nuclear accident phenomena and mitigation are widely recognized by the international community. Building on our work with fast-spectrum reactors, we now lead the core design and safety analysis efforts for the Versatile Test Reactor, one of the priority projects of DOE's Office of Nuclear Energy.

In addition, we use our nuclear fuel cycle expertise, along with our nuclear and radio chemistry capability, to develop methods for separating radioisotopes and recycling actinides to reduce nuclear waste generation. We also have applied our understanding of reactor physics, thermal hydraulics, and materials behavior to the conversion of fuel in research and test reactors around the world from highly enriched to low-enriched uranium.

Targeted outcomes of Argonne's nuclear engineering program are:

- Leading, in partnership with Idaho National Laboratory and Oak Ridge National Laboratory, innovation in design of next-generation reactor and fuel cycle systems and development of the Versatile Test Reactor and other vital components of the national infrastructure for nuclear energy

- Increasing fundamental understanding of nuclear energy materials, processes and systems, thereby enhancing the scientific basis for their safe use and efficient regulation
- Developing and validating advanced, mechanistic modeling and simulation capabilities to improve prediction of the performance characteristics and safety behavior of nuclear energy systems
- Leading the development of the science and technology basis for limiting proliferation risk from nuclear energy systems, including minimizing the use and availability of highly enriched uranium
- Advancing the DOE/SC-NP goals for isotope production and research

Mission relevance and funding

This capability supports the missions of DOE and other organizations to sustain the benefits of nuclear energy generation; develop new and innovative nuclear energy systems, including advanced testing facilities that support development of future nuclear systems; and enhance the security of nuclear technology applications worldwide. Current sponsors include DOE/ARPA-E, DOE/NE, DOE/NNSA, DOE/SC-NP, DHS, NRC, the nuclear power industry, and international organizations.

Nuclear physics

Capability

Argonne is a global leader in nuclear structure, nuclear astrophysics, fundamental interactions, and hadron physics as well as in the enabling areas of nuclear instrumentation and accelerator development. ATLAS remains at the cutting edge of discovery science with recent upgrades to deliver a capability set that is unique in the world. Capabilities include high-purity beams of radioactive isotopes from the Californium Rare Isotope Breeder Upgrade (CARIBU), stable beams at energies up to 20MeV/nucleon, and state-of-the-art instrumentation such as the helical orbital spectrometer (HELIOS). The recent addition of the Radioactive Ion Separator (RAISOR) further increases the availability of intense and clean light radioactive ion beams. This capability set enables Argonne staff and external ATLAS users to study nuclear structures that depend strongly on the neutron excess and are not readily apparent in stable nuclei, to investigate reactions and nuclear properties far from stability, to probe astrophysical processes generating the chemical elements, and to test nature's fundamental symmetries and interactions.

Our physicists are leaders in the theoretical and experimental study of quantum chromodynamics, the foundational force that binds protons, neutrons, and nuclei. They design, construct, and operate detectors at Thomas Jefferson National Accelerator Facility (TJNAF) and Fermilab to carry out these investigations. Argonne scientists are principal investigators for about 30% of all Jefferson Lab 12-GeV experiments. At Argonne, we test the limits of the Standard Model by searching for violation of time reversal symmetry in the electric dipole moment measurement of radium-225.

Argonne's experimental nuclear physics research is supported by our work in accelerator science and by theory efforts that make use of the ALCF and Argonne's computational capabilities. We are world leaders in quantum Monte Carlo calculations of nuclear structure and reactions and predictions of hadron and nuclear properties using nonperturbative methods in quantum chromodynamics.

We also apply our expertise to address national needs, such as characterization of spent nuclear fuel for reactor design; production techniques for medical radioisotopes in collaboration with Argonne's nuclear engineers; and atom trap trace analysis for geophysics, oceanography, and national security applications. Our one-of-a-kind national center for radio-krypton dating commenced operations in FY19. Argonne's accelerator R&D group supports ATLAS, but their expertise and facilities for cavity processing and fabrication are in high demand to support other accelerators funded by DOE/SC-NP, -HEP, and –BES: our capabilities in superconducting radiofrequency technology complement those of other national laboratories. In FY19, for example, this support included the design and fabrication of the bunch-lengthening system for the APS Upgrade as well as the half-wave cavities and cryomodule for Fermilab's Proton Improvement Plan II project.

Ongoing upgrades to ATLAS will provide unmatched critical capabilities to complement the strengths of the Facility for Rare Isotope Beams (FRIB) when it comes online. ATLAS will remain the premier stable beam user facility, providing unique opportunities for rare isotopes research. A proposed multi-user upgrade will address user demand by simultaneously delivering two beams of different species to separate experiments; it also will enable an expanded isotope production program at ATLAS.

We continue to work with ATLAS users to identify important new capabilities, such as the neutron-generator upgrade to CARIBU and production of neutron-rich nuclei in the N=126 region, essential for astrophysics and nuclear structure studies. We will continue our leadership role in the science and instrumentation at FRIB, leading the construction of the solenoidal spectrometer apparatus for reaction studies and making key contributions to instruments such as the Gamma-Ray Energy Tracking Array.

We also are developing leadership roles in new areas by leveraging our strengths in materials science, particle physics, accelerator and hard x-ray science, and advanced computing. For the proposed Electron Ion Collider (EIC), our goal is to make major contributions to the science program and the design and simulation of the detector and accelerator. Our detector R&D is aimed at bolometers and time projection chambers in support of neutrinoless double beta decay, silicon detectors for the EIC, and early-stage R&D on superconducting nanowire detectors. In QIS, our physicists will build on existing strengths in atom trapping, quantum sensors, and quantum algorithms for nuclear physics to build a strategy in collaboration with our materials and computing scientists and our CQE collaborators.

Mission relevance and funding

This capability supports the DOE/SC-NP mission. Additional current sponsors include DOE/SC-BES and HEP; IAEA; DTRA-J9; NSF; and universities in the United States and abroad.

Particle physics

Capability

Argonne's particle physics research advances understanding of the fundamental constituents of energy and matter, the nature of space and time, and the underlying symmetries of the fundamental interactions. This work, with a record of significant contributions and leadership roles, distinguishes itself through strong collaborative efforts across Argonne and the DOE complex and with UChicago and Northwestern University.

The study of the recently discovered Higgs boson as a tool for new physics is at the center of our experimental program at the Large Hadron Collider (LHC) at CERN in Switzerland. A focused analysis program studying jets with heavy quarks is significantly advancing understanding of the role that the Higgs boson plays in nature. We are heavily involved in the design and construction of a new pixel detector, development of state-of-the-art trigger hardware and software, and creation of meta-databases and new input/output frameworks that will enable full exploration of LHC data.

The theoretical high-energy physics program at Argonne focuses on high-precision calculations of Standard Model processes, interprets experimental data in terms of physics both within and beyond the Standard Model, and makes predictions for new, well-motivated experimental searches that attempt to answer a number of open questions.

Through the high-energy physics community's Center for Computational Excellence, co-led by Argonne, high-performance computing tools are being developed to ultimately use the power of exascale computing for high-energy physics. First-of-a-kind simulations of LHC particle collisions that were carried out using the ALCF have enabled publication of results from the LHC's ATLAS experiment that would otherwise not have been possible. Our particle theory research, using the ALCF, has provided the most precise theoretical quantum chromodynamics predictions ever for standard model processes, essential to the search for new physics.

Our research in theoretical and computational cosmology provides the most accurate, large-volume perspective on the dynamic evolution of the universe that is currently available. Our particle physicists, in collaboration with Argonne's computing researchers and staff from other DOE laboratories, play a leadership role in extracting science from current and future cosmological surveys. By developing the Hybrid/Hardware Accelerated Cosmology Code framework and the data analysis library CosmoTools, Argonne has become a leader in extreme-scale, high-resolution cosmological simulations. These computational tools are run at the ALCF and other DOE leadership computing facilities; they generate synthetic sky maps that enable current construction projects to exercise their data analysis pipelines and provide comparisons with actual observations to give, for example, new insights into the dark sector of the universe. Our goal is to provide advanced statistical tools to the cosmology community to extract science from next-generation DOE-, NASA-, and NSF-supported surveys. Our cosmology group also leads one of the exascale computing projects funded by DOE/SC-ASCR.

Through a multidisciplinary effort, we deployed, at the South Pole Telescope, the largest focal plane to date of transition edge sensors (TES) for the third-generation experiment to detect anisotropies in the cosmic microwave background (CMB) radiation and have taken a leading role in proposing a fourth-generation, definitive, ground-based, CMB experiment. Our unique capabilities in engineering superconducting TES arrays are being used to develop ultra-sensitive sensors that could be deployed in next-generation dark matter detectors. We also will draw on existing strengths in superconducting devices for QIS, in collaborations via the CQE. We are continuing to transfer to industry our pioneering large-area photo-detectors with picosecond timing resolution and are transitioning our instrumentation program to target key challenges for the field in support of science, building on Argonne's multidisciplinary strengths.

We are playing key roles in construction of Fermilab's muon-to-electron-conversion experiment, following our completion of the most precise magnetic field map for the muon g-2 experiment. We also recently provided critical engineering support for the protoDUNE long-baseline neutrino detector prototype, now deployed at CERN. Argonne was responsible for delivery of the high-voltage field cage and readout for the photodetectors; based on this work, we are exploring future roles in Fermilab's Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE). Argonne is responsible for delivering a half-wave cryomodule for Fermilab's Proton Improvement Plan-II project, which aims to deliver the most intense high-energy neutrino beam for LBNF/DUNE.

Mission relevance and funding

This core capability supports the DOE/SC-HEP mission and is fully aligned with the national high-energy physics roadmap. Additional current sponsors include DOE/SC-ASCR and -BES as well as NASA and NSF.

Systems engineering and integration

Capability

We bring together multiple engineering disciplines to integrate science discoveries into practical technological solutions that strengthen the US energy, environmental, and security portfolio and enhance the nation's economic competitiveness. We develop experimental facilities and analytical tools to advance understanding of urban environments, communications, transportation, critical infrastructure, and other large-scale systems. Our infrastructure work also draws on our capabilities in decision science and analysis.

For example, when Hurricane Maria struck Puerto Rico in September 2017, we deployed experts to support recovery. We provided on-the-ground infrastructure damage assessments, adapted our software tools for more-effective grid restoration, and trained local stakeholders to use those tools to better prepare the island for future storms.

As another example, we are nationally recognized for developing systems engineering methods to help overcome security, risk, resiliency, and interdependency challenges facing lifeline infrastructures. We have created tools for infrastructure analysis, design, experimentation, and computation that enable us to model the interdependencies of key systems to understand cascading effects and develop mitigations to strengthen infrastructure. Additionally, as part of the DOE Grid Modernization Laboratory Consortium and in partnership with industry, we are developing analytical and modeling tools, including advanced computational algorithms, to drive engineering improvements in our nation's electrical infrastructure.

Advanced computing at the ALCF is a core component of our systems engineering and integration work, including high-fidelity modeling of electric power grid systems, the mobility ecosystem, and engine combustion kinetics. In these research areas, we also apply emerging approaches, such as machine learning and artificial intelligence.

We apply the imaging capabilities of the APS to understand structure and processes in materials and chemistries, such as complex flows in engineered systems. For example, we use the APS to study fuel-injector spray dynamics and combustion chemistry in engines. This work is complemented by experiments at Argonne's Engine Research Facility, which is used to study in-cylinder combustion, fuels, and emissions under operating conditions.

We are developing a range of innovative concepts to enhance mobility through advances in areas such as autonomous vehicles; more-efficient intermodal transportation of freight; infrastructure and vehicle connectivity; and three-dimensional transportation, including electric aviation as well as unmanned and robotic mobility. With DOE/EERE support, we use our EV-Smart Grid Interoperability Center to conduct research to facilitate transatlantic interoperability between electric vehicles and their charging infrastructure, ultimately leading to smart-grid integration, grid resilience, and full infrastructure interoperability. A component of this work relies on understanding the potential for new technological paradigms enabled by discoveries in our science programs, such as concepts for advanced batteries. In this work, we draw on our expertise in vehicle energy consumption for US manufacturing job retention through our ongoing collaborations with the European Commission, industrial partners, and the United States – China Clean Energy Research Center's Clean Vehicles Consortium.

Mission relevance and funding

This capability supports the missions of DOE, DHS, other federal agencies, and industry. Current DOE sponsors include DOE/EERE, DOE/NE, and DOE/OE. Current DHS sponsors include the Federal Emergency Management Agency and the Cybersecurity and Infrastructure Security Agency. Current strategic partnership sponsors include DOD, DOS, DOT, NERC, and NGA.

Science Strategy for the Future

Argonne's strategy is grounded in the Laboratory's widely recognized leadership in taking on profound challenges in science and technology and delivering results that enable decades of further progress. Argonne's science strategy is designed to produce game-changing advances in both fundamental and applied research:

- The world's leading hard x-ray microscope – the upgraded Advanced Photon Source (APS)

- The nation's first exascale computer, Aurora, in the Argonne Leadership Computing Facility (ALCF)
- Cosmology and nuclear physics discoveries that illuminate long-standing mysteries of physical science
- Establishment of the basic scientific principles of multiscale assembly of functional matter
- Breakthroughs in scale-up and process technologies for manufacturing advanced materials
- New materials, devices, and software for quantum information science (QIS)
- Artificial intelligence (AI) approaches that transform the speed of scientific research

Argonne's exceptional research staff, powerful experimental tools and facilities, and rich network of external partners provide a broad foundation for our strategy. In addition, UChicago supports Argonne's goals through enterprise-level partnerships, most notably:

- Center for Molecular Engineering (CME), based at Argonne and established in 2019 as a partner to UChicago's Pritzker School of Molecular Engineering. Both the Center and the School grew out of the joint UChicago-Argonne Institute for Molecular Engineering formed in 2011. Through CME, Argonne and UChicago researchers jointly translate advances in materials science, physics, chemistry, biology and computation into new tools to address important societal problems.
- Chicago Quantum Exchange (CQE), formed in 2017 as an intellectual hub to advance QIS; the CQE is anchored by UChicago, Argonne, Fermilab, and the University of Illinois at Urbana-Champaign. It also includes the University of Wisconsin at Madison, Northwestern University, and six corporate partners.
- Joint Task Force Initiative (JTFI), launched in 2018 with Fermilab, to drive development of high-impact research programs drawing on the combined strengths of the three organizations
- Argonne@Chicago, a potential second location for Argonne staff on the UChicago campus, now in conceptual development, to strengthen local collaborations and support Chicago's growth as an innovation economy

We are pursuing our strategic goals through the major initiatives and emerging initiatives described below, to unlock new frontiers in science and technology.

Infrastructure

Overview of Site Facilities and Infrastructure

Argonne's site in suburban Chicago is overseen by DOE/SC. The average age of Argonne-operated facilities and infrastructure is 48 years, with 61% of the assets being more than 50 years old. Our facilities are roughly 90% occupied.

In addition to buildings operated by Argonne, the site includes the Howard T. Ricketts Regional Biocontainment Laboratory, operated by UChicago, and the Theory and Computing Sciences Building, a privately-operated building in which we currently rent about 240,000 sq ft.

In December 2018, a new lease agreement was signed for 30,000 sq ft of data center space at the Theory and Computing Sciences Building. When occupied, this new space will support exascale computing in addition to Argonne's advanced computing initiative. In FY19, we plan to lease 60,000-80,000 sq ft of multi-use space in support of the APS-U project.

Campus Strategy

We have developed a structured, 10-year site modernization plan – entitled *Facility and Infrastructure Strategic Investment Plan* – to revitalize and construct facilities and infrastructure to meet current and emerging mission needs. The plan addresses environmental performance, safety, legacy waste, obsolete facilities, new facilities, and operating and maintenance support. The plan prioritizes needs, with timing and sequencing of actions chosen to align with the mission and leverage resources available for execution. Four main principles guide our campus strategy:

- Support mission-critical programs. Argonne continues to commit internal resources and communicate needs for external funding to establish an executable plan for supporting immediate and future infrastructure investments required for mission-critical programs.
- Construct replacement facilities and re-use/renovate existing facilities. We renovate and modernize existing facilities to meet current and future scientific laboratory facility needs while reducing deferred maintenance, improving asset condition, and increasing utilization rates. These efforts apply overhead investment to enable re-use of facilities that, although obsolete due to age, retain positive structural and space characteristics that support modern scientific research.
- Address utility infrastructure. We use a rigorous process to assess site infrastructure conditions to prioritize and implement repairs and upgrades to meet capacity, reliability, and redundancy goals. The goal of our planned investments is to reduce our identified deferred maintenance backlog, with an ultimate target of achieving the DOE-established goal for "adequate" condition for all utility infrastructure.
- Address legacy waste and excess facilities. Removal of legacy waste and excess facilities is consistent with the DOE/SC goal of maximizing asset utilization and eliminating inadequate-condition facilities. It also supports complex-wide DOE requirements for overall footprint reductions via space banking and reduction in yearly operations and maintenance costs. We are aggressively consolidating radiological facilities and reducing inventories of radiological materials, while preserving the capability to perform mission-important activities. The biggest challenge in this area is securing external funding for disposition of contaminated facilities. As part of the FY20-FY24 DOE/EM budget call, Argonne submitted a five-year over-target request of $143 million with 14 subproject activities. Execution of the excess facilities strategy in the identified period is critical to the Laboratory's long-term deferred maintenance reduction and facility utilization strategy. Argonne will continue to work in close coordination with DOE/SC to obtain the needed funding and is prepared to respond to DOE/EM's FY20-FY24 budget call if invited to do so.

Key near-term investments to achieve Argonne's infrastructure strategy:

- *Materials Design Laboratory ($95 million SLI)*. Now under construction, the Materials Design Laboratory is on track for beneficial occupancy in FY19 within cost, scope, and schedule. This 115,000-sq-ft facility will enable continued consolidation of research space that began with the Energy Sciences Building, to support three core capabilities: condensed matter physics and materials science, chemical and molecular science, and chemical engineering. This high-performance laboratory building will include high-accuracy, flexible, and sustainable space needed to support scientific theory/simulation, materials discovery, characterization, and application of new energy-related materials and processes.
- *Electrical capacity distribution capability ($60 million SLI)*. An upgrade to Argonne's high-voltage power supply is required to support projected load increases associated with scientific growth and provide a fully redundant power supply to all site research programs, facilities, and systems. Argonne today receives power from a single location that has original 1960 equipment and installations. This condition increases the risk of an external power outage affecting the site and mission-critical programs, including the Advanced Photon Source (APS), Center for Nanoscale Materials (CNM), Argonne Leadership Computing Facility (ALCF), and Argonne Tandem Linear Accelerator System (ATLAS). The power upgrade also will provide additional capacity to support

increases in electrical usage associated with exascale computing efforts expected in the FY21 timeframe. This investment is considered enabling infrastructure; however, it directly addresses risks associated with the following core capabilities: accelerator science and technology; advanced computer science, visualization and data; chemical and molecular science; condensed matter physics and materials science; and nuclear physics.

- *Major utilities repair and modernization ($90 million SLI)*. This project replaces, repairs, and upgrades several critical utility systems (chilled water, domestic water, steam/condensate, and sewer) to reduce operational risks, eliminate deferred maintenance, and reduce the risk of unplanned service outages. Upgrades to central chilled water capacity and distribution will enable integration of isolated buildings, reducing operating and maintenance costs and decommissioning aging satellite plants and associated failing equipment. Repairs and replacements will address deteriorated and failed portions of steam and condensate distribution piping. The project also will replace an obsolete, unsupported control system for the steam plant. This investment is considered enabling infrastructure; however, it directly addresses risks associated with the following core capabilities: accelerator science and technology; advanced computer science, visualization and data; chemical and molecular science; condensed matter physics and materials science; and nuclear physics.
- *400-area facility, modernization (mechanical $7.1 million GPP, electrical $8.4 million GPP)*. Multiple investments are required to modernize the 400 area of the site to assure that several mission-critical facilities – APS, CNM and the Advanced Protein Characterization Facility (APCF) – can continue to function as 24/7 scientific user facilities. The main support facilities and utility distribution are original, installed approximately 26 years ago. Much of the cooling and electrical equipment has reached the end of its life and parts are becoming unavailable as emergency repairs increase. The roofs of all the original facilities also are aging, and leaks and water infiltrations are increasing. We propose to use Argonne repair funds for general facility roof replacements. Direct funding is required to replace the primary support cooling systems and the underground piping and electrical distribution. This investment primarily supports the following core capabilities: accelerator science and technology, biological and bioprocess engineering, chemical and molecular science, condensed matter physics and materials science, and large-scale user facilities/advanced instrumentation.
- *Building 350 legacy project and renovation ($44.1 million SLI, $8.9 million GPP)*. In FY17, DOE transferred operational responsibilities for Building 350, formerly the New Brunswick Laboratory, to Argonne. To make the building usable for future programs, we have initiated an SLI-funded project to de-inventory about 21,000 nuclear reference materials, clean out hazardous materials, and characterize the residual contamination. A parallel effort to renovate the facility is required to make it useable for research and radiological, safety, and health support operations.

Alternative financing approaches

Argonne continues to investigate alternative financing approaches to achieving the site's facilities modernization strategy. Through partnerships with the State of Illinois, Argonne has constructed several facilities, most recently the APCF.

To address future growth in several areas − energy storage, imaging, microscopy, and materials synthesis scale-up – we have proposed the Illinois Energy Storage Accelerator building (formerly known as the Energy Innovation Center), the Sensing and Imaging at Argonne building, and the Materials Scale-up Laboratory (formerly known as the Applied Materials Manufacturing Facility).

Site Sustainability Plan Summary

Argonne's site sustainability program supports our science and engineering mission by modernizing infrastructure and engaging site occupants while reducing Argonne's environmental impact. We have made sustainability improvements under four active energy savings performance contracts (ESPCs) and are now measuring the results. Improvements include the Combined Heat and Power Plant and efficiency upgrades in boiler house operations, site lighting, and building controls. We continue to participate in the DOE Facilities and Infrastructure Restoration and Modernization Program and have hosted experts from the Federal Energy Management Program to learn about implementing energy efficiency projects through a utility energy service contract (UESC).

In FY18, our sustainability accomplishments included completion of 23 energy and water efficiency projects, which provide $170,000 in annual savings to the Laboratory, and installation of an additional 40 kW of solar photovoltaics at Bldg. 300. In the second year of our Retrocommissioning (RCx) Program, our RCx contractor completed analysis and testing at Bldgs. 201, 208, 221, and 362 and recommended measures that will deliver $147,000 in annual savings to Argonne. We are incorporating RCx strategies specific to sustainable experimental laboratories through participation in the DOE Smart Labs Accelerator (SLA). We joined the SLA in FY18 and now are collaborating with partners to implement best practices to enhance safety and energy efficiency.

In July 2018, Argonne implemented a composting program that focuses on food scraps and paper towels and so far, has collected five tons of material monthly. We have documented 16 buildings as meeting High-Performance Sustainable Buildings Guiding Principles, meeting DOE's goal of 17% by FY25.

BROOKHAVEN NATIONAL LABORATORY

Lab-at-a-Glance

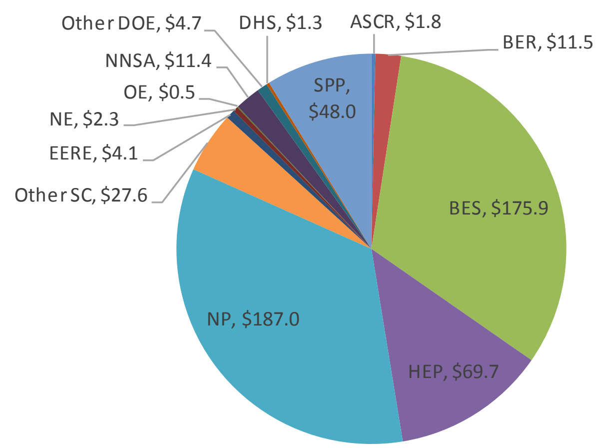
Location: Upton, New York
Type: Multi-program Laboratory
Contractor: Brookhaven Science Associates
Site Office: Brookhaven Site Office
Website: www.bnl.gov

- **FY 2018 Lab Operating Costs:** $545.8 million
- **FY 2018 DOE/NNSA Costs:** $496.5 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $48 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 9%
- **FY 2018 DHS Costs:** $1.3 million

Physical Assets:
- 5,322 acres and 315 buildings
- 4.84 million GSF in buildings
- Replacement Plant Value: $5.63 B
- 134,263 GSF in 20 Excess Facilities
- 0 GSF in Leased Facilities

Human Capital:
- 2,379 Full Time Equivalent Employees (FTEs)
- 139 Joint Faculty
- 121 Postdoctoral Researchers
- 188 Graduate Student
- 260 Undergraduate Students
- 3,198 Facility Users
- 2,176 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

BNL's mission is to deliver expertise and capabilities that drive scientific breakthroughs and innovation for today and tomorrow. Established in 1947, BNL brings unique strengths and capabilities to the Department of Energy (DOE) laboratory system and is the only multi-program Laboratory in the Northeast. BNL produces transformative science and advanced technologies, and does it safely, securely, and environmentally responsibly, with the cooperation and involvement of the local, state, and international scientific communities.

With a long-standing expertise in accelerator science and technology, BNL conceptualizes, designs, builds, and operates major scientific facilities in support of its DOE mission. These facilities serve DOE's basic research needs and reflect BNL/DOE stewardship of national research infrastructure critical for university, industry, and government researchers. The Relativistic Heavy Ion Collider complex, the National Synchrotron Light Source II, the Center for Functional Nanomaterials, and the Accelerator Test Facility serve nearly 3200 scientists/year. Seven Nobel Prizes have been awarded for discoveries made at BNL.

BNL's strong partnerships with Stony Brook University, Battelle, and the Core Universities (Columbia, Cornell, Harvard, MIT, Princeton, and Yale) are important assets in accomplishing the Lab's missions.

Beyond their roles in Brookhaven Science Associates, Stony Brook and Battelle are key partners in all of BNL's strategic initiatives, from basic research to the commercial deployment of technology. They underpin BNL's growing partnerships in the Northeast, especially its vital relationship with New York State.

Core Capabilities

Thirteen core technical capabilities and one that is considered as emerging (Computational Science) underpin activities at Brookhaven National Laboratory (BNL). Each one is comprised of a substantial combination of facilities, teams of people, and equipment that has a unique and often world-leading component and relevance to national needs, as well as to the education of the next generation of scientists from grades K – 12 through graduate school. These core capabilities enable BNL to deliver transformational science and technology that is relevant to the DOE/Department of Homeland Security missions.

Accelerator Science and Technology

BNL has long-standing expertise in accelerator science that has been exploited in the design of accelerators around the world, beginning with the Cosmotron in 1948, now including the Relativistic Heavy Ion Collider (RHIC) and National Synchrotron Light Source II (NSLS-II), and looking forward to a next generation Electron-Ion Collider (EIC) at BNL. Among the now "standard" and widely-used technologies developed at BNL are the strong-focusing principle and the Chasman-Greene lattice, which were transformational developments for modern accelerator and synchrotron light source facilities, respectively. With the construction of NSLS-II, the Laboratory adopted recent advances in accelerator technology to achieve unprecedented brightness.

Since 2015, NSLS-II has provided reliable, stable, and intense beams of synchrotron radiation to the user community. Major advances in reliability were accomplished by implementing improvements that targeted major machine subsystems. Over the past few years, the facility added 20 new insertion devices, with several narrow-gap in-vacuum undulators and increased the operating current to 400 mA, recently achieving 475 mA in beam studies. The storage ring emittance of 800 pm rad remains one of the smallest among operating light sources. NSLS-II is making important contributions to the Advanced Photon Source and Advanced Light Source Upgrade projects that will deliver unprecedented brightness. Core strengths of NSLS-II include expertise in physics of light sources, collective effects and novel ring lattices, designs of permanent magnet undulators and front-ends, RF, advanced control systems, and high-performance beam diagnostics. The wealth of knowledge accumulated at NSLS-II from early designs to today's operations lays a solid foundation for a future NSLS-II upgrade within the next decade.

BNL continues to aggressively extend the physics reach of RHIC. An order-of-magnitude additional improvement in RHIC luminosity for heavy ion collisions, now reaching nearly 50 times design luminosity in Au+Au collisions, was delivered with its cost-effective and rapid implementation of stochastic cooling for high-energy bunched beams. RHIC accelerator physicists pioneered acceleration of spin-polarized proton beams to high energy using Siberian snakes, thus making RHIC the only machine capable of exploring the polarization of quarks and gluons inside the proton. Bunched-beam electron cooling is being commissioned to enable higher luminosity at lower energies, thus enabling high statistics beam energy scans to search for the Quantum Chromodynamics (QCD) Critical Point. Core strengths in hadron cooling, superconducting RF, energy recovery linac (ERL) technology, and high-brightness electron storage rings are the foundation of the proposed development of an EIC at BNL, which will enable more detailed exploration of the fundamental constituents of matter. The RHIC injector complex also supports a broad range of secondary beams for users and applications at the Tandem Van de Graaff, NASA Space Radiation Laboratory, and the Brookhaven Linac Isotope Producer.

BNL's Superconducting Magnet Division (SMD) played a central role in the early development of superconducting magnets for high-energy colliders, thus enabling RHIC construction. The excellent performance of the SMD-supplied ring magnets directly contributed to the success of the RHIC physics program. SMD contributed to key RHIC advances through the helical coil magnets it provided for the polarized proton program and the precision solenoids it built for the RHIC electron lens system. A unique capability is its computer-driven "direct wind" technology – a specialized resource that has produced complex multi-function magnets for the interaction regions of colliders world-wide. SMD delivered magnets for the Large Hadron Collider (LHC) at CERN and continues to have a major role in constructing and testing magnets for the High Luminosity Upgrade of the LHC. Work at SMD to develop magnets based on high-temperature superconductors led to the fabrication, presently underway, of a very high field solenoid magnet to aid in the search for axionic dark matter, potentially one of the missing pieces in our understanding of the structure of the universe. SMD provides diverse capabilities that support all of BNL's accelerator facilities and that are essential for the construction of an EIC.

The Accelerator Test Facility (ATF) is the flagship user facility of the DOE Accelerator Stewardship Program in the Office of High Energy Physics (HEP). It supports a broad range of user-driven research in beam physics, novel radiation sources, and advanced accelerator technology and provides hands-on training for next-generation accelerator physicists. A unique feature is its combination of high-power pulsed lasers and high-brightness electron beams, which can be used individually or in combination. ATF's long wavelength infrared CO2 laser system recently demonstrated five-terawatt operation in a single 2.3 picosecond pulse. Further planned upgrades to deliver sub-picosecond pulses with peak powers well over 10 terawatts, together with its electron beam capability, will enable a world-class research program in laser-matter interactions and plasma-based acceleration of electron and ion beams.

BNL's strength as a world-class accelerator laboratory provides the foundation of the Lab's and DOE's research programs. The Lab is pursuing stronger integration of its Accelerator Science and Technology (AST) efforts across directorates to foster cross-fertilization of the R&D efforts for an EIC with R&D at the ATF and R&D for advanced synchrotron light sources. AST drives, both internally and externally, the projects currently envisioned to sustain the Laboratory. This includes collaboration with industry and academia on topics such as improved ion beam therapy facilities and the demonstration of a prototype multi-pass high-current ERL with large energy acceptance. BNL's AST efforts are closely integrated with developing the future leaders of the field through mentoring of students, lectures at leading universities, and engagement with the joint BNL-Stony Brook University (SBU) Center for Accelerator Science and Education (CASE). Roughly ten Ph.D. students conduct accelerator research at BNL under the auspices of CASE.

The Office of Nuclear Physics (NP), the Office of Basic Energy Sciences (BES), and HEP, as well as SBU, New York State Energy Research & Development Authority (NYSERDA), and Laboratory Discretionary Funds are the primary sources of funding for the ongoing AS&T efforts.

Advanced Computer Science, Visualization & Data

BNL science is dominated by the operation and support of data-rich experimental, observational, and computational facilities, such as RHIC, ATLAS, Belle II, NSLS-II, the Center for Functional Nanomaterials (CFN), the Systems Biology Knowledgebase (KBase), US QCD, and the Exascale Computing Project (ECP). Driven by their requirements, BNL has a long-standing research, development, and operational program in advanced computer and data science methods, applied mathematics, algorithms, tools, and infrastructures – making it one of the largest data science labs in the DOE complex.

BNL operates one of the top-five data archives in the world, with over 160 PB of actively managed data and 800 PB annually analyzed. Data traffic has reached up to 10 PB/month from data centers across the world and continues to grow as new facilities reach maturity. Data processing is supported by a variety of high-throughput and high-performance compute resources, amounting to ~6 PF of compute capacity, supported by 90 PB of disk capacity. BNL provides these capabilities 24/7 with a guaranteed availability of 99.5%.

A core focus of BNL's Computational Science Initiative (CSI) is the continued research and development of novel, extreme-scale data analysis and visualization paradigms that support data-based discovery at research facilities, including the following co-design activities.

Efforts in CSI's Computing for National Security Division deliver a comprehensive research program focused on testing and exploration of novel devices and architectures and their suitability for data-intensive workloads in open science and national security. The research includes novel architecture testbeds, design space exploration for materials, devices and systems for data-intensive computing through measurement and performance modeling, and development of new methodologies and tools for performance, power, and reliability modeling. Areas under investigation or active planning are optical networks, specialized architectures for machine learning, and quantum computing.

CSI's research into programming models, runtime systems for machine learning, and new performance portability approaches will provide a capability to enable the effective use of novel architectures. CSI researchers are developing programming models that will allow code developers to test different optimization strategies quickly and greatly reduce overall development time. An associated goal is to provide scientific users with an application layer agnostic of the hardware details, allowing use of as many computing resources as available, thus maximizing scientific productivity. Compiler optimization for performance portability improves the state-of-the-art by finding quality transformations that achieve superior or equal computational performance. This work automatically transforms code to optimize for locality and parallelism. It also allows developers to focus more on the core science.

The Center for Data Driven Discovery (C3D) is advancing a "Building Block" approach to workflows and data-intensive software systems - RADICAL-Cybertools. These allow for different points of integration with existing tools, which eliminate some of the reasons for workflow systems proliferation. Building Blocks facilitate performance portability and optimization of workflows/workflow systems. As validation and uptake of this research, BNL is designing the next-generation workload management system (PanDA) for ATLAS and working to enhance Fireworks (used extensively by the Materials Design community). C3D, established in part using New York State funding, will be at the forefront of translational research and developing production software systems, middleware, and scalable capabilities for streaming data and computational steering.

CSI has built an extensive research program in machine learning and artificial intelligence that focuses on scalable, robust, and streaming machine learning algorithms beyond deep learning. The program integrates computer science, applied mathematics, and domain knowledge to develop new machine learning libraries (including ECP ExaLearn and the Office of Advanced Scientific Computing Research [ASCR]-funded ROBUST). The new analytical capabilities were successfully applied to NSLS-II and CFN analytical workflows, ECP projects CODAR and NWChemEX, and in precision medicine. Efforts in artificial intelligence focus on developing new approaches to optimal autonomous experimental design (AEOLUS, Exalearn). Connected efforts explore new programming models and runtime systems for machine learning and research into new accelerator technologies that can effectively support machine learning.

Visual analytics research plays a key role in developing new paradigms for the effective and near real-time interpretation of extreme streams and volumes of data, in support of experimental steering. After focusing on single modality data streams, CSI research now addresses highly heterogeneous data streams and their visual analytics, tying innovative machine learning analytics into the visual representations. Targeted applications are synchrotron experiments and ECP online analysis workflows. Initial tools were deployed at NSLS-II.

The primary sources of funding come from ASCR, HEP, NP, BES, BER, New York State, Other Government Agencies (OGA), and Laboratory Discretionary Funds.

Applied Materials Science and Engineering

BNL engages in a broad range of activities related to energy storage and grid, including materials synthesis, characterization and functional electrochemical evaluation, high energy density cell technology, evaluation of thermal stability and functional limits of battery materials, and fundamental studies of charge and discharge mechanisms and associated material-structure evolution.

BNL has well-established expertise and capabilities for in situ characterization of energy storage materials by X-ray methods and growing expertise in integrating these studies with in situ neutron scattering and electron microscopy for more complete structural characterization, including of light elements (e.g., Li, Na). BNL has recently led novel X-ray-based micron-scale mapping studies of functioning batteries as part of the Battery500 multi-laboratory project and is establishing new capabilities for nanoscale imaging using micro-electrochemical cells for X-ray and electron microscopy under operando conditions. These capabilities are used to understand complex active electrochemical interfaces and to carry out research in high energy density cell technology.

BNL has become an important player in grid modernization, focused on the challenges of New York State and the Northeast, efficient and resilient electricity distribution systems with high penetration of renewables. BNL is a member of the DOE Grid Modernization Laboratory Consortium and plays a key role in several of its projects. BNL also supports New York State's efforts to restructure its electricity markets under the "Reforming the Energy Vision (REV)" initiative.

BNL has capabilities to study materials in extreme environments for nuclear applications. BNL has developed a specialized robotic system at NSLS-II for the rapid characterization of materials damaged in high-radiation environments, such as pressure vessel steels. BNL is using this capability to provide industry with unique information on the performance of advanced materials for nuclear applications. BNL has also developed and continues to develop a unique suite of environmental cells for the in-situ characterization of reactor materials and molten salt samples that are air and water sensitive, highly corrosive, and at high temperature. These cells are used to gain new insights on accelerated corrosion of advanced cladding materials for nuclear applications. In addition, BNL has installed X-ray diffraction computed tomography at the X-ray Powder Diffraction beamline at NSLS-II, which will provide 3D imaging of the microstructure of engineering-scale samples.

As part of the RaDIATE international collaboration, the 200 MeV proton beam of the Linac and the Brookhaven Linac Isotope Producer (BLIP) target facility are used extensively to investigate radiation damage by high-intensity proton and neutron beams of beam collimators, beam windows, and high-power targets.

The primary sources of funding are: BES, the Vehicle Technologies Program of the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Energy Delivery and Energy Reliability (OE), the Office of Nuclear Energy (NE), New York State, and Laboratory Discretionary Funds.

Biological Systems Science

The goal of BNL's program is to develop a systems-level understanding of complex biological processes relevant to the DOE mission with respect to energy and the environment. BNL's expertise integrates computational and experimental platforms to generate and test hypotheses using approaches that include molecular biology, biochemistry, structural biology, and imaging. Ultimately this work lays the foundation for desired manipulations of growth rates, biomass accumulation, resistance to stresses, and the accumulation of desired feedstocks for biofuels and bioproducts in organisms relevant to BER. This program is synergistic with programs in physical biosciences (funded by BES, Section 3.5).

BNL's Quantitative Plant Science Initiative (QPSI), addresses the grand challenge of "Enabling predictive biology." A key focus area is on "plant genomic dark space" and accelerating discovery of the functions of large numbers of genes for which there is currently little, or no knowledge of function. A genotype-to-phenotype discovery platform that was recently commissioned and validated enables genome-wide screening to define the roles of genes in core plant processes. Use of this capability is key to developing the knowledgebase needed to model plant processes to identify strategies for manipulating plants of economic importance to accumulate feedstocks for biofuels and bioproducts.

QPSI also makes use of the world-leading analytical capabilities at NSLS-II, in addition to existing capabilities within the CFN, to probe molecular structure and dynamics at unprecedented spatial and temporal resolutions. Using the beamlines at NSLS-II, cryo-electron microscopy (cryo-EM), and fluorescence resonance energy transfer, BNL researchers will perform structural analysis on complex biological systems at scales ranging from angstroms to the whole plant level. The bioinformatics and computational biology capability is an integral part of the BNL biological systems program. BNL researchers contribute to the KBase development team (led by Argonne, Lawrence Berkeley, and Oak Ridge National Laboratories).

NSLS-II continues to expand its science program for molecular characterization and imaging. The instruments being developed to resolve hierarchies of structure and function for biological and environmental sciences will be further developed for ease of use and reliability. Through a collaborative effort between NSLS-II and Instrumentation Division staff, BNL is developing a novel Full Field Fluorescence Imaging detector to enable rapid imaging of metal distribution in complex biological systems, such as plant-root/microbe systems. Imaging of molecules by cryo-EM will become a new capability complementing the world-leading performance of the X-ray diffraction and scattering programs. The unique combination of spatial, chemical, and molecular imaging capabilities of NSLS-II will be enhanced by cryo-electron tomography. New capabilities will enable examination of rhizosphere and plants under realistic conditions. All the developments will be supported through targeted training and dissemination.

Funding comes from BER. Recently, BNL partnered to secure the Center for Advanced Bioenergy and Bioproducts Innovation and three Biosystem Design projects (led by Berkeley, Cold Spring Harbor Lab, and the University of Illinois). Collaborations are also supported by Joint Genome Institute Community Science Programs, the Facilities Integrating Collaborations for User Science (known as FICUS), the Office of Advanced Scientific Computing Research, and National Nuclear Security Administration (NNSA)/Advanced Scientific Computing Exascale Computing Project. Additional support comes from New York State, the National Institutes of Health (NIH), a Cooperative Research and Development Agreement (CRADA), and Laboratory Discretionary Funds.

Chemical and Molecular Science

BNL's chemical and molecular sciences conduct fundamental research to support rational design of chemical and biological processes, focused in programs on sustainable energy and chemical conversion and on chemistry in extreme environments. The emphasis in sustainable energy research is on heterogeneous catalysis of C1 chemistry for fuels, light capture and catalytic conversion by molecular systems for solar fuels, and carbon capture conversion and storage in plants. The program on chemistry in extreme environments addresses radiation chemistry for mechanistic principles and stability of media for future nuclear energy systems. Research closely integrates core program expertise with BNL's leading national user facilities NSLS-II and CFN and the divisional Accelerator Center for Energy Research (ACER) electron radiolysis facility.

BNL expertise and unique capabilities in thermal heterogeneous catalysis are being applied to improve understanding of catalysts for conversion of difficult-to-activate small molecule feedstocks, such as abundant methane or CO2 to synthesize fuels and higher value chemical intermediates, with a focus on synthesis and study of highly active nanostructured metal-oxide and metal-carbide interfaces. Research in catalysis and electrocatalysis combines leading capabilities in operando studies of powder catalysts, in situ studies of model nanocatalysts, and quantum chemical computation. Operando and in situ research exploits high-brightness beamlines at NSLS-II for time-resolved studies of catalysts by X-ray scattering and spectroscopy, and state-of-the-art electron microscopes at the CFN for in situ and atom-resolved imaging of catalysts. Advanced ambient-pressure capabilities in the Chemistry Division for spectroscopy and scanning tunneling microscopy of surfaces under reaction conditions allow characterization of catalytic active sites and their interaction with reaction intermediates.

BNL catalysis scientists lead the Synchrotron Catalysis Consortium (SCC), which provides expert training and support to expand the use of synchrotron methods in catalysis science. The SCC returned to BNL in 2018 initiating operations at two NSLS-II X-ray beamlines (Tender X-ray Absorption Spectroscopy and Quick X-ray Absorption and Scattering) after interim operations at the Stanford Synchrotron Radiation Light Source. During its fourteen years of operation, SCC has supported advanced characterization and testing of model and real-world catalysts by researchers from more than 100 groups from universities, industry, and other National Laboratories. New in situ characterization efforts will expand SCC programs across multiple photon science and nanoscience capabilities.

The physical biosciences program focuses on fundamental understanding of plant regulatory and metabolic mechanisms related to the capture, conversion, and storage of carbon with emphasis on highly reduced, i.e., energy-dense forms of carbon, including lipids and phenylpropanoids. The program exploits synergistic team capabilities that include biochemical genetics, physical biochemistry, mass spectrometry, advanced metabolic modeling, computational chemistry, molecular imaging, and structural biology, together with multiple aspects of NSLS-II and CFN. The close interactions with BNL's membrane protein structural biologists and the commissioning of cryo-EM provide opportunities to deepen our understanding of the structure and dynamics of biosynthetic complexes.

BNL's program in solar photochemistry has world-recognized expertise in the design, synthesis, and characterization of inorganic molecular catalysts and chromophores to understand and improve chemical processes for solar-to-fuels conversion in artificial photosynthesis (AP). Research focuses on key AP reactions of water oxidation and CO2 or proton reduction. Expertise and capabilities for integration of molecular AP units into functional sub-assemblies are growing. Research exploits unique capabilities of ACER for mechanistic studies of key oxidation and reduction reactions.

The radiation chemistry program develops and applies advanced pulse radiolysis capabilities at ACER. Within ACER, the Laser Electron Accelerator Facility provides world-leading capabilities for ultrafast pulse radiolysis; a Van de Graaff accelerator supports kinetics studies on slower timescales; and two 60C sources enable irradiation studies. Time-resolved infrared spectroscopy uniquely probes specific chemical mechanisms in pulse radiolysis studies. This is enabling new investigations of chemical reaction pathways in radiation chemistry and artificial photosynthesis and providing new insights into processes of molecular charge generation and transport.

ACER is also a foundation for growing BNL capabilities in chemistry of extreme environments. The new Molten Salts in Extreme Environments Energy Frontier Research Center builds on ACER capabilities in radiation chemistry and is adding capabilities in handling, irradiation, and characterization of high temperature molten salts and their interactions with materials, including in situ studies at NSLS-II.

Fundamental chemistry and physical biosciences programs are funded by BES, New York State, and Laboratory Discretionary Funds.

Chemical Engineering

BNL has a small but high-impact effort in applied chemistry research that translates scientific discovery into deployable technologies. Electrocatalysis research builds on expertise in synthesis and characterization of nanostructured core-shell metal, metal-oxide, and metal-nitride nanostructures for design of cost-effective, durable electrocatalysts for electrical-chemical energy conversion in fuel cells and electrolyzers. BNL developed innovative electrocatalysts with the potential to solve problems of low energy-conversion efficiency and high platinum loading in fuel cells. These catalysts contain smaller amounts of precious metal than conventional ones, facilitating commercial applications of fuel cells, including in electric vehicles. Scale-up of some materials is underway with industry partners.

These programs are funded by BES, the EERE Hydrogen and Fuel-cells Technologies program, and through several CRADAs with industrial partners.

Climate Change Science and Atmospheric Science

BNL's atmospheric and terrestrial ecosystem science efforts aim to develop process-level insight into the role of aerosols and clouds on Earth's climate and the response of ecosystems to a changing climate. BNL researchers are advancing the understanding of interactions along the aerosol-cloud-precipitation continuum and their impacts on climate for the Atmospheric Systems Research Program. Research focuses on analysis of data gathered from the Atmospheric Radiation Measurement (ARM) Climate Research Facility; studies of the lifecycle and radiative properties of clouds and aerosols; and developing cutting-edge retrievals of cloud properties and processes from remote sensing observations. BNL scientific staff supports the ARM facilities as instrument mentors and as data science specialists, and by making contributions to the design and interpretation of ARM measurements. Climate modeling scientists support the Energy Exascale Earth System Model (E3SM) and the Large Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) project through their expertise in component development, model evaluation, and the strong observational data analysis they bring to these efforts.

Leveraging long-standing support by BER's Climate and Environmental Science Division and recent BNL investments in the CSI, BNL developed new capabilities in support of BER's needs in environmental data analysis, uncertainty quantification, and high-resolution atmospheric modeling. BNL has also established a mobile remote-sensing platform to support research in off-shore wind resource characterization, urban system studies, and national security applications.

BNL researchers in the Terrestrial Ecosystem Science and Technology group play a central role in the BER Next Generation Ecosystem Experiment (NGEE) in the Arctic. Research is focused on improving the representation of ecosystem processes in Earth System Models in polar regions and understanding what drives uncertainty in model structure and parameterization of these regions in order to increase the ability to understand and project global climate change. BNL scientists study processes that have a global impact on climate and focus on ecosystems that are poorly understood, sensitive to global change, and inadequately represented in models. They use state-of-the-art techniques to study ecosystem processes across a wide range of scales and biomes.

Funding comes from BER and Laboratory Discretionary Funds.

Condensed Matter Physics and Materials Science

BNL conducts frontier research in Condensed Matter Physics and Materials Science, focusing on new and improved complex, nanostructured, and correlated-electron materials for renewable energy, energy storage, quantum information science (QIS), and energy efficiency. This is accomplished through interdisciplinary and tightly coupled programs in materials synthesis, advanced characterization using a range of experimental techniques, both lab and facility based, and theoretical techniques.

As part of the Center for Mesoscale Transport Properties (an Energy Frontier Research Center), operando methods were developed that exploit existing and recently commissioned beamlines at NSLS-II. Materials characterization over multiple length scales is executed with multimodal approaches that provide fundamental information on transport properties and on the influence of the local environment.

A unique tool, known as OASIS (a leadership-class capability that combines oxide molecular beam epitaxy, angle-resolved photoemission, and spectroscopic imaging scanning tunneling microscopy), is fully operational and producing first science. OASIS brings together in one instrument the ability to fabricate thin films and examine their properties in situ using scanning tunneling microscopy and angle-resolved photoemission. The first experiments are focusing on the universality of the phase diagrams of high TC superconducting cuprate families.

As described in the Condensed Matter Physics and Materials Science (CMPMS) Division's strategic plan, all the groups in the Division are engaged in NSLS-II activities, but to different degrees. New capabilities in X-ray scattering and angle-resolved photoemission exploit the opportunities offered by NSLS-II, and BNL scientists are leading several proposals for new NSLS-II beamlines. Two of these proposals have begun their first phase of development.

The ultrafast electron diffraction (UED) capability is considerably enhancing the ability to explore non-equilibrium physics in strongly correlated materials. A planned upgrade includes an optical parametric amplifier and a double tilt sample stage, which will make it possible to separate the effects of different degrees of freedom in a strongly correlated material. In addition, LDRD funds effort toward developing an ultrafast imaging capability. The UED activities are complemented by a new ultrafast program that focuses on the unique science that can be performed at ultrafast facilities around the world, particularly the Linac Coherent Light Source at SLAC.

BNL's Center for Computational Design of Functional Strongly Correlated Materials and Theoretical Spectroscopy is developing software that will enable properties of strongly correlated materials to be predicted. The computer programs, which are becoming available to the scientific community free-of-charge, are expected to tie in into the activities of NSLS-II users and to be upgraded periodically by BNL, where they will permanently reside. The Center, in its fourth year of operation, has submitted renewal documents.

Within CMPMS, there is a new focus on QIS. New planned activities will take advantage of in-house strength in high TC superconductivity and chiral materials. An LDRD explores the possibility of enhancing coherence of the topological excitations of phononic materials. This LDRD has seeded the research that is being proposed in response to a recent QIS call from BES.

BES and Laboratory Discretionary Funds are the primary sources of funding for these ongoing efforts.

Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation

As a key part of its mission, BNL develops and operates user facilities that exceed the funding and expertise available at individual institutions. In FY 2018, BNL served nearly 3200 users at its DOE designated user facilities, i.e., ATF, RHIC (including NASA Space Radiation Laboratory [NSRL] and the

Tandems), NSLS-II and CFN, as well as additional users at the RHIC-ATLAS Computing Facility (RACF) and US ATLAS Analysis Support Center. BNL also supports the ARM Climate Research Facility.

NSLS-II is completing its fourth year as a User Facility having hosted 1365 unique users in FY 2018. Currently, 28 beamlines are in service, with 23 in General User operations. As of March 2019, NSLS-II was operating at 400 mA, with 97.4 % reliability year-to-date. NSLS-II has strong R&D programs in nano-focusing optics and nano-precision engineering and a strong partnership with the CFN, running four endstations together. Partnerships with the BES neutron sources in the areas of small angle scattering and powder diffraction facilitate the work of researchers using both X-ray and neutron techniques on a single problem. NSLS-II plays a leading role in next-generation data acquisition software (BlueSky), which is becoming the de facto standard for new beamlines across the complex, and in coordinating areas of common interest among the DOE light sources, particularly in data, optics, and detectors.

The CFN completed its first decade of operation in 2018, which that year led to 300 peer-reviewed publications. It supported the research of 581 external users in FY 2018. CFN's portfolio of nanoscience instruments includes capabilities for material synthesis by assembly of nanoscale components, and in situ nanomaterial characterization using electron, X-ray, and photon probes. Two new major instruments were added in 2018: a lab-based ambient-pressure X-ray photoelectron spectrometer and a high resolution (10 nm) atomic force microscope capable of near-field optical and photothermal microscopy, along with upgrades for electron microscopy sample preparation. Increasingly, the CFN is focused on incorporating data analytics to efficiently manage and analyze large, complex datasets.

BNL continues to expand the scientific reach of RHIC for its community of more than 1000 users by investing in detector and accelerator upgrades. The recently completed STAR iTPC upgrade and the Low-Energy RHIC electron Cooling upgrade enable a world-unique program of precision exploration of the QCD phase diagram. Forward upgrades of the STAR detector will keep the QCD Spin Physics community engaged by providing unique capabilities in this field. The sPHENIX upgrade, currently in progress, will enable measurement of rare probes of the internal structure of the quark-gluon plasma and bring participants in the LHC heavy ion program back as users of RHIC.

BNL envisions a new facility, an electron-ion collider to be developed in the latter half of the next decade. This facility would support a new generation of users who will use high-energy electron-ion collisions to study cold nuclear matter at extreme gluon densities and enable precision measurements of the structure and properties of protons and complex nuclei at the quark-gluon level.

BNL operates the ATF for the advanced accelerator science and technology community as part of the Accelerator Stewardship Program. This facility is unique in terms of the breadth of advance accelerator and laser experiments that it supports.

BNL also makes important contributions to international facilities – the LHC, and such future facilities as a Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) and the Large Synoptic Survey Telescope (LSST), which is under construction. This core capability (CC) is strongly tied to CC 1, 2, and 13.

Data collected from the Long Island Solar Farm at BNL has led to the creation of the largest data sets for a utility-scale solar plant in the U.S. (solar insolation, weather, power, and power quality), enabling development of advanced solar forecasting models to support grid operations.

BNL's Instrumentation Division provides cutting-edge support for the Lab's major scientific user facilities and national security applications through its development of state-of-the-art detectors, electronics, and optical and laser systems. Major contributions have been made to instruments and experiments at BNL and other accelerator- and reactor-based facilities worldwide. The Division supports such efforts from concept through construction and is known for its leadership in noble liquid detector technology, low-noise and cryogenic electronics, application-specific integrated circuit design, state-of-the-art silicon and neutron detectors, development of high brightness electron sources, and design of metrology systems for measuring synchrotron beamline optics. Major efforts are underway to develop advanced photocathodes for RHIC and EIC applications, to demonstrate and then develop experiments based on new QIST technologies, and to develop diamond detectors for advanced synchrotron radiation imaging at NSLS-II and for novel applications in proton and ion beam therapy.

The major sources of funding are: BES, NP, HEP, BER, Case Western Reserve University, the Department of Commerce, the Department of Homeland Security (DHS), the National Aeronautics and Space Administration (NASA), NNSA, New York State, NIH, and Laboratory Discretionary Funds.

Nuclear & Radio Chemistry

BNL's nuclear science programs span the range from applications in medicine to national security. The Brookhaven Linac Isotope Producer uses the high-energy linac and target processing facilities for the production of isotopes not commercially available, mostly for nuclear medicine. Facilities are used to produce Sr-82, the parent of Rb-82, for evaluating cardiac viability and coronary artery disease in 300,000 patients annually. BNL participates in a collaboration with Los Alamos and Oak Ridge to produce Ac-225 in sufficient quantities to support clinical trials for cancer. Ac-225 is an alpha emitter that is limited in supply and has demonstrated reduced toxicity and improved cure rates in clinical trials. Upgraded facilities and the installation of a rastered beam are enabling higher production yields. The 2015 Nuclear Science Advisory Committee-I report further recommends doubling of beam current and installation of a second irradiation site to increase output in the future. The irradiation facilities are also used to conduct radiation damage studies and support the RaDIATE project comprised of six international organizations evaluating new materials for reactors and accelerators. BNL hosts one of the two Nuclear and Radiochemistry summer schools that provides 12 undergraduates with hands-on experience in nuclear and radiochemistry lab studies and exposure to world-renowned lecturers.

BNL's expertise in accelerator development has led to a patent for a Rapid Cycling Medical Synchrotron and for low-mass beam delivery gantries, viewed as technologies of choice for the next generation of proton- and ion-based cancer therapy centers.

BNL has leading expertise in the application of ionizing radiation for diagnosis and treatment of cancer. The effects of ionizing radiation on living systems are studied at NSRL, a flagship international user facility supported by NASA. The NSRL facility also provides the unique capability to study the effectiveness of using carbon or other ion beams for cancer therapy.

The Lab's nonproliferation and national security programs offer a wide range of skills that include scientific and technical participation in the NNSA Radiological Assistance Program (RAP). BNL provides technical support to RAP's planned deployments to secure national government, sporting, political, and cultural events and to unplanned deployments to provide radiological support to local, regional, and tribal governments and private industry. RAP recently relocated into a renovated, state-of-the-art training, staging, and office facility. BNL also assists NNSA and DHS efforts to test and evaluate candidate hand-held and unattended systems for prevention of, and response to, nuclear and radiological events, domestically and abroad.

BNL has extensive expertise in nuclear nonproliferation and international nuclear safeguards that includes forty years of program management for the International Safeguards Project Office (ISPO), which provides technical and administrative management of the U.S. Support Program (USSP) to International Atomic Energy Agency (IAEA) Safeguards. ISPO is responsible for coordinating all U.S. technical and personnel support provided through the USSP to the IAEA's Department of Safeguards.

Brookhaven also develops curricula and provides safeguards implementation training for IAEA inspectors and officials from other countries where IAEA safeguards are applied and provides input to technical and policy papers for the NNSA and other sponsors. BNL is applying its expertise in machine learning to develop algorithms for analyzing IAEA surveillance data and delivers an annual training course in complementary access and design information verification for research reactors to IAEA inspectors.

BNL has a world-class capability for growing, fabricating, and characterizing semiconductor and scintillator crystals, designing readout application-specific integrated circuits, and assembling and testing radiation detector prototypes for incorporation into instruments. BNL's efforts are primarily directed towards nonproliferation and homeland security applications but are also being applied to medical uses for early detection of cancer.

BNL staff members have twenty years of experience in nuclear security analysis and technology from their involvement in the NNSA Materials Protection Control and Accounting program. This capability is now in demand by other countries, where there are similar nuclear material security concerns.

Funding in this area comes from sources that include NP, the Department of State, NASA, NNSA, DHS, and a CRADA.

Nuclear Physics

BNL conducts pioneering explorations of the most fundamental aspects of matter governed by QCD. Heavy-ion collisions at RHIC probe matter at temperatures and densities representative of the early universe, mere microseconds after its birth. RHIC experiments discovered that matter under these conditions, called the quark-gluon plasma, is a nearly perfect liquid that flows more easily than any other material. The RHIC results have led to profound intellectual connections with other physics frontiers. RHIC also probes the spin structure of protons by colliding polarized protons with each other – a capability that is unique in the world.

RHIC offers a synergistic environment for collaboration with universities, other National Labs, and industry. It currently has more than 1000 users from over 20 countries. To date, the RHIC program has produced more than 300 Ph.D. nuclear physicists. Nuclear theory efforts at BNL and throughout the international theory community guide and stimulate planning and interpretation of RHIC experiments.

Experimental, theoretical, and computational research is enhanced by the presence of the RIKEN BNL Research Center (RBRC). In addition to its contributions to the RHIC research program and its role in facilitating scientific collaboration with Japan, the RBRC continues to have a major role in the development of the U.S. nuclear science workforce by helping to establish faculty positions at leading research universities.

BNL develops advanced software and computing facilities for applications in nuclear physics experiments and theory. Key expertise has been developed in the management and processing of petabyte-scale data sets generated at high rates and distributed computing for analysis, facilitated by the RACF. Lattice QCD simulations utilize high performance computing facilities at BNL and at leadership class computing facilities elsewhere to study the QCD phase diagram.

Future addition of an electron accelerator would be a major step toward an Electron-Ion Collider. The EIC would facilitate collisions of a high-energy electron beam with the existing heavy ion and polarized proton beams to precisely image the quark-gluon structure of the proton and other nuclei and to explore a novel regime of super-high gluon densities predicted to be present in all atomic nuclei. BNL scientists, in collaboration with Jefferson Lab scientists, are leading an international effort to develop the science agenda and possible technical designs for a future U.S.-based EIC facility.

Development and enhancement of RHIC accelerator facilities benefit from BNL's strong program of advanced accelerator R&D (CC 1), while enhancement of the RHIC detector capabilities benefits from the support of the BNL Instrumentation Division (CC 9). Important upgrades of the RHIC accelerator complex and the RHIC detectors are either recently completed (RHIC electron cooling, STAR iTPC) or are in progress (sPHENIX), while the experimental program continues.

BNL maintains a world-leading nuclear theory group whose research is focused on the dynamics of relativistic heavy ion collisions and properties of QCD matter under extreme conditions. In 2016, BNL was named as lead institution for two Topical Collaborations in Nuclear Theory, called "Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD" (TMD collaboration) and the "Beam Energy Scan Theory Collaboration" (BEST collaboration).

BNL operates the National Nuclear Data Center (NNDC), an international resource for the dissemination of nuclear structure, decay, and reaction data that serves as the focal point for the U.S. Nuclear Data Program (USNDP) and reactor design. The USNDP provides current, accurate, and authoritative data in pure and applied areas of nuclear science and engineering through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. The program also addresses gaps in the data, through targeted experimental studies and the use of theoretical models. Last year, there were over four and a half million data retrievals from the NNDC websites.

Funding is provided by NP as well as New York State, RIKEN, and Laboratory Discretionary Funds.

Particle Physics

BNL has a key role in developing and operating particle physics experiments that seek answers to seminal questions about the composition and evolution of the universe, i.e., the source of mass, the nature of dark matter and dark energy, and the origin of the matter-antimatter asymmetry in the universe. BNL's major efforts are: host institution for U.S. contributions to the ATLAS detector at the LHC, including managing the U.S. ATLAS Operations Program and the upgrade projects; leadership in neutrino oscillation experiments, including serving as co-host lab of the International Project Office for DUNE; leading roles in the short-baseline experiments at Fermi National Accelerator Laboratory (FNAL) (MicroBooNE, ICARUS, and the Short Baseline Near Detector); hosting computing facilities for the Belle II experiment at KEK; and construction and data collection from the LSST cosmological survey.

These roles are enhanced by BNL high energy physics theory efforts and by BNL's international leadership in critical detector and advanced accelerator research and development, including superconducting magnets, for the next-generation collider facilities.

BNL's high energy theory effort has made distinct impact on the field in phenomenology of collider physics, precision electroweak calculations, long-baseline neutrino physics program, flavor physics, dark sector physics, and the development of lattice gauge theory and its applications, such as the calculation of muon g-2.

BNL develops advanced software and computing facilities for applications in high energy physics experiments and theory. Key expertise in high throughput computing has been developed in the management and processing of multi-petabyte-scale data sets generated at high rates and distributed computing for analysis, facilitated by the RACF, the Physics Analysis Software group. Since 2017, BNL's software and computing capability is also applied to the Belle II experiment at KEK. Particle physics software and computing development for both experiment and theory benefit strongly from synergies with RHIC facilities funded by DOE Nuclear Physics and with the RBRC, funded by the Japanese RIKEN Institute. Lattice QCD simulations utilize high performance computing facilities that include those at BNL's CSI and at DOE's computing facilities.

Thanks to major BNL contributions to construction and operation of the LHC accelerator and ATLAS detector, analysis of the data, and computing capabilities, the ATLAS experiment continues to be an effective tool for exploration at the energy frontier. BNL scientists pioneered the design and event reconstruction techniques for liquid argon Time Projection Chambers. These were successfully demonstrated in MicroBooNE at FNAL and protoDUNE at CERN. On the cosmic frontier, BNL is constructing the CCD sensors for the LSST camera, which will become a premier tool for the exploration of cosmic dark energy.

Funding for this work comes from HEP as well as RIKEN and Laboratory Discretionary Funds.

Systems Engineering and Integration

BNL solves problems holistically and across multiple disciplines on several levels in order to design and construct Large-Scale Facilities and Advanced Instrumentation that employ forefront technologies and perform at a world-leading level. Individual facility components (accelerators, detectors, beamlines, etc.) that are conceived, designed, and implemented at BNL are complex entities, requiring broad integration for their successful performance and, in turn, for their coupling with other systems. BNL's approach applies not only to engineering at the various stages of a single project, but also to developing cutting-edge technologies that fuel multiple large projects at the Laboratory.

A recent example is the highly successful construction of NSLS-II and its X-ray beam lines. NSLS-II leads the world in X-ray brightness and in FY 2018, four years after the start of operations, hosted over 1300 researchers and operated 28 beamlines. State-of-the-art technologies integrated into NSLS-II include novel RF and X-ray beam position monitors, high heat-load front-end components, novel X-ray optics and detectors, and a state-of-the-art open source python-based data acquisition, management, and analysis software stack.

Another example is the RHIC accelerator complex, the largest accelerator complex in the U.S. The cutting-edge technologies developed at BNL and employed at the complex include high-intensity ion sources, a high-power proton target for medical isotope production, rapid cycling synchrotrons, three-dimensional stochastic cooling, and two superconducting accelerators to produce high luminosity heavy ion and polarized proton collisions. Advanced beam cooling techniques developed to maximize the collision rate of the collider are now in the commissioning phase.

A third example is BNL's development of noble liquid detectors from concept, through demonstration, to implementation in major particle physics experiments (D0 at FNAL and ATLAS at LHC), with continuing R&D aimed at developing the very large liquid argon (LAr) time projection chambers (TPCs) that form DUNE. The cold electronics developed at BNL for LAr TPCs have been used in research and development of various modifications of TPCs, including LArIAT at FNAL and ARGONTUBE at the University of Bern.

Further, BNL's nuclear energy experts support sustainment of the current nuclear reactor fleet and development of next generation reactors through research on alternative fuel cycles, materials in extreme environments, and assessment of the role of nuclear energy in our Nation's energy future. BNL performs research for the Nuclear Regulatory Commission's (NRC) multi-year program on the licensing of non-light water reactor policy and provides technical guidance. It also supports NRC on developing a licensing framework for micro-reactors. BNL staff serve as the Light Water Reactor Computational Analysis Technical Area Lead in the Fuel Cycle R&D program within NE. BNL also uses state-of-the-art computer tools to analyze nuclear reactor performance and safety as well as fuel cycle designs for DOE, NRC, and the National Institute of Standards and Technology (NIST).

The major sources of funding for this core capability come from BES, HEP, NP, and BER, NE, NIST, NRC, and Laboratory Discretionary Funds.

Computational Science (Emerging)

BNL is dominated by its experimental facilities: RHIC and the Brookhaven Linac Isotope Producer (NP), LHC ATLAS, Belle II, and the ATF (HEP), NSLS-II and CFN (BES), and ARM (BER). Computing, both numerical modeling and data analytics, is essential to enabling advanced scientific discovery at BNL's facilities and supporting science programs; it underlies all aspects of research conducted at the Lab. Consequently, computational science was deemed a strategic direction for the Laboratory, commensurate with well-defined computing needs, challenges, and aspirations. To support that effort, significant BNL discretionary and New York State investments, supplementing funds provided by DOE, facilitated the launch of BNL's CSI. CSI is now the focal point for all scientific computational endeavors at the Lab, ranging from research to centralization of computing facilities. CSI has attracted recognized leaders in computational and computer science to advance and execute this strategy.

CSI's impact reaches further than BNL's facilities and their immediate user communities. The Lab's computational science capabilities impact many compute and data-intensive high-performance computing (HPC) applications. These include (but are not limited to) accelerator science, lattice QCD, computational chemistry (NWChemEx), computational materials science (Comscope), and weather and climate simulation. CSI's computer science, applied mathematics, and scientific application developments extend to areas beyond the Office of Science, e.g., power grid systems (EERE and OE), and engage multiple agencies within the Department of Defense and other federal agencies through a large and still-growing project portfolio.

Motivated by DOE applications and systems of interest, BNL's ASCR-funded projects provide essential technologies and building blocks for various computational science activities. Among them, Brookhaven is leading the development of the OpenMP programming model, a portable, scalable model used to develop applications for HPC platforms. While OpenMP is broadly engaged on ASCR's leadership-class systems, it also is used by numerous codes supporting Exascale Computing Project (ECP) applications to express parallelism within a computational node. In fact, almost all ECP application development and software technology projects will rely on OpenMP. Thus, OpenMP is vital for operating next-generation exascale systems (and beyond). OpenMP training provided by BNL has also opened new user communities for HPC, such as HEP experiments ATLAS and DUNE, through ECP and HEP Computational Center of Excellence funds.

The Lab is a partner in ASCR's new Mathematical Multifaceted Integrated Capabilities Center, Advances in Experimental Design, Optimal Control, and Learning for Uncertain Complex Systems (AEOLUS). The Center is working toward a unified optimization-under-uncertainty framework for: learning predictive models from data; and optimizing experiments, processes, and designs—all in the context of complex, uncertain systems. BNL also serves as the lead of ECP's co-design center, ExaLearn, which is cultivating and deploying exascale machine learning technologies. These include deep neural networks; reinforcement learning algorithms; and ensemble, kernel, and tensor methods. Some features of the machine learning methods being developed in ExaLearn include explainability and uncertainty quantification.

DOE benefits from Brookhaven's advances in research and library development for machine learning algorithms directly used for mission-critical data science applications, projects, and facilities. Brookhaven has invested LDRD funding for the development and deployment of machine learning techniques for real-time analysis of high-throughput data from advanced high-energy resolution beamlines at NSLS-II and experiments at the CFN and other BNL experimental facilities. Projects include: neural network, hierarchical, and graph convolution methods for time series forecasting for solar arrays; kernel methods for anomaly and change detection; deep learning methods for fast and accurate nanoparticle detection for Transmission Electron Microscope and cryo-EM data; physics-based image analysis, enhancement, and classification for X-ray scattering experiments; and on-the-fly nanoparticle structure determination. Other machine learning tools are enabling autonomous experimental design. The Lab's growing artificial intelligence-related activities include capabilities impacting the energy sector, such as accurately predicting solar energy production, precision energy load forecasting, and tools for streaming problem detection and diagnosis in dynamic power grid systems, and for computational biology using natural language processing algorithms.

Multidisciplinary teams of computer scientists, applied mathematicians, and domain scientists have long been a fundamental part of Brookhaven's research process. Continuing in this vein, an integrative, co-design-based approach is being employed to develop advanced computational tools. Along these lines, the Lab has contributed to various DOE Scientific Discovery through Advanced Computing (SciDAC) projects, including current research involving SciDAC computer science and high energy physics and past work with the National Computational Infrastructure for Lattice Gauge Theory SciDAC-2 effort.

The primary sources of funding come from ASCR, HEP, NP, BES, BER, New York State, OGA, EERE, OE, and Laboratory Discretionary Funds.

Summary: These core capabilities, along with BNL's proven expertise in large science project management, will enable the Lab to deliver its mission and customer focus, to perform a complementary role in the DOE laboratory system, and to pursue its vision for scientific excellence and pre-eminence.

Science Strategy for the Future

BNL has identified seven scientific initiatives that, when achieved, will help realize the vision for the Lab. These are major Laboratory thrusts that align with the DOE Strategic Goals in Science, Energy, and Nuclear Security and build on the Laboratory's core strengths and capabilities. BNL envisions that it will continue to distinguish itself by delivering transformative science, technology, and engineering in these areas. In order to reap the potentially transformational benefits of these initiatives, a key element of Brookhaven's strategy is to position the Lab's major user facilities – the Relativistic Heavy Ion Collider (RHIC), National Synchrotron Light Source II (NSLS-II), the Center for Functional Nanomaterials (CFN), and the Accelerator Test Facility (ATF) for continued leadership roles as they evolve.

The major initiative areas for BNL are: 1) exploit RHIC's unique capabilities to learn about the matter that makes up nearly all of the visible universe and set the foundation to transition to an Electron-Ion Collider; 2) integrate BNL's expertise, ideas, and facilities to focus on select timely goals in Materials and Chemical Sciences; 3) create solutions for experiment-related computing to enable near-real-time data analysis and experimental steering; 4) steward the participation of U.S. high energy physicists in global particle physics experiments that explore the Standard Model and search for phenomena that signal physics beyond the Standard Model; 5) build on the Lab's unique combination of accelerator-based facilities and broad technical expertise to support efforts in accelerator science and technology that range from innovations to applications; 6) accelerate genome-to-function understanding to advance fundamental discoveries in plant science relevant to the DOE mission in energy security; and 7) leverage BNL's expertise in materials, instrumentation and networking, codes and algorithms to develop infrastructure that will enable scalable, large, and effective quantum systems in partnership with leading quantum experts.

Infrastructure

Overview of Site Facilities and Infrastructure

BNL's scientific vision is structured around the achievement of seven initiatives as described in Section 4. Two additional operational initiatives: a renewed research campus and safe, secure, and efficient operations enable and ensure delivery of the research mission. The Lab's strategy for mission readiness will provide a revitalized physical plant to improve scientific productivity, promote the attraction and retention of the scientific work force, including the significant BNL user population, and assure the safe, reliable functioning of BNL's major scientific facilities.

BNL is in Upton, New York in central Suffolk County approximately 75 miles east of New York City. The BNL site, former Army Camp Upton, lies in the Townships of Brookhaven and Riverhead and is situated on the western rim of the shallow Peconic River watershed. The marshy areas in the site's northern and eastern sections are part of the Peconic River headwaters. Approximately 25% of BNL's 5,322-acre site is developed.

At the end of FY 2018, there were 315 buildings totaling 4,835,502 square feet (sf). All buildings are owned by the DOE Office of Science (SC). Other Structures and Facilities (OSF) assets are owned by SC, except for FIMS Asset ST0705, the High Flux Beam Reactor (HFBR) stack, which remains under the Office of Environmental Management (EM). BNL does not lease any facilities and the average age of all non-excess buildings is 45.2 years with fifty-eight active buildings (684,358 sf) dating back to World War II (WW-II). Major science (or science support) facilities, including the Research Support Building, Interdisciplinary Science Building (ISB), National Synchrotron Light Source II (NSLS-II), Relativistic Heavy Ion Collider (RHIC), and the Center for Functional Nanomaterials (CFN), were constructed during the last twenty years. The remainder of the research facilities were built predominantly in the 1950s and 1960s. Repurposing and renovation of existing facilities was a priority exemplified by the Renovate Science Laboratories (RSL)-I/II Science Laboratories Infrastructure (SLI) projects completed in 2013 and 2015, respectively. The Core Facility Revitalization (CFR) Project, scheduled to have beneficial occupancy in FY 2021, will repurpose a majority of the NSLS facility (B725), converting it into a contemporary central computing facility.

Overall asset condition ($M Replacement Plant Value [RPV]) for non-excess buildings is as follows:

	Adequate	Substandard	Inadequate
Mission Unique	505.8 (21%)	210.4 (9%)	22.3 (1%)
Conventional	409.0 (17%)	728.4 (29%)	550.4 (23%)

Overall asset condition ($RPV) for non-excess utilities is as follows:

	Adequate	Substandard	Inadequate
Conventional Utilities	120,30,450 (21%)	184,544,914 (32%)	266,021 (47%)

Facility Utilization (sf) for non-excess buildings is as follows:

	Utilized >39%	Underutilized 1% to 39%	Unutilized <1%
Mission Unique	1,470,756 (31%)	0 (0%)	16,463 (<1%)
Conventional	2,744,428 (59%)	428,545 (9%)	40,830 (<1%)

Currently funded projects will increase utilization; the largest of which, the CFR project, will shift 156,205 sf from underutilized to utilized. In addition, 202,357 sf of underutilized space will be declared excess in FY 2019. By consolidating staff and excessing Inadequate facilities, the percent Adequate should rise. This trend will accelerate with the completion of the Science and User Support Center (SUSC) building, and the proposed Craft Resources Facility later in the planning period.

Subject to availability of funds, EM (or its replacement organization) will remain responsible for the decontamination and decommissioning of the additional excess facilities, including B701 and the HFBR as identified in the EM-1 memorandum to SC-1 "EM Transfer Decisions for SC Excess Facilities and Materials," dated February 20, 2009 and in accordance with the HFBR Record of Decision.

The BNL Land Use Plan, being updated in 2019, can be found at: https://intranet.bnl.gov/mp/webfiles/LandUsePlan.pdf.

Campus Strategy

Modern science is enabled through capable and reliable infrastructure. A renewed and well-operated physical plant improves scientific productivity; promotes the attraction and retention of the scientific workforce, including the significant BNL user population; and along with the Lab's operational excellence, underpins the capability of its scientific facility portfolio.

The planned infrastructure investments will promote and support the scientific initiatives and the wide range of facilities that enable BNL's core capabilities. In addition, the Laboratory must provide world-class facilities that will support the recruitment and retention of premier staff.

BNL has tailored its campus strategy to support the programmatic scientific initiatives, thus enabling the Lab's research mission. The resulting strategy consists of four major elements:

1. Focus limited DOE investment in critical core buildings and infrastructure to enable the scientific agenda
2. Make research safe and cost effective by downsizing the campus and demolishing old buildings
3. Ensure scientific reliability through targeted investments in buildings and utility infrastructure
4. Support the growing population of scientific users through an innovative concept called "Discovery Park."

Element 1 - Investment in Critical Core Buildings and Infrastructure

Since many science buildings are 50+ years old, they require substantial sustainment and recapitalization investments in mechanical and electrical systems and architectural elements to meet the demands of modern research. Research labs merit renewal and modernization to include new fume hoods and casework. In addition, many research labs need state-of-the-art upgrades, including stringent environmental and vibration controls and "clean" environments. BNL has identified those "permanent" facilities that will form the platform for current and future core capabilities. To ensure facilities are mission ready, BNL has formulated a multi-pronged strategy of consolidation and rehabilitation. Facilities would be rehabilitated using a combination of indirect funds (Institutional General Plant Projects (IGPP), Deferred Maintenance Reduction (DMR), and DOE direct funds (SLI, GPP).

The most significant infrastructure issue facing the scientific organizations relates to computing and data management. Near-term computing needs will quickly eclipse the existing computing infrastructure. To address this, the Core Facility Revitalization (CFR) project will provide a contemporary computing facility and infrastructure that will meet the rapidly expanding scientific needs of the Laboratory. This project was endorsed by the Office of Science and has been fully funded. This investment will make cost-effective use of existing infrastructure by repurposing most of Building 725 (the former National Synchrotron Light Source) with construction beginning in FY 2019.

The most significant issue facing the mission support organizations is that many are still located in WW-II era wood buildings. To address this, the Science and User Support Center (SUSC) is proposed as a modern facility using SLI funding to consolidate support organizations and provide a Laboratory visitor building, training, and user services portal in synergy with the Discovery Park development. This proposal was also endorsed by the Office of Science and initial funding was appropriated in FY 2019. A similar issue is the scattered locations of BNL's craft resource shops also located mainly in WW-II era buildings, which are Inadequate due to condition and configuration. A centralized Craft Resources Facility is proposed for FY 2024 to increase energy and operational efficiency through collocation and to eliminate the backlog of repair needs and modernization costs.

An additional issue is the build-out of the laboratory buildings associated with the NSLS II to support the needs of the expanding number of multi-program operational beamlines. Recent changes in IGPP rules will require BNL to develop new strategies for funding the build-outs.

Element 2 – Optimizing the Campus Footprint

An important element of the overall infrastructure strategy is elimination of excess facilities and footprint reduction to realize operational efficiencies, improved safety of facilities, and improved utilization and quality of space. BNL is committed to reduce the building footprint of BNL by approximately 5% over the planning period toward an ultimate target of a 10% footprint reduction. The Infrastructure Investment Table and Integrated Facilities and Infrastructure (IFI) crosscut indicate the annual overhead investments needed to eliminate existing or anticipated future non-contaminated excess facilities and the requests for direct DOE funding for the costlier contaminated facility projects. Over the planning period, it is estimated that ~227,000 sf of excess space will be eliminated, of which ~187,000 sf is WW-II-era buildings.

To meet these infrastructure challenges, BNL has formulated a strategy to address the mission and operational needs based on the constraints and strengths of the various funding sources. Capital projects and other requested funding are shown in the Infrastructure Investment Table and indirect expensed projects, such as DMR, are reflected in funding plans shown on the IFI Crosscut, both of which are contained in Enclosure 4. In addition, non-capitalized betterment and alteration projects and infrastructure studies that BNL refers to as Other Infrastructure Projects (OIP), not requested as part of Enclosure 4, round out the Lab's investment strategy. Consistent with BNL's Mission Readiness approach, funding for the various categories of indirect funds (DMR, OIP, and IGPP) can vary year to year based on the projects selected.

In FY 2018, the demolition of B134 began (19,593 sf), completing in Q1 of FY 2019. At the end of FY 2018, there were 21 excess buildings totaling 134,480 sf, and one real property trailer (500 sf). In addition, parts of the NSLS accelerator and associated clean-up remain and the HFBR, Brookhaven Graphite Research Reactor, and Brookhaven Medical Research Reactor, await demolition.

In FY 2018, as part of continuing consolidation planning to right-size the campus, ten buildings totaling 36,237 sf were declared excess. In FY 2019 one building, comprising 16,463 sf, was declared excess and two additional buildings totaling 16,085 sf are in-process to declare excess.

Element 3 - Targeted Investment in Building and Utility Infrastructure

While BNL's utilities are currently reliable, they are aging and issues impacting reliability and capacity are increasing. In FY 2011, BNL completed a baseline study, which evaluated its utilities and recommended strategies to address critical needs. The study identified significant short-term needs confirming that the aging water, electric, chilled water, and steam distribution system components need replacement. Recapitalization resources to renew and replace BNL's utility infrastructure have been limited by very tight operating budgets. However, progress was made with the installation of new chillers to increase the Central Chilled Water Facility (CCWF) capacity and reliability to support growing science process cooling needs. In addition, a project was completed in early FY 2018, replacing the 28-

year-old wood cooling tower at the CCWF; however, the three associated 1,200 Ton electric centrifugal chillers, original to the plant, are overdue for replacement. BNL has two critical potable water projects: one to rebuild Potable Water Well No. 12 (IGPP), expected completion in FY 2020 and another to replace the WWII-era 300,000-gallon elevated water storage tank, which will be included in the Critical Utilities Rehabilitation Upgrade Project (CURP) SLI line item and is expected to be completed in FY 2023. The water storage tank recently underwent some urgent repairs to allow continued operation for a few more years.

The aging distribution systems present additional utility needs. Sections of the central steam distribution system date back to the 1950s. Leaks in the condensate return piping cause system inefficiencies that need localized repairs. Over the past several years, with an increasing number of water main breaks in the old “transite” (asbestos cement) piping, several sections are in critical need of replacement. Selective replacement and reinforcement of the 13.8kV primary electrical distribution system is also needed, including an additional feeder to provide backup to the CCWF and NSLS-II. Deficiencies associated with these distribution systems will be addressed in the proposed CURP line item and later in the planning period by the Critical Utilities Revitalization and Enhancement (CURE) project.

Element 4 – Advancing the Innovative Public-Private Partnership Concept Called “Discovery Park”

The Discovery Park concept is a key component of BNL’s infrastructure renewal plans and continues to make excellent progress. Discovery Park will repurpose approximately 60 acres of federal property at the entrance to BNL to enable joint federal and private development that replaces aging infrastructure and user housing and enables mission enhancing technology transfer opportunities. An Alternatives Analysis conducted for Discovery Park and reviewed with the Office of Science determined the preferred development pathway for Discovery Park is a mix of federally funded and privately funded development. Design of the Federal component and development of the ground lease for the first privately financed facility are underway with planned initial occupancy in the FY 2022/FY 2023 time-frame.

The plan for improving asset condition is multipronged and does not solely rely on maintenance investment, which was 1.1% of Replacement Plant Value for 2018. Key to BNL’s strategy is consolidation out of those assets not worth maintaining, ultimately followed by their demolition. Space consolidation, such as the ongoing efforts in FY 2019, will be enabled by renovation and alteration of underutilized buildings and through new proposed buildings, such as the SUSC as part of the Discovery Park development and the proposed Craft Resources Facility, allowing a major consolidation from inadequate WW-II-era buildings. In addition, there are some proposed GPP projects that would help jumpstart condition improvement efforts for certain critical assets through mission-enabling renovation of key laboratories, and by focusing on utility (water, steam) and facility improvements (roofing, HVAC, and electrical building systems).

The BNL Site Master Plan map (Appendix A) shows the location of the key investments of the campus wide strategy. The proposed capital funding for these investments is indicated in Enclosure 4.

Investment Strategy

The investment strategy relies on the following direct and indirect funding sources:

DOE SLI funds: Will be used to perform major building system revitalization or replacement in support of state-of-the-art research facilities that can readily support current and future missions. Over the planning period, BNL has proposed projects to improve the condition of existing buildings and re-task underutilized space that will help to achieve mission needs identified as part of its Site Master Plan process. The CFR project, which has received full funding, along with proposed projects, will revitalize several existing permanent facilities and will be more cost-effective than construction of new facilities and demolition of others.

- Core Facility Revitalization (CFR) (TPC $ 74.85M, FY 2017 start) will repurpose two-thirds of the first floor of building 725, a 156,000 sf building constructed in 1981 with additions in 1988 and the 1990s. It contains significant office and high bay space. This project is critical to the ongoing support of the mission need to provide computational and data storage support to current and planned experiments at RHIC and the US ATLAS effort at CERN. The space will support the planned growth of computing resources for the existing BNL Scientific Data and Computing Center as well as Belle II, NSLS-II, CFN, and other Laboratory users. The extensive underutilized high-bay space is well-suited for conversion to computing use. The scope of the project includes select revitalization of the building envelope, HVAC and other building systems, interior finishes, and building configuration as required for performing its new mission. The project received CD-0 in FY 2015; CD-1 in April 2017, CD-2/3a in October 2018, and CD-3b in January 2019. The project started preliminary design in March 2018 with a preliminary CD-3 date of June 2019 and a CD-4 completion date in FY 2023.
- Science and User Support Center (SUSC) (TPC Estimate Range $72M - $96M, FY 2019 start) will include construction of a federally funded office and support building, which will range from 70,000 to 120,000 sf in Upton Square at the Discovery Park site to enhance user support capability, address major DOE and BNL infrastructure needs, and as an added advantage, serve as a magnet for further development. This building will enhance operational efficiency by consolidating approximately 200 BNL support division staff, currently dispersed in several buildings, into a single modern office building meeting DOE sustainability goals. It will also enable further consolidation of other staff, ultimately allowing the demolition of ~ 62,000 sf or WW-II-era space with a combined backlog of maintenance and modernization needs of $17M. In addition to the efficiency gained by collocated staff, the facility's location at the BNL main entrance will enhance public access for education and commercial outreach for BNL outward facing organizations (such as Environment Safety & Health (ES&H), Finance and Fiscal, among others), while supporting BNL core functions. A new visitor center, designed as a highly efficient one-stop user access portal, will be the front door of the SUSC structure and will enhance the role of BNL as a major user facility laboratory. Scientific collaboration will also be enhanced through a new highly-configurable and accessible conference center, the third major element of the SUSC facility.
- Critical Utilities Rehabilitation Upgrade Project (CURP) (TPC Estimated Range $70-$95 M, FY 2020 start) will replace and rehabilitate key utility systems required for operation of mission critical research facilities. Significant portions of the utility systems are well beyond their useful life with over 60 – 70 years of service. Some, such as portions of the sanitary system, are over 100 years old. This project will: 1) Replace 30+ year old central chilled water system(s) that are beyond their useful life and no longer reliably serving critical facilities, such as CFN, ISB, RHIC-ATLAS Computing Facility, NSLS-II, and B911 Collider-Accelerator Center; 2) Replace portions of the 60+ year old underground steam & condensate piping system and select manholes that are failing due to extensive corrosion, leaks, and deterioration; 3) Refurbish equipment in the 75+ year old central steam facility, which is required to assure reliable steam service to the site; 4) Replace, repair, or reline the 75+ year old asbestos water main; 5) Repair and refurbish deteriorated sanitary lift stations; and 6). Refurbish and replace electrical feeders and switchgear with modern, safe, reliable electric equipment and systems that will reduce arc-flash hazards.
- Craft Resources Facility (TPC Estimated Range $75-$95 M FY 2023 start) will replace approximately 100,000 sf of buildings, trailers, and OSF assets. The project will collocate maintenance and operation resources that are dispersed in 12 buildings and 19 trailers and realize substantial operational efficiencies. Most of the buildings are WW-II era wood buildings, which have an Overall Asset Condition of Inadequate. It is anticipated there will be at least 20% reduction in administrative and shops space and 30% reduction in storage space, as well as a

significant reduction in common space, such as bath and locker rooms, breakrooms, and training space. There will also be an increase in operational efficiency due to collocation, shared facilities, more effective staffing and supervision, and energy efficiency. The facilities are located in three separate areas of the site and will be combined into one centrally located complex.
- Building 911 Renovation for Accelerator Science Center (TPC Estimated Range $50-$75M, FY 2024 start) will renovate approximately 50,000 sf of the 106,000 sf in the three-story structure that is currently occupied by approximately 290 staff. Work will include: updating mechanical and electrical systems, reconfiguration of space to improve efficiency and enhance utilization, improve sustainability, and modernize interior and exterior finishes to reflect a world class research facility.
- Critical Utilities Revitalization and Enhancement (CURE) (TPC Estimated Range $75-$100 M, FY 2026 start) will replace and rehabilitate key utility systems required for operation of mission critical research facilities. Significant portions of the utility systems are well beyond their useful life with over 70 – 80 years of service. Some, such as portions of the sanitary system, are over 100 years old. The project will: 1) Replace portions of the 70+ year old underground steam & condensate piping system and select manholes that are failing due to extensive corrosion, leaks, and deterioration; 2) Replace, repair, or reline the 85+ year old asbestos water main; 3) Repair and refurbish deteriorated sanitary lift stations; 4) Refurbish and replace electrical feeders and switchgear with modern, safe, reliable electric equipment and systems that will reduce arc-flash hazards; and 5) Replace utility plant key infrastructure to ensure operational control, efficiency, and reliability including electrical system and instrumentation components. This project is scalable to match available funding profiles.

GPP (DOE SLI) via the Infrastructure Crosscut: In response to the initial call for GPP projects that arose out of the Laboratory Operations Board (LOB) Initiative, major recapitalization needs to provide mission ready facilities and infrastructure were identified and prioritized. These cover several improvements to address the most urgent gaps including:

- Mission Enabling Renovations: B801 Hot Cell & Labs Facility Improvements ($8.5M, FY 2018)
- Building Renovations: B463 Revitalize Biology Labs; Mission Critical Building HVAC, Roofing, and Electrical Upgrades ($5M, FY 2018)
- Mission Critical Building Upgrades: Upgrade HVAC ($8.7M, FY20 request), Upgrade Electrical Distribution ($9.0M, FY22 request) and Replace Roofing ($8.8M, FY24 request).

Excess Facilities Disposition (EFD): In concert with the related infrastructure crosscut call for GPP, BNL proposed several high impact demolition projects for DOE direct funding. A long-range plan for low impact, lower cost demolitions funded from indirect operating funds was developed and will be prioritized with other indirect-funded infrastructure needs. EM committed to incorporating several SC assets (B491, 650, and 830) into its cleanup program for disposition, but the timeline is uncertain, and they may not be accepted by EM until 2030.

Indirect Funding: The Laboratory anticipates increasing overall infrastructure spending over the ten-year period. Infrastructure funds are for maintenance, including dedicated DMR projects, IGPP, and OIP. OIP projects are not part of the Investment Table but fund alterations, non-capitalized betterment projects, demolition, and infrastructure studies. These OIP projects totaled ~$2M in 2018 (14% of the project's budget) and are forecast at ~$4.5M (32%) in 2019. Recent changes to IGPP rules, as described in Chapter 24 of the DOE Financial Handbook, were incorporated into BNL's indirect planning process.

Collectively, this indirect funding is enabling the execution of the Lab's space consolidation plans, which when coupled with demolition, will help right-size the BNL footprint, and reduce operations and maintenance costs. Indirect funds are used for non-major recapitalization and sustainment needs using the following strategy:

- Prioritize all proposed investments in infrastructure and ES&H and program them to maximize the value of BNL's infrastructure, reduce risk, and support the Science &Technology programs
- Begin a program of targeted utility infrastructure investments aimed at revitalizing utilities to meet reliability and capacity needs
- Defer major investments in 70+-year-old wood buildings, while performing minimum maintenance to keep these buildings safe and operational. When opportunities arise, consolidate staff from these structures and demolish them.

Non-Federal Funding: As described previously, BNL is pursuing an innovative public-private partnership concept called Discovery Park as an opportunity to enhance BNL's DOE mission capability, address infrastructure deficiencies, promote user access, and contribute to local and regional economic development. The proposed privately funded development of housing and technology partnership facilities will be complementary to the SUSC SLI line item project.

Discovery Park is proposed as a repurposing of the existing BNL Apartment Complex and adjacent area into a publicly-accessible research park. This area is contiguous to BNL's Federal research core but is easily configured to be outside the security area. Its location, which is adjacent to the Laboratory entrance and the William Floyd Parkway, presents a unique opportunity for public/private development in the interest of the DOE. The initial development in Discovery Park comprised of the SUSC, private housing, and potential education outreach space, was designed to create a small mixed-use user community (Upton Square) that becomes a user housing community, an entry portal, and a location for scientific collaboration. The balance of the Park allows for collocation of complementary joint institutes, private companies, or other private, State, or Federal scientific facilities.

In short, Discovery Park is envisioned as a joint land use partnership that will leverage key "points of intersection" with external partners and enhance the DOE's investment and assets at BNL to provide:

- Sustainable Laboratory revitalization with the SUSC and renewed privately built (and operated) housing
- An enhanced guest and user portal for growth and sustainment of the scientific user community and user facilities
- Unique facilities for energy science, education, technology transfer, and Discovery to Deployment industrial partnerships.

The development and operating model being pursued will allow for flexibility in the widest variety of funding sources and ownership while maintaining appropriate synergy to BNL's Federal mission. The concept has received significant State and local support, including matching utility grants and has served as the focal point to enhance regional, national, and international connectivity through State investment in a relocated railroad station.

Utilization of non-federal funding at BNL was also recently demonstrated through a $12.7M Utilities Energy Savings Contract (UESC) project that was completed in May 2015. It included both utilities and building system improvements, and in its first three years after implementation, achieved between 95 and 98% of the originally estimated annual energy and green-house gas savings of ~80,000 MMBtu and 6,500 MTCO2e, respectively. The scope of a second UESC project was refined and an Investment Grade Audit (IGA) is expected to be completed by the end of June 2019. If the IGA confirms there are financially viable projects, a UESC Phase II project could begin the implementation process in FY 2020.

Site Sustainability Plan Summary

BNL continues to be on-track to meet most of the Site Sustainability Plan (SSP) goals. However, one of them, energy intensity reduction, will be a challenge. The Lab's past success in lowering its energy intensity by nearly 60% partially accounts for this. The most cost-effective projects were completed long ago, leaving a more expensive portfolio of projects to achieve additional gains. BNL continues to maximize the potential use of UESCs. A major component of BNL's sustainability effort is the use of alternative financing, as described in Section 6.3.5.

Another challenge is meeting SSP Goal 9.5 (Existing Data Center Power Use Effectiveness PUE). The ability to meet this goal is still uncertain at this time since BNL is funded for a new, modern data center facility (the CFR Project) that will be considerably more efficient than the existing data centers.

To meet the Renewable Energy and Clean Energy requirements, BNL continues to use a combination of on-site solar PV generation and the purchase of Renewable Energy Credits (RECs).

FERMI NATIONAL ACCELERATOR LABORATORY

Lab-at-a-Glance

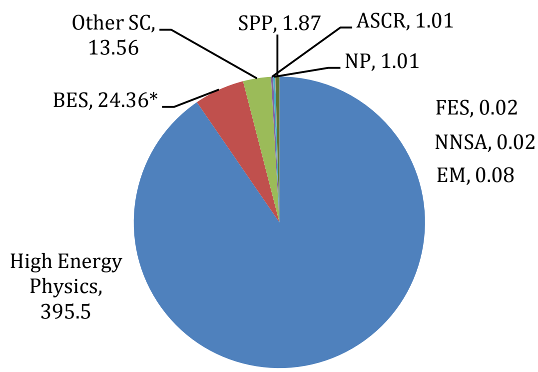
Location: Batavia, Illinois
Type: Single-program Laboratory
Contractor: Fermi Research Alliance, LLC
Site Office: Fermi Site Office
Website: www.fnal.gov

- **FY 2018 Lab Operating Costs:** $437.41 million
- **FY 2018 DOE/NNSA Costs:** $435.55 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $1.87 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 0.4%
- **FY 2018 DHS Costs:** $0 million

Physical Assets:
- 6,800 acres and 366 buildings
- 2.4 million GSF in buildings
- Replacement Plant Value: $2.21 B
- 9,616 GSF in 16 Excess Facilities
- 22,155 GSF in Leased Facilities

Human Capital:
- 1,782 Full Time Equivalent Employees (FTEs)
- 21 Joint Faculty
- 95 Postdoctoral Researchers
- 30 Graduate Student
- 73 Undergraduate Students
- 3,635 Facility Users
- 8 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

Fermi National Accelerator Laboratory is an international hub for particle physics located 40 miles west of Chicago, Illinois. Fermilab's employees and users drive discovery in particle physics by building and operating world-leading accelerator and detector facilities, performing pioneering research with national and global partners, and developing new technologies for science that support U.S. industrial competitiveness. The laboratory's core capabilities are particle physics; large-scale user facilities and advanced instrumentation; accelerator science and technology; and advanced computer science, visualization, and data. Fermilab's science strategy for the future delivers on the U.S. particle physics community's goals as outlined in the Particle Physics Project Prioritization Panel's 2014 report. The strategy's primary ten-year goal is a world-leading neutrino science program anchored by the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE), powered by megawatt beams from an upgraded and modernized accelerator complex made possible by the Proton Improvement Plan II (PIP-II). The flagship comprised of LBNF, DUNE, and PIP-II will be the first international mega-science project based at a Department of Energy (DOE) national laboratory.

Fermilab's particle accelerator complex is the only one in the world to produce both low- and high-energy neutrino beams for study. Fermilab integrates U.S. universities and national laboratories into the global particle physics enterprise through its Large Hadron Collider (LHC) programs; neutrino science, accelerator science, and precision science programs; and cosmic frontier experiments. Large-scale computing and storage facilities drive research in particle physics and other fields of science. The laboratory's R&D infrastructure and its engineering and technical expertise advance particle accelerator and detector technology for use in science and society. Fermilab's partnerships and technology transitions programs, including the Illinois Accelerator Research Center, leverage this expertise to apply particle physics technologies to problems of national importance in energy and the environment, national security, and industry.

Fermi Research Alliance, LLC, an alliance of the University of Chicago (UChicago) and the Universities Research Association, Inc. (URA), manages Fermilab for the DOE and provides guidance, advocacy, and oversight. UChicago is home to world-leading scientists that partner with Fermilab. For instance, a UChicago physicist is a co-spokesperson of DUNE and UChicago scientists collaborate with Fermilab on cutting-edge cosmic frontier experiments. Through the Joint Task Force Initiative, UChicago and Argonne National Laboratory bring considerable operational and intellectual assets to create a partnership for forefront research that is second to none. URA, through their member universities, sponsors and funds the Visiting Scholars program providing up to $450K per year to students, postdocs, and faculty from its member universities, as well as group awards to Fermilab, to perform research and carry out experiments at Fermilab.

Core Capabilities

Fermilab has unique and powerful infrastructure essential to the advancement of discovery in particle physics, including the nation's only accelerator complex dedicated to particle physics and a suite of particle detectors. Scientific research around the world is supported by Fermilab's facilities for design, fabrication, assembly, testing, and operation of particle accelerators and detectors; by its expertise and facilities for computing; and by a talented workforce with globally competitive knowledge, skills, and abilities. The laboratory is thus uniquely positioned to advance the DOE/SC mission in scientific discovery and innovation with a primary focus on high-energy physics (HEP) and capabilities that address mission needs for advanced scientific computing research (ASCR), particle accelerators for light sources (BES), nuclear physics (NP), and workforce development for teachers and scientists (WDTS). Fermilab has four core capabilities: Particle Physics; Large-Scale User Facilities/Advanced Instrumentation; Accelerator Science and Technology; and Advanced Computer Science, Visualization, and Data and is primarily funded by the DOE Office of High Energy Physics (DOE/HEP).

Particle Physics

Particle physics is the heart of the laboratory's science mission and is defined by four main science themes—neutrino science, collider science, precision science, and cosmic science—supported by theory, facilities, and workforce development.

Neutrino Science

Fermilab is the only laboratory in the world that operates two accelerator-based neutrino beams simultaneously, the Neutrinos at the Main Injector (NuMI) beamline and the Booster Neutrino Beamline (BNB). These two intense neutrino sources illuminate an important collection of experiments that are studying neutrinos over both short and long distances, allowing the Fermilab neutrino program to address questions such as whether additional (sterile) neutrinos exist and whether neutrinos violate matter-antimatter (CP) symmetry. The NOvA experiment operates on the high-energy NuMI beamline and explores the parameters of neutrino flavor transformation. This exploration will become comprehensive with the operation of the Deep Underground Neutrino Experiment (DUNE) in a new beamline created as part of the Long Baseline Neutrino Facility (LBNF) and powered by the Proton Improvement Plan II (PIP-II) accelerator upgrades. The Short Baseline Neutrino program on the low-energy BNB searches for sterile neutrinos through a suite of three experiments: the MicroBooNE detector that began operating with beam in 2015, the ICARUS detector that will begin operating this year, and the Short-Baseline Near Detector (SBND) that will follow in 2020. Experience with these liquid-argon detectors will also inform the future flagship international LBNF/DUNE program. This succession of neutrino experiments is prescribed by the P5 report and is being executed by collaborations of scientists enabled by the capabilities that exist at Fermilab.

Collider Science

The Large Hadron Collider (LHC) at CERN, the European center for particle physics, is the world's largest and most powerful particle accelerator. Operating at the center-of-mass-energy of 13-14 TeV, the LHC explores the energy frontier and probes the laws of nature by recreating the conditions of the early universe. Fermilab serves as the host laboratory for more than 800 university-based U.S. scientists and students working on the CMS (Compact Muon Solenoid) experiment, one of two large multipurpose detectors at the LHC. Fermilab is the leading U.S. center for LHC science and second-largest world center after CERN. The laboratory's globally distributed computational capabilities for the CMS experiment are unparalleled. Laboratory scientists are engaged in physics analyses of LHC data including studies of the Higgs boson and searches for new phenomena such as supersymmetry, extra dimensions, and dark matter. A skilled and talented workforce of scientists, engineers, and technicians leverages Fermilab's accelerator and detector R&D programs to contribute essential developments, improvements, and upgrades to the CMS detector and the LHC accelerator. Fermilab is leading the HL-LHC CMS Upgrade Project, the HL-LHC Accelerator Upgrade Project, and US CMS Operations.

Precision Science

Fermilab's precision science theme includes experiments that attempt to reveal gaps in the current understanding of the laws of physics by testing predictions to the highest accuracy and searching for phenomena that are either extremely rare or forbidden by current theories. Deviations from expectations are a possible indication of new particles and new interactions. Fermilab has reconfigured accelerator components to create muon beams, which began to deliver beam to the first experiment at the Muon Campus—Muon g-2—in 2017. The beams will increase in intensity over time, culminating with delivery of the world's most intense muon beam to the Mu2e experiment in 2022.

The Muon g-2 experiment will precisely measure a property of muons called the anomalous magnetic moment and investigate hints from previous experiments that the muon's magnetic moment may be different from what was predicted by the Standard Model of particle physics. If true, this could be an indication of new physics with far-reaching implications. The Mu2e experiment will search for the spontaneous conversion of muons to electrons. The experiment will be sensitive to new physics manifesting itself in rare processes and corresponding to energies several orders of magnitude higher than those achievable at the LHC, thereby complementing collider experiments' searches for new particles and new interactions.

Cosmic Science

Fermilab leads the Dark Energy Survey (DES), is a key partner in several world-leading cosmic science experiments and contributes to R&D efforts toward new dark energy, dark matter, and cosmic microwave background (CMB) experiments. Fermilab researchers built the camera and are currently leading the science collaboration for DES, which finished its sixth and final year of observations in 2019. Fermilab is working with other DOE laboratories to build three new large cosmic surveys (DESI, LSST, CMB-4). The laboratory is engaged in world-leading searches for particle dark matter, fulfilling major responsibilities for the construction and operation of second-generation experiments (ADMX and SuperCDMS SNOLAB). Fermilab plays an important role, together with other laboratories and the

University of Chicago, in the design of CMB-S4, which will establish the world's most sensitive constraint on the sum of neutrino masses and help explore the phenomenon of cosmic inflation.

The Dark Energy Survey (DES) is the world leader in exploring the mysterious phenomenon of dark energy. Fermilab both manages the operation and leads the analysis of this unprecedented survey. The survey has now finished its sixth and final year of data taking, with over 221 scientific papers submitted and 176 accepted or published. In mid-2017, DES published the first world leading weak lensing cosmology analysis, and in 2018 the first DES supernova cosmology results were published (see Figure). This is the first time a single survey has measured the energy density of both dark energy and dark matter independent of external datasets. Fermilab scientists led the cosmology analysis of the combined weak lensing/large scale structure results and played critical roles in the first public data release of DES data in early 2018. Our attention has turned to the combined three-year dataset for all four key projects. Fermilab scientists are developing the cosmological parameter estimation tool set used for these, co-leading the cluster cosmology effort, leading an effort to understand systematics in weak lensing and large-scale structure analyses via artificial galaxy injection into large scale re-reductions of the DES data set.

Fermilab's detector R&D program has supported many efforts in cosmic science. Fermilab leveraged its DES experience to pioneer the use of charge-coupled devices (CCDs) as low-threshold detectors in the DAMIC experiment. Fermilab researchers supported by the detector R&D program, a 2016 LDRD award and 2018 early career award developed even lower-noise CCD readout, enabling the detection of single electrons and opening a new window on ultra-light dark matter particles. The SENSEI project has now producing world leading results in e-recoil dark matter searches using these sensors. Fermilab has continued R&D towards next-generation detectors for cosmic science by developing an underground cryogenic test facility, in collaboration with Northwestern University, for the characterization and calibration of cryogenic solid-state detectors with sensitivity to sub-GeV dark matter (NEXUS).

Dramatic improvements in quantum sensing will be one of the first products of the ramp-up of the National Quantum Initiative, and Fermilab is at the forefront of the effort to apply novel quantum sensors to the detection of wave-like, ultralow mass bosonic dark matter, including the QCD axion. While current generation experiments are limited by the standard quantum limit in readout noise, future experiments probing higher masses and frequencies in the 10 GHz – 10 THz range will rely on new quantum techniques to bypass this constraint, utilizing superconducting technologies including Josephson junctions and microcalorimeters. Supported by a combination of grants awarded through the new DOE QuantISED program, LDRD funding, and private foundation funding, Fermilab is leveraging its capabilities in accelerator science and sub-Kelvin electronics to study high-quality-factor resonant cavities, single microwave photon detectors, and highly multiplexed readouts to enable future searches for bosonic dark matter.

Cosmic science provides a showcase for the benefits of broad collaboration among DOE laboratories and universities. As noted in the P5 report, particle physics drivers are intertwined, and cross-project expertise is required to extract the most science from the data. Fermilab scientists are leading these efforts. For example, the dwarf galaxies discovered by DES have led to dark matter constraints, and joint analyses of the DES and SPT data sets have placed new constraints on dark energy and gravity at large scales. Over the next decades, Fermilab will act as a central platform and host for understanding cosmic science data, maximizing the scientific output of experiments across the field.

Theory, Facilities, and Workforce Development

Fermilab's Theory and Theoretical Astrophysics groups perform research at the confluence of these four themes. The laboratory's accelerators and particle detectors, and its fabrication, assembly, testing, and computing facilities provide unique capabilities within DOE and for particle physics research. For example, the Fermilab Test Beam Facility is in high demand for R&D of advanced particle detector technologies. The Office of Education and Public Outreach and the Lederman Science Center support students and faculty in STEM education and the DOE WDTS mission.

Particle Physics is funded primarily by DOE/HEP with additional funding from DOE/BES (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Large-Scale User Facilities and Advanced Instrumentation

Fermilab's Large-Scale User Facilities/Advanced Instrumentation core capability encompasses two DOE/SC user facilities: the Fermilab Accelerator Complex and the CMS Center, which together supported more than 3,600 users in FY 2018. The laboratory has the human capital and infrastructure essential to developing, designing, constructing, and operating large-scale user facilities and advanced instrumentation.

Fermilab Accelerator Complex

The Fermilab Accelerator Complex is the nation's only accelerator complex dedicated to particle physics and the second-largest particle physics accelerator complex in the world. Research at this user facility has led to many discoveries over more than 40 years of operation, including the top quark, bottom quark, tau neutrino, determination of the properties of charm- and bottom-quark systems, and numerous precision measurements, including the discovery of new matter-antimatter asymmetries in kaon decays.

The Fermilab Accelerator Complex comprises seven particle accelerators and storage rings with particle-beam capabilities found nowhere else in the world. Future upgrades of the accelerator complex enabled by the Proton Improvement Plan II (PIP-II) project will provide megawatts of beam power to the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). Currently, Fermilab uniquely supplies two very intense neutrino sources (the low-energy Booster neutrino beam and the high-energy NuMI beam) that enable the physics programs of the NOvA, MicroBooNE, and MINERvA experiments. By 2020, the Booster neutrino beam will deliver neutrinos to all three detectors of the Short-Baseline Neutrino program: MicroBooNE (already operating), ICARUS (starting 2019) and the Short-Baseline Near Detector (SBND, starting 2020). Beams of muons are being delivered to the Muon g-2 experiment following successful reconfiguration and upgrades of the accelerator complex. Fermilab will become the world center for the study of muons when high-intensity muon beams are delivered to the Mu2e experiment. The Fermilab Test Beam Facility is the only U.S. location that enables detector R&D tests with high-energy hadron beams and is used by more than 200 international researchers annually.

CMS Center

For almost two decades, Fermilab has served as the host laboratory for the more than 800 scientists and students from about 50 U.S. universities who work on the CMS experiment at the Large Hadron Collider (LHC) in Geneva, Switzerland. Fermilab also leads the HL-LHC CMS Upgrades, the HL-LHC Accelerator Upgrade Project, and U.S. CMS Operations. Researchers using Fermilab's CMS facilities played leading roles in the 2012 Higgs boson discovery, and ongoing research promises to further revolutionize our understanding of the universe.

The CMS Center consists of the LHC Physics Center (LPC), CMS Remote Operations Center, and the U.S. CMS Computing Facility at Fermilab. The LPC is designed to engage members of U.S. CMS institutions distributed across the country in physics analyses of LHC data and in upgrades to the CMS detector. The LPC creates a thriving environment for collaboration among participating institutions by facilitating remote participation, conferences, classes, and other opportunities. Through the Distinguished Researcher and Guest and Visitor programs, collaborators are supported to spend significant time at the

LPC, and the CMS Data Analysis School draws over 100 participants each year. The Remote Operations Center enables physicist participation in remote operations and monitoring of the CMS detector and keeps scientists, students, and technicians connected to operations activities at CERN without the time and expense of European travel. The U.S. CMS Computing Facility at Fermilab is the largest and most reliable Tier-1 computing facility worldwide (after the CERN Tier-0 center). As part of a worldwide grid computing capability, this facility is available to qualified CMS researchers around the world.

Advanced Instrumentation

An experienced and talented workforce at Fermilab conceives and develops state-of-the-art particle detector technologies and uses them to construct detector systems. Achievements include the development of very-low-mass silicon detectors for particle physics collider experiments, CCD detectors for the Dark Energy Camera, scintillator detectors used for a wide variety of particle physics experiments, and liquid-argon time-projection chambers used by current neutrino experiments and the future flagship experiment, DUNE. Fermilab's advanced instrumentation capability is used to develop and construct upgrades for the CMS detector at the LHC, including innovative silicon trackers, a silicon-based calorimeter, readout electronics, and R&D for precision timing detectors.

Large-Scale User Facilities/Advanced Instrumentation is funded primarily by DOE/HEP (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation.

Accelerator Science and Technology

Fermilab's Accelerator Science and Technology core capability includes five core competencies, strategically aligned with recommendations of the 2015 HEPAP Accelerator R&D sub-panel: high-intensity particle beams; high-power target stations; high-field superconducting magnets; high-gradient and high-quality-factor superconducting radio-frequency (SRF) cavities; and accelerator science and technology training. These core competencies are enabled by unique accelerator and beam test facilities and world-leading expertise that sustain Fermilab's leadership role in high-intensity and high-energy accelerator applications. Fermilab has established strategic partnerships in accelerator science and technology with leading universities including Northern Illinois University, Illinois Institute of Technology, Northwestern University, Cornell University, and the University of Chicago. Fermilab's Illinois Accelerator Research Center (IARC) is uniquely positioned to cement partnerships with industry and universities to increase strategic partnership projects and to advance DOE's accelerator stewardship program.

High-Intensity Particle Beams

Fermilab operates the world's most advanced high-intensity proton accelerator complex dedicated to particle physics. The ongoing Proton Improvement Plan (PIP), an intermediate step of AIPs toward 1 MW of beam power, and a subsequent upgrade project (PIP-II) will maintain Fermilab's international leadership and support the next generation of neutrino and precision science experiments. PIP-II leverages laboratory capabilities in accelerating and transporting high-intensity beams in circular and linear accelerators and is needed as the next step to achieving a beam power of more than 2 MW for LBNF/DUNE and beyond. Results from accelerator R&D at Fermilab support the flagship neutrino science program and influence how U.S. and international accelerators are designed, constructed, and operated. Fermilab has achieved more than 700 kW beam power to the NOvA experiment through PIP and is running around $2x10^{17}$ protons per hour from the proton source to support the Short-Baseline Neutrino program and the Muon g-2 experiment.

High-Power Target Stations

Fermilab operates three high-power target stations: the 700 kW NuMI beam (to be upgraded to 1 MW); the Booster Neutrino Beam; and the particle production target station for the Muon g-2 experiment. A fourth target station is under construction for the Mu2e experiment. A fifth target station is under design for the LBNF/DUNE project. Each of these stations include specialized targets with capabilities up to 1.2 MW of beam power, as well as specialized focusing devices (magnetic horns, lithium lenses, graded solenoids), shielding, instrumentation, beam windows, remote handling, and other systems. Fermilab maintains this core competency through the development of these facilities and continuous improvement. Fermilab also executes a high-power targetry (HPT) R&D program directed at the challenges of future multi-MW target facilities. The laboratory leads the international RaDIATE collaboration researching new radiation- and thermal-shock-compatible materials and technologies. To ensure Fermilab's core competency in targets evolves to sufficiently support multi-MW operation, the HPT R&D program is launching a targetry materials science and technology initiative to create the needed infrastructure (expertise, equipment, and facilities).

High-Field Superconducting Magnets

Fermilab has a long history of developing, fabricating, and delivering advanced superconducting magnets, such as the world's first superconducting dipole magnets deployed in a circular collider (the Tevatron). The laboratory's core competency in high-field superconducting magnets, including novel superconducting materials and magnetic components, electromechanical magnetic designs, and technologies, is essential to the luminosity upgrades of CERN's LHC accelerator. This core competency is also critical to enable upgrades of the LHC for operations at higher energies, which require further increases in the maximum magnetic field achievable in accelerator-quality magnets. Infrastructure supporting Fermilab's magnet work includes a superconducting strand and cable testing facility, cable making and coil winding machines, collaring and yoking presses, reaction ovens, a cryogenic vertical magnet test facility for cold masses, a cryogenic horizontal magnet test facility for magnets in cryostats, and cryogenic infrastructure.

High-Gradient and High-Quality-Factor SRF Cavities

Fermilab's SRF expertise and infrastructure comprise a globally renowned core competency in the fabrication and testing of SRF technology. Laboratory staff members play an important role in the design and planning of linear and circular accelerators around the world that depend on SRF technology. This core competency enables Fermilab to be a key partner in the construction of the superconducting linear accelerator for SLAC's LCLS-II free electron laser, the highest-priority construction project in the DOE Office of Science. Fermilab's experienced staff and extensive infrastructure led the way in the design of SRF cryomodules and cryogenic infrastructure for LCLS-II and extended the state of the art for SRF cavity performance. By working with SLAC National Accelerator Laboratory and Thomas Jefferson National Accelerator Laboratory to establish LCLS-II as a world-leading facility, Fermilab is contributing its unique infrastructure and expertise to the broader scientific endeavor while simultaneously enhancing in-house capabilities for future projects like PIP-II. This infrastructure and expertise also position the laboratory to contribute to potential future accelerators and colliders. SRF infrastructure includes chemical processing and high-pressure rinsing of cavities, processing and brazing furnaces, cleanroom assembly facilities, inspection and testing capabilities for both bare and dressed cavities, cryomodule assembly stations, and a complete cryomodule test facility. The laboratory's core competency in SRF technology, including design and production of non-elliptical cavities such as those needed for PIP-II, is also essential to the luminosity upgrades of CERN's LHC accelerator through the application of crab cavities for luminosity control and levelling and to the high energy upgrade of the LCLS-II.

Beam Test Facilities

The Fermilab Accelerator Science and Technology (FAST) facility hosts a unique program of advanced accelerator R&D centered around its Integrable Optics Test Accelerator (IOTA) ring. As the world's only dedicated intensity-frontier R&D facility, its research program will address key technological and scientific challenges in the realization of next-generation, high-power accelerator facilities. The FAST facility also houses a state-of-the-art, high-brightness SRF electron injector, which principally serves the IOTA program. However, as the only operational SRF accelerator at Fermilab, the FAST injector also comprises a valuable R&D platform for SRF systems integration and operations.

Accelerator Science and Technology Training

Fermilab is making significant contributions to the nation's accelerator science and technology workforce training. The laboratory hosts the United States Particle Accelerator School (USPAS), which has trained over 4,500 students since its inception in 1981 and has undergone a restructuring that re-establishes the USPAS as a Fermilab-managed program. Fermilab also maintains a renowned joint university/laboratory doctoral program in accelerator physics and technology, as well as several undergraduate summer internship programs in collaboration with Argonne National Laboratory.

Accelerator Science is funded by DOE/HEP with additional funding from DOE/BES (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Advanced Computer Science, Visualization, and Data

Fermilab's expertise in Advanced Computer Science, Visualization, and Data enables scientific discovery. This core capability complements theory and experiments to increase scientific knowledge through data collection, storage, reconstruction, simulation, and scientific analysis. Fermilab has a remarkable history of developing, delivering, and deploying computing technologies for the scientific community and has been instrumental in the success of the ProtoDUNE experimental program through contributions to data acquisition (DAQ), data processing, event reconstruction and data analysis.

Fermilab is recognized for expertise in designing, developing, and operating distributed computing infrastructures and facilities, exascale scientific data management, and scientific workflows for data recording, processing, and analysis. The laboratory provides access to large-scale computational and data-management facilities for the CMS experiment at CERN, the LHC Physics Center, neutrino science and precision science experiments, the Dark Energy Survey, computational cosmology, lattice QCD, and accelerator simulations.

The laboratory is a leader in distributed computing, which has evolved to satisfy the rapidly expanding data needs of energy frontier and intensity frontier experiments. These tools and technologies are now in use by other areas of science, industry, government, and commerce. Fermilab scientific computing facilities has developed and is now operating the HEPCloud platform. The HEPCloud platform provides a unified portal technology for accessing and sharing resources for data processing, storage, and analysis across heterogeneous facilities and platforms. HEPCloud capabilities provide Fermilab computing users [cost] optimized access to DOE/ASCR HPC centers, internationally partnered facilities, university supported computing clusters, and commercial cloud resources. HEP Experiments including CMS, Mu2e, and NOvA are exploiting Fermilab's HEPCloud capabilities to accelerate their scientific discoveries.

Due to the collaborative nature of particle physics research, Fermilab does not develop scientific software or computing capabilities in isolation. The laboratory partners with all DOE/SC laboratories and international laboratories such as CERN, DESY in Germany, and KISTI, the Korean Institute of Science and Technology Information, to work on projects that include accelerator modeling, computational cosmology, and particle physics simulations. Fermilab's strategy is to leverage DOE/ASCR expertise where appropriate to respond to computational challenges presented by the DOE/HEP program through the judicious use of partnership programs such as DOE's Scientific Discovery through Advanced Computing (SciDAC) program, as well as periodic DOE/ASCR calls for proposals.

Fermilab's data center is the single largest U.S. high energy physics computing center with 80,000 processing cores, 40 petabytes of disk storage, and nearly an exabyte of data storage on robotic tape systems. State-of-the-art computational facilities enable the laboratory to develop new capabilities to support the DOE scientific mission. Fermilab plays an essential role in developing software and hosting scientific computing projects and three major computing facilities for the science community: a CMS Tier-1 Center; Lattice QCD Computing; and FermiGrid. All of these onsite facilities will be accessible through HEPCloud in the new institutional cluster model mentioned in section 3.3.

CMS Tier-1 Center: The CMS experiment uses a distributed computing model in which data distribution, processing, and delivery is handled by seven international Tier-1 centers together with university- and laboratory-based Tier-2 computing and storage facilities. This computing model satisfies the needs of particle physicists by providing data storage and processing power on an extreme scale, interconnected by the strongest networks. The CMS Tier-1 Center at Fermilab is the most powerful worldwide (after CERN's Tier-0 center) for the 3,000-member, 41-country CMS experiment.

Lattice QCD Computing: Quantum chromodynamics (QCD) is the theory that describes how quarks and gluons interact via the strong force and predicts the properties of hadrons such as the proton, neutron, and pion. QCD calculations involve numerical simulations performed on a lattice of space-time points (known as Lattice QCD) that can be extremely computationally intensive. Fermilab operates large computer clusters for such calculations as part of DOE's national Lattice QCD computational infrastructure. The new institutional cluster, that is being deployed for Lattice QCD calculations, will further align the laboratory with a path towards developing HPC optimized science applications, and provide additional computing capacity for non-Lattice QCD science.

FermiGrid: Fermilab is the host laboratory for several neutrino and precision science experiments and provides computing facilities for these experiments, including reliable resources for data recording and processing (the equivalent of the CERN LHC Tier-0 for neutrino and precision science). FermiGrid is the primary HEP facility for non-LHC computing and provides computing and storage resources that are shared among these experiments.

Advanced Computer Science, Visualization, and Data is funded primarily by DOE/HEP with additional funding from DOE/ASCR (and DOE/SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission.

Science Strategy for the Future

Fermilab's primary ten-year goal is to establish a world-leading neutrino science program led by the Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE) and powered by megawatt beams from an upgraded and modernized accelerator complex made possible by the Proton Improvement Plan II (PIP-II) project. Identified by the U.S. particle physics community in its consensus Particle Physics Project Prioritization Panel (P5) report as the highest-priority domestic construction project in its timeframe, LBNF/DUNE and PIP-II are attracting global partners willing to invest significant financial, technical, and scientific resources. A five-year program that includes current and near-term neutrino experiments, R&D platforms for the global community, and prototype detectors (ProtoDUNEs) at the European particle physics laboratory, CERN, is driving the development of capabilities and infrastructure planning to bring together the international community needed for LBNF/DUNE and PIP-II.

Combining the strengths and talents of its members, Fermi Research Alliance (FRA) enables this vision by providing guidance, advocacy, and oversight of the laboratory. Led by the University of Chicago (UChicago), the Joint Task Force Initiative (JTFI) aims to exploit opportunities for Argonne National Laboratory, Fermilab, and the university to drive breakthroughs in science, technology development, and to find efficiencies and share resources ranging from joint procurements, business management expertise, leveraged computing and storage, and engagement with state and federal sponsors. Through the UChicago Consortium for Advanced Science and Engineering, Fermilab scientists are granted a university affiliation and are given the opportunity to receive UChicago funding for supervision of graduate students working on Fermilab projects. Universities Research Association sponsors several named fellowship awards to recognize emerging U.S. faculty; the result is a series of sponsored opportunities for leading researchers to engage more substantively with Fermilab's science and technology programs. The FRA Board of Directors has added new members familiar with large projects, commercial construction, and government procurement strategies. UChicago's Polsky Center for Entrepreneurship and Innovation is an important touchpoint for Fermilab's plan to expand external engagement in support of U.S. competitiveness.

Infrastructure

Overview of Site Facilities and Infrastructure

Fermilab's 6,800-acre site and conventional infrastructure network provides the foundation for the laboratory's scientific research and development program. The Fermilab Accelerator Complex is DOE/SC's national science user facility at the laboratory. Fermilab's employees include scientists and engineers from around the world who work together with the international user community to use the laboratory's scientific infrastructure for their research. The laboratory's infrastructure is evolving to support the significant requirements of the international LBNF/DUNE and PIP-II projects.

All real property at Fermilab in Batavia, Illinois is used and owned by DOE. In addition, DOE has a 22,155 GSF real-property lease with the South Dakota Science and Technology Authority (SDSTA) at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The total Replacement Plant Value (RPV) for conventional facilities is $1.09B. The total RPV including programmatic accelerator and tunnel assets (OSF 3000) is $2.21B. Property use is predominantly comprised of research and development and administrative areas. Other land is maintained as restored prairie, tilled agriculture, or woodland, and is preserved for future science.

Fermilab is providing oversight of real property at SURF in both leased space and non-leased (SDSTA-owned) space as part of the LBNF/DUNE Project. The laboratory added project office space in a leased area and is working in concert with SDSTA to improve utility systems and construct underground detectors and support systems for LBNF/DUNE.

The Fermilab Campus Master Plan[2] supports the implementation of the laboratory's strategic plan and major initiatives. Executing the plan requires investment in demolitions to reduce the laboratory's excess facility operating burden. In FY 2018, overhead funds were used to complete demolitions totaling 13,689 GSF. Two trailers (2,384 GSF) were also archived in the DOE Facility Information Management Systems (FIMS). In FY 2019, Fermilab will demolish 5,014 GSF and archive 1,362 GSF. During FY 2018, Fermilab added one building and seven Other Structures and Facilities (OSF). Future demolitions will be included in strategic laboratory budgeting and project proposals to ensure a continued reduction in operating burden and risk.

The Laboratory Operations Board (LOB) infrastructure assessment in FY 2014 helped establish Fermilab's past strategy for facilities. As the laboratory stands up new initiatives to centralize facility management and matures its development of new facilities, campus planners recognize the need for a new analysis and plan to shore up Fermilab's utility and site infrastructure. The table below summarizes the number, area, and condition of Fermilab facilities. These condition assignments were based on the FY 2014 infrastructure assessment (and do not include Excessed assets in Shutdown status per FIMS reporting).

[2] http://fess.fnal.gov/master_plan/index.html

Types of Facilities	Number of Facilities			Gross Square Footage of Facilities		
	Adequate	Substandard	Inadequate	Adequate	Substandard	Inadequate
Other Structures and Facilities	54	0	0	--	--	--
Mission Unique Facilities	99	0	0	408,261	0	0
Non-mission Unique Facilities	216	12	59	1,830,249	21,288	187,219

Table: Types and Conditions of Facilities

In past years, two substandard OSF assets were reported: electrical substations and the industrial cooling water system. These two assets are now reported as adequate due to the success of the SLI-funded Utilities Upgrade Project that mitigated the laboratory's highest infrastructure vulnerability.

As Fermilab moves to reassess the condition of site infrastructure, the level of substandard and inadequate facilities is expected to grow for two reasons.

- First, the laboratory is moving from distributed facility management to a centralized facility management program. This change will increase efficiency and provide more accurate facility investment planning and reporting. The new program will have trained staff to manage and evaluate the material condition of facilities. This concept was piloted in FY 2018 and resulted in an increase in identified deferred maintenance. As the program is fully rolled out, more accurate condition assessments will yield more facilities classified as substandard or inadequate.
- Second, the laboratory is undertaking assessments of facility and utility condition. The first step, initiated in FY 2019, will be a strategic assessment of each asset portfolio, and will inform a detailed condition assessment of each. The detailed facilities and infrastructure assessments will likely lead to increases in substandard and inadequate levels due to a new understanding of extent of condition that goes beyond fault and repair history.

Campus Strategy

Fermilab's strategy and major initiatives, as described in Section 4, are the principal factors driving facilities and infrastructure planning. To support those initiatives, the laboratory is focusing on two distinct but related efforts regarding facilities management: improving sustainment of existing assets and planning for recapitalization of overaged, obsolete, and severely deteriorated aspects of the laboratory's infrastructure. Both efforts are necessary to ensure appropriate stewardship of the infrastructure investments and also provide modern, world-class facilities for scientific research.

Science and technology mission needs flow down laboratory strategy through the Campus Master Plan. The Fermilab Campus and Facility Planning Board ensures coordination, communication, and prioritization of facilities projects based on the Campus Master Plan in support of Fermilab's strategy and major initiatives. Infrastructure gaps are identified according to core capability and mission objectives and solutions are proposed accordingly. The laboratory's proposed facilities and infrastructure projects will close identified infrastructure gaps as noted in the following table: Infrastructure Gaps by Core Capability and Mission Objectives.

Gap #	Campus Need / Gap	Top Mission Objectives Affected	Infrastructure Solution
1	Reliable **utility service and capacity** for laboratory expansion	**All mission objectives; sitewide impacts**	Central Campus Infrastructure Project*, Utilities Upgrade Project 2.0*
2	**Accelerator science and technology facilities**	Accelerator Science[1] LBNF/DUNE[4] PIP-II[4]	Center for Accelerator Science and Technology*, Accelerator Controls Improvement Project*,

3	**Modern lab space** for detector and quantum science R&D and **space in the Central Campus** to co-locate engineers and technicians from geographically dispersed facilities	Quantum Systems[1], Quantum Computing[2], Quantum Sensors[3] Collider Science[3] Neutrino Science[3] Precision Science[3] LBNF/DUNE[4]	Integrated Engineering Research Center
4	**Office space** for users and collaborating institutions	Neutrino Science[3] LBNF/DUNE[4]	Wilson Hall Modernization, Wilson Hall Improvement Project*
5	**Detector halls** for the Muon Campus and Short Baseline Neutrino program	Neutrino Science[3] Precision Science[3] LBNF/DUNE[4]	Utilities Upgrade Project 2.0*, Technology Campus Improvement Project*
6	High bay **assembly and production facility**	HL-LHC AUP[1]	Industrial Center Building Addition GPP, Technology Campus Improvement Project*
7	Overnight **accommodations** for short-term visitors	All mission objectives	Hostel*

**Proposed*

Fermilab Core Capabilities:

1 - Accelerator Science & Technology | 2-Advanced Computer Science | 3 – Particle Physics | 4 – Large-Scale User Facilities

Sustainment

Fermilab is targeting investment improvements for sustainment of site infrastructure. The laboratory's annual Maintenance and Repair (M&R) spending has fallen consistently shy of 2% of the laboratory's overall RPV in recent years. The laboratory is working to adjust future financial plans to achieve the recommended 2% M&R spending level.

In FY 2020, Fermilab is planning to conduct a series of infrastructure condition assessments which will, over time, provide a more accurate picture of facility conditions. Combined with existing facility maintenance and repair records, the assessment data will be used to balance resources and make better risk-based investment decisions.

Finally, the laboratory is evaluating opportunities for centralizing facility management to develop best practices, share resources, drive consistency, achieve efficiencies from scale, and enable a lab-wide risk-based investment strategy. The laboratory began a pilot centralized facility management program in FY 2018 and is continuing to grow the program in FY 2019.

Recapitalization – Current

Based on the Campus Strategy, the Fermilab Campus Master Plan encompasses three themes: modernization of facilities; consolidation and centralization of dispersed and inefficient support facilities; and preservation of the laboratory's unique character and identity. Three SLI-funded projects support the themes of the plan.

The Integrated Engineering Research Center (IERC) is solving an urgent need to centralize, consolidate, and modernize scientific, technical, and engineering facilities. With the SLI-funded IERC project underway, the laboratory is prepared to bring scientific and technical resources that are currently scattered across the site into closer proximity to foster a more effective and efficient work environment. The IERC project received CD-1 ESAAB approval in April 2017. The project team has started the final design phase. The construction of this building begins to satisfy the most urgent needs to relocate resources to the Central Campus in accordance with the Campus Master Plan.

The Utilities Upgrade Project was completed in FY 2018 and provides the first step in recapitalization of the campus' utility network and represents the type of investment needed for utilities modernization across the site. The successful completion of this project increased lab capacity and reliability, provided the foundation for future utility upgrades to support the laboratory's science mission, and paved the way for future large-scale infrastructure investment projects at Fermilab.

The Wilson Hall Revitalization Project is improving efficiencies and modernizing density expectations in the laboratory's largest administrative building and includes enhancements that address Fermilab's role as host laboratory for LBNF/DUNE and PIP-II. The laboratory is nearing completion of the first phase of the Wilson Hall 2.0 modernization that began in FY 2016 with $9M from SLI's GPP program. This project increases density through standardized floor plans and implements a standard for reconfigurable walls and furniture. This project will also establish better connectivity with the IERC.

The Campus Strategy and Campus Master Plan themes are additionally addressed with recent DOE/HEP-funded infrastructure support.

The Industrial Center Building High Bay Addition will provide the needed capability for production capacity given the limited availability of production space. The Technical Campus houses fabrication, production, and testing facilities for LCLS-II and PIP-II cryomodules, high-field magnets for CERN's HL-LHC accelerator upgrade, and solenoids for the Mu2e project. This project is under construction with funds from DOE/HEP's GPP program.

Recapitalization – Future Strategy: Infrastructure

Fermilab is embarking on a new comprehensive laboratory strategic planning process to appropriately address programmatic and conventional infrastructure recapitalization needs. The initial outcome of the new process generated a recognition that the laboratory's utility infrastructure (core campus, accelerator support, and sitewide) requires significant investment to accommodate future mission needs. The laboratory is proposing a series of major infrastructure funding packages to efficiently mitigate risk associated with current infrastructure needs and shore up the laboratory's foundation for continued support of Fermilab's role as international host of world-class science.

To address this anticipated rise in deferred maintenance and improve site utility reliability, the investment funding profile through FY 2030 (see Enclosure 4) includes proposed significant investment packages to address standing infrastructure risks and the deferred maintenance backlog. Investments from both the DOE/HEP and DOE/SLI programs will be critical to improve utility reliability.

In FY 2019 and FY 2020, Fermilab proposes to start minor construction, general plant projects in advance of the significant investment packages. The lab will construct a new utility corridor to the developing accelerator campus and provide an electrical feed from the site's Master Substation to feed that campus. In addition, the laboratory is planning improvements to the technical campus to support the development of cryogenic infrastructure for PIP-II and other projects and will mitigate a loss of core campus parking, caused by construction of IERC, with a new parking lot.

A proposed Central Campus Improvement Project recapitalizes the heart of the core campus utilities by redeveloping the campus central utilities building (CUB) and replacing deteriorated and obsolete 50-year old supporting utility infrastructure. The CUB provides hot, chilled, and low conductivity water to the central campus (e.g., Wilson Hall, Proton/Muon Campus, Linac, Main Injector) for process and comfort loads. Most of the systems lack redundancy (i.e., single-point-of-failure), are continuously running (i.e., 24 hours a day, 365 days a year), and are beyond end-of-life. This has resulted in an increase in the number of repair activities that have resulted in outage time for accelerator operations.

Additionally, the envelope of the building is degrading. The 2-story window wall has deteriorated and is vulnerable to collapse. Finally, the utility network delivering CUB services to core campus facilities is largely original and subject to frequent breaks, leaks, outages and subsequent impacts on core campus activities. The proposed Central Campus Improvement Project would recapitalize end-of-life infrastructure, increase capacity for future projects, and provide reliable, critical infrastructure to support Fermilab's science mission.

Additional focus on the core campus is planned with a Wilson Hall Improvement Project. Wilson Hall is an iconic 45-year old DOE facility and home to 40% of Fermilab's staff. The facility was constructed using unique and frugal techniques. For example, interior and exterior windows do not meet current building codes (they were economically sourced from a patio door supplier). Elevators have reached end of life and were never designed to accommodate freight loads. Lighting controls are post-development additions and run on a homegrown network. Further consequences of the unique and frugal construction techniques include:

- As identified in the recent modernization project, the utilities within the building (e.g., plumbing, electrical, HVAC, etc.) have degraded and exceeded their useful life. A plumbing evaluation identified the condition of the existing risers and lateral plumbing require a total replacement.
- Degraded pipes have resulted in catastrophic failures. For example, a degraded hot water pipe that feeds the Wilson Hall heating system ruptured in January 2019. This resulted in a 24-hour loss of heating during the winter which resulted in an interruption to core campus business.
- Upgrades to the campus communication network has resulted in additional HVAC demands that are beyond the current capabilities of the aging HVAC system.
- The building's envelope requires regular maintenance on the concrete facade. This maintenance has been deferred for several years and is currently around $7.5M in backlog.

Therefore, the Wilson Hall Improvement Project will recapitalize the current infrastructure, focus on utility and envelope improvements, reduce the existing deferred maintenance, and prepare the building to be ready for another fifty years of occupation.

To address the aging condition of the miles of utility infrastructure traversing Fermilab's 6,800-acre (10 square mile) site, a Utilities Upgrade Project (2.0) builds on the Utilities Upgrade Project completed in FY 2018 and will provide the branch lines and feeders to support LBNF/DUNE as well as future scientific research. Fermilab's sitewide utility infrastructure requires expansion and recapitalization to meet the laboratory's mission. The utility infrastructure comprises 74% of the site's total FY 2018 deferred maintenance backlog ($24.9M of $33.8M). While the Utilities Upgrade Project, completed in FY 2018, successfully reduced deferred maintenance by $8.3M, it is anticipated that condition assessments planned to begin in FY 2019 will yield significant additional deferred maintenance and an increase in the site's levels of substandard and inadequate facilities and OSFs.

As an overview, Fermilab's utility systems include the following assets:

- Electric – 345kV power is received from utility grid at two primary substations, 280 secondary substations, 110 miles of cable (80 miles underground)
- Natural Gas – 22 miles of underground pipe
- Cooling Pond Water – 140 acres of ponds with return and supply channels
- Industrial cooling water – 27 miles of pipe
- Sanitary System – 16 miles of sewer collection pipe and lift stations
- Domestic water – 21 miles of underground distribution pipe

The majority of the laboratory's systems are greater than 35 years old and approach or exceed their end-of-useful life. For example, the bulk of the natural gas distribution system is approximately 40 years old and the number of repair activities has tripled over the last 20 years and continues to increase. Some end-of-life needs were mitigated by the Utilities Upgrade Project that replaced the backbone of ICW and electrical infrastructure. However, the project did not address the remaining secondary lines and the other utilities.

Recapitalization – Future Strategy: Science Mission Support

In addition to the new comprehensive laboratory strategic planning process, a planning effort was conducted in FY 2018 to identify opportunities to modernize facilities, increase efficiency, and reduce costs associated with operations of the Fermilab Accelerator Complex. In recent years, the accelerator complex has undergone a significant transition from colliding high-energy beams to producing high-intensity proton beams for neutrino and precision science. Even with the successful transition to a new operating mode, parts of the complex are more than 50 years old and require recapitalization to ensure the complex remains reliable and productive for the international DOE science mission well beyond 2040.

The laboratory's accelerator scientists and technical teams are developing transformational accelerator technologies for use across the DOE/SC complex and around the globe. These transitions, combined with the condition and age of Fermilab's accelerator facilities, drive the need to consolidate core research and operations functions and modernize key support facilities. A Center for Accelerator Science and Technology (CAST) would sustain the national and international accelerator science community with modernized R&D and operations capabilities. This building will upgrade working conditions for laboratory staff, will provide a modern workspace for visiting and collaborating national and international accelerator scientists, and will allow for decommissioning of end-of-life facilities.

To address aging utility infrastructure and new infrastructure needs for the accelerator campus, the Fermilab Accelerator Controls Improvement Project will recapitalize critical accelerator support systems. Additionally, the Technology Campus Improvement Project will provide a modern, centralized complex for the research, assembly, and testing of critical accelerator and detector components and technologies currently housed in inadequate, dispersed, and inefficient facilities.

Site Sustainability Plan Summary

In FY 2018, Fermilab included a commitment to environmental and sustainability stewardship as a main theme of the Fermilab Campus Master Plan. The Campus Master Plan builds on Fermilab's campus strategy which has four goals, one of which is to "Construct sustainable infrastructure that will attract international investment and the brightest minds to the world's leading laboratory for accelerator-based neutrino science."

These goals set the stage for the activities and programs associated with sustainable operations at Fermilab. In FY 2018, Fermilab achieved success in meeting the laboratory's sustainability goals. The following FY 2018 accomplishments are notable examples of sustainability progress which support Fermilab's ability to deliver on its mission:

- Fermilab participated in the DOE Facilities and Infrastructure Restoration and Modernization (FIRM) program to assess the potential for conducting "deep energy efficiency retrofits" at Fermilab and for using financing mechanisms (UESC, ESPC, etc.) to complete the work.
- A bikeshare program was introduced, which gives employees an alternative onsite transportation option.
- Fermilab published the FY 2018 Campus Master Plan, setting the stage for thoughtful, sustainable campus development.
- In cooperation with neighboring communities, Fermilab participated in a review of its village sanitary system which will yield information to feed into strategic utility planning efforts in FY 2019.

- Fermilab achieved CD-4 on its Utilities Upgrade 413 project which completed site improvements to industrial cooling water system efficiency and electric utility reliability/resilience.
- A new waste disposal contract was executed, including provisions for an expanded composting and educational program.
- Plans were developed for future high-performance sustainable building – existing building improvements.
- Several site resilience improvements were made, including adding a generator at the Fermilab Village Kuhn Barn, which now can serve as a warming shelter during extreme weather events/outages.
- For the eighth consecutive year, Fermilab's Grid Computing Center was awarded Energy Star status.

LAWRENCE BERKELEY NATIONAL LABORATORY

Lab-at-a-Glance

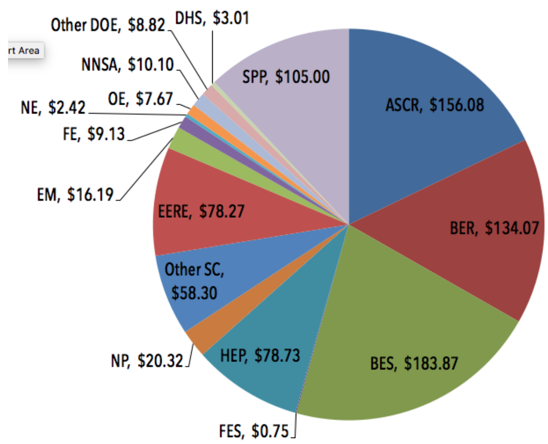
Location: Berkeley, California
Type: Multi-program Laboratory
Contractor: University of California
Site Office: Berkeley Site Office
Website: www.lbl.gov

- **FY 2018 Lab Operating Costs:** $872.72 million
- **FY 2018 DOE/NNSA Costs:** $764.71 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $105 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 12%
- **FY 2018 DHS Costs:** $3.01 million

Physical Assets:
- 202 acres and 97 buildings
- 1.7 million GSF in buildings
- Replacement Plant Value: $1.49 B
- 4,750 GSF in Excess Facilities
- 315,471 GSF in Leased Facilities

Human Capital:
- 3,129 Full Time Equivalent Employees (FTEs)
- 239 Joint Faculty
- 428 Postdoctoral Researchers
- 331 Graduate Student
- 110 Undergraduate Students
- 12,763 Facility Users
- 2,043 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

Established in 1931, Lawrence Berkeley National Laboratory (Berkeley Lab) plays an important and distinctive role within DOE's network of great national laboratories. Berkeley Lab delivers scientific breakthroughs over a remarkable range of science, with special focus on national challenges such as long-term energy security and economic competitiveness.

Berkeley Lab specializes in integrative science and technology, taking advantage of our world-renowned expertise in materials, chemistry, physics, biology, environmental science, mathematics, and computing. We advance the frontiers of science and technology through three approaches: advanced instruments and user facilities, large team science, and core research programs led by outstanding investigators. These three approaches are closely integrated to the benefit of DOE's entire research mission.

Berkeley Lab's mission, to bring science solutions to the world, runs deep within the organization. Our five national user facilities provide over 10,000 researchers with capabilities in high-performance computing and data science, chemical sciences, materials synthesis and characterization, and genomic science. The Lab's scientific strength is built upon its breadth of basic and applied science and its emphasis on collaboration with the national scientific community. We also collaborate closely with other national laboratories on a wide range of projects from subatomic physics to quantum information, biomanufacturing, environmental biology, and innovative energy technologies.

Berkeley Lab's close relationship with the University of California brings the intellectual capital of UC's faculty, postdocs and students to bear on the pursuit of DOE's science and energy missions. The Lab's scientific strength is enhanced by its deep integration of basic and applied science and its emphasis on collaboration with the national scientific community. We continue to find innovative ways to use our world class user facilities, capabilities, and expertise to solve the S&T challenges that define our time.

Core Capabilities

Each of Berkeley Lab's Core Capabilities involves a substantial combination of people, facilities and equipment to provide a unique or world-leading scientific ability to support DOE missions and national needs. Each is executed safely, with minimal impact on the environment and surrounding community. This section summarizes Berkeley Lab's Core Capabilities, their targeted missions, and their funding sources.

The Core Capabilities lend an exceptional depth to Berkeley Lab's broad research portfolio while enabling an integration of efforts to better support the DOE missions. To emphasize their strategic nature, the Lab has grouped these Core Capabilities into scientific themes: Large Scale User Facilities/Advanced Instrumentation; Basic Research in Energy; Biological and Environmental Sciences; Computing and Mathematics; High Energy and Nuclear Physics; Accelerator Science and Technology; and Applied Science and Energy Technology.

Large Scale User Facilities/Advanced Instrumentation

Since its inception as the first accelerator laboratory, Berkeley Lab has had an overarching Core Capability of designing, constructing and operating leading scientific facilities for large user communities. Among the national lab system, Berkeley Lab has the largest population of users; these researchers produce scientific breakthroughs because of their creative work at these facilities. Below are summary descriptions of the Laboratory's large-scale user facilities. Core Capabilities in other areas of this report, such as Basic Research in Energy, Computing and Mathematical Sciences, and Applied Science and Energy Technology, are key to the success of Berkeley Lab's advanced facilities and instrumentation.

The Advanced Light Source (ALS) is the world-leading facility for high-brightness soft X-ray science, with additional excellent performance ranging from the infrared through hard X-ray spectral regions. ALS researchers use the data they collect to understand, predict, and ultimately control matter and energy at length scales ranging from the atomic to the macroscopic. This research underpins many of DOE's Core Capability areas, including those involving chemical, material and biological systems. The ALS has more than 2,000 scientist users per year, and ALS-based results appear in nearly 1,000 refereed journal articles annually. Funded primarily by BES, it has an annual budget of ~$65 million.

The Molecular Foundry provides communities of users worldwide – 1,237 in FY18 – with access to expert staff and leading-edge instrumentation to enable the understanding and control of matter at the nanoscale in a multidisciplinary, collaborative and safe environment. Established 13 years ago, the Foundry's reputation as a world-leading center attracts expert scientists from around the globe to do cutting edge research. In FY18, the Foundry received user proposals from 31 states and 19 countries, and published nearly 375 peer-reviewed publications, 38% of which were in high impact journals. The Foundry encompasses facilities specializing in characterization, made up of the National Center for Electron Microscopy, along with the Imaging and Manipulation of Nanostructures facility;

Nanofabrication; Theory of Nanostructured Materials; and synthesis, focusing on Inorganic Nanostructures, Biological Nanostructures; and Organic and Macromolecular Synthesis.

The DOE Joint Genome Institute (JGI) is a national user facility carrying out projects of central relevance to DOE missions in alternative energy, global carbon cycling and biogeochemistry. JGI is the world's largest producer of plant and microbial genomes, with programs focused in three areas: large-scale generation of DNA sequences, development of innovative DNA analysis algorithms, and a strategic focus on functional genomics that includes a growing DNA design and synthesis program. It has nearly 1,600 capability users and over 8,500 active data users per year; its FY18 budget of ~$69 million is funded primarily by BER. In FY18, the JGI developed a strategic vision for integrative and collaborative genome science. The recently released plan lays out JGI's I5 Strategic Framework, encapsulating guiding principles for JGI's activities (identification, interrogation, investigation, integration, and interaction) to guide its transition to an Integrative Genome Science User Facility that will integrate sequence and functional capabilities for systems-level biology.

The National Energy Research Scientific Computing Center (NERSC) supports more than 7,500 users from universities, national laboratories and industry, representing the largest and most diverse research community of any DOE user facility. NERSC is the mission High Performance Computing center for the DOE Office of Science, providing resources for SC's six scientific program offices. NERSC hosts large-scale, state-of-the-art computing and data systems, networking, and expert consulting and support services. With the broadest workload of any computing facility, NERSC also has a responsibility to transition the DOE SC user community to exascale-era platforms. This transition began with NERSC's current premier system, "Cori," which uses an energy efficient many-core architecture. The Perlmutter system will continue the transition by introducing GPUs to the broad SC user community. In 2015, NERSC launched the NERSC Exascale Science Application Program (NESAP) that resulted in an average of 3x speedup on a portfolio of over 20 DOE SC applications. NERSC will continue partnering with application teams to accelerate codes on the Perlmutter system. A growing part of NERSC's workload is derived from data analysis requirements of DOE SC's experimental and observational facilities such as light sources, telescopes, accelerators, sequencers and sensors and supporting these new requirements has been a key focus at NERSC. As such NERSC has developed and deployed key technologies for supporting this growing workload including containers that run on HPC platforms, interactive notebooks for data analysis, and scaling machine learning and deep learning frameworks to take advantage of HPC scale resources. The NERSC-9 Perlmutter system is the first NERSC system to be designed from the start with large scale simulation and data analysis in mind and will build on many of the capabilities deployed and developed for the Cori system. NERSC's scientific impact is enormous: more than 2,000 scientific publications cite NERSC each year. In 2018 alone, its current systems, Cori (NERSC-8) and Edison (NERSC-7), provided more than nine billion computational hours to researchers. NERSC's FY18 funding was $105 million, provided by ASCR.

The Energy Sciences Network (ESnet) is the Office of Science's high-performance network user facility, delivering highly reliable data transport capabilities optimized for the requirements of large-scale science. ESnet serves as a vital "circulatory system" for the entire DOE national laboratory system, dozens of other DOE sites, and ~200 research and commercial networks around the world—enabling tens of thousands of scientists at DOE laboratories and academic institutions across the country to transfer vast data streams, access remote research resources in real-time, and collaborate on some of the world's most important scientific challenges, including energy, biosciences, materials, and the origins of the universe. In essence, ESnet is a force multiplier that enhances scientific productivity and expands opportunity for discovery. In the past year, the network transported roughly 910 petabytes of data. During FY18, ESnet achieved CD-1/3A for ESnet6, a strategic facility project to upgrade its network to meet the increasing data needs of science. In addition, ESnet is revamping its requirements review process across the SC program offices. ESnet's FY18 funding was ~$79M (ASCR).

Chemical and Molecular Science

Berkeley Lab has world-leading capabilities in fundamental research in chemical and molecular sciences that support DOE's mission to achieve transformational discoveries for energy technologies, while preserving human health and minimizing environmental impact. The Lab has integrated theoretical and experimental Core Capabilities and instrumentation to enable the understanding, prediction, and ultimately the control of matter and energy flow at the electronic and atomic levels, from the natural timescale of electron motion to the intrinsic timescale of chemical transformations.

Berkeley Lab has expertise in gas-phase, condensed-phase and interfacial chemical physics. State-of-the-art laser systems that generate ultrashort pulses of extreme-ultraviolet light; soft X-ray sources; photon and electron spectrometers; spectromicroscopy; in situ, operando and other capabilities are all used to advance the understanding of key chemical reactions and reactive intermediates that govern chemistry in realistic environments. The Lab has deep expertise in experimentation, simulation, and theory aimed at a first-principles description of solvation and molecular reactivity in complex interfacial environments. The Lab is a world leader in ultrafast attosecond and femtosecond probes of electron dynamics, electron momentum-imaging instrumentation, reaction microscopy, and theoretical methods that probe how photons and electrons transfer energy to molecular frameworks. These capabilities are key to understanding and ultimately controlling energy flow at the atomic scale.

Berkeley Lab's catalysis capabilities include basic research on homogeneous and heterogeneous chemical conversions for high efficiency and selectivity. The Catalysis Facility co-locates a suite of state-of-the-art instruments used for catalysis research and includes high-throughput dryboxes, a micromeritics analyzer, flow UV-vis spectroscopy, liquid chromatography, pressure reactors and FTIR instrumentation. The core strengths are in three pillars of catalysis: mechanisms, transformations, and environments, to elucidate fundamental principles in catalysis and chemical transformations at the molecular level. Research on both the catalytic center and its environment advance the field from discovery to catalyst design.

The Heavy Element Research Laboratory (HERL) has unique capabilities in electronic structure, bonding and reactivity of actinides, including the transuranic elements. The scientific personnel and instrumentation characterize, understand, and manipulate rare earth complexes for discovery and separation of alternative elements and critical materials, including those for energy storage, motors, solid-state lighting, and batteries.

Berkeley Lab has exceptional capabilities in solar photoelectrochemistry, photosynthetic systems, and the physical biosciences. These photosynthetic and photoelectrochemistry capabilities, together with novel spectroscopies and in situ imaging methods that utilize photon energies from X-rays to infrared at high temporal resolution, enable elucidation of the structure and elementary mechanisms of biological and artificial photon-conversion systems. The deep understanding of artificial and natural photosynthesis forms a basis for efficiently engineered solar-conversion systems. Berkeley Lab is lead lab partner for the DOE Energy Innovation Hub devoted to the development of new photoelectrochemical approaches to fuel production, the Joint Center for Artificial Photosynthesis (JCAP).

Novel instrumentation expertise at the ALS pioneers the application of vacuum ultraviolet and soft X-ray synchrotron radiation to critical problems in chemical dynamics and interfacial chemistry. The Ultrafast X-ray Science Laboratory (UXSL) develops laser-based ultrafast X-ray sources for chemical and atomic physics experiments and contributes to the knowledge base for future powerful FEL-based attosecond light sources.

This Core Capability is supported primarily by BES, with important contributions from ASCR. Other DOE contractors and SPP enable this Core Capability, which supports DOE's mission to probe, understand and control the interactions of phonons, photons, electrons and ions with matter; and to direct and control energy flow in materials and chemical systems.

Chemical Engineering

At Berkeley Lab, this Core Capability links basic research in chemistry, biology and materials science to deployable technologies that support energy security, environmental stewardship and nanomanufacturing. Leading capabilities are provided in the fields of chemical kinetics; catalysis; molecular dynamics; actinide chemistry; electronic, biomolecular, polymeric, composite, and nanoscale materials; surface chemistry; ultrafast spectroscopy; crystal growth; mechanical properties of materials; metabolic and cellular engineering applied to recombinant DNA techniques that create new chemical processes within cells; and new methodologies for genomic and proteomic analysis in high-throughput production that enable gene libraries that encode enzymes for metabolic engineering.

Other program components provide the capability to translate fundamental research in catalysis, chemical kinetics, combustion science, hydrodynamics and nanomaterials into solutions to technological challenges in energy storage and efficiency, as well subsurface energy and environmental science. The Advanced Biofuels and Bioproducts Process Development Unit

(ABPDU), supported by EERE and SPP, integrates biological and chemical unit operations through bioprocess engineering to understand and optimize processes for producing biofuels, renewable chemicals and proteins relevant to the industrial biotechnology industry. Berkeley Lab also has expertise in chemical biology and radionuclide decorporation, necessary for characterizing mammalian response and developing sequestering agents for emergency chelation in humans in case of heavy-element or radioactive contamination.

Berkeley Lab is a leader in materials for advanced battery technology, focusing on the development of low-cost, rechargeable, advanced electrochemical devices for both automotive and stationary applications. This effort includes the collaborative JCESR program. The related field of fuel-cell research enables the commercialization of polymer-electrolyte and solid-oxide fuel cells for similar applications.

This Core Capability is supported by BES, ASCR, BER, EERE, and SPP, including NIH, DoD, universities, and industry. It supports DOE’s missions to foster the integration of research with the work of other organizations within DOE, as well as other agencies, and applies directly to DOE’s energy security and environmental protection mission, including solar and fossil energy, biofuels, and carbon capture and storage.

Condensed Matter Physics and Materials Science

Berkeley Lab researchers develop experimental, theoretical, and computational techniques to discover, design, and understand new materials and phenomena across multiple time, length, and energy scales and in-situ and operando environments. These materials can have a direct and significant impact on solutions to grand challenges in energy, environment, security, and information technologies.

A key Berkeley Lab strength in this capability is in quantum materials, where quantum mechanics ultimately determine emergent properties, as well as the nature of associated ordered phases and the transitions that take place between them. This encompasses weakly correlated topological phases such as topological insulators and Weyl and Dirac semi-metals, and materials that exhibit novel forms of magnetic, electronic and geometric/spatial order, including 2D materials such as graphene or van der Waals heterostructures. Through its efforts within the BES core programs and the Center for Novel Pathways to Quantum Coherence in Materials, Berkeley Lab is targeting new paradigms for the creation and control of coherent phenomena in materials with an emphasis on elucidating and enhancing entanglement and transduction of quantum information between disparate modalities. Novel states of matter can be explored in the ultrafast time regime, including when the system is driven far from equilibrium.

Berkeley Lab has deep expertise in theory and computational simulations in conjunction with novel synthesis approaches that rely on machine learning and AI concepts, which are critical to the discovery and design of new materials. Berkeley Lab researchers develop models for understanding, predicting, and controlling complex materials with targeted properties. The Center for Computational Study of Excited-State Phenomena in Energy Materials develops new general software, theories, and methods to understand and predict excited-state phenomena in energy-related materials. Open access to analysis tools and computed information on known and predicted materials provided by the Materials Project helps the Lab to conduct computational work in high-throughput modalities.

The characterization of properties and behavior, including structure, function, and reactions, specifically at interfaces between various phases of matter, enable Berkeley Lab researchers to understand how new materials may perform in various energy-relevant environments. Efforts rely on developing instrumentation for time-domain approaches in spectroscopy, diffraction, and quantitative microscopy. Advancing X-ray, electron beam, and scanning probe techniques, including for operation under cryogenic conditions, and in situ and operando environments with near-atomic resolution, is a key focus. Unique characterization tools include time-resolved angle-resolved photoemission spectroscopy for studies of materials far away from equilibrium as well as ultrafast electron diffraction.

The Joint Center for Energy Storage Research (JCESR) seeks to understand electrochemical materials and phenomena at the atomic and molecular scale, and to use this fundamental knowledge to discover and design next-generation energy-storage technologies. Our understanding of materials and chemical processes at a fundamental level will enable technologies beyond traditional lithium-ion batteries. The Lab is a key partner of this hub, which is led by ANL.

We are addressing the looming challenges in microelectronics, often described as the era beyond Moore’s Law, through a co-design approach, where transformative materials discoveries driven by advanced computation and property characterization are integrated with the design of device and system architectures and scale-up processing. This approach establishes a powerful scientific ecosystem for driving the development of new concepts and technologies.

This Core Capability is primarily supported by BES, with important contributions by ASCR, EERE, and DoD, as well as other SPP sponsors from industry. It supports DOE’s missions to discover and design new materials and molecular assemblies with novel structures and functions through deterministic atomic and molecular scale design for scientific discovery, innovative energy technology, and improved homeland security.

Earth Systems Science

Berkeley Lab’s geoscience group, the largest in the DOE complex, develops knowledge and predictive models to describe the full range of complex subsurface processes and their impacts on energy and water systems as well as on above ground infrastructure. Researchers in this group use diverse laboratory and field methods to probe chemical, physical, thermal, and mechanical processes under relevant subsurface conditions and on length scales from nanoscale pores to reservoirs. A particular expertise lies in the development and use of high-resolution time-lapse imaging approaches, from in situ X-ray tomography at the ALS and the Rock Dynamics laboratory to field-scale monitoring of dynamic processes using acoustic and electromagnetic methods. Experimental efforts benefit from the Geosciences Measurement Facility (GMF). Unique across the complex, GMF provides exceptional expertise and tools to design, build, test, and deploy new equipment and instrumentation required for geoscience investigations, including large field scale deployments.

BES support enables geoscience researchers to discover the molecular-scale mechanisms of fluid-rock processes and translate molecular- and nano-scale insights to larger-scale models and capabilities. Historically, three fundamental geoscience programs at Berkeley Lab have been funded by the BES Chemical Sciences, Geosciences, and Biosciences (CSGB) Division—in geochemistry, isotope geochemistry, and geophysics. Beginning this year, these groups have launched a process of integration to form a flagship geosciences group that will be unique in the United States. This exciting effort will catalyze collaborations among the disciplines and the expertise needed for rigorously understanding how coupled processes change the properties of rock-fluid systems in response to stress and reactive fluids and solutes. The capabilities that are united in the new geoscience group include molecular simulation methods; dielectric–to–X-ray spectroscopies for aqueous solvation, ion transport, and reaction; stable isotope probes of mineral reactions; methods for imaging fracture creation and evolution across scales; laboratory mechanical measurements; and the geochemical and geophysics theory and simulation required for data interpretation and new model development. While the geoscience program is becoming integrated, all CSGB program leads at Berkeley Lab are working together to develop a unified vision, and to promote synergy and knowledge transfer across the Chemical Sciences, Geosciences, and Biosciences groups.

Translation of fundamental knowledge to increasingly accurate subsurface models is a cross-cutting goal and one that ultimately requires the use of high-performance computing. Berkeley Lab leads the only two subsurface exascale application projects in the complex. The Subsurface project focuses on scale-adaptive approaches to simulate, from the micro- to the reservoir-scale, the coupled hydrological, chemical, thermal, and mechanical processes that are critical to many subsurface energy applications, including geologic CO_2 sequestration, oil and gas extraction, geothermal energy production, and nuclear waste isolation. The EQSim project aims to increase the accuracy of earthquake hazard assessments by simulating for the first time, in a fully coupled approach, the effect of strong ground motion on infrastructural response.

This year, Berkeley Lab ended the EFRC on Nanoscale Controls on Geologic CO_2 (NCGC) which, over the past eight years, produced highly influential fundamental science on the storage of carbon dioxide in subsurface systems. NCGC accomplishments include establishing the fundamental mechanisms of the dominant CO_2 trapping mechanisms in aquifers, and the identification of unexpected chemical interactions between CO_2-bearing fluids and minerals that can increase reservoir storage capacity. Scientists are working on new opportunities to translate these accomplishments to future research that will increase the nation’s readiness for large-scale sequestration.

The Lab’s applied subsurface portfolio is supported by EERE-Geothermal, FE Clean Coal, FE Oil & Gas, NE Spent Fuel and Waste Disposition, and by several significant SPPs. The BES and applied energy programs at Berkeley Lab together are leading to an understanding of how fundamental processes influence reservoir-scale processes – and how reservoirs can be manipulated for beneficial utilization while minimizing environmental risks. Unlike other scientific fields where the bulk of the research can be explored in the laboratory, it is critically important to extend geoscience theory and approaches to the field scale, where research can be done under in situ conditions, across compartments and scales, and in the presence of natural forcings. To this end, Berkeley Lab has developed and is conducting significant research at several field-based subsurface energy test facilities. For example, Berkeley Lab’s Geothermal program seeks to realize enhanced geothermal systems (EGS) and more flexible geothermal energy production. In support of this effort, the Lab leads the multi-lab Geothermal Collab project, where novel stimulation and heat mining production methods are tested in situ in deep tunnels at the SURF facility in South Dakota. The Lab’s FE Oil & Gas portfolio includes efforts such as investigating hydrocarbon recovery processes from shales across scales including improved stimulation for more efficient hydrocarbon recovery, and new methods to improve oil recovery. In addition to traditional approaches, machine learning methods are being developed and used in the hope of providing another pathway to understanding the wide range of variables impacting subsurface fluids flow. Berkeley Lab continues to be instrumental in understanding relevant processes in gas production from gas hydrate, and in developing tools for assessment of production methods from hydrate resources. Berkeley Lab also participates in field-based research at the new Eagle Ford Unconventional Testbed in Texas. The Lab's FE Clean Coal research focuses on enabling an effective transition to a clean energy future. Key aspects include pairing fossil energy use with carbon sequestration at scale, evaluating carbon sequestration risks through DOE's National Risk Assessment Partnership (NRAP) program, and developing advanced monitoring and accounting solutions and testing them at demonstration sites in Decatur, Ill., and at the Aquistore site in Canada. The Lab is a key partner in the Brine Extraction Storage Test in Florida, developing synergistic approaches to couple CCS pressure management with brine desalination methods. Through NE research, Berkeley Lab is developing advanced approaches to enable safe long-term geologic disposal of nuclear waste and concomitant environmental protection.

Complementary to the DOE-supported research at Berkeley Lab are several significant new projects awarded by the California Energy Commission, including new approaches to monitor and evaluate risks associated with natural gas storage (such as the risks to natural gas pipelines arising from land subsidence), development of tomographic imaging methods for geothermal reservoirs, evaluation of the feasibility of flexible geothermal energy production, and the development of networked observational systems to detect methane fluxes over energy infrastructure using aircraft, towers, and intensive ground-based sensors.

Berkeley Lab's capabilities and involvement in research associated with critical infrastructure and natural hazards have realized substantial growth in the past years. Lab scientists have now established a significant program in this area and work with the DOE, the State of California, local governments, and local stakeholders on a number of critical infrastructure challenges. In a major effort supported by the Exascale Computing Program, the Office of Nuclear Safety, and NNSA, Berkeley Lab is leading development of transformational simulation tools for earthquake ground motion simulations with tight coupling to new computational models for predicting the nonlinear response of soil/structure systems. Leveraging DOE's HPC ecosystem, this work will yield an unmatched fault-to-structure simulation capability that can reduce current uncertainties in earthquake processes, with widespread applicability to the vast DOE enterprise and DOE sites, and spin-off applications to other sectors (e.g., energy, water, transportation). For example, a new project supported by DOE's Office of Energy will use these advanced simulation capabilities to assess hazard and risk associated with electrical and gas transmission systems as a basis for grid resilience and energy reliability planning. Berkeley Lab scientists are also working on exciting new characterization and monitoring methods to better constrain risk-relevant properties of natural and engineered systems. For example, LDRD support has been used to develop ultra-dense monitoring methods for subsurface parameters and ground motions. One of these methods utilizes unused telecom fiber optics cables, referred to as "dark fiber," to achieve spatially unparalleled acoustic sensing and ambient noise tomography in urban settings, and another focuses on upgrading hundreds of thousands of its smart electric and gas meter components in homes to include an acceleration measurement capability. Lab scientists have also developed and experimentally-tested advanced optical sensor and wireless communication systems that allow, for the first time, rapid determination of potential damage in critical building structures immediately after a natural hazard event. These technologies and tools can impact a wide range of infrastructure systems such as energy facilities, industrial complexes, pipelines, levees, bridges, and buildings.

Biological and Environmental Sciences

Many of the most pressing energy and environmental challenges of our time require an ability to understand, predict, and influence environmental and biological systems. For this we need a new and deeper understanding of fundamental biology, Earth processes, and their interactions. Berkeley Lab is transforming our ability to decipher and map the vast networks of these interconnected systems, the scale of which range from nanometers to thousands of kilometers, and from nanoseconds to centuries. This enables predictions for how environmental changes impact biological systems and vice versa; to harness biology for sustainable energy and other valuable products; and to develop understanding of dynamic, multi-scale Earth systems.

Biological and Bioprocess Engineering

Berkeley Lab's strengths in biological systems science are complemented by its unique capabilities for biological and bioprocess engineering to translate fundamental science discoveries to use-inspired solutions for energy and environment. The Lab has world-renowned capabilities in synthetic biology, technology development for biology, and engineering for biological process development. By leveraging resources such as the JGI, the DOE Systems Biology Knowledgebase (KBase), ENIGMA, the ALS, the Molecular Foundry, and NERSC, the Lab can develop the new technologies and processes needed to create renewable fuels and chemicals, remove environmental contaminants, and support biosequestration of carbon.

The Joint BioEnergy Institute (JBEI) is one of the four DOE BRCs whose mission is to advance science, engineering, and technology to support the maximum possible conversion of carbon from lignocellulosic biomass to liquid transportation fuels and bioproducts. Using molecular, computational, and robotic technologies, JBEI has successfully altered biomass composition in model plants and crops, and demonstrated that ionic liquids can deliver near-complete dissolution of plant biomass to facilitate its conversion to sugars needed to produce energy-rich fuels. The production of commodity chemicals from biomass brings environmental and economic benefits, as well as the possibility of producing diverse, novel molecules through biological conversion pathways that are challenging or currently impossible using chemical synthesis approaches. Industry realizes the economic potential of such breakthroughs, and licensed technologies from JBEI's activities are steadily coming out of the strong industrial affiliate program.

The Advanced Biofuels and Bioproducts Process Development Unit (ABPDU) provides capabilities for scale-up of biofuels pretreatment, saccharification, and fermentation methods. In collaborations with national labs and with industry, this facility develops new and optimizes existing processes for biofuels and bio-based chemicals and materials processes. In FY18, the ABPDU initiated nine new SPP projects with small companies, and since its inception in 2009, has partnered with over 40 companies. It has been instrumental in developing and optimizing new processes for bio-based chemicals and materials. Three ABPDU company partners have brought products to market as a result of the process improvements and optimizations enabled by projects with the ABPDU.

Successes from JBEI, the other BRCs, and other biological engineering programs have given rise to Berkeley Lab's Agile BioFoundry (ABF), with the potential to transform manufacturing practices through advanced bioconversion technologies in support of a bio-based economy. Supported initially with LDRD, DARPA, and EERE funding, the ABF was established in FY17 as an eight-lab consortium with funds from EERE's BETO. Led by Berkeley Lab, the ABF consortium leverages capabilities across the national laboratory system; its partners include ANL, INL, LANL, NREL, ORNL, PNNL, and SNL. The ABF integrates computer-assisted biological design, advanced metabolomics and proteomics techniques, machine learning, technoeconomic and sustainability analysis, and process integration to optimize biological process design and develop methods for predictable scaling. The ABF consortium continuously engages with private sector stakeholders through its industry engagement team and its advisory board of experts from companies in the bio-based products and biological computing fields. In FY19, the ABF is continuing nine projects (eight for industry, one for academia) resulting from a directed funding opportunity in FY17 and the BioEnergy Engineering for Product Synthesis funding opportunity in FY18. Ranging from technology integration into the ABF workflow (software, equipment) to the development of novel biological engineering technologies and pathways (biosensors, new pathways for novel products), these projects aim to solve problems of relevance to industry while building out the ABF's capabilities.

BER and EERE are the primary supporters of this Core Capability, building upon capabilities and programs established with BER funding. Other key sponsors include industry and other SPP; anticipated sponsors include USDA, DoD, and the NIH. This Core Capability supports DOE's objectives by applying understanding of complex biological systems to design systems; by creating technologies for bioenergy and bioproduct production; by increasing commercial impact through the transition of national lab-developed technologies to the private sector; utilization of national lab facilities and expertise; and demonstration and deployment for the economic, energy, and national security.

Biological Systems Science

As described below, Berkeley Lab sustains leading capabilities in systems biology, genomics, biodesign, structural biology, and imaging at all length scales (from protein structure to ecosystems). The Lab is also a national leader in microbial biology, cell biology, plant biology, microbial community biology, environmental sciences, and computational biology. The capability is further enhanced by instrumentation at the ALS, DOE JGI, the Molecular Foundry, NERSC, and JBEI. The Lab has the capability to characterize complex microbial community structure and function; manage highly complex biological data; visualize biological structure; and produce large-scale gene annotation.

The JGI provides a diverse scientific user base with access to state-of-the-art genomic technologies and scientific expertise to enable biological discoveries and applications in the DOE mission areas of bioenergy, nutrient cycling, and biogeochemistry. The JGI offers a suite of capabilities that are unique in their ability and scale to advance energy and environmental science. Having evolved beyond a production sequencing facility, the JGI now offers users a comprehensive set of integrative genome science technologies such as state-of-the-art sequencing technologies, advanced genomics data science and informatics, epigenomics, single-cell genomics, DNA synthesis, and metabolomics. This suite of capabilities enables users to derive deeper biological insights.

The DOE Systems Biology Knowledgebase (KBase) is an open source, open access software and data platform designed to address the grand challenge of systems biology—predicting and designing biological function from the biomolecular (small scale) to the ecological (large scale). KBase enables researchers to collaboratively generate, test, compare, and share hypotheses about biological functions; perform large-scale analyses on scalable computing infrastructure; and combine experimental evidence and conclusions that lead to accurate models of plant and microbial physiology and community dynamics. The KBase platform has expanded to over 200 analysis tools spanning reads management, genome and metagenome assembly and annotation, basic comparative genomics, RNA-seq analysis, and metabolic modeling of organisms and their communities.

The JGI-KBase partnership is developing complementary and integrated high-performance tools to provide users with the ability and infrastructure to explore complex and diverse datasets to extract deeper biological insights. The goals of this partnership are to create a JGI presence within KBase, build a diverse, engaged joint user community, and enable scientific discovery. Under the guidance of a new JGI-KBase Strategic Leadership Team, JGI and KBase have worked closely over the past year to develop systems within KBase, and hosted at NERSC, that allow users to import JGI public data sets, as well as JGI tools and pipelines. JGI and KBase have built working prototypes for both genome and gene homology services and will focus on beta testing these products with their joint user community in FY19. JGI and KBase have accelerated efforts to integrate JGI tools into KBase and have now integrated the JGI metagenome assembly pipeline and metagenome binning tools into KBase. Access to JGI data in KBase has been simplified, and high-value datasets like Phytozome and Mycocosm have been imported into KBase. Further datasets are under consideration for importation.

As both JGI and KBase exist to serve a broad scientific community, our focus is on expanding user engagement and partnership with other User Facilities. KBase will establish and coordinate user working groups (UWGs) on metabolism, microbiome, and functional genomics to organize efforts to integrate the data-types, data, tools, and analyses from DOE-sponsored groups operating in each topic area into either in the KBase platform itself, or in shared infrastructure run by KBase, JGI, and other user facilities (e.g., NERSC, EMSL). Additionally, these UWGs will partner with users to generate user-driven designs, science and data standards. Together, JGI and KBase have continued their practice of hosting joint outreach activities and booths and holding workshops. JGI has encouraged users who submit proposals to their Community Science Program to utilize KBase tools for their data analyses, and KBase members will participate in the review of these proposals to identify opportunities for KBase utilization. A JGI-KBase-NERSC call was launched in late FY18 under the Facilities Collaborating for User Science (FICUS) umbrella.

In partnership with JGI and NERSC, KBase is embarking on developing a scalable open platform for foundational genomics based on homology, taxonomy, and environmental sources of genomes and metagenomes. A prototype of the KBase Knowledge Engine (KE) computes key relationships among all public and shared data in the system and instantaneously returns the most biological relevant data to a user's interests and analyses on the system. The KE platform is being extended with new types of relationships using results of the large-scale analyses from our JGI co-development work and new tools being generated by the KBase team. Ultimately, this engine will make increasingly sophisticated inferences of function and behaviors of genes, organisms, and communities.

JBEI is a significant contributor to this capability through use-inspired fundamental research into complex biological systems. Research at JBEI establishes the scientific knowledge needed to engineer bioenergy crops with low susceptibility to disease and drought, and that can be readily deconstructed into useful intermediates; develop feedstock-agnostic deconstruction processes that use ionic liquids; engineer microbes with efficient metabolisms to simultaneously utilize sugars and aromatics from biomass; and for the underlying technologies that can meet future research needs.

ENIGMA (Ecosystems and Networks Integrated with Genes and Molecular Assemblies) is the multi-institutional Berkeley Lab-led BER-funded SFA that advances understanding of microbial biology and the impact of microbes on their ecosystems. By linking environmental microbial field studies to powerful meta-functional genomic and genetics tools, the identity and diversity of microbes along gradients of geochemical parameters can be understood, enabling predictions of how environmental perturbations may affect microbial community structure and their ecosystems. ENIGMA's computation efforts are aimed at integrating diverse, complex, large datasets for studies of dynamic modular microbial architectures across scales, from regulons (groups of genes regulated by one protein) to full community assemblages.

A collaborative, coordinated, and integrated mission-driven program, mCAFES (Microbial Community Analysis and Functional Evaluation in Soils) interrogates the function of soil microbiomes with critical implications for carbon cycling and sequestration, nutrient availability and plant productivity in natural and managed ecosystems. The project targets molecular mechanisms governing carbon and nutrient transformation in soil, with a focus on microbial metabolic networks.

Laboratory ecosystems hold the potential to bridge the gap between highly constrained lab experiments and field-scale experiments that are challenging to control, giving researchers the ability to dissect microbial community dynamics and effects in relevant environments. EcoFABs, small chambers with control of liquid flows and spatially defined imagining capabilities, have been employed in two BER-funded projects, mCAFES and TEAMS (Trial Ecosystems Advancement for Microbiome Science). EcoPODs, currently being developed at Berkeley Lab, are enclosed environments of several meters cubed that allow direct and intensive monitoring and manipulation of replicated plant-soil-microbe-atmosphere interactions over the complete plant life cycle.

Two ECRP awardees in the Earth and Environmental Sciences Area are focused on global change impacts on soil microbiomes and their consequences for global biogeochemical cycles and atmospheric feedbacks. One awardee is tackling the microbial metabolic response to permafrost thaw, using microbial communities as integrators of site conditions in an effort to predict forward trajectories of biogeochemistry following permafrost thaw. A second BSSD ECRP awardee focuses on drought in tropical systems and its impact on carbon processing and stabilization by the soil microbiome and implications for drought resilience and forest productivity. Both projects are developing advanced approaches to observe and manipulate soil microbiomes to build mechanistic understanding that directly translates to improved model process representation and parameterization. These projects are emblematic of Berkeley Lab's efforts to scale from microbial mechanisms to ecosystem processes.

In 2018, a new DOE-BER ECRP project was awarded that focused on advancing knowledge of plant cell walls, to enhance deconstruction and conversion into fuels and other bioproducts by microbial fermentation. This project builds upon research carried out in BER-CESD and connects climate relevant plant volatile emissions to biochemical roadblocks of biomass deconstruction, seeking to understand and manipulate these cell walls. The project will not only provide important knowledge on the physiology and ecology of plants but will also allow the generation of engineered bioenergy crops such as poplar for sustainable production of biofuels and bioproducts, addressing BER's goal of developing renewable bioenergy resources.

BER is the primary sponsor of the research in this core capability; others include EERE, NIH, DoD, industry, and other SPP. This Core Capability supports DOE's mission to obtain new molecular-level insight for cost-effective biofuels; make discoveries for DOE's needs in climate, bioenergy, and subsurface science; and coordinate bioenergy, climate, and environmental research across applied technology offices.

Environmental Subsurface Science

Watershed physical, chemical, biological and atmospheric interactions regulate the geochemical flux of life-critical elements and influence contamination mobility and migration. These interactions also influence water and energy security, including water available for energy, industry, agriculture and urban use as well as agriculture production. With support from BER, the Berkeley Lab Watershed Function SFA is developing a predictive understanding of watershed hydrobiogeochemical function from genome to watershed scales, including process coupling occurring across bedrock through canopy and terrestrial through aquatic interfaces, and along significant environmental gradients. A focus of this SFA is on developing new approaches to predict how watersheds respond to increasingly frequent perturbations, such as droughts, floods and early snowmelt, and associated downgradient water quality and quantity. As soil-microbe-interactions play a key role in water and biogeochemical cycling, the Watershed SFA is an anchor tenant of BioEPIC, and prototype a component of the BioEPIC new platform technologies (e.g., the EcoSense SMART Soils testbed) is being developed to enable the Watershed SFA goals. The Lab's Watershed Function SFA has also developed an active "community watershed" in the Upper Colorado River Basin and is performing coupled model-experiment-observation studies to quantify how early snowmelt, drought, and other disturbances will influence mountainous watershed dynamics at episodic to decadal timescales. Supported by the Geoscience Measurement Facility's custom instrumentation capabilities, new nimble and networked observation platforms are for the first time providing a virtual "window" to autonomously monitor fluxes across bedrock-soil-plant Earth compartments. ESS-Dive is preserving, expanding access to, and improving usability of critical data generated through terrestrial and subsurface science programs. To improve prediction of future watershed function, we are developing a first-of-a-kind scale-adaptive modeling approach to simulate hydrological and biogeochemical dynamics using variable and dynamic resolution. Complementary adaptive mesh refinement and other simulation capabilities are being developed through the multi-institutional Interoperable Design of Extreme-Scale Application Software (IDEAS) project funded by BER and ASCR. A new ExaShed effort plans to make advances in mechanistic and machine learning capability to dramatically improve our watershed system modeling capacity. The new 4D Digital Watershed sensing and numerical capabilities are being used to discover and predict how watersheds and their subsystems respond to variations in both the amount of snowpack and the timing of snowmelt, as well as the interplay among weather, water supplies, biogeochemistry, and energy resources.

Expertise and capabilities associated with monitoring and predicting hydrobiogeochemical watershed dynamics developed through BER-CESD were extended in 2018 to address challenges associated with agriculture, and environmental remediation, the onset of harmful algae blooms, and water quality impacts from wildfire. With support from ARPA-E's "ROOTS" program, we are developing new root imaging and modeling approaches that may lead to a new paradigm for remote field phenotyping and other applications. The Lab is using advanced methods to quantify the potential of the subsurface for storing water during dry years, and for manipulating agriculture sites for co-benefits to crop yield and soil health. With EM support, Berkeley Lab is developing a new paradigm of long-term monitoring of DOE's legacy contaminated sites, using the Savannah River site as a testbed. The aim is to take advantage of the recent advances in Big Data analytics and machine learning, as well as HPC capabilities for reactive transport modeling and prediction. The Lab also collaborates with the Japanese Atomic Energy Agency (JAEA) and other institutions on advanced modeling and data analytics important to support Fukushima's remediation and rehabilitation effort. In particular, the developed multiscale data integration software BDARM (Bayesian Data Assimilation for Radiation Monitoring) has been released as an open source software and adopted by JAEA for the standard method for radiation dose rate mapping. In a first attempt to take a watershed perspective toward understanding fire-water linkages, DOE-BER developed capabilities are being used and extended to address surface and groundwater quality in regions impacted by the recent significant California wildfires, and are providing the first watershed-based strategy for monitoring fire-water challenges. LDRD investments are extending BER-developed insights about coupled biological-environmental-climate systems to advance a systems approach for predicting the onset of harmful algae blooms.

Climate Change Science and Atmospheric Science

Berkeley Lab has developed an internationally recognized program in theoretical, empirical, and computational climate and atmospheric science. The Lab continues to make major advances in the theory governing how atmospheric convection, one of the fundamental processes governing the equilibrium of Earth's climate, will respond to further warming of the environment. The Lab has complemented this work with novel observations of how the terrestrial ecosystem serves as a critical carbon sink, and how elevated concentrations of greenhouse gases are leading to measurable increases in the atmospheric greenhouse effect. Lab scientists integrate this information to help DOE produce the most advanced models of the Earth system and to utilize those models to project the possible physical and biogeochemical impacts of further global climate change.

Berkeley Lab conducts internationally recognized research on advancing the understanding and prediction of ecosystem responses and feedbacks to climate. We lead the TES Belowground Biogeochemistry SFA, which contributes to developing a new paradigm for soil organic matter dynamics through basic research on soil carbon turnover, storage and loss. This SFA will produce new understanding and improved predictions of belowground biogeochemistry in the soil-plant-microbial system and the role of soils in global change. The Lab leads NGEE-Tropics, focused on a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers. NGEE-Tropics is utilizing airborne measurements before and after

Hurricane Maria in Puerto Rico to quantify hurricane impacts on tropical forests, and has established collaborations with the U.S. Forest Service, NASA, LTER, CZO, University of Puerto Rico, and other university and research partners to further investigate forest impacts. The Lab is advancing a representative, process-rich tropical forest ecosystem model (Functionally Assembled Terrestrial Ecosystem Simulator (FATES)), extending from bedrock to the top of the vegetative canopy-atmosphere interface, in which the evolution and feedbacks of tropical ecosystems in a changing climate can be modeled at the scale/resolution of an E3SM grid cell. The Lab is applying FATES to understand potential drought response and tree mortality in California as part of a DOE ECRP, and to model wildfire and vegetation distribution in the western U.S. as part of a UC-funded collaboration. Also a key partner in the NGEE-Arctic project, the Lab contributes its expertise in environmental geophysics, soil biogeochemistry and microbial ecology, and mechanistic modeling of ecosystem-climate feedbacks. In 2018, the team documented how the subsurface polygonal structures detected above ground control distribution of microbes and their metabolic potential; how evapotranspiration rates and CO2 and CH4 fluxes depend on interactions among these polygonal structures, hydrology, and vegetation; extended the E3SM land model to include redistribution of incoming snow and soil moisture to account for microtopography; and applied E3SM to show that shrubification offsets respiratory carbon losses through the end of the 21st C.

As described above, a new BER ECRP is focused on advancing knowledge of plant cell walls, which can be converted into fuels by microbial fermentation thereby making plant biomass a potentially important bioenergy resource. This ECRP seeks to understand and manipulate these cell walls. The project will not only provide important knowledge on the physiology and ecology of plants but will also allow the generation of engineered bioenergy crops such as poplar for sustainable production of biofuels and bioproducts, addressing BER's goal of developing renewable bioenergy resources.

Berkeley Lab also leads the AmeriFlux program, which measures ecosystem-atmosphere fluxes of carbon, water and energy that enable scientific and modeling advances from a network of sites maintained by partnering institutions and supported by instrumentation from the GMF. As of 2018, the number of registered sites increased by 36 to 341, including the addition of 14 NSF National Ecological Observatory Network (NEON) sites added under a new DOE-NSF MOU. During 2018, Berkeley Lab's AmeriFlux site data were downloaded more than 54,000 times by more than 870 scientists from around the world, and the community of registered users grew by 1,500. More than 300 publications have utilized AmeriFlux data in the last 1.5 years, including 17 in Nature. In October 2018, Agriculture and Forest Meteorology published the "20th Anniversary AmeriFlux Special Issue," containing 23 articles. AmeriFlux has been renewed through 2020 with a significant post-award augmentation for Data Management. Under this augmentation, the program has developed semi-automated QA/QC to accelerate processing of site data by 15-fold while simultaneously enforcing rigorous quality control.

Berkeley Lab is one of the primary science centers studying the atmospheric carbon cycle and land-atmosphere interactions, and currently leads several major BER projects in the Atmospheric System Research (ASR) and Atmospheric Radiation Measurement (ARM) programs. With five other National Labs, Berkeley has developed and operated the ARM Carbon Project and ARM Aerosol Observing System Infrastructure to conduct precise and accurate measurement of trace gases, contribute to multi-agency validation of satellite-based column CO2 estimates, and close the gap in U.S. emissions estimates for CH4. These data, along with numerous other datastreams from the DOE ARM program, supported the first observation in 2018 of the longwave surface radiative forcing from methane. The same year, the Lab initiated the ASR Convection and Land-Atmosphere Coupling in the Water Cycle project to improve climate prediction by improving representation of land-atmosphere coupling. The specific objectives are to better understand the mechanisms that link convective triggering and organization to land-surface states, and to parameterize feedback mechanisms to better predict drought and precipitation extremes. We are also pioneering the use of digital stereo photogrammetry as a tool to observe clouds, which play a critical role in weather and Earth's radiation balance. The Lab has deployed six new cameras ringing the SGP ARM site in Oklahoma that provide a 4D gridded view of shallow clouds. These generate a 50-m grid of cloudiness every 20 seconds, called Clouds Optically Gridded by Stereo (COGS). These new capabilities are providing unprecedented data on cloud sizes, lifetimes, and lifecycles—critical information for developing cloud schemes for the next generation of weather models.

Berkeley Lab is a major contributor to DOE's flagship Earth system modeling project (E3SM), including its integrated assessment component to create a fully coupled Earth system model that can project future interactions among energy, food, water resources, and climate using state-of-the-science treatments of physical, chemical, and biogeochemical processes. Lab researchers have served as members of the E3SM council and as leadership for the land model group and NERSC exascale applications. The Lab's contributions to the E3SM Land Model (ELMv1) include improved representation of the soil, plant, and abiotic processes responsible for constraining the global carbon budget, developing an extensible and scalable three-dimensional hydrology and thermal module, integrating and applying the FATES dynamic vegetation model, and developing capabilities to represent tracer (e.g., nitrate) exchanges across the Terrestrial Aquatic Interface and biogeochemistry in rivers. These contributions culminated with the public release of E3SM v1 in 2018, and the Lab is now further enhancing the treatment of terrestrial ecological processes for future release in E3SM v2.

The Calibrated and Systematic Characterization, Attribution and Detection of Extremes (CASCADE) SFA aims to understand how and why extreme weather and climate events have changed in the observational record and how and why they might change in the future. CASCADE successfully synthesized the team's interdisciplinary expertise in physics, statistics, and atmospheric and computer science to tackle large scientific questions that require innovative datasets, computational tools, and statistical methods. In 2018, the Lab quantified the attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey, as well as the anthropogenic influences on the intensity and rainfall of major tropical cyclone events. Several recent deliverables illustrate this success, including publication of the Toolkit for Extreme Climate Analysis (TECA) and the software tool climextRemes, both of which allow sophisticated analysis of extreme events in massive datasets.

Advanced Computer Science, Visualization and Data

Berkeley Lab has longstanding expertise in performance analysis and algorithms research, with multiple award-winning papers on application performance analysis and the efficient use of emerging computer architectures for scientific applications. Technologies developed by the Berkeley Lab-led ExaGraph ECP Co-Design Center, which investigates graphical computational motifs, such as traversals, matching, etc., were recently incorporated into the sparse linear algebra libraries SuperLU and STRUMPACK resulting in a 300X speedup over prior techniques. This expertise also finds its way into widely deployed tools, for example, the visually intuitive Roofline Model, which can be used to bound the performance of various numerical methods, has been incorporated into an Intel product. The Roofline Model has recently been extended to support Nvidia GPU architectures.

The design and deployment of a highly usable, energy-efficient exascale system presents research challenges in programming languages, system software, and tools. Berkeley Lab is a world leader in programming languages and compilers for parallel machines and utilizes this experience in the design of programming models for future systems. The Lab's Exascale Global-Address Space Networking (GASNet-EX) communication layer was recently used to build a discrete event simulator for transportation system modeling with significantly better scalability than other implementations. In addition, GASNet-EX is used in the ECP application development HipMer extreme scale genome assembler, and also in the UPC++ and Legion programming environments which are parts of the ECP Software Technologies portfolio.

While ASCR's main focus – and ours – is on exascale technology, we have also begun to explore extreme heterogeneity, specialized architectures for edge-computing, possible new digital devices, and alternative computing paradigms such as quantum computing to address the anticipated end of transistor density scaling. For digital computing, we have focused on application-specific accelerators, and tools to model extremely heterogeneous systems allowing exploration of large complex architectural design spaces. Additionally, we have begun to explore edge-computing by designing low-power processors that can be placed on the same silicon as, or very near, a detector, offering functionality such as real-time data reduction. For quantum computing, our computer science work has focused on the design of a RISC-V based instruction-set architecture for a classical processor enabling fast and flexible control of a quantum processor.

Berkeley Lab is one of the primary developers of new capabilities in high performance parallel I/O and data-intensive visualization and analysis. Key developments include new features in the SENSEI in-situ visualization and analysis infrastructure, where the visualization algorithms run concurrently with simulations; and more scalable algorithms to deal with increasingly larger datasets. By using innovative Convolutional Neural Network-based algorithms, lab researchers have developed sophisticated feature detection pipelines for crystallography and micro-CT experiments, and tools for scientific image retrieval based on pictorial similarity. Our work in delivering efficient parallel I/O for future systems via the ExaHDF5 project has already delivered considerable speedups for a variety of ECP application development projects.

The Lab is a pioneer in scalable solutions for scientific data, including management, curation, quality-assurance, distribution, and analysis. For example, Berkeley Lab leads the data processing and curation aspects of the BER-sponsored AmeriFlux program, described in the Climate Change Science and Atmospheric Science core capability, which focuses on distributing high quality, standardized datasets to a variety of end users. We have also developed the Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), whose mission is to preserve, expand access to, and improve usability of critical data generated through DOE-sponsored research of terrestrial and subsurface ecosystems. We are a partner in the FE-funded Institute for the Design of Advanced Energy Systems (IDAES) project that is developing a next generation modeling and optimization platform to aid in the design of novel energy systems. In IDAES, we lead the Software Architecture, Algorithms, and Distributed Computing tasks, which primarily involves managing, navigating, and guiding the development of the data management framework, solvers, and user interface. In the related Carbon Capture Simulation for Industry Impact (CCSI2) project, Berkeley Lab was a significant contributor to the recently open-sourced CCSI Toolkit.

Berkeley Lab is a leader in developing troubleshooting and performance-analysis tools for complex, distributed applications, such as the PERFormance Service Oriented Network monitoring ARchitecture (perfSONAR) application, which is now deployed at over 2,000 sites worldwide in national laboratories, commercial and research networks, universities, and corporations. ESnet's On-Demand Secure Circuits and Advance Reservation System (OSCARS) technology, deployed in over 50 networks worldwide, operates like a dynamic expressway, creating uncongested paths between endpoints. ESnet is also exploring a model-based approach to allow scientific workflows to orchestrate end-to-end network paths along with optimized data-transfer nodes via the SENSE project. The project maintains a persistent testbed that spans multiple institutions and is integrating this approach with science applications. In addition, ESnet is researching the application of machine learning techniques on network traffic prediction in order to optimize traffic engineering and routing of large scientific flows over uncongested paths.

ASCR is the primary support for this Core Capability, with additional support from EERE, IARPA, and DoD, and significant benefits accrue for all SC offices and other elements of DOE, as well as strategic partners such as the DoD. This capability supports SC's mission to deliver computational and networking capabilities that enable researchers to extend the frontiers of science and to develop networking and collaboration tools and facilities that enable scientists to work together and share extreme-scale scientific resources.

Applied Mathematics

Berkeley Lab has world-leading capabilities for developing mathematical models, algorithms, tools and software for high-performance computing. The Lab has a large pool of highly recognized experts in applied mathematics, many of whom are SIAM Fellows and/or members of NAS and NAE.

Berkeley Lab has unsurpassed expertise in algorithms for modeling and simulating compressible, incompressible, and low-Mach-number flows in many applications, from terrestrial combustion processes, to ice-sheet formation and retreat, to nuclear flames in supernovae. AMR techniques pioneered at the Lab are globally recognized as a key enabling technology, and Berkeley's AMR Co-Design Center for the Exascale Computing Project has publicly released AMReX, a new software framework designed to leverage exascale computers that supports ECP and SciDAC scientific simulation codes for combustion, astrophysics, cosmology, accelerator technology and multi-phase flow.

The development of new algorithms with reduced communication requirements and increased arithmetic intensity will be essential to support the effective use of future exascale computing platforms. We have developed a new algorithm and high-performance implementation for solving Poisson's equation, which has 1/10 the communication cost of previous methods. This advance will enable new multiscale simulations of scientific problems in astrophysics, plasma physics, and fluid dynamics, which spend significant resources solving Poisson's equation.

In collaboration with New York University and San Jose State University, Berkeley Lab has also made significant strides in the development of methodology for simulating the dynamics of physical systems at microscopic and mesoscopic scales. This fluctuating hydrodynamics (FHD) technique has allowed researchers to study the effect of thermal fluctuations in small-scale electrokinetic devices including electro-osmotic and catalytic micropumps. It has also been applied to the study of reactive fluids at the mesoscale, enabling direct, detailed observations of the dynamics of a reactive system that show the correct behavior for small numbers of reactants, where the classical Langevin equation-based approach does not. The Berkeley Lab team has also been able to match experiments of mixing in zero gravity where diffusion is enhanced by microscopic fluctuations.

Berkeley Lab mathematicians, in collaboration with plasma physicists at PPPL, have developed the first fully conservative, adaptive finite element discretization of the Landau collision integral, which is the gold standard for integrating many-body dynamics into Vlasov's equation, the standard phase space model for fusion plasmas. This has been implemented in code optimized for the KNL processors on NERSC's Cori HPC system.

The Center for Applied Mathematics for Energy Research Applications (CAMERA), an integrated, cross-disciplinary center aimed at developing and delivering the fundamental new mathematics required to support DOE user facilities, has delivered numerous advances. The 2016 BESAC Facility Upgrade Assessment cited CAMERA as "highly effective" in enabling researchers to analyze light source data. For example, the new multi-tiered iterative phasing (M-TIP) algorithm developed at Berkeley Lab was used in a collaboration with SLAC, the European XFEL, and Uppsala University that resulted in the first ever reconstructions of two virus structures (RDV and PR772) from the angular correlations of single-particle LCLS fluctuation X-ray scattering data from the LCLS at SLAC. CAMERA scientists have also invented a mathematical approach for driving autonomous X-ray scattering experiments. By capitalizing on mathematical optimization methods, their algorithm automatically chooses the next, most appropriate experimental parameters from a large, high-dimensional landscape of possibilities. This capability is currently being used on beamlines at NSLS-II and augurs a new generation of efficient experimentation at DOE light sources.

In numerical linear algebra, Berkeley Lab is the only SC lab that has expertise in large-scale eigenvalue calculations and direct solutions in sparse matrix inversion. Lab scientists have recently developed new parallelization strategies for sparse factorization algorithms that reduce inter-process communication by exposing task parallelism and vectorization for irregular loops involving sparse indirect addressing to better use on-node resources. They have also developed low-rank approximate factorization algorithms with quasi-linear arithmetic and communication complexity. These advances have been integrated into higher-level DOE algebraic solvers such as hyper, PETSc, and Trilinos, which provide critical technology for many extreme-scale DOE multiphysics and multiscale simulation codes.

By continuing to improve application performance and accuracy by incorporating carefully designed choices of basis sets and eigensolvers into density functional theory algorithms, Berkeley Lab has recently created novel strategies for the simulation of systems with 1000s of electrons, applicable to metals and insulators alike. Speedups of 3–15X have been achieved when compared with traditional state-of-the art approaches, while still providing chemical accuracy in energies and forces.

Berkeley Lab's mathematics work is a point of leverage for exascale science impact. The algorithms and models are designed for parallel scalability and to reduce expensive data movement, with special attention to the hardware features emerging in next generation systems. They are incorporated into open source software libraries and frameworks that are used at NERSC and other centers across DOE, and will enable higher resolution, more details, and new models of scientific phenomena.

These capabilities and their applications are sponsored primarily by ASCR, with support from other DOE program offices and SPP. These capabilities support DOE missions in fusion energy science, biological and environmental research, high-energy physics, nuclear physics, basic energy sciences, environmental management and fossil energy. They also support the development of mathematical descriptions, models and algorithms to understand the behavior of climate, living cells, and complex systems related to DOE mission areas of energy and environment.

Computational Science

Berkeley Lab is a leader in connecting applied mathematics and computer science with research in many scientific disciplines, including biological systems science, chemistry, climate science, materials science, particle and nuclear physics, subsurface science, fossil energy, environmental management, and all Core Capability areas described in this Plan. The Lab has a successful track record of effectively integrating these research areas in conjunction with HPC resources to obtain significant results in many areas of science and engineering. Within the national lab network, Berkeley Lab plays a very visible role in the SciDAC Program. Out of the 30 science partnership projects, we are involved in 14 of them, providing advanced computer science methods and robust applied math techniques and algorithms for enabling and accelerating scientific discoveries. These successes also make use of the results from two SciDAC Institutes related to our Applied Math and Advanced Computer Science, Visualization and Data core capabilities. In particular, staff members are playing key leadership roles in the Applied Math and Computer Science SciDAC Institutes. Furthermore, the Lab plays key roles in providing computer science and applied math expertise in 12 Application Development activities in the Exascale Computing Project. A few of the many examples of this work are illustrated in the remainder of this section.

To increase the speed and reduce the errors in identifying astronomical objects, computational scientists at Berkeley Lab have teamed with the Zwicky Transient Facility to construct a deep co-addition pipeline consisting of machine-learning methods to perform basic calibration and image differencing. One of the goals is to find recent Type 1a supernovae which are lensed by an intervening galaxy. Gravitationally lensed Type 1a supernova may be key to measuring the rate of the universe's expansion with unprecedented accuracy and distribution of matter in the cosmos. On a related note, the Lab is deeply involved in the DOE-HEP and NSF project CMB-S4, which targets crossing critical thresholds in testing inflation, determining the number and masses of the neutrinos, constraining possible new light relic particles, providing precise constraints on the nature of dark energy, and testing general relativity on large scales.

Working with the industrial partner PPG, and funded via the HPC4Mfg, Lab mathematicians have developed a high-order accurate fluid flow modeling method that is scalable to the largest DOE SC HPC systems to study the rotary-bell painting process used in automotive painting. The paint shop consumes a significant proportion of the energy used in assembly and understanding; optimizing the process by which paint is sprayed has the potential for significant energy savings.

Theoretical astrophysicists and applied mathematicians are working on a new scalable modeling application integrating known fundamentals of everything from atomic and nuclear physics to electromagnetism, general relativity, and hydrodynamics as part of the Exascale project. Led by the Berkeley Lab, the project will make use of the AMREx modeling framework.

A multidisciplinary team working on the Quantum Algorithms for Chemical Sciences project is investigating optimizers that are able to converge quickly with noisy quantum hardware in hybrid quantum-classical algorithms has made progress in modifying the variational quantum eigensolver to be more fault tolerant, and contributed to the theory for the first quantum computer-based simulations on determining mechanisms of information-scrambling.

The recently formed Computational Biosciences Group has brought together experts from our core capabilities of Computational Science, Applied Mathematics, Advanced Computer Science, Visualization and Data, and Biological Systems Science with a focus on coupling data analytics and statistical machine-learning with simulations to understand the dynamics and multi-scale nature of many biological problems.

Key collaborations connected with DOE's EFRCs and JCESR continue, targeting quantum materials, materials design and synthesis, gas separation and storage, and batteries. The mathematical methods and computational tools developed also have applications in many other scientific domains, such as improving catalysts for hydrogen fuel cells and storage.

Although ASCR is a key source of support for this Core Capability, all SC offices sponsor computational applications and software development for their respective areas of science. Other federal agencies such as NASA and DoD also benefit from and contribute to the research effort. This Core Capability supports all of DOE's science, energy, environmental and security missions. For SC's discovery and innovation mission, it provides the mathematical models, methods and algorithms to enable scientists to accurately describe and understand the behavior of complex systems.

Cyber and Information Sciences

Berkeley Lab conducts research into a broad array of cyber and information sciences including data provenance, as well as security for high-performance computing environments, high-throughput networks, "open science" computing workflows, and the power grid. Example applications include identifying misuse of HPC resources (e.g., cryptocurrency mining), and denial of service attacks on high-throughput networks. Ongoing, current, and future work is being performed to ensure both the integrity and the confidentiality of scientific computing in the face of accidental or malicious threats, without significant cost to either usability or performance. Novel research techniques are also being used to leverage the "physical" aspects of cyber-physical systems, such as the power grid, to detect cyber-attacks against equipment controlling the power grid. Because these systems must act within the laws of physics, these properties can be exploited to detect maleficence or failing sensors.

In addition to Berkeley Lab's cybersecurity research, ESnet provides an integrated set of cyber security protections designed to efficiently protect research and operational data while enabling cutting edge research. ESnet's unique 100G SDN network testbed provides an international research platform for cybersecurity research at all network layers. The Lab leads the world in developing technologies to optimize science data transfers across local and wide-area networks. Developing the "Science DMZ" model, ESnet has championed an architecture to transfer data securely across the national and international research and education community. Work continues on developing the Science DMZ as many data sets have special privacy and security concerns. In particular, the "Medical Science DMZ" was designed to help address the concerns of HIPAA/HITECH while supporting the high performance needs of big data science.

Formerly known as Bro, the Zeek network security analysis framework started at Berkeley Lab in 1995 to monitor network traffic in open scientific environments. It is now deployed in National Labs, major universities, supercomputer centers and, particularly through the Corelight commercial spinoff, Fortune 100 companies. Starting in 2010, Zeek went through a major overhaul to support next generation networks at 100Gbs, with one of the first production 100Gbps deployments at Berkeley Lab in 2015. Currently, ESnet is exploring novel techniques to apply Zeek on a WAN environment where geographically dispersed, asymmetric traffic breaks the assumptions of most network security monitors.

ASCR, the CEDS program in CESER office, and NSF are the primary supporters of this Core Capability, with additional previous support from OE, OCIO, NNSA, NSF, and DoD. Significant benefits accrue for all SC offices and other elements of DOE, as well as strategic partners such as the DoD and NIH. This capability supports SC's mission with disciplines, technologies and practices designed to protect, analyze and disseminate information from electronic sources, including computer systems, computer networks and sensor networks and network-connected scientific instruments and user facilities.

Particle Physics

Berkeley Lab has a long record of excellence in particle physics and cosmology, with two premier programs: one in the Energy Frontier on the ATLAS experiment, with many contributions and leadership roles over more than two decades; and one in the Cosmic Frontier, where the Lab is leading next-generation projects in both dark energy and dark matter and developing technologies for a future ground-based CMB polarization experiment to study inflation. In addition, the Lab has a small but focused effort in the Intensity Frontier, where we are making key contributions to the Mu2E and DUNE experiments at Fermilab while completing analysis on the Daya Bay reactor neutrino experiment.

Berkeley Lab's experimental program is fully aligned with the P5 roadmap, and is enabled and enhanced by our traditional strengths in instrumentation and detector R&D, expertise in software and computation enhanced by our proximity to NERSC and connections to the Computational Research Division, and a strong theory group in partnership with UC Berkeley. Strong connections with UC Berkeley bring faculty and students to collaborate in our experimental HEP programs as well, providing significant leverage and opportunities for enhanced funding support through fellowships and other non-DOE resources.

On the Energy Frontier, Berkeley Lab is playing leading roles in the ATLAS pixel and silicon strip tracking upgrades, computing and software systems, and physics analysis. The Lab plays a leading role in the international R&D program on pixel readout for both ATLAS and CMS and developed the silicon strip stave concept that has been adopted by the ATLAS collaboration. The Lab leads the Strip detector and Global Mechanics upgrade in the U.S. ATLAS HL-LHC Upgrade project.

Physicists and computational scientists also play leading roles in the ATLAS software framework, and more recent efforts have focused on the applications of machine learning and quantum computing techniques, as well as more efficiently harnessing the HPC capabilities at NERSC. Over the years, Lab scientists have led all aspects of ATLAS, including as Physics Coordinator (twice), Deputy Spokesperson, Upgrade Coordinator, Simulation Convener (twice), Upgrade Physics Working Group Convener, SUSY Working Group Convener and Higgs Working Group Convener. Lab scientists are also playing lead roles in both the pixel and strip inner tracking detectors for the HL-LHC ATLAS upgrades, serving in management positions on both the U.S.-ATLAS and the international ATLAS upgrade teams.

Berkeley Lab is a world-leading center for the search for dark matter. The Lab led the Large Underground Xenon (LUX) experiment, managed the science operations at the Sanford Underground Research Facility in South Dakota from 2012 to 2017, and is currently leading the construction of the LUX-ZEPLIN (LZ) experiment. LUX completed data taking in 2016 and produced results that are still among the most sensitive limits in the search for dark matter. The LZ experiment received CD-3 in February 2017 and the construction of the apparatus is nearing completion. The experiment will begin operations in 2020. Berkeley Lab plays many leading roles in LZ, including the Project Director, the Operations Director, and as of 2019 the LZ Collaboration Spokesperson. Berkeley Lab will continue its leadership role during the Operations phase of the experiment. More recently, Berkeley Lab has begun R&D on low-mass dark matter detection techniques supported by a new QuantISed consortium grant to develop new quantum-enabled sensors and readout.

The Lab is leading the design and construction of the Dark Energy Spectroscopic Instrument (DESI), a Stage IV BAO experiment to create the largest 3-D map of the universe, with over 30 million galaxies. DESI successfully passed CD-3 in Spring 2016 and installation on the Mayall telescope at Kitt Peak began in Feb 2018; the project is on track to start in early 2020. The Lab is developing DESI's operations plan and will continue to manage it during the five-year survey. Berkeley Lab staff are playing many leading roles in DESI including Project Director, Project Scientist, and Operations Director.

A critical Berkeley Lab contribution to the Cosmic Frontier has been the development of advanced detectors. Red-sensitive charge-coupled devices (CCDs) were invented in the MicroSystems Lab (MSL) and are the technology of choice for all Stage III and IV dark energy experiments, including BOSS, the Dark Energy Survey (DES), DESI, and the Large Synoptic Survey Telescope. With LDRD support, pioneering R&D on Germanium CCDs has been underway at MSL since 2017. The Lab also developed detectors and a multiplexed readout for cosmic microwave background (CMB) measurements, including the South Pole Telescope (SPT) and POLARBEAR/Simons Array. Located in Chile, the Simons Array has three identical telescopes with advanced multichroic polarization detectors, also invented at Berkeley Lab. With support from the Simons Foundation, the Chile site is being developed as the Simons Observatory, encompassing both the Simons Array and the ACT experiment, with the addition of several CMB telescopes. Four multi-year LDRDs have been awarded to support the development of CMB detectors, readout and polarization modulators and computing pipelines at the Lab, paving the way for the future CMB-S4 experiment.

On the Intensity Frontier, the Lepton Flavor group is involved in two flagship experiments at Fermilab. On Mu2e, Berkeley Lab leads the Software and Computing group and played an important role in building and operating the first working prototype of the straw tube tracker and in the development of the tracker readout electronics. On DUNE, the Lab has made significant contributions to the conceptual design of the Near Detector and is also making key contributions to protoDUNE. A novel ASIC for low-power, cryogenic pixelated readout of the DUNE ND developed at Berkeley Lab has led to the selection of this technology for the baseline design and also resulted in a DOE ECRP in 2018. The Lepton Flavor group is also finishing up the analysis of Daya Bay, a ground-breaking reactor neutrino experiment which was conceived of and led by Berkeley Lab. Daya Bay made the first observation of the third neutrino mixing angle and has the most precise measurements to date, resulting in many awards and prizes.

Computation has become an increasingly important aspect of our program. We have taken a leading role in software, simulation and computing for ATLAS, Daya Bay, Mu2e, BOSS, DESI and CMB experiments, and successfully leveraged resources at NERSC and the Lab's Computing Research Division for HEP and incorporated machine learning as a tool in several of our simulation and analysis efforts. The Center for Computational Excellence has provided additional resources to take advantage of the NERSC HPC for HEP, and we have successfully obtained other resources from ASCR. We are poised to take advantage of the latest advances in HPC and are working on cutting edge techniques that will benefit all HEP projects, including investigation of quantum computing algorithms with support from a QuantISed grant.

Berkeley Lab Theoretical Physics Group is closely integrated with the UC Berkeley Center for Theoretical Physics (BCTP) and plays a crucial role in our particle physics program, working with experimentalists to define future programs and develop strategies for data analysis. The Particle Data Group provides a unique service to the international physics community through its compilation and analysis of data on particle properties.

DOE's HEP is the primary sponsor of this Core Capability, with important contributions from ASCR, NNSA, NASA, NSF, and DHS. It supports DOE's missions to understand the properties of elementary particles and fundamental forces at the highest energy accelerators; the symmetries that govern the interactions of matter; and to obtain new insight on matter and energy from observations of the universe.

Nuclear Physics

Since the Lab's inception, nuclear science has been a Core Capability. Current programs provide world leadership in neutrino research, heavy-ion physics, medium energy hadronic physics, nuclear structure, and nuclear instrumentation. Machine learning techniques are being applied across the NP programs at Berkeley Lab, e.g., for pattern recognition in nuclear instrumentation and heavy-ion physics, as well as in theoretical analysis of complex multi-variable information such as hadron jets and quark gluon plasma properties.

In the study of neutrinos, Berkeley Lab's critical role in the discovery of neutrino oscillations at the Sudbury Neutrino Observatory has been widely recognized. KamLAND and IceCube resulted in the first observations of geo-neutrinos and ultra-high-energy cosmic neutrinos, respectively. Experiments also search for the rare nuclear process known as neutrino-less double-beta decay, which will demonstrate if the neutrino is its own antiparticle, may provide information on the absolute neutrino mass scale, and determine if lepton number is conserved. Berkeley Lab scientists are playing important roles in the Majorana Demonstrator (MJD) SNO+, and the Cryogenic Underground Observatory for Rare Events (CUORE); both experiments published their first results this year. New detector technologies are being developed at the Lab to enhance the physics sensitivities by two orders of magnitude in the next-generation experiments: the Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay (LEGEND), and the CUORE with Particle Identification (CUPID) experiments.

Berkeley Lab scientists study the structure of exotic nuclei, especially those with the largest neutron excess or the heaviest masses. Such nuclei push the boundaries of explanation by the nuclear shell model and require modern accelerators and instrumentation to characterize. The Lab has a long and distinguished history in developing new detector systems for gamma-ray spectroscopy. These include Gammasphere and GRETINA, which run with beams of rare isotopes at NSCL at Michigan State, and also carry out experiments at ANL's CARIBU facility. This tradition continues with the next-generation Gamma-Ray Energy Tracking Array (GRETA) which received CD-1 in 2017 and CD-3A in 2018.

A core capability within Nuclear Science is Berkeley Lab's long-standing leadership in ion source development. Lab scientists pioneered VENUS, a versatile Electron Cyclotron Resonance (ECR) ion source that provides intense, highly charged heavy-ion beams. The next generation of accelerators, such as EIC, and FRIB- and ATLAS-upgrades, will require higher beam intensity than what can be delivered by current sources. A new superconducting magnet design for ECR sources – the Mixed Axial and Radial field System (MARS) – is under development at the Lab, with the goal of achieving a sufficiently high magnetic field for future state-of-the-art ECR sources.

The Lab's strong nuclear theory group is building the science cases for the next-generation of advanced nuclear physics facilities to be built in the U.S. Notable is work that elucidates the nature of gluonic matter and the structure of the nucleon, which is of great relevance to the next generation Electron-Ion Collider. There is also a growing competency for HPC to study nuclear physics, especially in subfields of quantum chromodynamics on the lattice (lQCD) and nucleosynthesis in supernovae and neutron star collisions. The world-leading work on nucleosynthesis in the cosmos is being carried out with an Exascale Computing Project award to Berkeley Lab theorists.

With respect to quark-gluon plasma (QGP), Lab scientists made seminal measurements showing that the QGP flows with the lowest possible viscosity allowed by the laws of physics. Berkeley Lab's theoretical and experimental role in discovering the quenching of energetic "jets" was pivotal; the result indicates that the QGP has unprecedentedly high density. The Lab led construction of the ALICE EMCal and DCal, large electromagnetic calorimeters that enable the ALICE experiment to carry out unique jet measurements. We also led the construction of the STAR Heavy-Flavor Tracker (HFT), a next-generation silicon pixel tracker with unparalleled resolution and thinness, for reconstructing decays of charmed mesons amid the high particle multiplicities at RHIC. HFT results show that heavy charm quark production is quenched, similarly to jets, including charm quarks at relatively high momenta. Berkeley Lab is now leading U.S. participation in an upgrade to the Inner Tracking System of ALICE at the LHC, utilizing the next generation of silicon pixel technology pioneered in the STAR HFT. Recently, the Lab has taken on leadership roles in defining physics goals and detector components for the future Electron-Ion Collider (EIC). Berkeley Lab scientist Barbara Jacak received the 2019 Bonner Prize from the American Physical Society in recognition of her leadership in the discovery and characterization of the QGP.

The Lab initiated and formed a consortium to develop detectors for the EIC. Seeded by the UC Multi-campus Research Programs and Initiatives (MRPI) program, this consortium involves LBNL, UC Berkeley, UC Davis, UCLA, UC Riverside, LANL, and LLNL. The consortium will focus on its core competencies in developing tracking and calorimetry for the EIC.

In collaboration with NERSC, Lab scientists from the STAR experiment reconstructed half a petabyte of raw data in record time and resource usage efficiency. This demonstration established the feasibility of using HPC platforms to perform data crunching for future data-intensive nuclear physics experiments. This achievement has led to regular use of NERSC HPC machines for reconstruction and simulation studies for STAR, and large-scale simulation efforts for the ALICE experiment. Development of infrastructure to allow user analysis of large data sets from these experiments is underway.

The Lab's Applied Nuclear Physics program is growing, with applications ranging from international safeguards, radiological monitoring, biomedical applications, and detectors for astrophysics. This work takes advantage of the Lab's capabilities in innovative instrumentation, including the world-renowned Semiconductor Detector Laboratory (SDL), and attracts many cross-divisional collaborations at the Lab.

The U.S. Nuclear Data Program concentrates on evaluating and organizing nuclear data for national interests. Nuclear data is used in many applications, including nuclear reactor design, nuclear safety, and many security applications. This program has embarked on a series of targeted measurements at the Lab's 88-Inch Cyclotron to address gaps in existing data, and to provide cross section and beam energy optimization information required by the U.S. Isotopes Program. This effort is joint with UC Berkeley's Nuclear Engineering Department and attracts many young scientists. The Nuclear Data Program continues to support existing nuclear structure and reaction databases and is embarking on the development of new gamma-ray databases for nuclear reaction modeling.

The 88-Inch Cyclotron operates to support three programs. The premier user of 88 beam time is a local research effort focused on the physics and chemistry of super-heavy nuclei. This program is unique in the U.S. and has recently achieved the first direct mass measurement of a super-heavy nucleus using the FIONA mass separator. The aforementioned Nuclear Data and Isotopes Program targeted measurements represent the second thrust for the Cyclotron. The third key area in which the 88-Inch Cyclotron contributes to the nation is in radiation hardness testing of electronics and materials destined for high altitude flights or for space.

Berkeley Lab's Nuclear Physics Core Capability includes innovative equipment and instrumentation, and commensurate handling of big data from experiments that produce multiple petabytes of data per year. The Lab leads the development of next generation ECR ion sources essential for next generation accelerator facilities, including FRIB at MSU, and the future EIC. The Majorana Demonstrator is now taking data, utilizing multiple components produced by Berkeley Lab. CUORE is also taking production data at Gran Sasso in Europe, and the Lab has a strong lead role. GRETINA is producing data, and GRETA has commenced the purchase of detector modules and design of other systems. In heavy ion collisions, the Electromagnetic Calorimeter (EMCal) and Di-jet Calorimeter (DCAL) for ALICE, and the high precision, silicon-based STAR HFT have already taken substantial data. Construction is currently underway on two Monolithic Active Pixel Sensor layers for the ALICE inner tracker upgrade. Researchers are determining how best to apply this novel silicon pixel technology for the sPHENIX experiment at RHIC, and for an eventual Electron Ion Collider detector. The Semiconductor Detector Lab provides world-class instrumentation for development of advanced germanium and CdZeTe detectors.

Support for this Core Capability is primarily from NP, with contributions from NNSA, ASCR, DoD, and DHS. This capability supports DOE's missions to understand how quarks and gluons assemble into various forms of matter; how protons and neutrons combine to form atomic nuclei; the fundamental properties of neutrons and neutrinos; and to advance user facilities and instrumentation that reveal the characteristics of nuclear matter.

Accelerator Science and Technology

Berkeley Lab has core expertise in synchrotron radiation sources and free-electron lasers (FELs); high performance magnetic systems; laser-plasma accelerators (LPAs); accelerator controls and instrumentation including novel laser technology; accelerator front-end systems, high brightness electron and ion sources. It is a center of excellence and community leadership in advanced accelerator modeling. We support SC's mission of scientific discovery and innovation, and conceive, design, and construct scientific user facilities.

Through a series of key upgrades, the 25-year-old ALS continues to operate as the world's brightest soft X-ray source. A major upgrade (ALS-U) now underway will provide up to three orders of magnitude brighter, fully transversely coherent soft X-ray beams. This highly cost-effective upgrade leverages the existing investment and infrastructure and will enable premier soft X-ray source based research for decades to come.

We are a partner in construction of the LCLS-II FEL, delivering the injector source and hard- and soft-X-ray undulators, and contributing to linac systems, rf controls, and accelerator physics. Leveraging the development of the LCLS-II injector is the High-Resolution Electron Scattering (HiRES) apparatus, funded through the BES Early Career Research Program. Here we develop ultra-high repetition rate ultra-fast diffraction combined with intense laser pulses to study ultrafast structural dynamics studies with atomic resolution.

The Berkeley Center for Magnet Technology (BCMT) develops state-of-the-art superconducting high-field magnets, undulators, and specialty magnets for science and applications. We are the designated lead lab for R&D on high field accelerator magnets under the multi-institutional U.S. Magnet Development Program (MDP) and a key member of the LHC Accelerator-Research-Program (LARP), as well as the High-Luminosity-LHC-Accelerator-Upgrade-project (HL-LHC AUP), which is contributing half of the new high-field interaction-region magnets for the LHC upgrade. The project was recently awarded CD-2/CD-3b, enabling baselining of cost and schedule as well as the procurement of critical long lead items. In 2018 the BCMT delivered the fully tested magnet system for the FRIB 28GHz ECR Source, which is slated to come online for the facility in the next years.

Berkeley Lab is the world leader in ultrahigh-gradient laser-driven plasma acceleration technology. Its Petawatt BELLA laser is used for research in support of the SC-HEP mission, including reaching 10 GeV from a sub-meter-scale accelerator, and staging of two independently powered 5 GeV modules. BELLA Center has completed two new 100 TW class laser systems for LPA applications. One system, funded by the Moore Foundation and BES, will be used for LPA-driven FEL studies. The other system, funded by NNSA, studies LPA use for nuclear security applications. Expansion of the BELLA program includes BELLA-i, which uses the present BELLA laser for ion acceleration and high energy density physics, and k-BELLA, which would be a new 1 kHz multi-J-class laser for high-repetition-rate LPA science and applications.

The Lab is a world leader in developing simulation tools and techniques that model advanced accelerators and high-intensity laser-matter interaction physics. This advanced computation and its connections to Exascale Computing are further described in the Computational Science Core Capability.

The Berkeley Accelerator Controls and Instrumentation Program brings together decades of deep expertise in electron and ion acceleration, innovative RF structure design and engineering, and femtosecond synchronization including novel high average power laser technology.

Supported by HEP and BES, with further sponsorship from FES, ASCR, NE, NNSA, DHS, DoD, ARPA-E, other federal agencies, and industrial partners, this core capability supports SC’s missions to conceive, design and construct scientific user facilities; to probe the properties and dynamics of matter; to advance energy security; and to support DOE’s other scientific discovery and innovation missions.

Plasma and Fusion Energy Science

Berkeley Lab has an emerging core capability in Plasma and Fusion Energy Science. The Lab has significant expertise in developing ion sources (including BELLA-i) and low-energy beam transport systems. It is developing novel accelerator architectures based on micro-electromechanical systems (MEMS) for fusion plasma heating and manufacturing applications. A series of projects funded by ARPA-E are led by FS-IBT staff, including the imaging of carbon in soil with neutrons, and the development of multi-beam RF linacs made using low cost MEMS techniques. We are developing a compact plasma device for studies of light ion fusion at relatively low energies, as they are present in the sun; this work is funded by Google. Advanced plasma-based coating techniques are used to support the needs of ALS-U, LCLS-II. Core capabilities in superconducting magnet technology are being applied to future fusion reactors. Topics of interest include development of advanced materials such as RECBO-based cable and novel quench detection methods for protection of HTS fusion magnets.

Applied Materials Science and Engineering

Berkeley Lab’s research emphasizes the design and synthesis of advanced materials for energy, information technology, structural, and other applications in a wide range of physical environments. This capability develops materials that improve the efficiency, economy, environmental impact, and safety for applications, including energy generation, conversion, storage, transmission, and utilization. Underlying expertise includes nanoscale phenomena, advanced microscopy, physical and mechanical behavior of materials, materials chemistry, and biomolecular materials.

Berkeley Lab's applied materials science and engineering research involves advanced materials and nanotechnology for clean energy, including electrochemical energy storage, the catalytic production and storage of fuels, and nanostructured light-emitting diodes. The Lab has world-leading expertise in the tailoring of the optical properties of window materials, including the characterization of glazing and shading systems, the chromogenics of dynamic glazing materials, and low-emittance coatings for solar performance control. Berkeley Lab has led the scientific community in the development of plasma-deposition processes to enable improved window coatings.

Berkeley Lab has a strong development program directed toward advanced sensors and sensor materials to control industrial processes to reduce the waste of raw materials on manufacturing lines, increase the energy efficiency of manufacturing processes, and minimize waste. The Lab also studies high-temperature superconductors for electrical transmission cable that could substantially reduce losses during transmission. Capabilities include analyzing the mechanical behavior of novel materials and designing novel materials with enhanced mechanical properties. Berkeley Lab also has extensive expertise in using waste heat for electricity. In addition, the Lab conducts next-generation lithography and supports the development of tools and metrology for size reduction in the next generation of microelectronic chip manufacturing, largely sponsored by industry.

Berkeley Lab focuses software and hardware technology development on novel pathways to sense the grid at unprecedented temporal resolution, systems level integration of automated demand response, and renewables as elements of the next generation grid.

In the area of thermal materials and advanced metrology, Berkeley Lab's overall goal is to develop breakthrough solutions using thermal materials to address the fundamentally intermittent character of thermal energy supply and use in buildings and industry, an issue becoming ever more important in our renewable future. We have created a science-to-systems approach, building on fundamental advances in thermal storage and nonlinear thermal elements, that aims to impact large-scale applications in building and industrial sectors at low and moderate temperatures. Specific goals include:

- Design a new thermal storage fluid with enhanced heat capacity exceeding benchmarks like water and industry standard fluids. Similarly, design all-solid thermal storage materials surpassing paraffin benchmarks;
- Develop a new voltage controlled thermal switch with high contrast ratio;
- Leverage the new storage materials and nonlinear thermal devices to develop unprecedented thermal topologies, and model their impacts on building and industrial applications; and
- Develop advanced thermal metrologies to understand and optimize the thermal performance of these new thermal storage materials both at nano-scale and design level.

This research will establish Berkeley Lab as a leader in thermal energy storage, non-linear thermal elements, and novel thermal topologies, all aimed at building and industrial impacts.

This Core Capability is sponsored by BES, EERE, DHS, ARPA-E, and SPP programs, including DoD and industry. It is underpinned by DOE-supported basic chemistry, materials, and computational research, and contributes to DOE missions in energy, the environment, and national security. This work benefits DOE technology programs such as water desalination, solar-energy conversion, electrical-energy storage and transmission, solid-state lighting, energy efficiency, and the study of materials in extreme energy environments.

Nuclear and Radio Chemistry

Here, the Lab's capabilities include fundamental nuclear measurements; actinide chemistry; the irradiation of electronic components for industry and the government, including post-irradiation and materials characterization; the design, development and deployment of advanced instrumentation;

compact neutron and gamma-ray sources for active interrogation; nuclear data management; and substantial modeling and simulation expertise. Work for DOE's SC includes actinide chemistry with application to chelating agents; for NNSA, advanced detector materials, compact gamma and neutron sources, detection systems and algorithms development, and background data management and analysis. Our work for DOE NE through the Spent Fuel and Waste Disposition Campaign (SFWD) includes subsurface modeling and testing to evaluate and improve on the current technical bases for alternative prospective geologic environments for high-level nuclear waste disposal.

Applied Nuclear Physics

Berkeley Lab is a world leader in instrumentation to measure ionizing radiation, including scintillators and solid-state detectors that combine high density with excellent energy resolution and high-performance electronics for detector read-out. Complete detection and imaging systems are used for a variety of applications, including nuclear medical imaging, nonproliferation, and homeland security, as well as fundamental explorations of high-energy and nuclear physics. Unique materials-screening and crystal-growth capabilities in the Semiconductor Detector Laboratory enable optimized high-throughput development and design of scintillation and semiconductor detector materials. Capabilities include large-volume germanium and CdZnTe detector development emphasizing position-sensitive and low-noise systems, gamma-ray imaging using coded aperture masks, and Compton scattering telescopes.

Testing of critical space-based electronic components by the National Security Space Community (NSSC) uses heavy-ion beams at the Lab's 88-Inch Cyclotron. This facility's key national role was confirmed in an NAS study of U.S. chip testing needs and capabilities. "Cocktail beams," composed of a mixture of elements that mimic the composition of cosmic rays encountered by satellites, provide a unique national asset to greatly speed the testing of critical space-based electronic components. Other core facilities are the crystal growth facility, BELLA (where compact tunable monochromatic gamma sources are under development for NNSA and DoD), and the Semiconductor Detector Lab.

Berkeley Lab collects high-quality gamma-ray background data in urban and suburban environments with support from DHS. The Lab plans to fully characterize the gamma-ray background based on data collected from detectors in conjunction with visual imagery, light detection and ranging (LIDAR), weather, and other geospatial data that may affect distribution of incident gamma rays. The Lab also obtains and evaluates background gamma-ray data from aerial environments containing complex topographical and isotopic variations. For example, areas of elevated radiation in the contaminated Fukushima region were recently mapped by the novel High-Efficiency Multimode Imager mounted on a remotely controlled helicopter. NNSA supports a feasibility study to explore an advanced system for data storage, as well as analysis and dissemination of gamma-ray background data, including detailed annotation. Standardization and analysis frameworks developed at the Lab for the HEP and cosmology communities will vastly increase the scope of the data being analyzed in the future. This Core Capability is sponsored by SC (NP, HEP, and BES), NNSA, and NE, as well as DHS, DoD, and the NRC. It contributes to DOE missions to integrate the basic research in SC programs with research in support of NNSA and DOE technology office programs.

Systems Engineering and Integration

Berkeley Lab's demonstrated abilities to successfully engineer, construct, and integrate complex systems underpin many of the core capabilities described in this section, and those of the major user facilities described above. Within DOE's SC, the Lab is uniquely configured with a centralized organization that makes engineering, systems and project management, and technical support available to all of the Lab's scientific endeavors.

Our internationally recognized advanced instrumentation skills (e.g., accelerating structures, detectors, data acquisition systems, lasers, magnets, and optics) have enabled many of the scientific breakthroughs described in this Plan; these are the direct result of the holistic coordination and deployment of engineering and technical resources. Solutions and approaches developed for one application are routinely leveraged, adapted, and applied to others. This disciplined integration and systems approach is a critical part of Berkeley Lab's contribution to the LCLS-II upgrade, where we have completed the LCLS-II injector and are responsible for the injector, undulators, and low-level RF systems. The Lab also responsibly leads the GRETA, US-CUORE, LUX, DESI, and LZ collaborative projects. The same approach has been used to assure that ALS-U is staffed with engineers that have prior experience from similar technically challenging projects. Other examples of successfully integrated systems and project management include: the ATLAS inner detector, US-CUORE, LUX, the GRETINA and ALICE nuclear physics detectors, and the Transmission Electron Aberration-corrected Microscope. Further illustration of this integrating, crosscutting systems approach is Berkeley Lab's world-leading expertise in integrated silicon detectors for high-energy physics detectors that has been adapted and applied to the development of massive scientific-grade CCD detectors for astronomical applications. This expertise was further adapted and improved to provide radiation-resistant high-speed X-ray and electron detectors. These direct X-ray detecting CCD systems are deployed at national and international light sources.

In addition to Berkeley Lab's demonstrated abilities to engineer and integrate complex systems for basic science, we are the recognized leader in energy efficiency in commercial and residential buildings and industrial facilities. We develop and transfer new energy-efficient building and industrial technologies from the laboratory to the industrial and commercial world, and stimulate the use of high-performance technologies through innovative deployment programs. The Lab is also a leader in developing cool surface materials for roofing, pavement, and architectural glazing, and in understanding large-scale urban heat-island effects that impact energy consumption and smog formation.

Within the national lab network, Berkeley Lab leads management of transmission reliability programs (CERTS); collaborates with DOE, independent power authorities, and states (with the Demand Response Research Center); and collaborates with other national labs on energy storage for ancillary services and renewable integration.

In addition to SC, these efforts contribute to technology research programs funded by EERE, FE, EDER, and ARPA-E, as well as the DHS Chemical and Biological Security program. Berkeley Lab leverages DOE's investment by working with state and other federal and SPP sponsors, including the Federal Energy Regulatory Commission and the California Energy Commission. The Lab partners with national and international organizations to develop technical standards.

Decision Science and Analysis

Berkeley Lab performs integrated research on energy policies to mitigate carbon emissions and climate change while minimizing externalities such as health burdens, air quality impacts, economic disruptions, and water resources impacts. The Lab investigates the economic impact of energy-efficiency performance standards in industrial and commercial building equipment and systems, and for consumer products. We provide technical assistance to federal agencies to evaluate and deploy renewable, distributed energy, as well as demand-side options to reduce energy costs; manage electric power-grid stability; and assess the impact of electricity market restructuring, e.g., employing large-scale electric-energy storage systems. Research efforts integrate techno-economic analysis and lifecycle assessment with basic science and technology development to ensure sustainable scale-up.

For this core capability, Berkeley Lab's role within the national lab network is to provide analysis of energy efficiency, clean energy, and electricity market policies and standards for energy efficiency requiring complex interconnected technical, economic, and environmental analyses. This capability contributes to DOE's mission by assisting government agencies to develop long-term strategies, policies, and programs that encourage energy-efficiency in all sectors and industries. It is sponsored by EERE, OE, FE, and NE, as well as the CEC and the California Public Utilities Commission.

Mechanical Design and Engineering

Berkeley Lab's applied research addresses energy technology design and development, processes, models, networks, systems, and energy efficiency. The Lab leads the world in accelerating the transition of battery technology from lab to market (e.g., CalCharge), window technology and performance analysis, modeling of energy-saving technologies in building, whole-building, and component systems, and evaluating and tracking energy savings in industrial facilities. As a leader in the R&D of battery systems for automotive and stationary applications, the Lab is a lead partner in JCESR. Battery systems research encompasses the development of new materials, theoretical modeling, and systems engineering. In addition, the Lab applies its extensive experience in subsurface science to underground compressed-air energy storage. The research in large-scale subsurface energy storage encompasses numerical simulations of coupled processes in the porous reservoir.

The built environment is responsible for 40% of U.S. energy consumption and 70% of U.S. electrical usage; Berkeley Lab performs research on buildings energy efficiency, energy simulation, modeling of whole building systems and components, walls, windows, heating, cooling, ventilation, plug loads, roofing systems, and refrigeration. New areas of research include analysis and development of model predictive control systems, fault diagnostics, measurement and verification, agent-based IT, energy information and management systems, and using machine learning and advanced in data science for model training and validation. The Lab is also a leader in the research of indoor environmental quality, lighting quality, ventilation and health.

Berkeley Lab researchers develop and test environmental sensing technologies for both indoor and outdoor air quality. Advanced sensing and metrology systems are also being developed to evaluate the thermal performance of advanced insulating materials and windows. New approaches are being developed to evaluate window shades and glare.

As part of DOE's grid modernization effort, the Lab advances research on electric grid storage and stationary use, electricity grid modernization through technologies for smart grid, distributed generation (microgrids), energy management and Demand Response, and improved grid reliability. This core capability is sponsored by EERE, OE, ARPA-E, EPA, other federal agencies, the State of California, and utilities. It supports DOE's mission to develop and deliver market-driven solutions for energy-saving homes, buildings, and manufacturing, as well as sustainable transportation.

Berkeley Lab has initiated a new set of research activities to support DOE's Grid Interactive Efficient Buildings Program that includes modeling the capability of building end-use loads to provide flexible loads, evaluation and development of control and automated communication technology, new technology development, and electric utility system modeling. Similarly, there is a growing research portfolio to develop and evaluate control of distributed energy resources that include EVs, demand response, electrical and thermal storage, PV, and other DERs.

FLEXLAB, or the Facility for Low Energy eXperiments in buildings, consists of testbeds and simulation platforms for research, development, testing, and demonstration of low-energy building technologies, control systems and building systems integration. FLEXLAB maintains a network of industry partners for research, demonstration, and deployment. It enables development of cost-effective integrated technology solutions to meet 50% whole-building energy savings — a feat that cannot be met solely by the use of single-component or technology upgrades alone. Our major sponsors are DOE (BTO, OE), GSA, SCE, PG&E, and CEC. With the addition of solar PV and energy storage, FLEXLAB is now fully equipped to address the cutting-edge problems at the confluence of renewable integration with storage and demand response as the pathway to the next generation of energy management systems.

Power Systems and Electrical Engineering

The Lab leads the world in advanced sensing modeling and short-term control in the distribution grid and microgrids. We developed key analytics around grid measurement and Distributed Energy Resources Customer Adoption Model (DER-CAM) for dispatch and the control of microgrids. We also developed hierarchical control schemes and data analysis for large distributions of local power generation including solar, storage, electric vehicles to enable multi-level dispatch, and standards development of the interconnection of renewables and smart grid, all to enhance, modernize, and support the future distribution grid.

In the National Lab network, Berkeley Lab leads and collaborates within the grid modernization activities, including program management. Collaborators include LLNL, LANL, SNL, ORNL, ANL, SLAC, and PNNL. This core capability contributes to DOE's efforts to drive electric grid modernization and resiliency in the energy infrastructure, and the development of grid science for a high renewable penetration future. This work at Berkeley Lab is supported by EERE-OE, ARPA-E, DoD's DARPA and ESTCP, and the CEC. The GMLC is a DOE-wide activity that is funded by EERE and OE.

Science Strategy for the Future

To sustain our ability to provide critical research to the nation requires prudent stewardship of our world-class user facilities and infrastructure and of our outstanding corps of researchers. Berkeley Lab's enterprise-wide priorities and initiatives are carefully chosen to provide this stewardship and thus to maximize the opportunities for scientific breakthroughs in the future. The priorities represent enduring commitments that ensure the Laboratory remains a world-leading research institution. The Lab-wide strategic initiatives explore new scientific directions that can leverage our unique capabilities in science and technology to address the nation's most important scientific and technological challenges.

Infrastructure

Overview of Site Facilities and Infrastructure

The Facilities and Infrastructure Strategy supports Berkeley Lab's Core Capabilities and meets the Campus Strategy objectives (listed below) effectively, safely, and efficiently. It addresses new construction, asset protection through predictive, preventive, and corrective maintenance, asset modernization through upgrades and replacements, and demolition of facilities and utilities no longer needed to support DOE's mission. This section provides an overview of existing infrastructure and integrates approved and planned investments from DOE and alternative sources (e.g., UC, philanthropic, other Federal agencies), as well as from the Lab, to comprise our 10-year strategy.

The main Berkeley Lab campus is located adjacent to UC Berkeley, on 202 acres of (UC) land, of which 84 acres are leased to DOE. The site is located within the boundaries of Berkeley and Oakland, Calif., however, local land use restrictions are not applicable to Berkeley Lab. Information on Berkeley Lab land use planning is available in the Berkeley Lab Long-Range Development Plan.

Structures on the main campus consist of 1.71 million gross square feet (gsf) of DOE-owned buildings (1.69 million gsf) and trailers (.19 million gsf). Here is a summary of the overall asset condition of mission unique/non-mission unique facilities, as reported at the close of FY18:

Overall Condition – Mission Unique Facilities				
Condition	RPV	% of RPV	GSF	Asset Count

Adequate	$139.2M	38.3%	131,999	3
Substandard	$224.6M	61.7%	308,977	10
Grand Total	**$363.9M**	**100.0%**	**440,976**	**13**
Overall Condition – Non-Mission Unique Facilities				
Condition	RPV	% of RPV	GSF	Asset Count
Adequate	$112.3M	14.2%	198,319	37
Substandard	$146.1M	18.5%	270,325	20
Inadequate	$531.6M	67.3%	795,221	48
Grand Total	**$790.0M**	**100.0%**	**1,263,865**	**105**

There are 244,135 gsf of UC-owned facilities at the main site that are used for DOE purposes under occupancy agreements with UC, i.e., Shyh Wang Hall (B59) and Chu Hall (B30). There are also 24,317 nsf of UC-owned space within the Advanced Light Source building. The Guest House (B23) is UC-owned and operated.

As of September 30, 2018, Berkeley Lab leases or has licenses for nine off-site facilities totaling 316,271 gsf. In FY18, the Lab extended its lease for space in Emeryville that houses part of the Joint BioEnergy Institute and the Advanced Biofuels and Bioproducts Process Development Unit. In FY20, following completion of the Integrative Genomics Building (IGB) and program moves, Berkeley Lab plans to terminate the leased space currently used to house the Joint Genome Institute (JGI). In fiscal year FY20, the Lab also plans to extend the lease of a facility in Emeryville that houses OCFO functions. As of December 2018, Berkeley Lab also has no-fee use of 49,429 nsf of UC space on the UC Berkeley campus.

At the close of FY18, the Lab currently had five excess facilities, including buildings, trailers, and an environmental monitoring station, totaling 5,768 gsf. There is also a diesel generator and fuel tank in excess status. Three additional facilities are planned to enter excess status in FY19, including B4, B14, and B51F. The Lab continues to make progress in dispositioning its excess facilities, with prioritization given to those facilities in the Lab's major redevelopment areas.

Building and Trailer Utilization Summary for Non-Excess Facilities. The Lab's utilization of its operational (non-excess facilities) is periodically surveyed. The non-excess building and trailer utilization summary, at the close of FY18, is summarized below. *Note: the two unutilized buildings (B4 and B14) identified below are planned to be excessed and demolished in FY19.*

Building/Trailer Utilization			
Category	Building	Trailer	Total
Underutilized	1	1	2
Unutilized	2	0	2
Utilized	94	20	114
Grand Total	**97**	**21**	**118**

The Lab's utilities infrastructure includes domestic and treated water, low conductivity water, sanitary sewer, storm drain, natural gas, compressed air, electrical, life safety and technology systems (telecommunications, optical fiber, etc.). These systems and their respective components vary greatly in age and condition, reflecting generations of alterations and betterments over the institution's long history. Below is a summary of the overall asset condition of utility systems at the Lab.

Overall Condition – Utilities Condition as $ of RPV				
Condition	Mission Critical	Mission Dependent, Not Critical	Not Mission Dependent	Grand Total
Adequate	$415.1M	$14.2M	$0.4M	$429.7M
Inadequate	$0.7M			$0.7M
Substandard	$91.9M	$86.9M		$178.8M
Grand Total	**$507.7M**	**$101.1M**	**$0.4M**	**$609.1M**

Overview of 10-year Campus Strategy and Summary of Investments Needed

Berkeley Lab's multiyear strategy is based on four objectives that address new facilities construction, reclamation of sites for future development, utility infrastructure transformation, and existing facilities modernization. Taken together, these objectives are intended to transform Berkeley Lab's aging facilities and infrastructure into a modern, integrated, interactive, sustainable, and fully mission-aligned environment for ground-breaking science.

This is the fourth year of sustained mission focus around infrastructure at Berkeley Lab. As such, many of the projects we have planned during this period have progressed toward design and execution. A key component of the Laboratory's plan has now shifted to the critical interfaces between the execution of scientific mission and infrastructure objectives. The interfaces include strategic integration of activities (e.g., laydown areas, outage coordination) as well as tactical periodic coordination of ongoing activities. LBNL is committing additional resources to the support of science and infrastructure projects, included training and tools that have been developed and implemented by the Project Management Office. Additionally, the Operations Directorate is taking steps to improve the integration and efficiency of conventional project delivery. These improvements include consolidating the Building Code Official function, aggregating project planning subject matter expertise, and promoting project support through a centralized support services group. Efforts are also in progress to enhance the core project delivery staff and capabilities to successfully deliver on its portfolio of projects. This shift in emphasis is required to efficiently deliver the increased scale of projects required to support the Lab's infrastructure transformation.

Objective 1: Construct new facilities to advance research collaborations: This includes the IGB, currently nearing construction completion, BioEPIC, and early redevelopment planning at the former Old Town site for a multi-purpose Advanced Materials Discovery building and a Chemical Sciences building. BioEPIC and future facilities envisioned for the area will integrate research programs from dispersed leased and substandard onsite spaces onto the Bayview research cluster to advance interdisciplinary priorities, such as the SFAs ENIGMA, Watershed, TES and mCAFEs. As the Lab nears completion of the Old Town Demolition (OTD) Project, early planning is underway for the development of a novel neighborhood built to complement the potential of an upgraded ALS. The first structure being planned is a new Advanced Materials Discovery building that will bring together core programs in energy storage, materials synthesis, and related research programs.

Finally, the Lab is pursuing CD-1 approval for the Seismic and Safety Modernization Project. Safe and mission-capable research space is fundamental to DOE's scientific mission objectives. The newest earthquake forecast, the third Uniform California Earthquake Rupture Forecast, shows that there is a 98% probability that an earthquake of magnitude 6.0 or higher will occur in the next 30 years (before 2043) in the San Francisco region. Though 19 operational buildings are rated seismically poor across the site, the highest risk buildings based on population and functions housed are Health Services (B26), Food Services (B54), and the Fire Department living quarters (B48). The cafeteria replacement, as well as the retrofit of B48, will improve the Lab's operational continuity in the event of an emergency, create a central hub for Operations provided services, and improve vehicular and pedestrian circulation in the area.

All of these planned new facilities will accelerate the Lab's progress towards vacating and demolishing legacy facilities with seismic deficiencies.

Objective 2: Reclaim sites for future development: UC and Berkeley Lab agreed to limit all new construction to brownfield sites; thus, this objective includes demolishing old facilities and cleaning up legacy waste to enable Objective 1 (construction of new facilities), much of which entails the OTD Project and Bayview Site Preparation activities. The former, which includes the razing of an aging cluster of research buildings and removal of some legacy contamination, is currently underway. Phase V of OTD encompasses the structural demolition of B4 and B14. Phase VI, which includes the deactivation, characterization, and demolition of building 7, will begin in 2019 and extend through 2020. Smaller indirect investments are being made site-wide, as funding becomes available, to remove substandard trailers that no longer serve the Lab's needs. These investments, while modest when compared to the Old Town and Bayview efforts, help free up scarce space for parking, equipment staging, and potential future building sites.

Objective 3: Transform utility infrastructure for expansion and reliability: Significant and ongoing investments in utility systems will be necessary to adequately serve the future needs of science and support operations. A phased replacement strategy, coordinated with redevelopment activities, is one way to cost-effectively execute large component and branch replacements. The Lab is in the process of seeking CD-0 approval for a Utilities Infrastructure Upgrade line item project that will address mission critical replacements and system upgrades to the natural gas, supply water, storm sewer, electrical and communication/data systems. This major investment, along with ongoing Lab funded replacements and upgrades, such as the IGPP funded Bayview Site Utility Replacement Project (SURP), are needed to increase service reliability, minimize environmental risk, and improve maintainability. The Lab is also in the process of executing the Supply Water (CMLC) Replacements and Storm Drain Repair and Replacement GPPs that will address the highest priority risks related to those systems. Besides the immediate improvements all of these investments will provide to the Lab's core utility infrastructure, they will also better align sitewide utility service capabilities with the vision being realized though Objectives 1 and 2 above.

Berkeley Lab will use redevelopment opportunities to transition towards the use of common utility corridors and modular utility plants (MUPs), such as those begun in the Bayview neighborhood. Common utility corridors are geographically practical and will provide easier access for maintenance and future modifications, lowering lifecycle costs and minimizing disruption of services. MUPs provide an energy-efficient, more redundant, and more economical means to meet the chilling and heating loads of building clusters, rather than each building functioning as self-supporting. Over the next decade, Berkeley Lab's generational infrastructure renewal on the Bayview and Old Town sites will provide a unique opportunity for this transition. Taken together, common utility corridors and MUPs will transform Berkeley Lab's utility infrastructure into a modern, sustainable and cost-effective configuration that has become standard among physical plants throughout the world.

The three Lab-funded Grizzly Peak Substation upgrade projects, including the Switch-AO Installation, the Bank 1 Transformer Replacement, and the Bank 2 Transformer Replacement, will allow the Lab to meet forecasted increases in electrical demand, while maintaining redundant service between two main transformer banks at this, its furthest upstream, substation. The design work for these projects is in progress, with construction of the Bank 1 Transformer Replacement to begin in FY20. Construction for the Switch-AO Installation will occur in FY21; construction for the Bank 2 Transformer Replacement is planned for FY21.

The Lab has also developed a strategy to systematically mitigate all known high risk electrical safety hazards that pose unsafe work environment over the next ten years. As part of this strategy, the Lab has analyzed its arc flash hazards, identifying existing electrical equipment that have incident energy levels greater than 40 Cal/cm2 and over-dutied (i.e., where the available fault current exceeds the panel short circuit rating) panelboards that require either a replacement or upgrade. As of February 2019, a total of 146 electrical panels have been identified as requiring mitigation work, of which 43 have been replaced or otherwise mitigated. Compensatory measures for these panels include labeling indicating the hazard and a requirement that switching be performed by a qualified electrical worker wearing full personal protective equipment. An IGPP project, the Sitewide Electrical Safety and Maintenance Upgrades Phase 1, will address deficient and aged electrical equipment at two existing buildings (B50A and B70A) and an electrical switch station. This project will greatly reduce deferred maintenance and decrease safety risks to maintenance workers.

Most site-wide telecommunications infrastructure used by network, telephone, mobile phone antennas, and EH&S alarms is old and deteriorating, including underground conduit paths and communication vaults, copper trunks, and fiber optic trunks. Telecommunications rooms in many buildings are too small and don't have enough power or cooling to support modern resilient network and telecommunications equipment. Most investments in these spaces have been reactive to maintain existing service levels to leaks, corrosion, rodent damage, and ground movement. Planning to prioritize and execute proactive investments to modernize this infrastructure is underway.

Objective 4: Modernize existing facilities for evolving scientific needs: In anticipation of the planned ALS upgrade, the Lab is analyzing its supporting core infrastructure for current and future mission readiness, for example, a highly successful ALS HVAC Controls GPP project completed construction in FY18, and the ALS Fire Alarms (Smoke Evacuation) IGPP project completed construction in FY19. Additional new projects are being planned to mitigate potential end-of-life failures, including replacement of a subset of electrical transformers supporting the ALS and other nearby facilities, and a modernization of the main fire alarm systems at the ALS and its support buildings.

Several significant improvements to the Engineering Division complex (B77 and B77A) are either in progress or are being planned to improve production and assembly capabilities in support of several Berkeley Lab programs and DOE complex projects, such as LARP, HL-LHC-ATLAS, HL-LHC-AUP (Accelerator upgrade), LCLS-II, ALICE, and eventually ALS-U. An IGPP project to build a structural addition to B77A will begin construction this year, allowing the Laboratory to better utilize its scarce high bay space and optimize assembly, composite production, and fabrication capabilities throughout the complex. The Lab is also seeking funding to develop space at or near B77 to allow the Engineering Division a better equipment configuration arrangement, as it plans to increase its activities over the next several years. Smaller maintenance projects are also being planned at this complex to improve building controls, and to retire risks related to over-dutied electrical panels (as described previously).

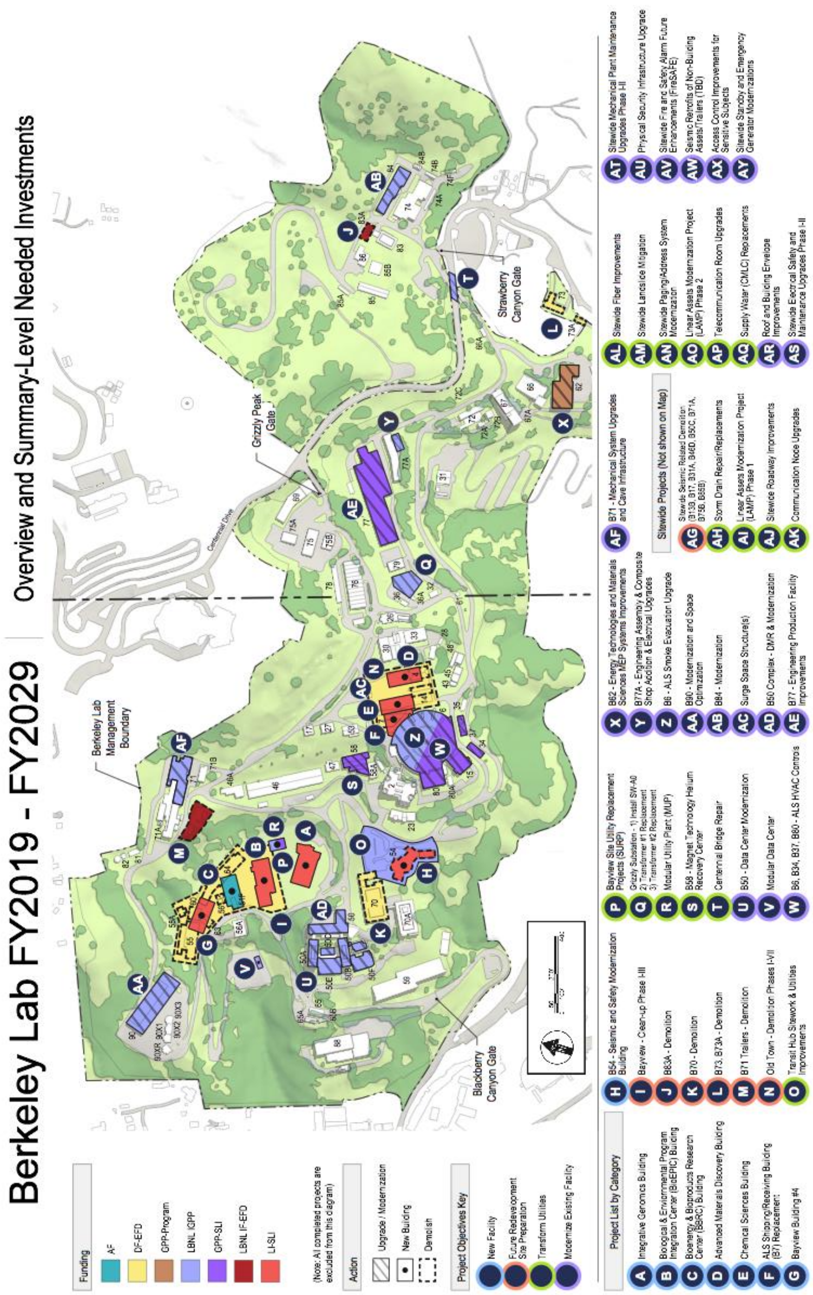
As the Lab continues to seismically evaluate numerous buildings, trailers, and non-building assets for safety risks, it is also making progress in addressing known deficiencies. Following a design effort in FY18, the Lab plans to perform construction this year to replace 11 existing balcony guardrails and 2 existing concrete rooftop pergolas located at the western edge of B50A and B50B with new concrete precast guardrails and new steel framed pergolas. This work will greatly improve the seismic safety profile for these buildings.

A new IGPP Sitewide Mechanical Plan Maintenance Upgrades Phase 1 project will address several age-related deferred maintenance items that pose reliability risks and unnecessarily increase the cost of day-to-day maintenance activities. This project will begin construction in FY19 with the upgrade of boilers and controls at B62, with renewal of the chiller plant at B2 and replacement and upgrades of the sitewide compressed air plant at B43 to follow in future fiscal years. Several mechanical maintenance (non-capital) replacements in progress include boilers in B66, B88, and B2, and a chiller in B88.

The IT Division provides scientific computing support; it requires additional data center capacity for new high-density HPC systems to support the expected growth in use of computation and large data sets from almost every one of the Lab's scientific divisions. Over the last two years, due to a lack of data center capacity, we have been forced to turn away government- and SPP-funded projects requiring additional HPC. Plans call for increasing the existing institutional data center computing power capacity to 1.5 MW by modernizing critical cooling/heating and electrical infrastructure, as well as the addition of high-efficiency 800 kW modular data center spaces to meet growing demand from scientific computation.

Related to the objective of modernizing existing facilities is a subset of projects that would retire high-risk compliance items such as seismic issues, fire alarm upgrades, and security system improvements.

The campus map on the following page provides a summary-level overview of the needed infrastructure investments and highlights of our multi-year strategy. This section concludes with details of Berkeley Lab's 10-year facilities and infrastructure strategy as compared to current and future infrastructure gaps, as well as funding required to achieve the objectives outlined here.



Current and Future Infrastructure Gaps

Bayview Site Remediation and Tunnel Demolition: The Integrative Genomics Building is planned to complete construction in FY19. Berkeley Lab's multi-year strategy includes a proposal to construct facilities to support integration of biosciences programs adjacent to the IGB on the Bayview site. The first of these buildings is the proposed BioEPIC, which will bring together biological and environmental research and house exciting new capabilities. BioEPIC's construction footprint is impacted by legacy underground site features related to the former Bevatron, including concrete utility tunnels, ancillary equipment, and contaminated soil. An Environmental Management (EM) funded effort to address these site features is planned to begin in FY19 and occur through FY20 and FY21 at an estimated cost of $23.5M.

Facility and infrastructure Objective 1 includes facilities for biosciences integration, as well as joint physical, energy, and technology sciences collaborations. To achieve this objective, several seismically deficient or otherwise dated lab and research office buildings (B51F, B55, B56, B60, B63, B64) will be vacated and demolished. B51F will be become excess in FY19 with demolition planned shortly thereafter. B64 is the next large building at Bayview that will need to be demolished to facilitate future redevelopment, though this action will need to follow construction of BioEPIC to allow for availability of new space to house a subset of current occupants at B64.

The Lab's Seismic Study, completed in 2008, identified 42 buildings at the site that could be anticipated to perform poorly in a large earthquake. After more than a decade of mitigation efforts, the number of remaining buildings rated as seismically poor and very poor buildings is down to 19. All but one of the inadequate facilities itemized in the Core Capability Gap table below are in that status due to seismic deficiencies. Approximately 1,000 people occupy these buildings; these assets represent 20% of the Lab's buildings, or total of 258,404 gsf. Following completion of the Seismic and Safety Modernization Project, the current Health Services Building (B26) can be demolished. B70 is also near the top of the Lab's prioritized mitigation schedule due to its inadequate condition and poor seismic condition. Its occupants would need to be dispersed across the main campus, including the new facilities envisioned for the Old Town Site. Buildings 73 and 73A are unoccupied and unusable due to severe seismic deficiencies. These assets were constructed under 1940's–1970's building codes and estimates indicate it is not cost-effective to retrofit them.

Core Capability Gap				
Core Capabilities	**Adequate**	**Inadequate**	**Substandard**	**Grand Total**
SC01 Accelerator Science and Technology		2	7	9
SC03 Applied Materials Science and Engineering	1		2	3
SC05 Biological and Bioprocess Engineering		1		1
SC06 Biological Systems Science	3	1	1	5
SC09 Climate Change Sciences and Atmospheric Science	2		4	6
SC10 Computational Science	1			1
SC11 Condensed Matter Physics and Materials Science			2	2
SC13 Decision Science and Analysis			1	1
SC14 Earth Systems Science and Engineering		2	1	3
SC15 Environmental Subsurface Science	4			4
SC16 Large-Scale User Facilities/R&D Facilities/Adv. Inst.	3	2	9	14
SC19 Nuclear Engineering		1		1
SC20 Nuclear Physics			2	2
SC21 Particle Physics			1	1
SC23 Power Systems and Electrical Engineering			1	1
SC24 Systems Engineering and Integration	2	2	1	5
SC25 Enabling Infrastructure	24	9	26	59
Grand Total	**40**	**20**	**58**	**118**

Table: Core Capability Gap

FireSAFE: The average age of the Lab's fire protections systems is 25 years old. Frequent equipment failures have led to costly building evacuations and operational interruptions at the Lab. The Fire and Safety Alarm Future Enhancements Project will replace and upgrade the site's existing fire and safety alarm systems nearing their end-of-life. The plan is sequenced over a funding-dependent, multi-year period based upon building risks, operational priorities and the condition of the existing systems.

Access Control: Several security systems, including personnel badging production equipment and access control endpoint electronics, are obsolete and well beyond useful life. The Lab is planning to replace these systems building by building as funding becomes available. The first access control system replacements are being performed this fiscal year to demonstrate proof of concept and develop stronger cost estimates for use at other buildings.

B7 Replacement and Chemical Observatory: The B7 location is the envisioned location for the multi-programmatic Chemical Observatory concept. The OTD Project will raze the aging cluster of research buildings that are adjacent to the ALS, remove legacy contamination, and prepare a two-acre site for productive reuse. The buildings that remain to be addressed through this project include: B4, B7, 7C, and B14. A current Investment Gap identified in the Infrastructure Investments Enclosure is the replacement of B7's support functions. This is a Lab priority to improve and expand this critical support function, in conjunction with enhanced research infrastructure on the site of B7. Based on the current timing of the OTD Project and the ALS-U, it is likely that the replacement of B7 will follow these projects, allowing the associated acreage to be used for staging and other activities in the interim.

Berkeley Center for Magnet Technology (BCMT). Many Lab science programs involve experiments and facilities operating at cryogenic temperatures; these require a Helium liquefier, or an upgrade to the present equipment. The HEP-funded Superconducting Magnet Program (SMP) within the BCMT is one such facility. SMP has made recent investments to improve Helium gas recovery and storage, but the liquefier itself is antiquated and its performance no longer satisfies program needs. BCMT management's cryoplant upgrade plan leverages the prior He storage investments while satisfying broader LHe needs. The most critical element is the procurement of a new liquefier, which would provide liquid directly to the magnet test facility and provide liquid in transportable dewars to other users. The procurement would include associated elements such as LHe storage dewars and piping for gas recovery from experimental users at the ALS and Materials Science (B6 and B2). Engineering would run the cryoplant facility and support science programs within ATAP, ALS, MSD and others.

Electron Microscopy Lab-wide Initiative. This initiative will enable Berkeley Lab to remain an international electron microscopy powerhouse. Infrastructure that incorporates a number of synergistic characterization plans across the Lab would result in a renewed state-of-the art, world-leading electron imaging capability for a broad range of programs for a diverse set of scientific challenges in areas such as materials synthesis, catalysis, earth and environmental science, soft matter characterization, and structural biology. Instruments to be developed requiring state-of-the-art facilities include ultrafast electron diffraction imaging capabilities; novel in situ, time-resolved and cryo-EM instruments, and an analytical TEM with high energy resolution.

B71 Mechanical System Upgrades. Mechanical, water, and HVAC System upgrades are necessary to bring this currently out-of-date building to current standards. This includes providing redundancy for current single points of failure, replacing aging systems, and increasing capacity. The building currently does not maintain temperature well under all conditions for work that requires using equipment sensitive to minor temperature changes and air currents. This utility infrastructure will be increasingly important as multi-program activities and user operations in the building increase, and the costs of down time or nonperformance escalate. These include current operations, the new second beam line and short focal length beamline project extensions of the existing BELLA petawatt laser (which do not add significant load but do add operational urgency), and future projects such as kBELLA. Sources of funding are being investigated.

B71 Experimental Cave Infrastructure. The Lab needs to provide the utility infrastructure to support the installation of a future high average power laser system, kBELLA, to enable high repetition rate applications of laser plasma accelerators. This would include a new radiation shielded target area, a lab clean space for the laser and control room, and associated mechanical, electrical, and HVAC infrastructure. Sources of funding are being investigated.

Deferred Maintenance (DM). The DM trend forecast for 2019 will decrease by approximately $9.7M to $232M and continue trending lower throughout the planning period. Increased investment in DM reduction funding by the Lab and SLI will provide the means for continuing to trend DM down during this period. If the plan described in these pages is implemented as proposed, the projected year 2030 DM value would be reduced to the $104M stated herein. Additional details of this plan are documented in the Berkeley Laboratory Deferred Maintenance and High Risk Safety/Compliance Deficiencies Reduction Plan.

Maintenance and Repair. As discussed in section 4.1, the Lab has named infrastructure renewal a top priority. Following many years of insufficient maintenance investment, the Lab was able to attain the recommended 2% RPV maintenance investment index (MII) in FY16. The overall level of MII in both FY17 and FY18 exceeded 2% and the Lab is forecasting a similar level of MII for FY19. Executing to the strategy outlined in this 10-Year plan will result in meeting or exceeding 2% of RPV MII throughout the planning period, which in turn will provide the physical infrastructure needed to support the scientific mission.

Plan for Increasing the Number of Adequate Buildings/Trailers. The Lab's investment plan as described in this section will increase the number and GSF of adequate facilities across the site, per the FIMS overall Asset Condition data element.

Plan for Decreasing the Number of Unutilized or Underutilized Buildings/Trailers. The Lab's inventory of unutilized or underutilized buildings/trailers is relatively small. In FY18 there was only one facility in operation that qualified as unutilized/underutilized. Though the number and GSF may fluctuate over the planning period, the forecasted variability over time is related to vacating these facilities to ready them for disposition. The year-by-year details can be located in the IFI crosscut.

Site Sustainability Plan Summary

Berkeley Lab pursues three broad initiatives to reach sustainability goals driven by requirements of the federal government, California state law, and University of California policy: Climate: Improving buildings, greening the energy grid, and low-carbon commutes; Waste: Rethinking waste through composting, recycling, and smart purchasing; and Water: Upgrading fixtures, stopping leaks, and encouraging conservation.

While Berkeley Lab continually makes advances in many areas of sustainability, its key current sustainability strategies include:

- Improving building operations with ongoing commissioning to generate and sustain significant energy and water savings;
- Optimizing the efficiency of HPC by tuning cooling systems at NERSC;

- Demonstrating deep savings in lighting through a comprehensive, visible, LED lighting modernization effort;
- Leading the way with sustainable new construction driven by Berkeley Lab's Sustainability Standards for New Construction;
- Making energy and water management standard practice by implementing ISO 50001, an international energy management standard; and
- Working towards zero waste through better data and engagement.

Recent highlights include:

- As of spring 2019, the Lab is maintaining annual energy savings of 7.0 million kWh and water savings of over 19 million gallons, which equal 1.6 times the annual energy use of the 88-inch Cyclotron facility and is approximately equivalent to the output of a 4.5 MW solar photovoltaic array in Berkeley, which would occupy 14 football fields. These savings are being generated primarily through improvements in facility operations. The Lab has paid particular attention to reducing natural gas, and use has decreased sitewide 9% since fiscal year 2015.
- The Lab completed an initial two years of ongoing optimization of its HPC center and has verified annual maintained savings of 2.0 million kWh – more than 40% of the baseline "non-compute" electricity use – and 790,000 gallons of water.
- The Lab is now 17 months through a two-year project to align energy and water management activities to ISO 50001, an international energy management standard.
- New tools to reach zero waste including a mobile-friendly website to help staff improve waste sorting and expanded waste audits to better target activities.
- Expansion of the staff electric vehicle charging program, now with over 150 permit holders and over 80 regular users. The Lab swapped out ten of its leased gas-powered fleet vehicles for nine EVs and one plug-in hybrid.
- The soon to be completed Integrative Genomics Building is designed to meet deep energy efficiency targets, use no natural gas, and offset about 15% of its total energy use with rooftop photovoltaics.

As of the end of FY18, the Lab has 14% of buildings by count and 17% of buildings by square footage that meet Guiding Principles (with a federal goal of meeting 15% of buildings by count by FY25). Compliance with the 15% goal is expected in FY 2019.

OAK RIDGE NATIONAL LABORATORY

Lab-at-a-Glance

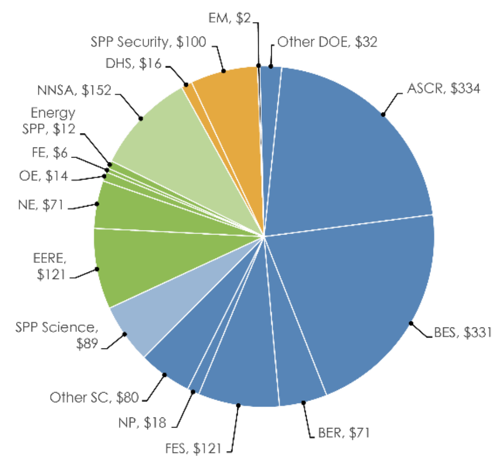
Location: Oak Ridge, TN
Type: Multi-program Laboratory
Contractor: UT-Battelle, LLC
Site Office: ORNL Site Office
Website: www.ornl.gov

- **FY 2018 Lab Operating Costs:** $1,570.5 million
- **FY 2018 DOE/NNSA Costs:** $1,353,1 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $201 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 12.8%
- **FY 2018 DHS Costs:** $16.4 million

Physical Assets:
- 4,421 acres and 272 buildings
- 4.8 million GSF in buildings
- Replacement Plant Value: $6.9 B
- 1.4M GSF in 61 Excess Facilities
- 1.1M GSF in Leased Facilities

Human Capital:
- 4,708 Full Time Equivalent Employees (FTEs)
- 196 Joint Faculty
- 281 Postdoctoral Researchers
- 382 Graduate Student
- 554 Undergraduate Students
- 3,289 Facility Users
- 1,533 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

The mission of Oak Ridge National Laboratory (ORNL) is to deliver scientific discoveries and technological innovations needed to realize solutions in energy and national security and provide economic benefit to the nation. ORNL focuses an extensive set of core capabilities, closely coupling basic and applied research, to enable science breakthroughs and address challenges faced by the US Department of Energy (DOE), other sponsors, and the nation.

Established in 1943 as part of the Manhattan Project, ORNL had as its original mission the development of processes for the production and separation of plutonium. After World War II, ORNL led early work on nuclear energy, radioisotopes for medicine and other applications, radiation-resistant materials, and the effects of radiation on biological systems.

Today, ORNL is a world leader in materials, neutron, and nuclear science and engineering and in high-performance computing and data analytics. These signature strengths and other core capabilities are combined across the spectrum of basic to applied research and development (R&D) to support a wide range of programs. ORNL also applies its exceptional resources in project management to manage the Exascale Computing and US ITER projects for DOE.

Several distinctive ORNL facilities are open to the science and engineering community. The Spallation Neutron Source and High Flux Isotope Reactor offer unmatched capabilities for understanding the structure and dynamics of materials, and robust plans for upgrades will ensure sustained US leadership. The Center for Nanophase Materials Sciences is home to leading capabilities and expertise for synthesis, fabrication, modeling, imaging, and characterization at the nanoscale.

The Oak Ridge Leadership Computing Facility hosts forefront computational resources, including the world-leading 200+ petaflop Summit system, and advanced data infrastructure. Other user facilities, such as the Manufacturing Demonstration Facility, provide tools for developing and testing new technologies in collaboration with industry.

From its genesis, ORNL has had a history and culture of solving difficult problems with national scope and impact. R&D carried out at the laboratory has produced advances in science and technology that have led to improvements in our fundamental understanding of the natural world, energy production, national security, human health, and the environment, and to innovations that are creating new products, businesses, and jobs.

Core Capabilities

The 23 core capabilities assigned to Oak Ridge National Laboratory (ORNL) by the US Department of Energy (DOE) provide a broad science and technology (S&T) base that catalyzes fundamental scientific advances and technology breakthroughs that support DOE's mission of addressing the nation's energy, environment, and nuclear challenges through transformative science and technology solutions. These capabilities, each of which has world-class or world-leading components, reflect a combination of exceptional people, equipment, and facilities. Synergies among these core capabilities enable scientific discovery and translational research to accelerate the delivery of technology solutions and allow ORNL to respond to changing priorities and the critical needs of the nation.

We are taking steps to recruit the highest-quality and most diverse pool of talent by establishing long-term relationships with key universities. We are emphasizing staff development, helping our people to build distinguished careers in research and development (R&D), and challenging them—individually and collectively—to reach their full potential. We also maintain and expand ORNL's research capabilities through strategic investment in facilities and equipment. With the resulting combination of highly performing and world-recognized staff and state-of-the-art facilities and equipment, ORNL seeks to be the world's premier research organization.

Accelerator Science and Technology

ORNL has exceptional expertise in the basic physics of high-intensity hadron beams and the technology to support the production, acceleration, accumulation, and utilization of such high-intensity, high-power beams. The Spallation Neutron Source (SNS) accelerator complex, operating at 1.4 MW beam power on target, is currently the world's most powerful pulsed proton accelerator and the world's sole superconducting linear accelerator (linac) for hadrons. The SNS enables ORNL to lead investigation of the dynamics of high-intensity hadron beams and the development of high-power proton targets.

Other ORNL leadership areas include expertise in negative hydrogen ion sources and low-energy beam chopping and manipulation; superconducting radio-frequency (RF) technology; laser technology; high-power target systems; high-power and low-level RF systems; pulsed-power technology; sophisticated control systems for the manipulation of high-power beams; beam-tuning algorithms; high-level real-time accelerator modeling and analysis; and instrumentation to measure properties of high-intensity, high-power hadron beams. In addition, ORNL's strengths in computational science are used to develop beam dynamics modeling (including 6D models) and data management tools to design next-generation spallation neutron sources, high-intensity linacs, storage rings, and associated radiation shielding. The combination of state-of-the-art beam dynamics modeling tools and access to robust experimental data on collective, halo-formation, and instability effects in high-intensity hadron linacs and accumulator rings is unique to ORNL. These strengths underpin laboratory efforts to systematically increase the power level at which SNS operates reliably.

Another area of expertise is the design and improvement of mercury target systems and systems dedicated to neutron production, such as the SNS inner reflector plug (IRP) integrated with the neutron moderator. Three targets per year are necessary to support neutron production at SNS at current power levels, and target design improvements are integrated with the operations cycle. IRP-2 was installed to replace IRP-1 after more than 10 years of operations. The current 1.4 MW power level and ramp-up to 1.7 MW enabled by the Proton Power Upgrade (PPU) project will require a new IRP every 4–5 years. Design for IRP-3 is nearing completion, and procurement of selected components has begun.

The comprehensive Cryogenic Test Facility (CTF) supports a robust research program that has led to the development and successful deployment of a novel in situ plasma-cleaning technology that has increased the peak gradients of selected superconducting high-beta accelerator cavities by up to 25%. ORNL is transferring this technology to other important accelerator projects in the DOE portfolio. It is also developing capabilities for laser-based stripping of energetic H– ions to facilitate high-power beam injection into advanced rings, pursuing novel approaches to power conversion technology for klystron modulators, and developing beam instrumentation systems. Continued advances in high-level real-time applications, in combination with improvements in warm accelerator structure vacuum systems, have led to significant reduction in the time required to complete facility turn-on after planned outages.

ORNL has constructed and commissioned a low-energy beam test facility (BTF). The spare radio-frequency quadrupole (RFQ) structure was commissioned to full power and installed in the main SNS linac front-end; the old RFQ was installed in the BTF in summer 2018 and recommissioned with beam in January 2019. A new and improved instrumented focus-drift–defocus-drift (FODO) cell opens the unique capability of the BTF to carefully observe and characterize halo formation, in addition to the already established capability of reconstructing the full 6D phase space of low-energy hadron beams. The upgraded beamline, in addition to beam halo in high-intensity hadron accelerators, will be used to develop novel neutron moderator technologies. The SNS accelerator complex, in combination with CTF and BTF, provides an essential resource to enhance accelerator science opportunities that attract, engage, and retain staff with the expertise to drive innovation in all facets of accelerator science and technology relevant to the ORNL mission. The measurement and reconstruction of the 6D phase space of a hadron beam was a first in accelerator science.[3]

The impact of ORNL's research in high-intensity beam dynamics and technology spans all fields of science enabled by high-power hadron accelerators. DOE's Office of Science (SC) is the funding source.

Advanced Computer Science, Visualization, and Data

ORNL staff are deeply engaged in R&D to enable deployment of the scalable computing infrastructure to support the DOE mission, with an emphasis on the facilities and programs at ORNL. ORNL participates in numerous Scientific Discovery through Advanced Computing (SciDAC) application teams and leads several components of RAPIDS (a SciDAC Institute for Resource and Application Productivity through Computation, Information, and Data). ORNL staff are prominent in the Software Technology focus area of the Exascale Computing Project (ECP), leading several projects and participating in several co-design

[3] B. Cathey et al., *Phys. Rev. Lett.* **121**, 064804 (2018).

projects. In addition, Jeffrey Vetter leads the development tools element and is participating in the Hardware and Integration focus area.

Two areas of emphasis distinguish the ORNL computer science program: accelerated node computing, and developing the tools and methods needed to federate facilities in support of the DOE mission. ORNL is committed to developing the tools and technologies needed to advance accelerated node computing, from extreme-scale systems deployed by the Oak Ridge Leadership Computing Facility (OLCF) to the Experimental Computing Laboratory (ExCL). The high-performance computing (HPC) resources of OLCF, including the 200 petaflop (PF) IBM AC922 Summit, are available to users to advance knowledge in areas such as designing fusion reactors, designing new materials, engineering proteins to treat diseases, efficiently releasing energy from biomass, and understanding climate change impact. Systems available through ExCL explore a wide range of accelerated processing technologies, from quantum and neuromorphic processors to near-memory computing systems, such as Emu Chick and systems with field-programmable gate arrays. ORNL is leading capabilities in predictive performance and future-generation high-end computing architectures. Additionally, ORNL is leading one of the SC Advanced Scientific Computing Research Program (ASCR) Quantum Testbed Pathfinder teams.

ORNL is equally committed to developing tools and approaches that support the evolution of applications needed to effectively utilize the computing capability enabled by computational accelerators. ORNL staff are deeply engaged in the standards activities related to directive-based programming systems, including OpenMP and OpenACC, to ensure that these standards address the needs of DOE applications. ORNL staff are also developing tools aimed at supporting the transformation of scientific software. For these and other applications, ORNL researchers bring significant expertise in system software, component technologies, run-time optimization, architecture-aware algorithms, and resilient computations.

In recent years, the DOE community has begun to recognize the need for advanced computer science, visualization, and data capabilities to provide a deeper understanding of data generated at DOE user facilities, such as light sources, neutron sources, and nanoscience centers. For example, bringing OLCF resources to bear at SNS can provide a deeper understanding of materials samples. To this end, ORNL has established research programs in workflow systems (including ADIOS, BEAM, and ICE), system science (including networking), and data and information visualization (including EVAL, Eden, and Origami). Compute and Data Environment for Science (CADES) provides a focus for deploying these research capabilities. Launched internally to provide a fully integrated infrastructure offering compute and data services for researchers, CADES is now being applied to the needs of users at SNS, HFIR, and Center for Nanophase Materials Sciences (CNMS). With this platform, researchers can process, manage, and analyze large amounts of data using scalable storage, data analysis, and visualization tools.

ORNL also enables scientific discovery and accelerates deployment of technologies in energy and national security by developing, managing, and accessing scientific data repositories (e.g., the Atmospheric Radiation Measurement [ARM] Data Archive, Distributed Active Archive Center [DAAC]), Earth System Grid Federation, National Extreme Events Data and Research Center, and A Large Ion Collider Experiment [ALICE] USA Tier 2). Through software and architectural advances such as quantum and neuromorphic computing for next-generation architectures, ORNL accelerates the deployment and utilization of petascale- and exascale-capable systems that will contribute to solving critical national challenges in science, energy assurance, national security, advanced manufacturing, and health care. ORNL also applies its capabilities in advanced computer science, visitation, and data in the area of geographic information system R&D. ORNL hired Yan Liu to provide novel expertise in high-performance geocomputation and Kelly Sims with expertise in open-source geographic data analysis for population modeling.

ORNL is committed to growing the nation's capabilities in data analytics and visualization through a data science and engineering PhD program offered by the University of Tennessee–ORNL Bredesen Center for Interdisciplinary Research and Graduate Education (Bredesen Center). This capability is supported by SC, the Office of Electricity (OE), and Strategic Partnership Projects (SPP) sponsors, including the US Department of Homeland Security (DHS), the Intelligence Community (IC), the US Department of Defense (DoD), and the US Department of Health and Human Services (HHS).

Applied Materials Science and Engineering

ORNL possesses exceptional expertise in experimental, theoretical, and computational materials research and strongly couples a leading fundamental condensed matter and materials science program funded by the SC Basic Energy Sciences Program (BES, see Sect. A.11) to the development of new materials for energy and national security applications. The combined use of characterization and theory and simulation tools with experimental approaches provides an opportunity to deliver highly innovative materials science solutions that can be readily translated to high-impact applications.

ORNL is also developing new materials for optimized performance, especially in extreme environments. For example, grid-to-rod fretting (GTRF) in a pressurized water reactor may cause wear-through of the fuel cladding, resulting in a risk of radioactive fuel leaks. Industrial assembly GTRF tests are very expensive, and most studies documented in the literature used unrealistic testing conditions. ORNL, in collaboration with industry, recently developed a bench-scale autoclave fretting test rig to allow studying GTRF of actual claddings and grids in a relevant environment[4]. Good agreement has been achieved between ORNL's bench-scale fretting results and Westinghouse Electric Company's assembly reactor core simulator data. Innovative research such as this is essential in developing new approaches for energy efficiency. Further, ORNL has exceptionally broad capabilities for the design, synthesis, prediction, and characterization of materials with specified structure-property relationships and for understanding the role of defects in controlling materials properties and performance. This core capability supports the development of materials that improve efficiency, economy, and safety in energy generation, conversion, transmission, and end-use technologies.

A distinguishing characteristic of applied materials science research at ORNL is the close coupling of basic and applied research to develop next-generation structural materials for applications in fission and fusion energy, transportation, buildings, high-efficiency steam generation, and power cycles utilizing supercritical CO_2 and concentrated solar power. Research associated with this core capability is the source of the majority of ORNL's patents. Novel processing techniques for manufacturing include advanced manufacturing (AM) of metals, alloys, and polymer composites. For example, AM can be used to "print" high-performance magnets, as demonstrated by ORNL with partners from the Critical Materials Institute, Ames Laboratory, Magnet Applications Inc., Tru Design, and Momentum Technologies, with support from the Advanced Manufacturing Office in DOE's Office of Energy Efficiency and Renewable Energy (EERE). In addition, we can now print conventionally nonweldable nickel-based superalloys in complex geometries. The material properties are on par with conventionally processed alloys and will be tested in a land-based gas turbine with an industrial partner later this year. In support of the DOE Office of Nuclear Energy (NE), ORNL has initiated R&D activities for the Transformational Challenge Reactor (TCR), including exploration of materials development in conjunction with machine learning (ML) and AM tools.

Specialized capabilities in applied materials science and engineering include materials joining, surface engineering and processing, corrosion studies under harsh but well-controlled conditions, mechanical testing in a variety of environments, and physical property determination. Specific materials expertise

[4] S. Lazarevic et al., *Wear* **412-413**, 30–37 (2018).

exists in alloys, ceramics, nanomaterials, carbon fiber and composites, nanostructured carbons, polymers, and thermoelectrics. For example, ORNL is developing a Li-ion battery thermal runaway risk database for energy storage systems. This joint effort with Sandia is managed by OE.[5] Furthermore, ORNL has discovered a vapor processing route to encapsulate liquid metal in a ceramic silicon carbide shell for modular, tunable thermal energy storage that can be used with concentrating solar, nuclear, and fossil power plants.

ORNL's applied materials science and engineering program takes advantage of state-of-the-art capabilities for materials development and testing: SC user facilities, such as CNMS, SNS, HFIR, and OLCF; Carbon Fiber Technology Facility (CFTF) and Manufacturing Demonstration Facility (MDF), both supported by EERE; and other facilities, such as the Low Activation Materials Development and Analysis (LAMDA) laboratory and the Irradiated Materials Examination and Testing hot cell facility. ORNL recently demonstrated that high-throughput computational thermodynamics approaches can provide advanced scientific features (e.g., precipitate volume fraction, elemental solubilities/activities within key phases) that can be used to generate hypotheses with the potential to significantly accelerate high-temperature alloy design within the context of modern data analytics, consisting of correlation analysis and ML.[6]

Funding comes from EERE, OE, DOE's Office of Fossil Energy (FE), NE, the National Nuclear Security Administration (NNSA), DHS, the Advanced Research Projects Agency–Energy (ARPA-E), DoD, and other SPP customers.

Applied Mathematics

ORNL's applied mathematics capability includes extensive expertise in the development, approximation, and analysis of innovative, massively scalable, and resilient mathematical and computational approaches for scientific (model) discovery as well as decision sciences. ORNL researchers are developing extreme-scale, architecture-aware, and resilient mathematical and computational approaches to take advantage of and realize the potential of future computing platforms, including exascale. The broad scope of R&D in ORNL's applied mathematics program encapsulates both theoretical and numerical solutions of complex deterministic and stochastic systems, with immediate impact on a number of applications sponsored by SC's programs. Algorithms developed within the applied mathematics program are a critical component of ORNL's modeling and simulation (M&S) capabilities and are widely recognized and used beyond ORNL. Examples of these capabilities include:

- A new scientific computing framework that offers wide support for ML algorithms, including compressed sensing, convex and nonconvex regularization schemes, and integral-based deep neural networks. This framework employs CUDA along with C/C++ libraries for processing vast amounts of training data and is designed to scale the production of models and provide overall flexibility.
- A unified and massively scalable computational Toolkit for Adaptive Stochastic Modeling and Non-Intrusive Approximation (TASMANIAN). This toolkit represents an architecture-aware, predictive capability for applications that dominate the focus of the DOE mission, particularly in exascale computing.
- Ensemble propagation techniques at the scalar level of the simulation through the Stokhos package in Trilinos and integrated within the Kokkos package for many-core performance portability, allowing this technique to be applied in a portable manner to existing central processing units (CPUs), graphics processing units (GPUs), and accelerator architectures.

[5] S. Kalnaus et al., *J. Power Sources* **403,** 20–26 (2018).
[6] D. Shin et al., *Acta Mater.* **168**, 321–330 (2019).

- The high-level software environment MADNESS (Multiresolution Adaptive Numerical Environment for Scientific Simulation), designed for the solutions of integral and differential equations in many dimensions, using adaptive and fast harmonic analysis methods with guaranteed precision based on multiresolution analysis and separated representations.
- The Data Transfer Kit (DTK), supporting multiphysics and multiscale simulations, that has been developed as part of ECP.
- An exascale model of stellar explosions based on a massively scalable and innovative combination of neutrino transport, implicit-explicit time integration schemes, and discontinuous Galerkin spatial discretizations, developed in support of ECP's ExaStar project and run on Titan and Summit.
- GPU-accelerated, probabilistic approaches for predicting mitigating plasma disruptions in fusion tokamaks. This tool enables real-time runaway electron prediction in three-dimensional (3D) magnetic fields with complex geometries.
- Development and maintenance of high-quality mathematical software, including EISPACK, LINPACK, BLAS, LAPACK, ScaLAPACK, Netlib, PVM, MPI, NetSolve, ATLAS, and PAPI.

ORNL has also enabled R&D in support of SC missions by building on research for non-DOE sponsors in imaging, cybersecurity, and quantum information science (QIS).

ORNL applied mathematicians provided the core of the laboratory's Artificial Intelligence initiative and have developed key results for efficient and robust learning algorithms focused on dimension reduction and stochastic optimal control using reversible networks, uncertainty quantification (UQ), and image classification. These algorithmic improvements have enhanced several applications, including medical imaging and materials design.

ORNL's applied mathematics program spans four highly visible and externally recognized areas of research: (1) multiscale M&S, (2) ML from scientific data, (3) high-dimensional approximation and UQ, and (4) accelerated solvers for extreme-scale architectures. ORNL mathematicians have received many international awards and honors (including two DOE Early Career Research Program grants, a National Academy of Sciences Kavli Frontier of Science Fellow, and a Simons Fellow). They present multiple invited plenary talks, chair international conferences, serve in leadership roles of international societies and on the editorial boards of the top-ranked mathematics journals, and publish significant papers in the highest-impact mathematics journals.

ORNL provides a strong partnership between mathematicians and researchers across ORNL to address the challenges faced by experimental scientists, such as deep data analytics for electron microscopy in the BES materials science program. In addition, the applied mathematics program supports additional experimental facilities, including CNMS, MDF, and National Transportation Research Center (NTRC), through the development of supervised and unsupervised learning algorithms. This effort builds on strengths in UQ, optimal reconstruction from both sparse and extensive noisy data, optimization, control of high-dimensional physical and engineered systems, and linear and nonlinear solvers.

Funding comes primarily from SC, DoD, the National Science Foundation (NSF), HHS, and other SPP sponsors.

Biological and Bioprocess Engineering

ORNL brings substantial strength in fundamental biology to bioprocessing and bioengineering to address DOE mission needs in bioenergy production, carbon biosequestration, and environmental contaminants processing. ORNL is (1) leading the Center for Bioenergy Innovation (CBI), a nexus for research on biomass utilization for biofuels and bioproducts (e.g., higher alcohols, esters, jet fuel, and lignin co products); (2) characterizing the largest population of Populus genotypes for biomass deconstruction gene discovery and expanding that analysis to switchgrass; (3) developing new microbial platforms for the conversion of biomass to products; (4) coupling fundamental and applied research in biomass production and conversion (both thermochemical and biochemical conversion) for high-value materials and chemicals, fuels, and power; and (5) making sustained contributions to assess biomass feedstock supplies at regional and national scales.

ORNL leverages its broad capabilities in chemical engineering, chemistry, materials science, HPC, and systems engineering to accelerate translation of research outcomes into demonstrable improvements in bioproducts and biofuels and to move bioremediation research from the laboratory to the field or pilot level. Integrated teams at ORNL bridge science to applications. ORNL uses expertise in plant sciences, microbiology, molecular biology, molecular dynamics, and bioinformatics, in combination with facilities such as the common gardens, high-throughput phenotyping equipment, neutron sources (SNS, HFIR), and computing resources (CADES, OLCF) to address bioproduct and biofuels production. ORNL applies materials and chemical sciences capabilities to mitigate the degradation (corrosion, wear, and erosion) of materials for use in biomass processing and conversion systems; to characterize catalysts to understand their fundamental durability and lifetime mechanisms; and to convert waste CO2 to valuable fuels and chemicals.

ORNL is a recognized leader in multiple aspects of bioenergy production, including biofeedstock sources and sustainability analyses, with emphasis on an integrated systems approach (e.g., landscape design) at multiple landscape scales (from hectare to nation) for applied impacts. This leadership has been leveraged to assess the potential for carbon management through bioenergy for carbon capture and sequestration and of sustainability metrics and analysis, including resources for water impacts. ORNL also leads in the use of a suite of biomass conversion processes: novel microbes and applied systems biology, computational chemistry and physics modeling for biomass conversion, and biofuels and bioproduct upgrading to advance bioenergy production. ORNL has continued to develop innovations in bioengineering and bioprocessing, resulting in patents and licenses (e.g., ENCHI Corporation and Technology Holdings LLC) by building on the identification of key genes that can be manipulated to improve bioprocessing for fuel and co-product production.

This core capability draws on ORNL user facilities, including SNS, HFIR, CNMS, OLCF, NTRC; facilities will include the high-throughput phenotyping equipment to be housed in a new headhouse to be completed in FY 2019. ORNL will continue to upgrade and update other high-throughput analysis instruments to accelerate the rate of gene discovery. ORNL has hired Stephanie Galanie (formerly of Codexis, Inc.) to provide additional expertise on high-throughput analysis and Stan Martin (formerly of Bayer Crop Sciences) to provide additional expertise in data science.

SC and EERE are the primary sponsors of this work. ORNL also performs impact analyses for the US Environmental Protection Agency (EPA) and bioremediation design projects for DoD. Other current sponsors include National Institutes of Health (NIH), the US Department of Agriculture, and ARPA-E.

Biological Systems Science

ORNL's core capability in biological systems science directly improves understanding of complex biological systems through (1) integration of plant sciences with synthetic biology, ecology, computational biology, and microbiology; (2) discovery of gene function; (3) foundational research in plant science that enables development of sustainable plant feedstocks for bioenergy and bio-derived materials; (4) the use of neutron science and exascale computing to characterize protein structure and interaction; and (5) development of imaging at multiple spatial and temporal scales. The fundamental understanding delivered through application of this core capability is essential to solving challenging societal problems in bioenergy, nutrient cycling, climate change, carbon management, and environmental remediation. Our Genes to Ecosystem (G2E) framework integrates our capabilities in biological systems science, climate change science, and environmental subsurface science to improve predictions of ecosystem structure and function, drawing on resources in field-scale data and modeling. Many environmental challenges, such as the design of plant microbiomes to improve crop yield, reduce nitrogen input, and minimize fertilizer runoff, can be tackled through targeted biological discovery and design.

ORNL is the host institution for CBI, which is in its second year. Building on the success of the BioEnergy Science Center, CBI is leading improvements in the economics and sustainable production of biomass and its conversion to bioproducts and biomaterials. Fundamental research will rapidly advance the understanding of cell wall structure and plant feedstock systems. ORNL leads the shift in focus in bioproducts research to sustainability and a more diverse set of bio-derived materials and fuels obtained through lignin valorization and biomass processing.

Within the framework of the Science Focus Areas (SFAs) established by BER, ORNL is expanding research on biocomplexity to facilitate understanding of the structural organization, functional dynamics, and emergent properties that underlie molecular transport, metabolism, compartmentalization, and signaling within and between cells, whole organisms, and microbial communities and their physical and chemical environments. ORNL research within the Plant-Microbe Interfaces SFA characterizes the soil and plant microbiome and elucidates fundamental aspects of plant–microbe signaling and symbiosis leading to chemical cycling in the terrestrial biosphere. These data-rich experimental efforts interface with bioinformatics expertise in microbial annotation and in computational investigation, including artificial intelligence (AI) approaches and modeling for interpretation of complex systems biology data.

ORNL has strategic strengths in plant biology that have largely focused on more than 1,000 genome-sequenced *Populus* lines. ORNL is continuing to work with. Thomas Juenger (University of Texas) to develop a similar resource for switchgrass that will be used in CBI and other research. ORNL has demonstrated that these resources allow for efficient identification of gene functions by measurement of phenotypes tied to precise genome-wide association studies (GWAS). ORNL plans to add to these capabilities by purchasing a state-of-the-art multispectral imaging system that will enable a new level of high-throughput phenotyping of plant systems. Additional bioimaging capabilities being developed within newly funded BER projects will facilitate 3D mapping of plant-microbe interactions along with the study of plant signaling via nanofiber arrays.

Biological systems science at ORNL also focuses on biological transformations of critical DOE-relevant pollutants such as mercury, nitrogen, nutrients, and carbon. Capabilities in biological systems sciences, neutrons, and computing combine to benefit the Biofuels SFA (biomacromolecular interactions) and the Critical Interfaces SFA. ORNL is applying nanoscale, multimodal spectroscopic and neutron imaging to plant–microbe interfaces research in newly developing projects. Additionally, ORNL partners with other national laboratories on BER projects such as DOE's Systems Biology Knowledgebase (KBase) and the Ecosystems and Networks Integrated with Genes and Molecular Assemblies (ENIGMA), a multi-institutional consortium managed by Lawrence Berkeley National Laboratory. A newly funded project at ORNL will add the first tools for protein structure modeling into KBase, allowing Joint Genome Institute metagenomic data to guide restraints on protein folding. ORNL also recently joined the National Microbiome Data Collaborative, in a role that will facilitate the translation of information between the biological and environmental scales. Our integrated G2E capabilities position us uniquely to lead this effort.

SNS can support the G2E framework through the Center for Structural Molecular Biology (CSMB), including the Biological Small-Angle Neutron Scattering (Bio-SANS) instrument at HFIR. CSMB takes advantage of ORNL's specialized facilities for sample deuteration, neutron scattering, and HPC. A new BER-funded effort is prototyping a multimodal SANS instrument for the SNS Second Target Station (STS), and we are developing the computing pipelines needed to set up experiments, interpret their results, and train predictive models. Example systems are being chosen from poplar GWAS results, with several intriguing examples arising in studies of inter-species signaling between plants and microbes. In addition, ORNL has capabilities in both solid and solution nuclear magnetic resonance spectroscopy, optical spectroscopy, and multiple modalities of imaging. Research in this core capability uses SNS, OLCF, CNMS, the Joint Institute for Biological Sciences facility (JIBS), and state-of-the-art greenhouses, environmental chambers, and characterization laboratories. ORNL also makes use of BER user facilities at other laboratories, such as the Environmental and Molecular Sciences Laboratory and Joint Genome Institute, to support its research.

Recent hires include Stan Martin, who has expertise in biological databases and microbial metagenomics; Amber McBride, who has expertise in nanoscience and biosecurity; Stephanie Galanie, who has expertise in metabolomics and mass spectrometry; Omar Demerdash, who has expertise in ML and molecular biophysics; Michael Garvin, who has expertise in bioinformatics and GWAS; and Brian Sanders, who has expertise in structural biology and biochemistry.

SC and EERE are the primary sponsors of the work within this capability. Additional work is sponsored by DHS, NIH, ARPA-E, DoD, and EPA.

Chemical and Molecular Science

ORNL's core capability in chemical and molecular science is focused on understanding, predicting, and controlling (1) chemistry at complex interfaces, (2) reaction pathways in diverse environments, (3) chemistry in aqueous environments, and (4) charge transport and reactivity over a broad range of length and time scales. This portfolio includes research programs in catalysis, separations, geochemistry, and interfacial science and provides fundamental knowledge for the development of new chemical processes and materials for energy generation, storage, and use; for mitigation of environmental impacts of energy use; and for national security. The ORNL-led Fluid Interface Reactions, Structures and Transport (FIRST) Energy Frontier Research Center focuses on developing a fundamental understanding and validated predictive models of the atomic origins of electrolyte and coupled electron transport under nanoscale confinement by taking advantage of neutron and X-ray scattering, spectroscopy, and other characterization tools, coupled with precise synthesis and computational modeling. The FIRST Center has integrated an experimental and modeling approach, consisting of neutron scattering, X-ray pair distribution function analysis, and electrochemical measurements with molecular dynamics (MD) simulations, to provide a fundamental understanding of the behavior of room-temperature ionic liquids inside carbon electrodes with complex pore architectures and surface chemistries.[7]

Designing new materials for efficient chemical separations is a strength of the ORNL Chemical and Molecular Science program. ORNL has developed a simple system for direct air capture of carbon dioxide using environmentally friendly aqueous amino acid sorbents based on fundamental structural, thermodynamic, and mechanistic studies.[8] In another study, porous liquids, a new, emerging class of materials that couple the features of porous solids and liquids, have been synthesized using ionic liquids that show enhanced CO2 adsorption capacities compared to ionic liquids alone.[9] Fundamental advances in ORNL's Chemical and Molecular Science program are being applied to address key challenges for many DOE applied programs, such as the EERE-funded Critical Materials Institute. For example, by combining the Titan supercomputer, X-ray diffraction, and surface calorimetry, the extraction yield of rare earth elements was increased by the discovery that displacing adsorbed water on the bastnaesite

[7] B. Dyatkin et al., *Carbon* **129**, 104–118 (2018).
[8] F. M. Brethomé et al., *Nat. Energy* **3**, 553–559 (2018).
[9] W. Shan et al., *ACS Appl. Mater. Interfaces* **10**, 32–36 (2018).

and calcite surfaces is critical to collector binding, because it enables ligands to recognize the structural differences between the two minerals.

ORNL is a leader in the application of neutron scattering to address fundamental problems in the structure and dynamics of fluids, solids, and interfaces. For example, neutron diffraction with isotope substitution coupled with classical MD simulations was used to determine the solvation shell, i.e., the water coordination number, around the nitrate ion in aqueous solution, which helps us understand the formation of ion pairs and clusters, which are potential rate limiting processes in crystal nucleation.[10] Neutron scattering is also used to gain mechanistic insights into hydride species, which are common catalytic intermediates, in heterogeneous catalysis. A recent minireview article discusses advances in the study of the adsorption, dissociation, spillover, and reactivity of hydride species over supported metal and oxide catalysts by in situ inelastic neutron vibrational spectroscopy.[11] Researchers also use CNMS and OLCF for specialized synthesis, characterization, and computational tools. For example, atomic-resolution scanning transmission electron microscopy combined with in situ IR spectroscopy was used to study the evolution of the morphology, elemental segregation, and phase transition for individual FePt-FeOx nanoparticles as a function of post-synthesis treatments.[12] The chemical and molecular science core capability also comprises novel characterization tools including surface sampling mass spectrometry and femtosecond laser spectroscopy, which are being applied to problems in biological systems sciences in which a multimodal imaging platform is being developed to yield 3D spatiotemporal chemical information in bulk and at the interface in biological systems in situ. Mass spectrometry is also being used in nuclear and radio chemistry in the quantitative characterization of stable and radioactive isotopes and for nuclear forensics and is the basis of the electromagnetic separation capabilities established for the DOE Isotope Program.

ORNL hired Ashley Shields with expertise in uranium chemistry to expand the research team exploring the behavior of uranium compounds in the environment.

Funding comes primarily from BES. Applied programs sponsored by DOE's Office of Environmental Management (EM), NE, FE, and EERE and applications to BER and NP programs are closely coupled to the chemical and molecular science core capability.

Chemical Engineering

ORNL's capabilities in chemical engineering leverage core capabilities in chemical and molecular science, nuclear chemistry and radiochemistry, condensed matter physics and materials sciences, applied materials sciences and engineering, biological and bioprocessing science, and computational science. Leadership in chemical separations, catalysis, isotope production, isotope enrichment, high-efficiency clean combustion, and biofuel production enables ORNL to develop new chemical processes and separation technologies that improve efficiency, economy, environmental acceptability, and safety in energy generation, conversion, and utilization. Research in isotope production and separation, environmental remediation, and actinide separations is also underpinned by this capability.

Technology development through chemical engineering builds on and impacts (1) BES-sponsored fundamental research in materials design, synthesis, and characterization; (2) BES-sponsored research in chemical separations, catalysis, and computational modeling; (3) BER-sponsored research in bio-based fuels and chemical production; (4) NP-sponsored research in production of radioisotopes and stable isotopes and stable isotope enrichment; (5) EERE Vehicle Technologies Office and Bioenergy Technologies Office–sponsored research in applied chemical separations, fuels, pyrolysis, and catalysis

[10] H.-W. Wang et al., *J. Phys. Chem. B.* **122**, 7584–7589 (2018).
[11] F. Polo-Garzon et al., *ChemSusChem.* **12**, 93–103 (2019).
[12] X. Liu et al. *Nano Energy* **55**, 441–446 (2019).

development; and (6) FE-sponsored research in CO_2 separation and conversion. Example results include polymeric materials to extract uranium from seawater and novel materials to separate and capture CO_2. This capability also enables ORNL to develop methods for purification of multiple isotopes used in medical treatment, large-scale recovery and purification of ^{238}Pu to fuel the nation's space exploration missions, and production of ^{63}Ni to enable sensitive explosives detection at airports. ORNL is also developing separations methods for recovering rare earth elements such as neodymium, dysprosium, and praseodymium from scrap magnets, as part of the Critical Materials Institute (CMI), and its separations expertise was used to develop the Next-Generation Caustic Side Solvent Extraction process for the extraction of cesium from alkaline waste, enabling the cleanup of more than 34 million gallons of high-level tank waste at DOE's Savannah River Site.

As the national steward of uranium science and processing technology, ORNL applies expertise in chemical engineering to advance the understanding of fuel cycle operations associated with processing, purifying, and enriching uranium. Related ORNL separations expertise, in both electromagnetic and gas centrifuge techniques, is also enabling advances in stable isotope enrichment that are being applied in the design and construction of the Stable Isotope Production Facility and the newly conceived Stable Isotope Production and Research Center. Innovative chemical processes being developed for recovery and recycle of nonnuclear materials from used nuclear fuel (UNF) assemblies have great potential for simplifying secure UNF disposition pathways and for reducing the mass and volume of the waste stream.

With the current national interest in nuclear reactor technologies, ORNL has developed capabilities, laboratories, and systems for producing and characterizing molten fuel and coolant salts for fast and thermal MSR concepts. These facilities allow us to produce and characterize beryllium- and chloride-based salts in high-temperature environments to measure and understand thermophysical and chemical (e.g., corrosion) properties with various metal alloys. This expertise also enables ORNL to contribute to advances in energy efficiency, renewable energy, fossil energy, waste management and environmental remediation, and national security. For example, physical and chemical techniques for carbon capture, with applications for reducing greenhouse gas emissions, are being examined using novel adsorbents, including nanostructured materials and ionic liquids.

Chemical engineering research at ORNL makes use of resources that span radiological laboratories and nuclear facilities (including Isotope and Nuclear Materials Complex [INMC]), biochemical laboratories for investigating environmental and biofuels technologies, and chemical and materials laboratories for synthesis and characterization resources. These include SNS, HFIR, CNMS, OLCF, and NTRC.

Funding for chemical engineering originates from several sources, including SC, EERE, NE, EM, DHS, NNSA, and SPP sponsors.

Climate Change Science and Atmospheric Science

ORNL's core capability in climate change and atmospheric science is focused on improving understanding of the causes, impacts, and predictability of climate change by (1) conducting large-scale, long-term, complex ecosystem experiments and observations; (2) leading DOE Earth system model (ESM) development in biogeochemistry (e.g., Energy Exascale Earth System Model project [E3SM]); (3) integrating multidisciplinary research connecting data, terrestrial and atmospheric science, and large-scale computing; (4) developing novel software to improve the credibility and scalability of next-generation climate models in preparation for exascale computing (e.g., the International Land Model Benchmarking project, Land-Ice Verification and Validation Toolkit, and E-PRIME, for model assessment targeting the human dimensions community); (5) coupling ESMs to components of human systems, such as land use and land cover change, that incorporate significant feedback to the climate system; and (6) utilizing computing expertise and HPC data and infrastructure to improve climate-modeling tools for improved fidelity and efficiency. ORNL plays a major role in leveraging ASCR capabilities via the SciDAC program, where a research focus is development of better strategies for model evaluation and connection to observational data.

ORNL advances next-generation integrated models of the Earth system by improving the characterization of ecosystem processes and land–atmosphere exchange of carbon, nitrogen, nutrients, water, and energy as well as human–climate-system interactions. The Spruce and Peatland Responses Under Changing Environments and Next-Generation Ecosystem Experiments (e.g., NGEE-Arctic) projects are large-scale experimental and observational studies being conducted in a variety of climate-sensitive ecosystems. ORNL leads in the use of knowledge derived from these long-term experiments to improve the representation of key plant and microbial traits in terrestrial biosphere models (e.g., spanning scales from genes to ecosystems) and their contributions to carbon and other biogeochemical cycles. ORNL advances a transformative watershed predictive capability (i.e., ExaSheds project) that leverages ML to integrate diverse data with river basin-scale simulations of unprecedented spatial resolution and mechanistic detail. Approaches that merge data-driven ML and physical process representation are an important next step in understanding hydrological systems. This is required to not only to inform model inputs, but to assist in model-data integration and create surrogate models to support scaling of observations to river-basin scales. ORNL also contributed to the release of E3SM v1 and its new high-resolution capabilities to simulate aspects of Earth system variability and decadal changes that will critically impact the US energy sector. These sophisticated computer models are increasingly including components of human-dominated systems (e.g., urbanization) and critical interdependences among energy infrastructure and water resources. ORNL is the premier data resource for the ARM program, which provides key atmospheric radiation measurements from around the world to improve understanding of atmospheric dynamics and cloud processes. Capabilities in climate and atmospheric sciences allow ORNL researchers to investigate and evaluate the risk of climate change and associated extreme events on terrestrial ecosystems, aquatic ecosystems, and coupled energy and water systems. By incorporating that knowledge into decision-support tools, ORNL provides insights into adaptation strategies and energy security implications. These efforts provide the scientific basis to enable a more resilient and secure US energy infrastructure.

ORNL infrastructure supporting climate change science and atmospheric science activities includes leadership-class computing (OLCF), which supports M&S and big data applications; state-of-the-art greenhouses; field and laboratory facilities (e.g., SPRUCE); and neutron sources (SNS, HFIR), which enable characterization of soil organic matter and multimodal imaging of whole plant/soil systems and plant–water interactions. A review of these assets leads to the realization that research to explore a federation of instruments for data collection (i.e., mathematical and computer science investments in workflow and data processing strategies to automate and streamline data collection and analytics) is urgently required. Documentation regarding all facets of model/data integration also requires automated, robust software to track data attributes.

Ben Sulman, previously at the University of California, Irvine, joined ORNL as the Climate Model Development and Validation liaison between NGEE Arctic and E3SM. His background in models, measurements, and theory across a wide range of spatial scales prepares him to bridge the modeling and empirical communities and to transfer knowledge between experiments and models. Cory Stuart was hired as a member of the ARM Data Center, where he serves as Data System and Cyber Security Manager for the DOE ARM Program. Yan Liu arrived at ORNL in March 2019 and has expertise in HPC for the multisector dynamics community.

SC is the primary sponsor for these efforts; NNSA, NASA, DoD, DHS, the US Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and the US Department of Agriculture's Forest Service (USDA-FS) also sponsor or collaborate on activities that leverage and enhance DOE investments in climate change and atmospheric science to generate solutions for the nation. For example, NOAA investments target analysis of regional climate behavior stemming from E3SM and other models within CMIP6. These contributions enable scientific insights resulting from new capabilities in these models. Specifically, the NOAA efforts investigate the regional-scale Earth system responses to internal and external climate forcing, and the USDA-FS SPP employs computational methods and sampling site and network representativeness approaches that incorporate in situ and satellite data to identify threats to forest ecosystem health.

Computational Science

Computational science at ORNL is focused on the development and delivery of scalable computational applications. This core capability is built on multidisciplinary teams that tackle science and engineering problems of national interest through the development and application of scalable algorithms requiring tightly coupled workflows that combine theory, experimental data, data analytics, and M&S.

This core capability resides within the world's most capable complex for computational science, which comprises outstanding staff, infrastructure, and computers dedicated to a research portfolio that covers the full span of ORNL's interests. Integrated teams of domain scientists, computational scientists, computer scientists, and mathematicians provide scalable computational and analytical solutions delivered through integration of algorithms, M&S, software technologies, computer and information sciences, and HPC infrastructure.

Over the past decade, the ability to efficiently capture, analyze, and steward large volumes of highly diverse data has become increasingly important to ORNL's sponsors. In addition, data-centric discovery is one of the new frontiers of S&T. ORNL responded to this situation by creating CADES, an integrated compute infrastructure for delivering data science solutions and workflows that is sustained and updated by both institutional and programmatic investments. CADES is effectively creating a new environment for scientific discovery with its diverse computing and data ecosystem, enabling scientists to manage, manipulate, and process large data sets.

These solutions enable transformative science applications that span computational design of new nanomaterials; predictive understanding of microbial, molecular, cellular, and whole-organism systems; simulation of nuclear fission and fusion systems; supernovae simulations; reliable predictions of climate change at the regional scale, including biogeochemical feedbacks; and stringent model evaluation to bracket uncertainties and impacts to communities. The capability also supports early-stage research that addresses problems that are only tractable using HPC for companies of all sizes, including SmartTruck Systems, GE, Rolls-Royce, Ford, Arconic, and Boeing.

Example applications under active development for current and future leadership computing platforms include Consortium for Advanced Simulation of Light Water Reactors (CASL) Virtual Environment for Reactor Applications (VERA); DCA++ for simulation of superconducting materials; QMCPACK for simulation of electron structure of atoms, molecules, and solids; AMPERES for multiphysics simulation of electrochemical and renewable energy storage; and DataTransferKit, a parallel solution transfer service code for multiscale, multiphysics simulations. ORNL support for the ECP includes leading the Applications Development focus area; leading groups of projects in the energy sector that are building new simulation capabilities for SMRs (Steven Hamilton), AM (John Turner), and quantum materials simulation (Paul Kent); and contributing to another 10 of 22 ECP Applications Development projects. Further, a joint ASCR–BES SciDAC award to a team led by Thomas Maier is enabling new capabilities in quantum Monte Carlo simulation of superconducting materials.

These capabilities are applied to deliver integrated, scalable solutions to complex problems of interest to DOE and other sponsors, including materials design, advanced manufacturing, electrical energy storage (batteries and supercapacitors), nuclear reactor efficiencies and lifetimes, fusion plasma containment, climate change science, weather prediction modeling, health and quantitative biology, and scalable analytics to address complex problems associated with DOE missions in energy and national security.

ORNL hired Theodore Papamarkou, whose strengths in computing environments and deep learning platforms are critical for DOE's exascale computing program and the AI mission.

Funding for this work comes from SC, NE, and EERE; OE, DoD, IC, HHS, NOAA, and NSF also sponsor or collaborate on activities that leverage DOE investments in computational science.

Condensed Matter Physics and Materials Science

ORNL has the nation's largest materials R&D portfolio with world-leading capabilities for predicting, synthesizing, characterizing, and ultimately controlling materials systems over broad temporal and spatial scales. This makes it possible to ultimately design materials with specific functionalities by connecting the fundamental understanding of complex materials to applications in energy generation, storage, and use. The scientific themes of this portfolio include (1) mastering the origin of quantum phenomena; (2) understanding and tailoring excitations and transport; (3) elucidating how functionalities emerge at interfaces; and (4) understanding and controlling defects and disorder to yield new materials and properties. For example, the Energy Deposition Defect Evolution (EDDE) Energy Frontier Research Center led by ORNL focuses on elucidating the origin of radiation damage using a set of high-entropy alloys combined with atomic-level characterization and computational approaches. The information obtained will be invaluable for designing the next generation of radiation-resistant alloys for nuclear and other applications.

Synthesis of materials for energy and functional quantum matter enables the studies of fundamental properties that ultimately lead to the discovery of novel materials with remarkable properties. ORNL has specialized expertise in synthesis of single crystals, thin films, artificial heterostructures, alloys, nanophase materials, polymers, and polymer composites. For example, synthesis of quantum heterostructures led to the discovery of a hidden ferromagnetic insulating state that emerges in Sr_2FeReO_6 films when the material's local ionic order is disturbed by a small modification in cation ratio.[13] In a study in which bulk synthesis was combined with density functional theory, evidence was discovered that heat "hops" randomly from atom to atom in thermal insulators—an idea originally proposed by Einstein.[14] Synthesis of thermoelectric materials identified atomic-size defects that suppress the ability of boron arsenide to conduct heat, providing an effective route to manage heat in electronics.[15]

In addition, ORNL develops approaches for characterizing the structure and behavior of materials, making extensive use of key DOE user facilities at ORNL. Neutron scattering is employed to gain an understanding of quantum matter by examining how topology, interfacial coupling, spin-orbit coupling, and strong fluctuations intertwine to produce new states of matter. Neutron scattering also plays an important role in understanding how hybridized atomic vibrations control energy transport and functionalities in energy materials. For example, using neutron scattering, researchers made the first observations of the supersonic propagation of pure lattice energy (heat) in the piezoelectric fresnoite ($Ba_2TiSi_2O_8$).[16] Simulations of the aluminum-containing high-entropy alloys $Al_xCoCrFeNi$ predicted

[13]C. Sohn et al., *Adv. Mater*. **31**, 1805389 (2019).
[14]S. Mukhopadhyay et al., *Science* **360**, 1455 (2018).
[15]Q. Zheng et al., *Phys. Rev. Lett.* **121**, 105901 (2018).
[16]M. E. Manley et al., *Nature Commun.* **9**, 1823 (2018).

composition-dependent phase transformations that were validated by in situ neutron scattering and microscopy experiments.[17]

Leadership capabilities in materials imaging, including in situ electron microscopy, scanning probe microscopy modalities, atom probe tomography and chemical imaging, are made available through the user program at CNMS. These imaging capabilities provide a fundamental understanding of materials; e.g., nanoscale control over redox chemistry of copper in a layered van der Waals thiophosphate was recently demonstrated using locally applied voltages.[18] A new QIS project, sponsored by BES, will create, enhance, and stabilize entangled and correlated quantum states through direct control over dopants, defects, and material geometry, enabled by electron beam atom-by-atom manipulation, to locally tune electronic energy gaps, electronic wavefunctions, and phonon modes, and to provide the conditions under which nontrivial band topology emerges to form protected quantum states that can persist at elevated temperatures.

ORNL's experimental condensed matter and materials science efforts are deeply integrated with theory, modeling, and simulation. ORNL has strengths in the development and application of scalable computational approaches and code (e.g., quantum Monte Carlo, Locally Self-Consistent Multiple Scattering) that take advantage of leadership-class computational facilities, including OLCF. Via powerful algorithms run on high-performance computers, the spin dynamical structure factor was calculated for the first time in a realistic multiorbital model of correlated electrons, revealing exotic acoustic/optical modes in iron-based superconductors.[19] Moreover, a new computational approach for improving the resolution of magnetic excitation spectra has been developed using the density matrix renormalization group (DMRG) method.[20] Application of the quantum Monte Carlo method revealed the excitation energies of localized defects, demonstrating accurate calculations of energy emission lines that are urgently needed to facilitate identification and characterization of defects.[21] ORNL is developing approaches to apply these codes to next-generation exascale computation as part of a BES project, "Computational Materials Science Center," and another ECP project. A joint ASCR-BES project supported through SciDAC, "Computational Framework for Unbiased Studies of Correlated Electron Systems," is also being conducted to develop a computational framework for controlled and unbiased studies of strongly interacting electron systems in quantum materials.

Activities within this core capability are important contributors to advances in applied materials science and engineering and impact multiple DOE energy and national security mission areas. This core capability also provides fundamental understanding that has led to new materials and enhanced US competitiveness, as illustrated by licenses to industry for innovations in superconducting cables, thin-film batteries, and alumina-forming austenitic steels, for example. In addition, resources developed in this core capability underpin the technologies being developed by CMI.

ORNL hired Matthew Brahlek, who has expertise in molecular beam epitaxy of quantum materials and heterostructures, and Gabor Halasz, a quantum field theorist who will conduct research in quantum materials and QIS.

This work is primarily supported by BES; expertise in this area supports other programs, including EERE, NE, ARPA-E, DoD, the Nuclear Regulatory Commission (NRC), NASA, and other SPP programs.

Cyber and Information Sciences

[17] L. J. Santodonato et al., *Nature Commun* **9**, 4520 (2018).
[18] N. Balke et al., *ACS Appl. Mater. Interfaces*, **10**, 27188 (2018).
[19] J. Herbrych et al., *Nat. Commun.* **9,** 3736 (2018).
[20] A. Nocera et al., *Sci. Rep.* **8**, 11080 (2018).
[21] K. Saritas et al., *J. Phys. Chem. Lett*., **10**, 67 (2019).

ORNL's cyber and information science core capability includes expertise and resources in visual analytics, data analytics, ML and deep learning, database architectures, secure communications, signals analysis, and information security to (1) collect, share, intelligently store/retrieve, analyze, and classify enormous and heterogeneous collections of data; (2) create knowledge from disparate and heterogeneous data sources; and (3) understand, defend against, and defeat known or unknown adversaries to protect the nation's energy, economic, and security infrastructures.

Cybersecurity is a domain where human-centric operations drive the efficacy of network security architectures. ORNL has substantial capability in developing technologies that optimize and enhance the defensive value of cybersecurity operations. Outcomes from this core capability are translated from R&D to deployment through partnership with operational cyber infrastructure and co-located expertise. ORNL is successfully transferring technologies based on rigorous mathematical results to address cyber and information security challenges. Situ (cyber situational awareness), Oak Ridge Cyber Analytics (ML-based network security for DoD), Akatosh (forensics), Beholder (cyberphysical protection), and other tools have been licensed to multiple parties or operationally fielded within the US government. In addition, ORNL is developing a new capability for the study of mathematical and ML methods applied to cybersecurity, including adversarial ML, the pragmatic evaluation of applications of ML in cybersecurity operations, and software vulnerability discovery.

Information science and data play a crucial role in both scientific discovery and mission-oriented decision making. The grand challenge is how to collect, organize, and structure the complex and voluminous data so it is useful and informative for end-use scenarios. Solutions to this problem require complex, sophisticated, and interdisciplinary approaches based on data science and data preparation. ORNL is among the national leaders in methods for heterogeneous big data management, data curation, smart storage/retrieval, and feature engineering that leverage resources such as OLCF, Knowledge Discovery Infrastructure, and CADES. ORNL researchers apply strong mathematical rigor and computationally intensive methods to solve cybersecurity and information science challenges at scale and/or in near-real time. ORNL's resources allow for deep learning on HPC systems, which provides unparalleled insights into the behavior of malicious and nefarious cyberspace actors.

QIS R&D is providing game-changing capabilities for secure communications and control systems, especially in protection of the electric grid, where new programs have been awarded by OE's Cybersecurity for Energy Delivery Systems R&D program. The combination of these cyber security and quantum communication capabilities spans areas such as cyberphysical systems protection, trusted and secure communication architectures, and persistent threat detection and mitigation in networks. Further, ORNL develops mathematical methods for identifying the impacts of complex attacks on cyber infrastructures, including software-defined networks, and game-theoretic strategies for ensuring infrastructure resilience in the presence of intentional and incidental disruptions. This capability extends to supercomputing, where assurances in computational/data integrity can guard against adversaries who attempt to influence policy by manipulating HPC processes, data, or results. ORNL hired Joel Dawson to provide additional expertise in cyberphysical security.

ORNL infrastructure supporting this core capability includes the Distributed Energy Communications and Control Laboratory (DECC), classified HPC systems, the Center for Trustworthy Embedded Systems, the Vehicle Security Laboratory, and the Resilient Cyber Physical Systems Laboratory. This infrastructure, along with multidisciplinary staff proficiencies throughout ORNL in power systems, power electronics, nuclear power systems, and transportation, enables the laboratory to tackle cyber and cyber-physical security challenges for multiple systems that include the electric grid, smart transportation systems, vehicles, and sensitive data/information storage/compute platforms.

Funding for this work comes from SC, OE, EERE, NNSA, IC, the US Department of Transportation (DOT), DHS, Department of Veterans Affairs (VA), and DoD.

Decision Science and Analysis

ORNL's decision science and analysis core capability assists a wide variety of decision makers who grapple with compelling local, regional, national, and global issues. Quantitative and qualitative social, institutional, and behavioral research is conducted on topics as diverse as technology acceptability, market transformation, societal implications of emerging technologies, linkages between science or technology and their intended users, and decision making itself. ORNL's data-driven methods, models, analyses, and tools create knowledge and insights useful in anticipating, planning for, managing, and understanding responses to and the impacts of numerous events and technologies.

ORNL scientists operating at this nexus of technology and decision analysis have established critical capabilities and expertise in the practice of data-driven decision science, risk analysis, and UQ and uncertainty propagation. These resources are necessary to address impacts of technologies on environmental systems, market dynamics, regulation, and other social factors. Such impact assessments are complex, cross-disciplinary, data driven, and often computationally demanding. Validation tools within a more comprehensive UQ framework are being applied to Earth system models that, in turn, provide quantitative estimates of model uncertainty and expand the utility of models for directing observation campaigns. ORNL's capabilities and expertise enable the observation, modeling, analysis, and simulation of physical, social, economic, and governance dynamics with unprecedented spatial and temporal resolution, providing an unparalleled opportunity for scenario-driven analyses and evaluation of the consequences of current and future technologies and policies.

To cite two noteworthy examples, ORNL uses geographic information science for decision/risk analysis of critical infrastructure expansion and population mapping. For critical infrastructure, ORNL supports DOE and other agencies in strategic planning and program direction, policy formulation, and implementation. ORNL is a leader in performing risk analysis of extreme events to aid in siting critical infrastructure and in understanding population dynamics for emergency response, collateral damage assessments, and urban planning. For population mapping, ORNL is now mapping and modeling the environment in which humans occupy space (i.e., both built and natural environments) at unprecedented scale and resolution. ORNL has expanded its capability in human dynamics modeling to support DoD, IC, and humanitarian organizations. This work includes endeavors such as mapping polio vaccination distribution programs and conducting rapid assessments of population dynamics in crisis and conflict areas, which supports collateral damage estimates. Researchers are now leveraging and coalescing these existing investments in geospatial technologies and data to develop and deliver global building intelligence that captures information about human occupancy, materials, geometry, morphology, and function with high spatial, temporal, and attribute detail for the world. These key pieces of information are critical to address broad issues, including vulnerability and resilience; they also can be used for consequence assessment, estimating shielding protection for a variety of hazards, understanding the implications of various land use configurations and urban morphologies for future growth scenarios, and generating new insights into the impact of human activity on changing energy and transportation behaviors. ORNL hired Srinath Ravulaparthy to enhance ORNL's expertise in using geographic data to model travel behavior.

ORNL is a demonstrated leader in a number of areas within this capability, including (1) spatial demography, geographic data analytics, and technosocial analytics; (2) data-driven decision science, risk analysis, UQ, design of experiments, and probabilistic risk assessment; (3) dosimetry and development of dose coefficients and cancer risk factors for human exposure to radionuclides; (4) power plant siting and fuel cycle performance; (5) climate change impacts, adaptation, and vulnerability modeling and assessment; (6) energy economics; (7) learning for heterogeneous biomedical data with UQ; and (8) development of decision support tools for a variety of national security challenges, including support of cyber security, military, and IC missions. To provide additional expertise in multi-modal analytics and modeling for national security missions, ORNL appointed Dr. Hector Santos-Villalobos to a key position in the National Security Sciences Directorate.

ORNL has initiated the TCR project, which will enable a full demonstration of the potential for combining advanced manufacturing, data science, and materials science to develop advanced nuclear energy systems. Cutting-edge data science and computation may allow autonomous sensor and control systems, as well as utilize ML for component, system, and material design and optimization.

Funding for this work comes from SC, NE, EERE, DHS, DOD, IC, the Federal Emergency Management Agency, NRC, National Cancer Institute (NCI), and the Food and Drug Administration.

Earth Systems Science and Engineering

ORNL researchers analyze the ecological interactions of, and develop quantitative indicators for, the impacts of human activities, natural disturbances, and varying climatic conditions on spatial patterns and processes on the Earth's surface and near-surface environmental systems. Activities enabled by this core capability include (1) linking a fundamental understanding of mercury biogeochemistry to engineering applications to develop transformational solutions for DOE legacy mercury contamination; (2) applying highly sensitive tracers in CO_2 capture and storage to validate the integrity of CO_2 geosequestration; (3) identifying and modeling ecological functions of rivers and streams within the site selection, design, and operational decision support systems for hydropower; and (4) developing and assessing sustainability indicators for bioenergy feedstock production and hydropower development through integration of landscape and aquatic ecological science and socioeconomic analyses.

This capability supports DOE's energy and environmental missions and contributes to the technical basis for policy decisions. ORNL takes advantage of laboratory- to field-scale resources and expertise in geochemistry, hydrology, microbial ecology and genetics, aquatic ecology, and engineering to evaluate the impacts of energy production, transmission, distribution, and use on the environment.

Relevant leadership areas for ORNL include (1) novel integrated sensor and monitoring networks for long-term assessment of environmental change in response to energy production and use; (2) understanding of contaminant cycling and fate in ecosystems to inform the development of innovative remediation technologies and improve risk-based decision-making; (3) assessing impacts of energy production and distribution systems, including existing and hydropower developments, on aquatic ecosystem integrity through sensor systems, novel geospatial analyses, and modeling to identify thresholds and promote adaptability of monitoring and management regimes; (4) modeling and assessing biomass feedstock resources and the logistical and environmental effects of supplying biomass to facilities producing biomass-based fuels, power, heat, or bioproducts; and (5) technologies, systems analysis, and decision support for sustainable hydropower and other energy production and water use.

ORNL's Earth system science and engineering projects take advantage of world-class experimental and computational infrastructure, including neutrons at SNS and HFIR, data infrastructure (CADES), HPC infrastructure (e.g., OLCF), state-of-the-art greenhouses, field and laboratory facilities (including the Environmental Science Laboratory, Aquatic Ecology Laboratory, Mercury SFA Field Site, and the Y-12 Integrated Field Research Challenge site), JIBS, and CNMS. Funding comes from SC, EM, EERE, FE, NNSA, DoD, NE, and NRC.

Environmental Subsurface Science

ORNL's core capability in environmental subsurface science is foundational to advancing the fundamental understanding of processes that control biogeochemical transformation and fate of trace metals in complex, heterogeneous, and multiscale environmental systems. Examples of activities supported by this core capability include (1) delivery of a predictive understanding of complex, heterogeneous, multiscale environmental systems to describe uranium fate and transport in subsurface systems (e.g., through the ENIGMA consortium's demonstration of "founder" effect and memory response in subsurface microbial communities); (2) field- to molecular-scale geochemistry and microbiology to elucidate the coupled physical and biogeochemical processes that govern mercury transformations in headwater streams and their surrounding watersheds (explaining the role of stream periphyton biofilms on net methylmercury production in East Fork Poplar Creek); (3) state-of-the-art subsurface hydrology and reactive transport model development; and (4) integration of neutron scattering, neutron imaging, and exascale computing to understand enzymatic mechanisms for metal transformation in subsurface systems, the distribution of pore-sizes in heterogeneous solid matrices (e.g., soils and rocks), and to estimate fluid uptake rates by plant roots.

ORNL's strengths in predicting the state, flux, and residence times of trace metals, nutrients, and contaminants in environmental systems contribute to basic and applied R&D programs focused on extraction of fossil fuels, disposal of nuclear waste, and cleanup of DOE legacy contamination. ORNL leads one of the world's largest ongoing efforts in mercury research. The Critical Interfaces SFA is a multi-institutional, interdisciplinary program that integrates ORNL's leadership expertise in molecular- to field-scale hydrology, geochemistry, microbial ecology and genetics, biochemistry, and computational modeling to determine the fundamental mechanisms and environmental controls on mercury biogeochemical transformations in metabolically active transient storage zones in low-order stream systems. The ENIGMA consortium also takes advantage of ORNL's expertise and field site to improve the understanding of complex, heterogeneous, multiscale environmental systems with an emphasis on the role of subsurface microbial communities in regulating groundwater chemistry.

This core capability comprises a wide range of state-of-the-art facilities at ORNL, including the Critical Interfaces SFA Field Site, the Y-12 Integrated Field Research Challenge site, SNS, HFIR, OLCF, and CNMS. DOE user facilities at other national laboratories (e.g., Stanford Synchrotron Radiation Lightsource, Advanced Photon Source, Environmental Molecular Sciences Laboratory) are also utilized. Funding comes from SC, EM, FE, NNSA, DoD, and NRC.

Large Scale User Facilities/Advanced Instrumentation

ORNL has a distinguished record in developing and operating major facilities for DOE and in designing and deploying instrumentation. ORNL is noted for the breadth of the facilities and instrumentation that it develops and deploys for DOE and for its integration of these assets to deliver mission outcomes. The user facilities at ORNL attract thousands of researchers and support the development of the next generation of researchers.

SNS and HFIR together provide the world's foremost neutron-based capabilities for studying the structure and dynamics of materials, biological systems, and basic neutron physics. SNS is currently the world's most powerful pulsed spallation neutron source. For neutron scattering experiments that require a steady-state source, HFIR offers thermal and cold neutron beams that are unsurpassed worldwide. Thirty neutron scattering instruments are available to scientists at SNS and HFIR, and the Fundamental Neutron Physics Beamline (FnPB) is available at SNS. Significant investments in instrument improvements, sample environment, and data analysis capabilities make ORNL's neutron scattering instruments world leading. As part of a three-source strategy for ORNL, a high-brightness, long-wavelength STS design, has been developed and externally reviewed. The PPU project and STS leverage DOE's investment in neutron sciences. PPU will increase the neutron peak brightness and flux at SNS, increasing scientific capacity and capability on currently oversubscribed instruments. The PPU project also provides the platform for the STS. ORNL will pursue CD-2 and CD-3b approval for the PPU project in early FY 2020 and move toward construction following approval. ORNL will be prepared for CD-1 approval for STS in FY 2019. In addition, HFIR's capabilities for radioisotope production, materials irradiation, neutron activation analysis, and neutrino research make it an asset for isotope, materials and fuels testing, high energy physics, irradiation, and nuclear security science programs. HFIR is well positioned for the next 20 years with a new beryllium reflector design, which will support improved neutron production while maintaining its performance for neutron scattering. ORNL is evaluating upgrade paths for HFIR to provide world-leading capabilities in serving SC missions well into the future. Considerations will include optimal fuel, neutron moderation, and integration of neutron scattering with isotope production and materials irradiation.

The HPC resources of OLCF, including the IBM AC922 Summit, are available to users to solve computationally intensive scientific problems and to accelerate innovation for industry partners. ORNL's other strategic HPC resources include the Cray XC40 Gaea system, operated for NOAA to facilitate multiagency cooperation and R&D partnerships across the climate research community. Summit is now in full user operations. This pre-exascale, hybrid platform provides 200 PF of computing power for M&S and more than 3 exaops of computational power for AI applications and research. The OLCF-5/CORAL-2 system, Frontier, has received CD-2/3 approvals, and a build contract has been awarded. OLCF will decommission the Cray XK7 Titan supercomputer in August 2019 after 6 successful years of productive operational use delivering billions of compute hours. In 2018, ORNL entered into a strategic partnership with the US Air Force to provide mission-critical regional and global weather products that maximize America's war fighting power through the exploitation of timely, accurate, and relevant weather information. The research portion of this partnership will develop weather models for advanced architectures through acceleration of Air Force models using techniques that can be leveraged within DOE. The partnership relies on ORNL's National Center for Computational Sciences to provide high-availability, production-hardened HPC systems and services.

CNMS provides world-leading synthesis, characterization, and theory/modeling capabilities and expertise to the greater user community. Specific capabilities include synthesis, modeling, and characterization of inorganic nanomaterials (1D, 2D, and 3D nanomaterials and quantum materials) and organic polymers. These capabilities are focused on understanding the structure, dynamics, and functionality of nanostructured materials. Studies of nanoscale structure in soft matter use site-specific deuteration capabilities that enable neutron experiments. Development of instrumentation and characterization methods emphasizes new imaging capabilities, with a focus on quantitative measurements of functional properties using scanning probe microscopies, state-of-the-art scanning transmission electron microscopy, atom probe tomography, helium ion microscopy, and chemical imaging. New capabilities are also being provided to the nanoscience user community; in FY 2019, CNMS is adding a Raith VELION system for direct writing of nanostructures and performing single ion implantation; an electron energy loss spectrometer (EELS) to the MAC-STEM; and a new high-throughput pulsed laser deposition platform for 2D materials synthesis. Theoretical, computational, and data analytical approaches underpin the research activities across all areas of work at CNMS.

ORNL is home to three major R&D facilities sponsored by EERE: MDF, which includes the pilot-scale CFTF; the Buildings Technology Research and Integration Center (BTRIC), which includes the Maximum Building Energy Efficiency Laboratory (MAXLAB); and NTRC. These facilities enable R&D and demonstration of innovations in renewable electricity generation; energy-efficient homes, buildings, and manufacturing; and sustainable transportation. This cluster of industry-facing facilities enhances engagement with industry and provides a linkage to SC user facilities with complementary capabilities.

Large-scale user facilities and instrumentation are fundamental to ORNL's ability to deliver on its mission for DOE, especially supporting the broader user community. Work in this area is supported primarily by SC and EERE.

Mechanical Design and Engineering

ORNL deploys extensive expertise in mechanical design and engineering to support the development of a wide range of projects (e.g., reactors, accelerators, fusion experimental devices, enrichment technology) and instruments. For example, this core capability supports the US ITER project, the PPU project at SNS, the Majorana Demonstrator project, the Materials Plasma Exposure Experiment (MPEX) project, and the neutron electric dipole moment (nEDM) experiment. In many cases, mechanical design and engineering efforts have drawn upon expertise across ORNL. For example, expertise in mass spectrometry has contributed to the development of large-scale stable isotope enrichment systems. Expertise in the analysis of stress, strain, and thermal effects in composite materials, fluid dynamics, and dynamic analysis of rapidly rotating devices has been key to the development of advanced isotope separation devices. Further, ORNL capabilities in basic science and associated characterization tools have been exploited to provide innovative solutions in support of mechanical engineering applications. For example, HFIR's neutron scattering capabilities have been applied to map residual stress in manufactured components, helping to improve material reliability in various devices, including additively manufactured heat exchangers and fuel injectors. Further, ORNL's mechanical design and engineering capabilities provide breakthroughs in energy-efficient manufacturing; in the energy efficiency and durability of building envelopes, equipment, and appliances; and in transportation (including multicylinder combustion R&D and exhaust after-treatment development).

Mechanical engineering capabilities at ORNL have been used to developed remote systems for SNS, INMC, and, most recently, the Facility for Rare Isotope Beams (FRIB) at Michigan State University. Also, ORNL combines its expertise in mechanical design and engineering with other disciplines to support a range of nuclear capabilities, including the thermal/hydraulic design of HFIR irradiation experiments, the HFIR closed-loop supercritical-hydrogen cold neutron source, a novel molten salt experimental loop facility, the SNS mercury target systems, and the high-heat-flux divertor components for the Wendelstein 7-X superconducting stellarator. Foundational capabilities for remote operations have also been translated into the development of big-area AM devices for the 3D fabrication of very large builds.

ORNL's applied research facilities (MDF, CFTF, BTRIC, NTRC, and the remote systems development high-bay facility) support work by staff with expertise in robotics and remote systems design, thermal hydraulics, energy-efficient manufacturing, transportation, and residential and commercial buildings. Funding in this area originates from several sources, including SC, NE, EERE, NNSA, and SPP sponsors.

Nuclear and Radio Chemistry

A major focus of ORNL's nuclear and radiochemistry research is the development of highly selective separation techniques for the production of isotopes for a broad range of applications, including cancer treatment, commercial uses, and research. For example, development of methods for the separation of ^{249}Bk from ^{252}Cf enabled the recent discovery of four superheavy elements, including tennessine. Other actinide separations techniques, such as those for the separation of decay-enriched ^{251}Cf and ^{248}Cm from ^{252}Cf sources, are supporting the search for new superheavy elements in the approach to the island of stability. These capabilities have also enabled the development of specialized sources (including radioisotope power sources and sources used in the generation of specific nuclear signatures) and have inspired new ultra-trace characterization methods (such as isotope dilution mass spectrometry). ORNL's nuclear chemistry and enrichment expertise is also involved in maintaining and improving our nation's uranium enrichment capabilities. ORNL maintains and distributes the US inventory of enriched stable isotopes and radioisotopes for NP's National Isotope Development Center. Production-level separation processes based on electromagnetic and gas-centrifuge separation techniques are being advanced for both radioisotopes and stable isotopes.

HFIR, which provides the world's highest neutron flux, is used to irradiate target materials for production of various radioisotopes through the DOE NP Isotope Program and other sponsors.

Separations are conducted in INMC facilities, including Radiochemical Engineering Development Center (REDC), laboratories and hot cells in Buildings 4501 and 3047, and other radiological laboratories. As part of the IP, ORNL is also examining long-term needs for radiochemistry facilities to support radiopharmaceutical development. ORNL, supported by NP, is the nation's sole producer of ^{252}Cf and high-specific-activity ^{63}Ni, both of which are important in security and industry. Capabilities also exist for recovery of ^{225}Ac, an increasingly important medical isotope, from ^{229}Th. ORNL radiochemists use hot cells and radiological facilities to process and characterize other important radioisotopes, such as ^{75}Se, used in radiography, ^{63}Ni used in explosives detection, ^{133}Ba used as a calibration source, and medical isotopes ^{188}W, ^{227}Ac, ^{89}Sr, and ^{212}Pb. ORNL has established production capability for delivery of ^{227}Ac for medical applications and launched an effort to identify the resources needed to meet the increasing demand for this radioisotope. Funding provided by NASA supports production of ^{238}Pu for use in radioisotope power supplies and heat sources for planetary science missions. An automated target-processing system for the ^{238}Pu Supply Program will increase plutonium oxide production from about 50 to 400 g/year[22].

ORNL's nuclear and radiochemistry expertise, extensive radioanalytical capabilities (especially mass spectrometry), and neutron activation analysis capability at HFIR provide world-leading resources for ultra-trace analysis with applications that include environmental analysis, forensics, and security. For example, the Neutron Activation Analysis Laboratory, located within the HFIR complex, is the sole provider of routine analysis of International Atomic Energy Agency pre-inspection samples. Expertise in radiochemical separations, analyses, and nuclear material examinations is being applied to the management of nuclear material such as UNF; the detection of materials important to the management and security of the nuclear fuel cycle; the development of safer, more efficient nuclear fuels; and improvements in nuclear waste treatment. Funding in this area comes from several sources, including SC, NE, NNSA, DHS, DoD, NASA, NRC, and other government agencies.

Nuclear Engineering

Early work at ORNL demanded expertise in handling and processing unirradiated and irradiated nuclear materials and fuels, developing and operating nuclear reactors, and detecting radiation. These are the very foundations of the discipline of nuclear engineering. Today, ORNL leads the development of new materials and systems for fission and fusion, taking advantage of specialized facilities and core capabilities in materials science, chemistry, chemical engineering, computing, and other areas. ORNL has a wide range of specialized facilities for nuclear materials development and characterization. Capabilities include a complete "cradle to grave" suite, spanning materials irradiation capabilities at HFIR and post-irradiation characterization facilities at LAMDA, as well as hot cells within INMC. ORNL is also a leader in M&S for reactor physics and radiation transport, reactor systems, nuclear criticality safety, and reactor safety; radiation detection and imaging; and radioisotope production. Supporting all of these activities is the ability to develop, benchmark, and distribute validated M&S tools.

ORNL's nuclear-engineering expertise is critical to the continued viability of the nuclear power industry, including improved operations and life extension of the existing fleet. ORNL's expertise in the design and postirradiation examination of HFIR irradiation capsules is used to study reactor materials and accident-tolerant fuels. ORNL applies modern tools to carry out optical, scanning electron, and transmission electron microscopy as well as chemical, physical, and mechanical property measurements on irradiated fuel and structural materials in support of reactor and UNF systems R&D. ORNL contributes to next-

[22]R. M. Wham, R. S. Owens, R. J. Vedder, J. H. Miller, and S. Pierce, "Automation of Neptunium Oxide-Aluminum Target Fabrication," presented at NETS 2019—Nuclear and Emerging Technologies for Space, Richland, WA, February 25–28, 2019. Available at http://anstd.ans.org/NETS-2019-Papers/Track-5--Radioisotope-Power-Systems/abstract-118-0.pdf (accessed June 21, 2019).

generation reactor technology through the development and testing of new fuels, materials, and salts; improved instrumentation and controls; regulatory research; thermal-hydraulic experiments; and innovative system concepts. ORNL is the world leader in molten salt reactor (MSR) technology, collaborating domestically and internationally, and leading NE's MSR R&D program to advance the concept's maturation through M&S, development and operation of liquid salt flow loops for component and material testing, and system studies to ensure safe and efficient operations. ORNL is engaged with industry on the development of MSRs, gas-cooled reactors, and other advanced reactor concepts. ORNL recently initiated R&D activities for the TCR, including exploration of materials development in conjunction with ML and AM tools.

Through the development and application of computational analysis tools and nuclear data to advance the scientific understanding of observed phenomena, ORNL is solving complex problems that improve the efficiency and safe utilization of nuclear systems. The ORNL-developed SCALE code system is applied worldwide to perform design and safety analysis for reactor and nuclear facilities. ORNL's hybrid deterministic Monte Carlo methods have transformed computational radiation transport and have enabled reliable, high-fidelity solutions for large-scale, complex problems. ORNL leads CASL, which combines nuclear engineering and HPC to develop a high-fidelity virtual reactor capability that has been validated using operating cycles of the Tennessee Valley Authority's Watts Bar pressurized water reactors (PWRs) and is being applied to key industry operational and safety challenge problems. CASL continues to provide scientific understanding to improve the operation of PWRs, boiling water reactors, and small modular reactors (SMRs). In support of ITER, ORNL has developed innovative neutronics-modeling tools such as ADVANTG, making it possible to calculate neutron fluxes faster and more accurately for very large facilities and structures.

ORNL hired Pradeep Ramuhalli, a world-leading expert in sensing, who will bridge research in materials performance, sensors, and nuclear structures and Pablo Moresco to expand capabilities in computational physics modeling for nuclear forensics research that supports related efforts in nuclear engineering. Jason Nattress was hired as an Alvin M. Weinberg Distinguished Staff Fellow to develop new capabilities for material identification using multiparticle, multienergy transmission radiography.

ORNL nuclear engineering efforts employ HFIR, the hot cells of the Irradiated Fuels Examination Laboratory, the Irradiated Materials Examination and Testing Laboratory, the LAMDA laboratory, various hot cells and other radiological facilities within INMC, and OLCF. Funding in this area comes from several sources, including NE, SC, NNSA, DHS, the Defense Threat Reduction Agency, NASA, NRC, and other government agencies.

To preserve the expertise that is vital to this core capability, ORNL is incorporating knowledge transfer and succession planning into its hiring, recruiting, and retention practices as it continues its efforts to attract and retain staff in key leadership positions.

Nuclear Physics

ORNL's core capability in nuclear physics makes crucial contributions across the spectrum of DOE's Nuclear Physics portfolio, in both discovery science and applied programs. It spans theoretical and experimental research that is relevant to DOE's mission of developing an understanding of nuclear matter and fundamental symmetries that will help unlock the secrets of how the universe is put together.

Low-energy nuclear experimental research at ORNL focuses on understanding properties of nuclei far from the "valley of stability" through beta-decay spectroscopy, low-energy nuclear reactions, and gamma-ray spectroscopy. A team including physicists from ORNL recently performed a series of measurements on ^{110}Ru and ^{104,106}Mo at the CARIBU facility at Argonne National Laboratory, confirming theoretical predictions of triaxial nuclear shapes (where all three shape axes have different lengths).[23] Recent experiments at RIKEN in Japan have studied the beta and beta-delayed neutron decays of very neutron rich nuclei beyond doubly magic ^{78}Ni in unprecedented detail. Also, at RIKEN, a new search for the superheavy element 119 is under way using ^{248}Cm targets and digital electronics supplied by ORNL.

ORNL leads gas jet target development for nuclear astrophysics experiments using secondary beams at FRIB and helps lead aspects of the Separator for Capture Reactions. More recently, ORNL also assumed leadership roles for the FRIB Decay Station project to design and construct instrumentation for radioactive decay studies at FRIB. The decay station will also include the existing ^{3}HeN and Modular Total Absorption Spectrometer detector arrays from ORNL.

In nuclear theory, OLCF is used to investigate the structure and reactions of neutron-rich rare isotopes and nuclear astrophysical processes. ORNL develops world-leading approaches to relevant nuclei based on *ab initio* methods, HPC, and effective field theory, in addition to developing world-class core-collapse supernova (and soon neutron-star merger) simulations. Recent developments include the first quantum computing application in nuclear physics to calculate the binding energy of the deuteron.[24]

ORNL has special expertise in fundamental neutron physics enabled by the Fundamental Neutron Physics Beamline (FnPB) at SNS. Final results from NPDGamma have been published, and data analysis for the n-^{3}He experiment has been completed. Nab, the next experiment at the beamline, will make the most precise measurement of the electron-neutrino correlation parameter during a neutron decay. Both the superconducting magnet and the shielding required for Nab were recently installed, and the magnetic field was precisely mapped. The next experiment planned for FnPB is the ORNL-led search for nEDM with a design sensitivity a factor of 50 to 100 over previous experiments. ORNL leads development of light-collection devices and low-temperature electrodes for the experiment, drawing on its core capabilities in materials science. For example, ORNL-designed deuterated polymers are used in the nEDM electrodes.

ORNL leads research supporting the ton-scale ^{76}Ge LEGEND (Large Enriched Germanium Experiment for Neutrinoless Decay) experiment to search for the hypothesized neutrinoless double-beta decay mode of nuclei. The Majorana Demonstrator (MJD), a feasibility demonstration for the ton-scale experiment, is currently taking data at the Sanford Underground Research Facility in South Dakota. ORNL is the lead laboratory for MJD and made crucial contributions to the detector operation and data analysis. The LEGEND experiment will use a type of Ge detector invented at ORNL and developed with NP support. An LDRD project at ORNL is exploring even larger Ge detectors and active scintillators for LEGEND components.

ORNL expertise in the design and development of specialized electronics and detectors is also relevant to research at the Large Hadron Collider (LHC), at CERN, where ORNL researchers conduct relativistic heavy-ion collision experiments to investigate the physical properties of the quark-gluon plasma. ORNL continues to lead project upgrades of the Time Projection Chamber and Inner Tracking System of the LHC's ALICE heavy-ion detector. In FY 2019, ORNL developed a proposal for a Forward Calorimeter for ALICE and will participate in development of a letter of intent for future participation in the Electron-Ion Collider at NLB. ORNL also leads physics analysis of aspects of the ALICE data from Run 2, including jet shapes, jet substructure, photon-jet and jet-hadron correlations, and direct photons.

ORNL's nuclear data program includes cross-section measurements, development of evaluation and data analysis methods, and data processing. These activities provide nuclear data libraries for radiation

[23] J. M. Allmond and J. L. Wood, *Phys. Lett. B* **767**, 226–231 (2017).
[24] E. F. Dumitrescu et al., *Phys. Rev. Lett.* **120**, 210501 (2018).

transport analysis. Further, ORNL leads the ENDF/B Formats Committee to standardize all nuclear data formatting.

Funding in this area originates from SC and defense programs (NNSA and SPP sponsors).

Plasma and Fusion Energy Sciences

ORNL is DOE's lead laboratory for fusion nuclear science and fusion materials, which are required to fully enable fusion energy. ORNL scientists are experts in pellet fueling systems and are responsible for addressing challenges associated with closing the fusion fuel cycle, a requirement for a fusion pilot plant. Materials scientists at ORNL conduct experiments to support development of alloys and silicon carbide composites, which have been leveraged to develop a suite of economical high-strength radiation-resistant steels that derive their properties from a fine dispersion of engineered precipitate nanoclusters. These radiation-tolerant materials will be required to make a fusion pilot plant reliable and economical. ORNL's core capability in plasma and fusion energy sciences, coupled with its demonstrated abilities in large-scale project management, international collaboration, and computational simulation, is applied to support the mission of the FES program.

ORNL is well positioned to support the recommendations of the National Academies' Committee on a Strategic Plan for US Burning Plasma Research, which completed its report in 2018.[25] ORNL addresses the Committee's first recommendation, "the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant," through its leadership of the US ITER Project, its R&D and fabrication of US contributions to ITER, and its active participation in research related to burning plasmas and ITER technology. ORNL addresses the Committee's second recommendation, "the United States should start a national program of accompanying research and technology leading to… a compact pilot plant that produces electricity from fusion at the lowest possible capital cost," by leadership and collaborations in fusion technologies needed for a compact pilot plant.

As directed by DOE, ORNL leads the US ITER project and executes the program in conjunction with its partner laboratories, Princeton Plasma Physics Laboratory and Savannah River National Laboratory. US ITER fabrication activities and participation in the project will lead to the capability for creating, sustaining, and studying burning plasmas, the next step toward fusion energy as noted in the 2018 National Academies report. US hardware contributions include the world's highest-stored-energy pulsed superconducting magnet; superconductor for ITER toroidal field coils; a 1 GW cooling water system; high-power, long-pulse plasma heating systems; electrical power system components; parts of the tritium exhaust system; plasma instrumentation; and plasma disruption mitigation systems. The US ITER Project Office also works with the ITER Organization and other ITER domestic agencies to achieve the required integration of management, design, and procurement activities. Much of the R&D is also executed at ORNL.

ORNL has made progress towards the demonstration of the science and engineering to sustain a magnetically confined plasma with the properties needed for a compact fusion pilot plant. In parallel with US ITER efforts, ORNL applies its broad experimental and theoretical expertise in plasma science, strong synergies with materials in extreme environments, and computational science programs to develop materials and components that can meet the demands of a burning plasma environment and enable fusion energy. ORNL scientists are designing and building the Material–Plasma Exposure

[25]National Academies of Sciences, Engineering, and Medicine, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research,* National Academies Press, Washington, D.C., 2018 (doi: https://doi.org/10.17226/24971).

Experiment (MPEX) to address the challenges associated with exposing materials to high-energy, high-density plasmas. MPEX will provide world-leading capability where power plant level fluxes and fluences of particles will be incident on neutron-irradiated materials in prototypic geometries. MPEX will require development of superconducting magnets, an area where ORNL must grow to meet project and programmatic goals.

Facilities supporting this core capability include HFIR for materials irradiation; INMC (including hot cells for materials handling and testing and the Irradiated Materials Examination and Testing Laboratory and the LAMDA laboratory for materials characterization); the Fusion Pellet Laboratory for commissioning systems for use on fusion experiments around the world; and Proto-MPEX for testing the source concept for MPEX.

ORNL hired Charles Kessel, an expert in fusion nuclear science and fusion energy system studies, to lead the fusion blanket and fuel cycle studies.

SC funds the work in this area, including the US ITER project. Additional funding is received via SPP sponsors.

Power Systems and Electrical Engineering

ORNL researchers deliver innovations in power flow, electric grid modernization, energy-efficient buildings and transportation, and smart manufacturing. For example, ORNL developed high-performance inverters and converters for electric vehicles (EVs) and demonstrated the first wireless bidirectional charging and energy management system for a building and a vehicle operating as an integrated energy system. This core capability (1) delivers advances in high-temperature, high-power-density applications; (2) enables high-efficiency transportation and electrification systems to reduce US reliance on foreign oil; (3) develops technologies for power flow control, grid monitoring (e.g., FNET/GridEye), and grid protection that support development of a secure and reliable 21st century electricity delivery system; and (4) creates advanced building sensors, communications, and controls for power management systems to maximize energy efficiency.

Through DOE’s Grid Modernization Laboratory Consortium (GMLC), ORNL addresses the challenges of integrating conventional and renewable electric generating sources with energy storage and smart buildings while ensuring that the grid is resilient and secure to withstand growing cybersecurity concerns (see Sect. A.12). ORNL tests controllers in multiple environments, including both simulation and full hardware environments on different scales of power and voltage levels (24 to 480 V) as well as different grid configurations and communications protocols. A strong partnership with the Chattanooga Electric Power Board (EPB) reinforces this core capability by providing real-world understanding and commercial-scale implementation of emerging technologies.

ORNL leads in the creation of alternating-current power flow control systems for grid control and increased resilience. An advanced grid requires new materials for power electronics and energy storage devices. ORNL is a leader in power electronics R&D (serving as the Vehicle Technologies Office lead laboratory for power electronics) and is taking advantage of resources at NTRC to develop high-power devices to improve reliability and reduce costs. ORNL is leading the way in innovative wireless charging of EVs. In addition to providing an autonomous, safe, and convenient option for charging EVs, wireless charging when applied to dynamic or quasi-dynamic scenarios can provide virtually unlimited range to EVs, removing “range anxiety” and long charging times because the vehicles can be charged continuously while they are in motion. Recent achievements include developing 120 kW vehicle wireless charging at 97% efficiency.

ORNL designs, develops, and tests new materials capable of supporting cost-effective and higher-performing electricity control devices and systems. ORNL collaborates in developing power electronics from concept to prototype and applies its expertise in materials to develop innovative electronics and sensors.

Enhanced cybersecurity measures are required to prevent malicious attacks on energy infrastructure. ORNL's Acceleration Project for the Smart Grid is a high-profile activity that will improve the efforts for securing smart grid systems.

Expertise gained in supporting a stable energy infrastructure for ORNL operations has been leveraged to facilitate large science experiments at other sites, such as LHC and FRIB. Current activities leverage broad expertise in electronics for extreme environments, compact high-voltage power supplies, pulsed power conversion, the IoT (connected sensor and internet framework), RF, and communications capabilities for intelligent systems support.

ORNL supports DOE's energy mission by providing resources that can be used to catalyze the timely, material, and efficient transformation of the nation's energy system. Work in this area is conducted using the NTRC Power Electronics and Electrical Machinery Laboratory, the DECC microgrid, and the Powerline Conductor Accelerated Testing Facility; resources for thin-film deposition (inkjet printing, ultrasonic spray, sputtering, evaporation, low-temperature photonic curing); and tools for characterization of materials, devices, and communications. EERE, OE, and DOE's Office of Policy are the primary sponsors. SC also benefits from ORNL expertise in this area.

Systems Engineering and Integration

ORNL's core capability in systems engineering and integration takes advantage of the full range of capabilities across the laboratory. Solutions to pressing S&T challenges are developed by integrating expertise in fundamental science, technology, and project management in multidisciplinary and multi-institutional teams. This allows us to accelerate research innovation in managing scientific projects of various sizes through partnerships across ORNL and with universities, other national laboratories, and private industry. Examples of recent accomplishments in working with private industry include modeling of combustion processes, understanding materials properties for AM, and modeling the energy use of buildings at the community scale.

ORNL's strength in pursuing solutions from concept to implementation and in spanning fundamental to applied research ensures the success of national and international projects, such as SNS, OLCF, Proto-MPEX, the ^{238}Pu process development project, the MJD project, the nEDM experiment, ALICE at CERN, and ITER. ORNL also relies on deep systems-engineering capabilities to deliver innovative solutions for manufacturing, transportation, and buildings by applying broad capabilities in materials science and engineering, computational science, decision science and analysis, mechanical design and engineering, nuclear engineering, chemical engineering, and power systems and electrical engineering. In addition, ORNL has a successful track record of delivering innovative tools and technologies as a lead and partner on Energy Innovation Hubs (CASL, CMI), the Institute for Advanced Composite Materials Innovation, and other multi-institutional collaborations (Fuels/Engine Co-Optima, GMLC, Lightweight Innovations for Tomorrow, Clean Energy Smart Manufacturing Innovation Institute).

Additionally, ORNL's EERE R&D facilities (NTRC; BTRIC, including MAXLAB and DECC; MDF; and CFTF) build on ORNL scientific systems infrastructure to develop and deliver market-driven solutions for energy-saving homes, buildings, and manufacturing; sustainable transportation; and power generation. Capabilities and scientific expertise available within these facilities are highly sought after by industry and other sponsors. Recent achievements include combining materials and AM to fabricate 72 turbine blades for a 5 MW Solar Turbines engine.

ORNL has hired Hong Wang, to grow the laboratory's capability in cross-discipline control frameworks for operational optimization of complex systems in transportation, manufacturing, and grid/buildings interactions; Tom Kurfess, to build capabilities in next-generation digital manufacturing and IoT; Scott Smith, to advance capabilities in hybrid manufacturing, machining, and machine tool development; and Ron Salesky to provide new capabilities in special communications to support emerging autonomy research. Vlastimil Kunc has been appointed to lead the newly established Manufacturing Science Group to integrate materials science with AM processes for multiphase metallic materials and fiber reinforced polymer composites.

The primary sponsors for these efforts include SC, EERE, OE, NE, and NNSA. Some support is also provided by DHS, NRC, DoD, and other SPP sponsors.

Science Strategy for the Future

ORNL's science strategy for the future reflects the same sense of urgency and purpose that drove the creation of the laboratory in 1943, when it was established to deliver transformative science and technology (S&T) for the Manhattan Project. In that spirit, we are focusing on strengthening areas in which we have demonstrated scientific leadership and leveraging these strengths to build new capabilities for solving compelling problems.

- We are undertaking major improvements at the Spallation Neutron Source, including the Proton Power Upgrade and the Second Target Station, as well as the design of instrumentation and supporting data analytics, to provide unprecedented capabilities. By delivering the world's highest peak brightness cold neutrons, the Second Target Station will provide new insights into the assembly of hierarchical materials (e.g., polymers and protein complexes) and enable in situ and operando studies of dynamic processes. We are planning a series of cost-effective improvements to the High Flux Isotope Reactor to sustain its world-leading capabilities for neutron scattering, materials irradiation, and isotope production into the future.
- We will continue to deliver and exploit the world's most powerful computing systems for science. Our 200 petaflop Summit system is also capable of >3 exaops of mixed-precision calculations and is the world's most powerful artificial intelligence (AI) platform; its successor, the exascale Frontier system, will maintain our tradition of pioneering innovative technologies to provide unprecedented capabilities to the S&T community. To support next-generation application accelerators, we are deploying qubits to users via the cloud and exploring quantum materials, devices, and algorithms for future architectures. We continue our leadership of the Exascale Computing Project to provide the ecosystem needed to enable the application of exascale systems to emerging research areas and national needs, and we are expanding our capabilities in data analytics, AI, and machine learning for applications ranging from data classification to structure-to-function relationships to cybersecurity.
- As the nation's leading materials laboratory, we will continue to expand our expertise and capabilities in nano-, functional, and structural materials. Our focus in quantum materials and enabling S&T for quantum information science (QIS) builds on our strengths in strongly correlated materials, supported by expertise in single-crystal and layered materials synthesis, atomic-level characterization, neutron scattering, and computing. We have invested in specialized equipment to support our QIS research, and construction of the Translational Research Capability facility will allow us to consolidate our resources. We are also focused on establishing leadership in polymer S&T, drawing on growing capabilities at the Spallation Neutron Source, at the Center for Nanophase Materials Sciences, and in our core programs, including strategic hires in polymer synthesis and modeling. Our leadership in materials under extreme conditions, advanced manufacturing, and carbon composites has its origins in ORNL's materials portfolio and continues to contribute to and benefit from these underpinning capabilities.

- Leveraging strengths in nuclear S&T that can be traced to the very origins of ORNL, we are pursuing a new concept in nuclear technology design, the Transformational Challenge Reactor, with the goal of realizing affordable, sustainable, and broadly available electricity. In addition to leading the US ITER project, we are leading the development of next-generation fusion devices, with a focus on new materials and modeling and simulation. Building on our resources in nuclear chemistry and separations science, we are expanding our world-leading capabilities for producing radioisotopes and stable isotopes, including scaling up bench- and pilot-scale operations to full production levels.
- We will continue our efforts to advance the understanding of complex biological and environmental systems, applying our strengths in neutrons, materials (e.g., mass spectrometry and imaging), and computing and our core capabilities in relevant fields to advance the work of the Center for Bioenergy Innovation, underpin our ability to understand systems at levels from the gene to the ecosystem, and inform our development of new applications in biosecurity.

Our science strategy will also sustain broad efforts in applied research that lead to new energy technologies, drive innovations that contribute to the nation's economic prosperity, and contribute to national security to meet the mission needs of the US Department of Energy (DOE) and other sponsors.

Infrastructure

Overview of Site Facilities and Infrastructure

ORNL, located 10 miles southwest of the city of Oak Ridge, Tennessee, occupies about 4,421 acres of the federal Oak Ridge Reservation (ORR; 34,000 acres). Daily, ORNL hosts approximately 6,500 people, comprising UT-Battelle's roughly 4,700 employees, other prime contractors' staff, subcontractors, and guests. To support its R&D missions, ORNL provides a wide variety of on-site services, including operation and maintenance of all supporting utilities and infrastructure, 24/7 security, dedicated fire and emergency response, medical facilities, fabrication and assembly services, a guest house, and other support functions. Work is performed in 208 operational SC buildings (4.7M gross square feet [GSF]); in addition, there are 74 operational buildings (0.37M GSF) assigned to DOE's Office of Environmental Management (EM). Forty-nine buildings in shutdown status, owned by SC, EM, and NE, represent 0.30M GSF of ORNL's building inventory.

All SC mission-unique facilities (1.2M GSF) have an adequate condition rating. Of SC's non-mission-unique facilities, 90% are rated adequate, with the balance rated substandard and inadequate. Substandard buildings, typically more than 50 years old, will be repurposed or excessed. For SC's operating Other Structures and Facilities (OSFs), 88% are rated adequate with the remaining 12% rated substandard. Building 4500N (363,980 square feet) is the largest substandard building on campus, with $4.7M in operating costs and deferred maintenance (DM) of $22M. This facility is an important focus of modernization efforts, along with aging utility systems (i.e., substandard OSFs).

Research is also conducted in off-site leased facilities (11 facilities totaling 0.32M GSF), providing ready access for industrial partners. ORNL's Hardin Valley Campus, about 7 miles from the main campus, hosts the MDF and NTRC. Growing demand for ORNL capabilities in advanced manufacturing has led to the expansion of the MDF into additional leased space. The CFTF is located at a separate site in Oak Ridge, 5 miles from the main campus. ORNL's leased space portfolio is evaluated frequently to better support mission needs and identify consolidation or reduction opportunities.

ORNL's *Site Wide Master Plan* can be found at https://services.ornl.gov/ronweb/Media/ORNLswmp.pdf.

ORR land use is governed by the current ORR Land Use Plan (*Oak Ridge Reservation Planning: Integrating Multiple Land Use Needs. FY2012 Update*. DOE/ORO/2411, Oak Ridge National Laboratory, Oak Ridge, Tennessee).

Campus Strategy

ORNL's campus strategy is focused on advancing distinctive scientific missions. The execution of this strategy relies on achieving four primary objectives:

1. Advance science and energy leadership by:
   - Advancing the science and impact of neutrons,
   - Scaling computing and data analytics to exascale and beyond for science and energy,
   - Accelerating the scientific basis for breakthrough nuclear technologies and systems, and
   - Enhancing strategic capabilities in isotope R&D and production.
2. Establish a modern, adaptable infrastructure to support research.
3. Return the ORNL Central Campus to productive science missions.
4. Reduce excess facility liabilities.

Critical infrastructure needs related to each objective are identified and addressed through ORNL's annual Mission Readiness process, culminating in the planned facilities and infrastructure investments shown in the figure below. These four objectives will be accomplished, in part, through successful completion of the following projects.

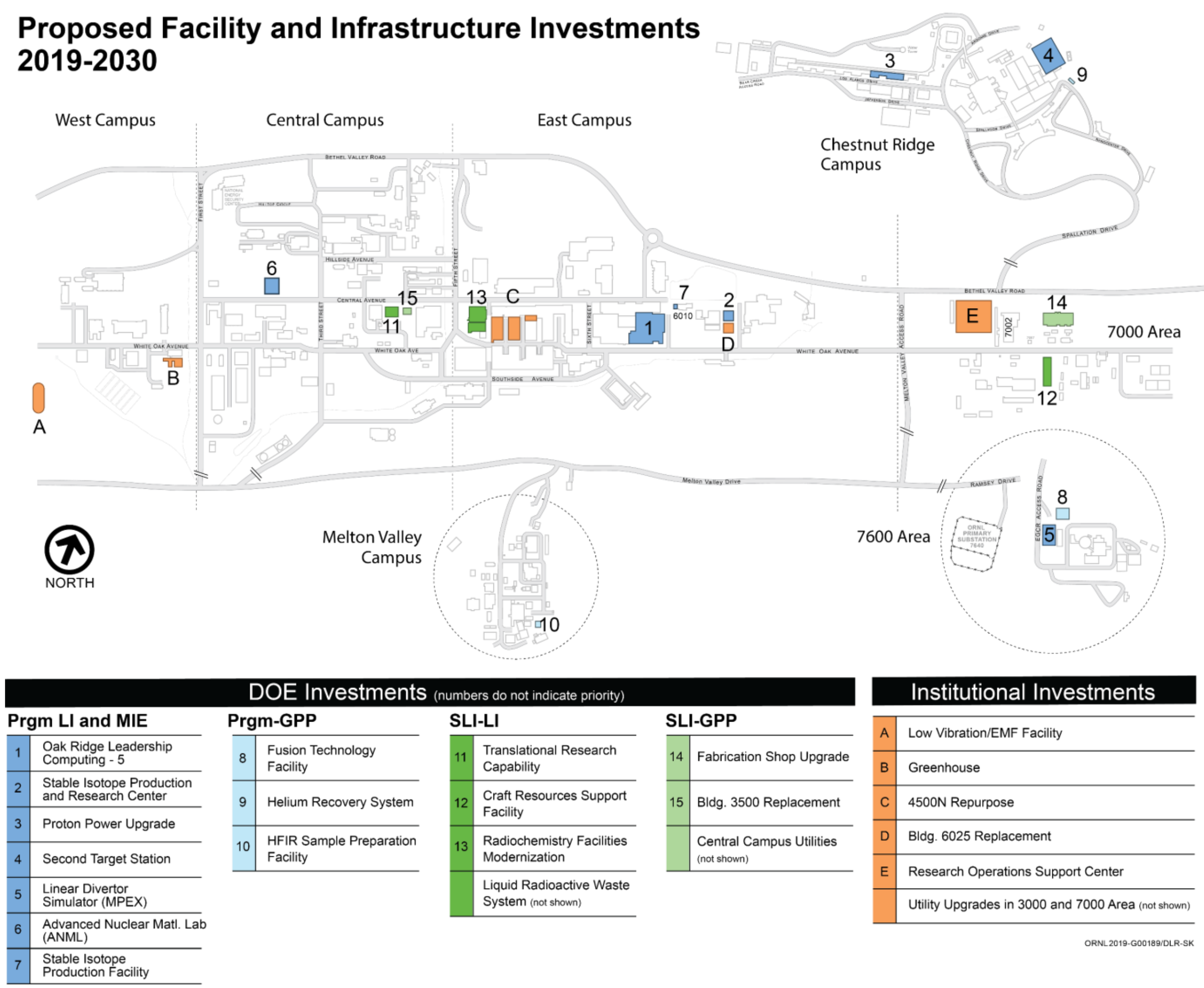


Figure: Proposed facility and infrastructure investments

Four programmatic line item construction projects:

- SNS PPU, supported by BES (CD-1 and CD-3a approved)
- SNS STS, supported by BES (CD-1 in process)
- SIPRC, supported by NP (CD-0 approved)
- ANML, supported by NE (CD-0 in process)

Two lease-to-own leadership-class computing systems:

- OLCF-4 (Summit), supported by ASCR (complete)
- OLCF-5 (Frontier), supported by ASCR (CD-3a approved, CD-2/3 achieved in March 2019)

Two MIEs:

- MPEX, supported by SC Fusion Energy Sciences Program (FES) (CD-0 for Linear Divertor Simulator approved)
- SIPF, supported by NP (progressing toward CD-2/3 equivalent)

Four Science Laboratories Infrastructure (SLI) line item construction projects:

- TRC facility (CD-3a approved, CD-2/3 in process)
- Liquid Radioactive Waste System (CD-0 approved)
- Craft Resources Support Facility (CD-0 approved)
- Radiochemistry Facilities Modernization (proposed for FY 2023–2025)

Three programmatic General Plant Projects (GPPs):

- Fusion Technology Facility (proposed for FY 2021–2023)
- HFIR Sample Preparation Facility (proposed)
- Helium Recovery System (proposed)

Four SLI GPPs:

- Fabrication Shop (Building 7012) heating, ventilation, and air conditioning upgrade (scheduled for completion in FY 2019)
- Building 3500 Replacement (proposed for FY 2020–2021)
- Central Campus Utilities (proposed for FY 2020–2021)
- Decontamination and Decommissioning (D&D) of Aging Facilities (proposed)

Numerous smaller projects supported through Institutional GPP (IGPP) funding.

Each of these projects is discussed in more detail below.

Objective 1: Advance Science and Energy Leadership

Our campus strategy focuses on five areas of infrastructure investment to advance ORNL's science and energy leadership and enable accomplishment of the major initiatives described.

Advancing the science and impact of neutrons. Continued operation of SNS and HFIR as world-leading neutron scattering user facilities requires two major programmatic investments. The PPU at SNS will increase power delivered to the FTS to 2 MW, increase neutron flux on available beamlines, and provide additional neutron flux capacity to support construction of the STS. Addition of the STS to SNS will provide ORNL with three complementary neutron sources, ensuring US leadership in neutron sciences for the foreseeable future. HFIR has operated for 53 years and is a key scientific asset with capabilities unlikely to be eclipsed by new reactor designs. Upgrading HFIR with a new reactor vessel along with strategic facility improvements would improve and extend the reactor's capabilities for another half-century at a fraction of the cost of new construction. Teams are beginning to evaluate multiple options to ensure the sustainment of this important asset well into the future. Growth in the use of ORNL's neutron scattering facilities will increase demands on research support functions, requiring one additional, smaller infrastructure investment in the near term: a GPP-funded sample preparation facility at HFIR. GPP funding is also requested for a helium recovery system to be installed on Chestnut Ridge.

Scaling computing and data analytics to exascale and beyond for science and energy. Leadership-class computing underpins nearly all scientific disciplines. Thus, continued development of ORNL's HPC infrastructure as part of OLCF is a high priority. DOE's well-defined path to maintain leadership in HPC includes continued operation of the pre-exascale Summit machine (OLCF-4) in 2019 and acquisition, installation, and operation of an initial exascale system, Frontier (OLCF-5), in 2021–2022. To leverage significant prior investments (about $100M) in power and cooling water systems, Frontier will be housed in Building 5600, Room E102, and Building 5800 is being reconfigured to increase power and cooling capabilities for the computing complex. Construction of the proposed TRC will provide additional resources for housing novel capabilities in quantum and neuromorphic computing and will free up space in Building 5800 for deployment of exascale computing hardware and HPC infrastructure.

Accelerating the discovery and design of new materials for energy. Accelerating design, discovery, and deployment of new materials and manufacturing processes requires specialized instrumentation and facilities. Over the past five years, ORNL has made discretionary investments to secure new world-class tools for materials science, including a secondary ion time-of-flight mass spectrometer, a MAC-STEM, X-ray tomography, and a low-temperature four-probe scanning tunneling microscope. Further investments are planned to support our quantum materials and QIS initiative. To support increasingly sensitive imaging equipment, $10M in institutional funds has been allocated, and design is under way to provide a low-vibration, and low-electromagnetic field (EMF) facility. Renovating Building 4500N, Wing 1, will provide modern laboratories for materials R&D. In preparation for TRC, a proposed investment of $100M, ORNL has successfully completed CD-3a with CD-2/3b in process.

Advanced manufacturing is an important component of our materials portfolio. UT-Battelle has leased off-site space for MDF since 2010 to assist industry in adopting new manufacturing technologies and to provide expertise in materials synthesis, characterization, and process technology. Growing demand for these activities has led ORNL to lease additional space in an adjacent building.

Advancing the scientific basis for breakthrough nuclear technologies and systems. ORNL's nuclear capabilities support several SC programs (NP, FES, and BES), DOE programs (NE and NNSA), and sponsors in areas that span fission energy technologies, fusion R&D for plasma materials and fuel cycle, radioisotope production and R&D, and nuclear security. These capabilities are dependent on:

- HFIR operation as a high-flux irradiation source. Challenges include sustained programmatic operations support, new fuel fabrication, spent fuel shipment, and annual funding sufficient for planned maintenance and life extension projects. Investments above fixed operating costs will be needed to address fuel fabrication process improvements as production activities resume at BWXT. In addition, a new permanent reflector and four new beam tubes will need to be fabricated in preparation for the beryllium outage scheduled for FY 2023.
- INMC operation for radioisotope production, and processing and handling of irradiated and nuclear materials. INMC comprises five nonreactor nuclear facilities, including the Radio-chemical Engineering Development Center (REDC), four primary radiological facilities, and various research and support facilities in Bethel and Melton valleys. Significant program growth, particularly in isotope production, is challenging the capacity of INMC, and a mission-oriented steward, consistently funding INMC operation, would ensure long-term sustainability and

compliance with DOE's nuclear safety standards. An SLI line item has been proposed for FY 2023 to preserve and improve currently operating radiochemistry facilities in Buildings 4501 and 4505. The demand for new approaches to realizing next-generation nuclear energy systems has driven an effort to pursue mission need approval (CD-0) by NE for ANML to expand ORNL's capabilities for world-class nuclear-related materials research, development, analysis, testing, and qualification. ANML is envisioned as a radiological space, and several options are being considered, including renovation of an existing facility.

- A new Fusion Technology Facility. Programmatic GPP investments ($20M) are proposed for FY 2021.

Enhancing the strategic capabilities of isotope production and R&D. The DOE Isotope Program is grounded in ORNL's research and production facilities: HFIR, ESIPP, and INMC (including REDC).

- Stable isotope portfolio: ORNL proposes to meet national demand for critical isotope production and eliminate national dependence on foreign suppliers by completing the SIPF MIE by 2025 and continuing to expand stable isotope research and production capabilities through a number of major initiatives. A new NP programmatic line item, SIPRC was proposed and approved at CD-0 in FY 2019 to greatly expand research and production capabilities for stable isotopes using a number of different enrichment technologies. In close association with SIPRC, ORNL proposes to optimize all aspects of the stable isotope portfolio: electromagnetic, gas centrifuge and other isotope enrichment technologies, R&D and other supporting laboratories, stable isotope storage and dispensing operations, and technical services for preparing special isotope forms through physical and chemical conversions.
- Radioisotopes: Increased demand is projected for radioisotopes for basic science, medical applications including treatment of various cancers, and applied R&D. To support this programmatic growth, ORNL is considering expanding its radioisotope infrastructure by repurposing existing facilities with new modular hot cell configurations and developing greenfield options to construct new radioisotope facilities that are fully optimized to carry this vitally important capability into the future.

Objective 2: Establish a Modern Adaptable Infrastructure to Support Research

Managing radioactive waste. As EM works toward completion of its Oak Ridge legacy waste mission, continued reliance on the EM infrastructure for management of gaseous, liquid, and transuranic debris waste from ORNL nuclear and radiological facilities is increasingly problematic. This infrastructure is 30–60 years old, oversized, and not designed for the waste generated by today's isotope production and nuclear R&D missions. EM will shut down portions of the existing infrastructure once legacy waste missions are completed, so with this deadline as motivation, ORNL has been developing independent capabilities to achieve waste management self-sufficiency. IGPP investments have created a remote-handled waste loading station at REDC, and additional investments are proposed to construct a local high-efficiency particulate air filtration system and exhaust ventilation stack at Building 3525, enabling its removal from the EM-operated central stack. Future infrastructure investments will be needed, most notably a liquid waste treatment capability for high-activity radioactive liquids, which will require an SLI line item in the FY 2021–FY 2024 timeframe. The mission need (CD-0) for this capability has already been established, but effort over the past few years has been devoted to waste minimization efforts, with a focus on reducing the capital investment ultimately required to provide this important capability. There is no long-term waste management strategy agreed upon by SC and EM; therefore, it is important for SC to engage EM in the development of the next ORR EM cleanup contract to ensure that the correct scope is addressed from an SC perspective.

Revitalizing the ORNL craft resource facilities. The last portion of the ORNL campus to undergo modernization is the 7000 Area. This section of the laboratory enables our ~600 craft employees to support ORNL's research and operations. A new shipping and receiving facility, constructed using IGPP funding, was the first phase of modernization in 2013–2014. Construction of a new Research Operations Support Center (ROSC) is under way, also using IGPP funds, with estimated completion in 2021. This facility will house emergency response and security personnel, allowing us to exit and complete D&D on two 1940s-vintage facilities in the Central Campus area. SLI GPP investments addressing longstanding environmental control challenges in our fabrication and machining facility (Building 7012) are scheduled for completion in FY 2019. Finally, ORNL is proposing a new SLI line item in the FY 2021–FY 2022 timeframe that would provide a facility housing a vehicle garage and shops for sheet metal, carpenters, mechanics, and electricians. This facility would complete the 7000 Area modernization and enable the D&D of 10 or more 1950s-vintage facilities.

Enabling biological and environmental research. Construction of a greenhouse/headhouse (~$6.1M) with modern-day, automated phenotyping equipment began in FY 2018 and supports CBI, Next Generation Ecosystem Experiments (NGEE)–Arctic, SPRUCE, and other environmental systems studies for rapid, data-rich collection and assimilation. The new phenotyping system will be operational by the end of FY 2019 and we anticipate adding additional data systems in FY 2020 to accommodate the flood of data coming from the new system.

Objective 3: Return the ORNL Central Campus to Productive Science Missions

ORNL's strategy to revitalize the Central Campus includes five primary components: (1) construct the TRC, (2) construct or renovate an existing facility for ANML, (3) renovate or replace Building 3500 to provide modern office space near several important scientific facilities, (4) vacate 1940s-vintage mission support facilities, and (5) advocate for accelerating EM cleanup work.

Construct TRC. The TRC facility will be constructed in the 3000 area of the ORNL campus, linking the East and West Campus areas through the Central Avenue pedestrian spine. The TRC will foster scientific excellence in the delivery of vital research by providing world-class, highly flexible, and collaborative laboratory facilities to advance the core science missions of ORNL. This facility will provide modern, adaptable space in response to the pressing demand to support advances in computing, materials science, and a wide range of multidisciplinary research while enhancing multiple ORNL core capabilities and supporting DOE science missions. Finally, TRC construction will enable deployment of exascale computing by freeing up space for HPC infrastructure. ORNL has received CD-3a approval with CD-2/3b in process.

Establish ANML. This facility will support development of materials designed to withstand extreme environments (e.g., temperature, pressure, chemical, radiation, plasma) and to develop approaches leading to "born qualified" materials for these environments. ANML is envisioned as a radiological facility providing world-class capabilities for research, development, analysis, testing, and qualification of materials to surpass current performance limits and to extend service life in extreme environments. ORNL intends to submit a Mission Need Justification to NE in FY 2019. Along with options for construction, serious consideration is being given to renovation of an existing facility to support this need.

Renovate/Replace Building 3500. A proposed FY 2020 SLI GPP investment will support replacement of existing space in the Central Campus area (e.g., Building 3500) to provide much-needed contemporary work/office space for staff who are still housed in 1950s facilities; it will also eliminate $2M in DM.

Vacate aging mission support facilities. With the construction of the ROSC in the 7000 Area, ORNL will vacate the fire station (Building 2500, built in 1943) and protective force station (Building 3037, built in 1951). Buildings 2518, 2523, and 2621, all more than 55 years old, are also slated to be vacated. Collectively, these facilities represent 45,000 square feet of excess space that can be demolished.

Advocate for accelerated EM cleanup. ORNL's Central Campus, a prime location for future development, currently houses a number of excess facilities pending final demolition. The presence of these aged facilities hinders modernization and increases liabilities and risks. EM is currently planning cleanup activities in ORNL's Central Campus. Decommissioning and demolition of these aged excess facilities is vital to current and future mission readiness.

Objective 4: Reduce Excess Facility Liabilities

ORNL expends approximately $3.2M annually on excess facilities to minimize environmental and safety risks. These costs are expected to grow if these facilities are not demolished soon. Additionally, several of these facilities represent barriers to continued campus modernization. Working with DOE's Excess Contaminated Facilities Working Group, ORNL has prioritized excess facilities into four groups:

- SC and NE facilities at the Y-12 National Security Complex (Y-12),
- Several facilities on ORNL's Central Campus,
- 7000 Area facilities (see Objective 2 above), and
- Balance of buildings for demolition

SC and NE facilities at the Y-12 National Security Complex. Due to deteriorated condition and size, ORNL facilities at Y-12 represent the highest ORNL cost risk. In FY 2017, Biology Complex facilities (Buildings 9207, 9210, and 9401-1) at Y-12 were characterized in preparation for pending demolition, and two small Biology Complex facilities (Buildings 9770-2 and 9743-2) were demolished in July 2018. Although the allocation in FY 2018 of funding for D&D of the former Biology Complex was encouraging, and the Tennessee Historical Commission recently approved the demolition of Buildings 9207 and 9210, significant challenges will remain, with three very large Y-12 facilities (Buildings 9201-2, 9204-1, and 9204-3) continuing to pose liability after the removal of all former Biology Complex buildings.

Several facilities on ORNL's Central Campus. EM continues to perform maintenance and surveillance for numerous excess facilities at ORNL, including several facilities in the Central Campus. The continued presence of hazardous materials in these areas presents an increased risk to staff and missions and impedes laboratory modernization by blocking prime real estate from redevelopment. EM is currently planning a campaign to address these issues in the Central Campus.

Balance of buildings for demolition. Following closure of the Holifield Radioactive Ion Beam Facility as a user facility in 2012, NP funded partial decommissioning through FY 2017. To avoid additional cost and liability, given EM's proposed D&D schedule, sufficient resources must be provided to stave off deterioration and ensure that the building will be safe to enter.

Future Infrastructure Gaps within a 10-Year Window

Much of ORNL's utility system has been upgraded, but key aspects remain as improvement priorities, including upgrades to the secondary and tertiary sewage treatment facilities and replacement of an aging chiller plant (to be achieved through chilled water system interconnections). ORNL is also subject to the risk of complete shutdown due to a single-point failure of the water supply; this supply has been disrupted several times over the past 5 years because of system breaks, and additional breaks are expected, given the age of the supply lines. Plans to mitigate this risk are under active discussion.

Infrastructure Investment Summary

Over the last 17 years, institutional investments have been the predominant funding mechanism for continued site modernization. Since FY 2002, when ORNL began using IGPP for core infrastructure improvements, 95 projects have been completed at a total cost of $203M. Over the next decade, we expect to continue investing $25M–$30M per year in infrastructure to recapitalize and sustain aging assets, some of which are 75 years old. Funding priorities for disposing of excess facilities are identified in the Campus Strategy.

Maintenance and repair investments are between 2% and 4% of the replacement plant value. Thirty-three percent of ORNL's operational non-mission-unique facilities, representing approximately 48% of the total gross square footage, are more than 50 years old and carry nearly 91% of DM.

Site Sustainability Plan Summary

The ORNL Site Sustainability Plan (SSP) was submitted in December 2018 through the DOE Sustainability Performance Office (SPO) Energy Data Dashboard Process. Executive Order (EO) 13834, Efficient Federal Operations, issued on May 17, 2018, directs federal agencies to manage their buildings, vehicles, and overall operations to optimize energy efficiency and environmental performance, reduce waste, and cut costs. The targets and goals of prior years have been replaced with directions to follow statutes. As DOE sites await new targets and mandates, data are being collected and recorded in the SPO Dashboard. The current SSP focuses on operational practices and efficiencies. At ORNL:

- Greenhouse gas (GHG) emissions have been reduced 3% relative to the FY 2008 baseline, which was not on target to meet previous DOE goals. Future GHG targets are being developed. ORNL faces a challenge in meeting any GHG reduction goals because of mission-driven growth in energy demand.
- Energy use intensity (EUI) has experienced a reduction of 32% since the FY 2003 baseline, exceeding the target set in the past.
- Water use intensity (WUI) has been reduced 30% from the previous FY 2007 baseline and is on track to reach a 36% reduction by FY 2025.

High Performance Sustainable Buildings (HPSBs)

ORNL maintains a portfolio of 15% of applicable buildings that meet all HPSB Guiding Principles (GPs). ORNL has documented GP compliance for 20 of 133 applicable buildings and expects to meet or exceed the FY 2025 DOE goal of 17% HPSB inventory.

Energy Savings Performance Contracts (ESPCs)

The ESPC with Johnson Controls is currently in its eighth performance period. DOE, Johnson Controls, and ORNL conduct regularly scheduled meetings to review performance. Improvements to the central steam plant and steam distribution system continue to drive the energy savings of the ESPC, supported by additional energy conservation measures and operations and maintenance cost savings. Annual energy savings include 12,258 million watt-hours of electricity, 17 million watts of electrical demand, 707,019 million Btu of natural gas, 18,864 million Btu of fuel oil, and 170 million gallons of water. The energy, fuel, and water savings contribute to the EUI and WUI reductions discussed in the previous paragraphs.

Electricity Use, Historical Cost, and Cost/Use Projections

The historical and projected electricity use and cost graph includes ORNL, SNS, and off-campus leased facilities, following the annual SSP guidance and SPO Dashboard reporting process. Estimated costs include escalation in Tennessee Valley Authority and municipality rates through FY 2025.

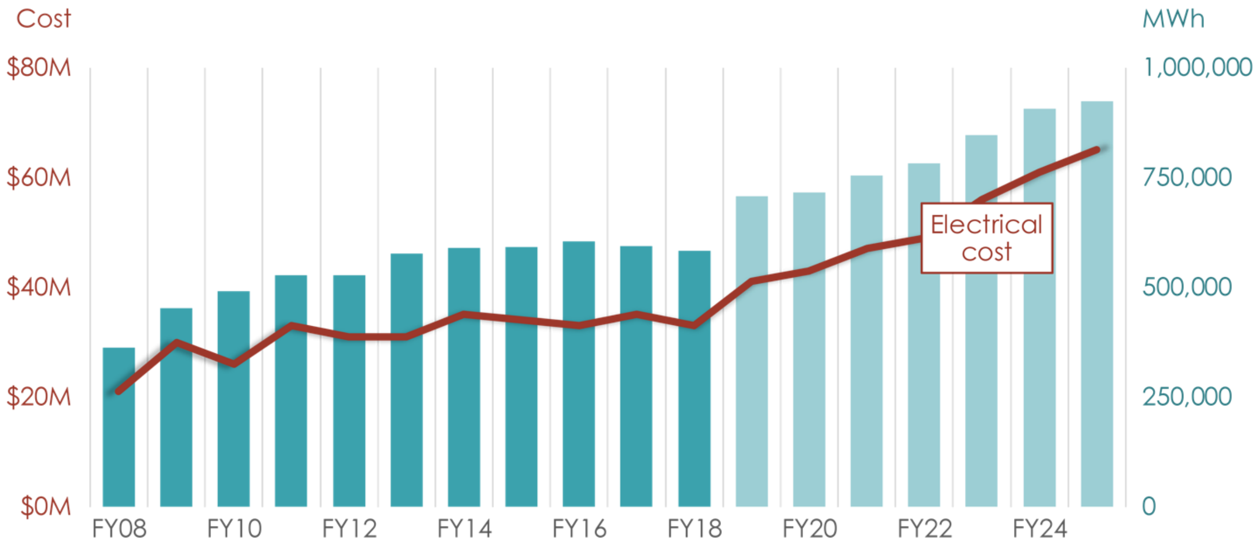


Figure: Electricity cost and use history and projections

PACIFIC NORTHWEST NATIONAL LABORATORY

Lab-at-a-Glance

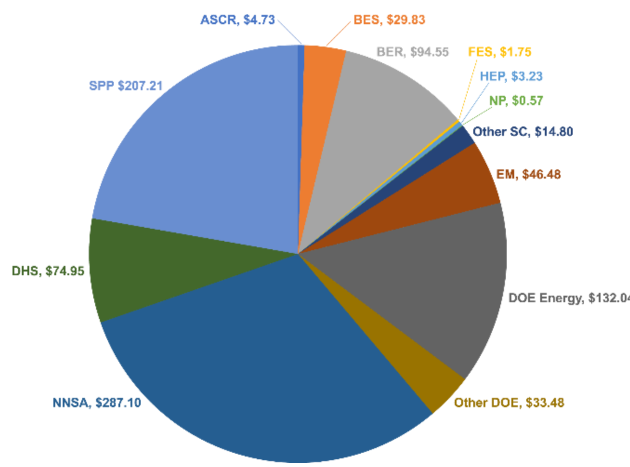
Location: Richland, Washington
Type: Multi-program Laboratory
Contractor: Battelle Memorial Institute
Site Office: Pacific Northwest Site Office
Website: www.pnnl.gov

- **FY 2018 Lab Operating Costs:** $930.7 million
- **FY 2018 DOE/NNSA Costs:** $648.6 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $207.2 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 23.4%
- **FY 2018 DHS Costs:** $75 million

Physical Assets:
- 455 acres and 77 buildings (DOE & Battelle Facilities)
- 927,000 GSF in buildings
- Replacement Plant Value: $819 M
- 973,000 GSF in 31 Leased Facilities (not including Battelle)
- 420,000 GSF in 21 Battelle Buildings

Human Capital:
- 4,177 Full Time Equivalent Employees (FTEs)
- 112 Joint Faculty
- 223 Postdoctoral Researchers
- 394 Graduate Student
- 343 Undergraduate Students
- 1,734 Facility Users
- 60 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

The Pacific Northwest National Laboratory (PNNL) is a premier chemistry, earth sciences, and data analytics Department of Energy (DOE) Laboratory. We apply our deep science and technology capabilities to advance scientific discovery and address our nation's toughest energy resiliency and national security challenges.

As a DOE Office of Science (SC) Laboratory, PNNL's focus is on discovery science. In chemistry, we are inspired by biology to design improved chemical catalysts and chemical pathways for the production of new fuels, feedstocks, and energy storage materials. In earth systems, we work to improve the predictive capability and utility of DOE's earth system models, with a particular emphasis on earth systems in transition. In data science, we combine machine learning, data visualization, and modeling to transform "big data" from experiments into new knowledge. PNNL operates two DOE user facilities, the Environmental Molecular Sciences Laboratory (EMSL) and the Atmospheric Radiation Monitoring (ARM) Research Facility, to further scientific explorations of molecular and atmospheric earth system processes.

PNNL research enhances energy resiliency. We extend our domain expertise in system situational awareness and high-performance contingency analysis to understanding how the North American electric grid functions. These insights enable us to design, test, and evaluate technologies for power grid security, resiliency, and optimization. We apply our chemistry and materials science capabilities to the development of new advanced energy storage solutions to further enhance grid resiliency.

PNNL's national security capabilities are deeply rooted in our Hanford heritage. We combine our security expertise with data analytics, applied mathematics, and computational science to protect U.S. critical energy and defense infrastructures from emerging cyber threats. Our nuclear science capabilities enable us to advance nuclear nonproliferation, nuclear and radiological security, the cleanup of radiological and hazardous wastes, processing and disposal of nuclear fuels, nuclear forensics, and the production and delivery of medical isotopes.

Beginning in 2015, PNNL embarked on a 10 year, $250M facilities transformation plan funded through internal investment. Now at the mid-point in its implementation, PNNL has invested approximately $125M in recapitalization and is on track for a total investment in excess of our goal.

Core Capabilities

PNNL's ability to meet changing DOE needs relies on the strength of 19 core S&T capabilities resident at the Laboratory. Eighteen of these core capabilities are discipline-based and are grouped into four categories—Biological and Earth Sciences, Chemical and Materials Sciences, Engineering, and Computational and Mathematical Sciences. The nineteenth capability, User Facilities and Advanced Instrumentation, is pertinent to two DOE-SC BER user facilities managed by PNNL—EMSL and ARM.

Stewardship of core capabilities is an essential responsibility. To understand and manage this, PNNL has begun assessment of the health of its core capabilities using multiple indicators in an Integrated Capability Management (ICM) framework that addresses health/quality of our 1) staff, 2) facilities and infrastructure, 3) equipment and assets, and 4) research portfolio. Each of these four critical components is assessed against six questions:

1. Sufficiency: Do we have enough?
2. Quality: Do we have the best?
3. Risks: Is the team/portfolio/collection of assets and infrastructure resilient?
4. Weaknesses: Do we have gaps/weaknesses?
5. Mitigating Factors: Are we pursuing mitigation strategies to address our risks and weaknesses?
6. Prognosis: Is the near-term expectation for the health of this capability improving, staying steady, or declining? What is the demand forecast?

PNNL's *Integrated Capability Management (ICM) Program Description Document – April 2019* provides a complete description of our capability health assessment process and the underlying data sources. Wherever possible, PNNL has chosen indicators that are quantifiable and comparable across laboratories. Scholarly output rankings used the key words in the DOE definition of each core capability as search queries in Scopus' Sci Val to collect metric data across laboratories. A brief summary of relevant highlights of this assessment is included as the last paragraph discussion of each core capability below.

Chemical and Material Sciences

Chemical and Material Sciences includes core capabilities in 1) chemical and molecular science, 2) condensed matter physics and materials science, 3) applied materials science and engineering, and 4) nuclear and radiochemistry.

Chemical and Molecular Sciences

Chemical and molecular sciences advance the understanding, prediction, and control of chemical and physical processes in complex, multiphase environments. PNNL has significant domain expertise in condensed phase and interfacial molecular science, chemical physics, catalysis science, chemical separations, geochemistry, theoretical and computational chemistry, physical biosciences, and actinide science. This core capability has strong ties to the condensed matter physics and materials science, computational science, and applied mathematics core capabilities, leveraging expertise in those areas to advance our understanding of complex phenomena at molecular liquid-solid interfaces and produce high-fidelity simulations of molecular processes controlling macroscopic phenomena. A key strength of our chemical and molecular sciences capability is the close and purposeful integration of experiments and theory, achieving rapid feedback for understanding and control of interactions, transport, and reactivity in multiphase, multi-component systems.

The Laboratory has the largest fundamental research effort within the national laboratory system in catalysis science and condensed phase and interfacial molecular science, which provided the foundation for establishing the Institute for Integrated Catalysis. These capabilities were essential for the second renewal of an Energy Frontier Research Center in Molecular Electrocatalysis from DOE's BES program and an award from DOE-SC's Early Career Research Program for the project "Combined Capture and Conversion of CO_2," selected by BES. Contributing to PNNL's strength in this area is EMSL's computational chemistry software suite (NWChem), which is used worldwide to efficiently address large molecular science problems on computing architectures ranging from workstation clusters to high-performance leadership class computer architectures. A major redesign of the architecture of NWChem is underway (in the PNNL-led NWChemEx project) to dramatically improve its scalability, performance, extensibility, and portability to take full advantage of exascale computing technologies. While NWChemEx will target the development of high-performance computational models for the ground states of complex systems that will be used for the production of advanced biofuels and other bioproducts, further computational capabilities targeting excited states are being designed in the Scalable Predictive methods for Excitations and Correlated phenomena (SPEC) project, which will deliver scalable, open-source electronic structure software libraries required to address challenges in excited-state and correlated phenomena in complex chemical systems and are appropriate to interpret the signals obtained at DOE's light source facilities. Novel computational chemistry tools for catalysis, photo-induced charge transfer, and actinide chemistry studies are utilizing emerging QIS technologies, enabling optimal design of accurate many-body frameworks that will take advantage of the evolving quantum and classical resources to describe complex electron correlation effects in molecular systems. Capability stewardship efforts, such as those proposed in the ESC project, will accelerate scientific discovery in chemical transformations by enabling close integration of synthesis with dynamic characterization capabilities and real-time computational capabilities.

This capability receives support from programs in BES, BER, DHS, EERE (geothermal, biomass, and hydrogen; fuel cells; and infrastructure technology), the Office of Fossil Energy (FE) (carbon- and co-sequestration), EM (environmental remediation), NNSA (nonproliferation), the Department of Health and Human Services (DHHS), and the DoD. In addition to our primary DOE-SC sponsor (the Catalysis Sciences program in BES CSGB), a number of applied programs rely on our chemical and molecular sciences capabilities for improvements in energy technologies, catalysis and reaction engineering, hydrogen storage, biomass conversions, environmental remediation, and carbon capture/sequestration. BER's support of EMSL capabilities also greatly enhances this core capability through the continued focus on molecular transformations that occur in batteries and catalytic systems (including biocatalysts), as well as at complex interfaces.

Health: Scholarly Output trend is stable (Rank 2) and this core capability is benefitting from strong partnerships (17 incoming/17 outgoing Joint Appointments plus three Joint Institutes). A majority of the staff have been at the Lab less than five years, bringing new vitality to this important area. Some existing space shortfalls will be addressed with construction of the ESC.

Condensed Matter Physics and Materials Science

PNNL is an emerging leader in condensed matter physics and materials science, a core capability that provides the knowledge base for discovery and design of new materials with novel structures, functions, and properties. This knowledge serves as a basis for development of new materials for energy generation, storage, and conversion, as well as manipulating quantum effects and mitigating materials degradation due to environmental factors. The Laboratory has domain expertise in the synthesis of nanostructures, biomolecular materials and heterointerfaces, interfacial dynamics of solid-solid and solid-solution liquid interfaces, electrical energy storage, *in situ* electron and scanning probe microscopy, radiation effects and degradation in materials, and computational materials science. This core capability has strong ties to the chemical and molecular sciences, applied materials science and engineering, computational science, and applied mathematics core capabilities. In combination, these capabilities advance our ability to understand and manipulate complex phenomena at solution-solid and solid-solid interfaces, design and direct synthesis of hierarchical matter, and develop computational tools that elucidate the mesoscale principles linking atomistic details of structure and interactions to outcomes of synthesis and function. Capability stewardship efforts enabled by the ESC project will strengthen the strategic link with our world-class efforts in the predictive design and understanding of chemical transformation processes. The ESC project will provide close integration with the chemical and molecular sciences capabilities through emphasis on predictive synthesis of hierarchical materials, enabling a strategic link to this core capability through the need to translate an understanding of catalytic processes into multifunctional catalytic materials.

PNNL has a distinctive strength in the emerging science of materials synthesis, to which it brings synthesis of hierarchical materials, both inorganic and organic; the most advanced imaging and spectroscopy tools, many of which are applied *in situ* and *operando*; and computational approaches that draw on PNNL's long-standing leadership in computational chemical physics, as well as new capabilities in condensed matter theory and computation. PNNL's capability is particularly strong in understanding the complexity at interfaces, specifically their role in synthesis and their control of electronic, magnetic, and quantum properties, as well as transfer of matter and energy. These strengths have advanced PNNL's research in the JCESR, an Energy Innovation Hub led by Argonne National Laboratory, which was renewed at the end of FY 2018, and in the Center for the Science of Synthesis (CSSAS), an Energy Frontier Research Center led by UW, which was newly awarded in late FY 2018. The latter includes a thrust that brings together deep learning approaches for data analytics and modeling machine learning for molecular design.

This capability forms the basis for PNNL's sponsor-funded, fundamental science programs in synthesis and processing, biomolecular materials, electron and scanning probe microscopy, mechanical behavior, and radiation effects. Applied programs to which this core capability contributes include radiation effects in materials, multiscale behavior of structural materials, design and scalable synthesis of materials and chemicals that bridge the mesoscale fuel cells and energy storage, electric and lightweight vehicle technology, nuclear reactor safety assessment, regulatory criteria and life extension, and legacy waste forms. This capability receives support from programs in BES, BER, DOE's Offices of Electricity Delivery and Energy Reliability (OE), the Office of Nuclear Energy (NE), EERE, and NIH. BER's support of EMSL capabilities (*e.g.,* Quiet Wing and the High Resolution and Mass Accuracy Capability) greatly enhances this core capability. Staff members are housed primarily in the Physical Sciences Laboratory, EMSL, and Life Sciences Laboratory (LSL) II.

Health: Scholarly Output trend is improving (Rank 5) and a majority of the staff have been at the Lab less than five years, bringing new vitality to this important area. Overall, this core capability is smaller than optimum; leadership effort is attending to this. Some existing space shortfalls will be addressed with construction of the ESC.

Applied Materials Science and Engineering

PNNL's capability in applied materials science and engineering emphasizes the development and validation of materials synthesis, manufacturing, and device fabrication concepts that are relevant to DOE mission needs and readily scalable for industry adoption. PNNL has made significant contributions over the years to the commercialization of automobile catalysts, organic light-emitting devices, biofuels, redox flow batteries, and many other clean energy technologies. PNNL holds domain expertise in materials characterization; materials theory, simulation, design, nucleation, and synthesis; solid phase processing methods for the fabrication of alloys and semi-finished products; the role of defects in controlling material properties; and materials performance in hostile environments, including the effects of radiation and corrosion. This capability includes the ability to engineer enabling nanostructured and self-assembled materials, as well as tailored thin films, ceramics, glasses, metal alloys, composites, and biomolecular materials. PNNL is also leveraging this capability to develop advanced waste forms (*e.g.*, glass, ceramic, metallic, cementitious), key process control models, and tactical processing strategies to ensure safe and successful operations for the immobilization and processing of nuclear wastes around the DOE complex.

The Laboratory leverages its applied materials science and engineering capability to develop new materials and strategies to enable a variety of technology areas, including grid- and transportation-scale energy storage, solid oxide fuel cells, solid-state lighting, absorption cooling, lighter-weight vehicles, next generation reactors, magnetics, separations, and nuclear waste management. To support these R&D efforts, PNNL has built a number of unique laboratory facilities, including high- and low-dose radiological facilities, laboratories for material synthesis and deposition, the Solid Phase Processing Facility, the Advanced Battery Facility, and the Solid-State Lighting Test and Analysis Facility. PNNL is currently in the planning stage for a new OE-funded battery materials development facility to consolidate and augment existing PNNL capabilities. Working in collaboration with academia, industry, and other national laboratories, PNNL plays a critical role in high-impact national programs such as BES's JCESR and the Vehicle Technologies Office's Battery500 and LightMat consortia.

The applied materials science and engineering capability forms the basis of PNNL's sponsor-funded research programs in materials synthesis and fabrication; radiation effects in materials; multiscale behavior of structural materials; modeling, design, and scalable synthesis of materials and chemicals that bridge the mesoscale; fuel cells and electrochemical energy storage; gas and liquid separations; electric and lightweight vehicle technology; nuclear reactor safety assessment, regulatory criteria, and life extension; and legacy waste forms. These efforts are funded by a variety of DOE programs, including the Office of Science (BES), and many of the Applied Energy Offices (EERE, NE, FE, ARPA-E, EM, NNSA, and NRC). This capability is also leveraged in support of research programs for DoD and for the private sector through SPPs.

Health: Scholarly Output trend is improving (Rank 4) and this core capability benefits from strong partnerships (10 incoming/two outgoing Joint Appointments plus two Joint Institutes). Increased demand in this core capability has created a staffing gap that is being addressed through intensive recruiting. The need for additional space will be addressed by the ESC and GSL, with backfill from off-site leases primarily into LSL2 after ESC is occupied.

Nuclear and Radiochemistry

PNNL possesses expertise in interfacial chemistry, radiochemical separations, analytical measurement techniques, actinides, separations, irradiated materials characterization, spectroscopy, and microscopy. The Laboratory processes and measures plutonium and its fission products across a wide range of highly radioactive samples that require the use of hot cells to tiny samples that undergo ultra-trace measurements in clean rooms. PNNL possesses a unique combination of in-depth knowledge of sample analysis combined with instrumentation, including a focused ion beam and state of the-art measurement systems such as the Aberration-Corrected Nuclear Scanning Transmission Electron Microscope. Mission-ready instrumentation includes suites of microscopy, mass spectroscopy detection, magnetic resonance, and specialized ultra-low-background radiation detectors; numerous specialized wet chemistry laboratories; and ultra-trace radio analytical and radiometric facilities, including a shallow underground lab, providing one of the largest collections of instrumentation and expertise at any single institution in the world.

At the core of PNNL's nuclear and radiochemistry capability is leadership in plutonium production and waste processing knowledge (specifically in Hanford's legacy waste), forensic signatures of plutonium production, post-irradiation examination of materials, and tritium target fabrication. This includes the development and deployment of the world's most sensitive radionuclide detection systems. This year, a system called "Xenon International," a high-performance, next generation detection system for use in nuclear explosion monitoring networks, received an Interagency Partnership Award because of the project's success in bringing together various U.S. government agencies, including the Department of State, DOE, and DoD, as well as a commercial manufacturer, Teledyne Brown Engineering. In mitigation of the nation's nuclear waste legacy, PNNL researchers are developing new real-time sensors and radiochemical insights to enable EM to expand waste processing operational windows, enable new treatment alternatives, and accelerate the waste processing timelines at Hanford waste treatment facilities. PNNL is also leading two international teams, one on glass corrosion and another on ancient analogs, to predict the long-term performance of glass wasteforms, which are the basis for high level waste disposal.

PNNL stewards a set of facilities unique to the DOE complex. These facilities include Hazard Category II and III nuclear assets such as the RPL. The RPL has the capability to perform an extraordinary range of S&T in a fast and flexible fashion, process materials adjacent to world-class assay technology, and perform testbed scale operation with a wide operational envelope. At the RPL, PNNL can work with micrograms to kilograms of fissionable materials and megacurie activities of other radionuclides. Programmatic support for nuclear and radiochemistry includes scientific discovery [Office of High Energy Physics (HEP), NP, and BES] in the search for dark matter and neutrino mass. EM depends on PNNL for rapid understanding of legacy waste behaviors, pilot-scale testing and validations, and the development of new processing options. The NNSA-Defense Nuclear Nonproliferation R&D office relies heavily on these capabilities for next generation nuclear detection systems, along with the DTRA.

Health: Scholarly Output trend is stable (Rank 2) and a majority of the staff have been at the Lab less than five years. This portfolio is strong in applied research and operational projects; leadership emphasis now is on growing the more fundamental aspects of the research portfolio. In addition, PNNL will be upgrading the infrastructure to support operations with special nuclear materials. PNNL will also be upgrading insufficient ventilation at the Radiation Detection Laboratory to support radiochemistry research. Options to address some shortfalls in high bay and limited purpose space are being considered as part of the new federally owned facility in the higher hazard zone of the PNNL Richland Campus.

Computational and Mathematical Sciences

Advanced Computer Science, Visualization, and Data

PNNL has depth and breadth of expertise in energy-efficient computing; performance, power, and reliability modeling; exploration and design of novel computing architectures; runtime and system software; and data-driven discovery at extreme scales. Specific domain areas include predictive modeling and simulation of complex architectures, programming models, resiliency, machine learning, architectural testbeds, fault tolerance, information visualization, data analytics, and data management. PNNL is also advancing the state-of-the-art in QIS and its application to address problems in various domains, including computational chemistry and computational materials science. Our work is recognized internationally by scientific peers in areas of performance, power and reliability modeling for co-design of systems and applications, design space exploration and optimization, visual analytics, and deep learning.

PNNL has advanced the state-of-the-art in the application of deep learning to DOE missions such as biology, the power grid, and cybersecurity; and has developed new approaches for domain-aware machine learning to accelerate training and interpretability of classifiers as well as few-shot learning to accelerate scientific discovery. PNNL is making new investments in DMC to integrate the historically distinct computing platforms for HPC (particularly for its use in physical simulation), data analytics, and machine learning. Our expertise in programming models for extreme-scale computing is demonstrated through toolkits such as Global Arrays, which powers NWChem and other important scientific applications, including subsurface flow modeling code Subsurface Transport Over Multiple Phases (STOMP) and power grid modeling code GridPACK™. PNNL data scientists lead research in data exploitation, workflow, and provenance at extreme scales for science, energy, and security domains (*i.e.*, the Belle II, ARM, and Cooperative Protection Program efforts). In the field of visualization, PNNL has developed new techniques for visual analysis of high-volume streaming data and visual interfaces for interactively tuning machine learning algorithms. PNNL is also making significant advances in graph analytics, including hybrid architectures for exploiting large graph datasets and algorithms for scalable graph query on multi-threaded systems.

Special facilities in support of this core capability include the CENATE, an advanced architecture testbed capability for measuring performance, power, thermal effects, and cyber vulnerabilities to assess their overall potential and guide their designs; computing resources, such as the 3.4 petaflop Cascade supercomputer, the Constance research computing cluster, the Marianas cluster (including a state-of-the-art NVIDIA DGX-2 system) optimized for machine learning workloads, and research cloud; and human-computer interaction research laboratories for visual interfaces, including emerging virtual reality environments. These resources are housed primarily in the Computational Sciences Facility (CSF) and EMSL. This capability receives support through programs from ASCR, BES, BER, HEP, EERE, FE, NNSA, DHS, and other sponsors, including DHHS and DoD.

Health: Scholarly Output trend is stable (Rank 4). Recruiting and retention is an area of focus for management; portfolio, infrastructure, and equipment are good. Demand in this core capability is extremely strong. This demand, coupled with strong private sector demand for relevant hot skills and associated high compensation levels, makes this core capability one of three in which staffing shortfalls are significant and being addressed through intensive recruiting and cross-training.

Computational Science

Computing permeates all research domains at PNNL. The Laboratory actively employs HPC to solve compelling, extreme-scale scientific problems, and has a long history of developing computational tools and application codes built collaboratively by multidisciplinary teams composed of domain scientists, computer scientists, and applied mathematicians. More recently, through investments from BES and internal LDRD, PNNL has been exploring the application of quantum computing platforms to applications in computational chemistry and materials science. PNNL maintains strong capabilities in many computational science domains, including computational chemistry, computational materials science, high energy physics, computational engineering, computational biology, computational geochemistry with subsurface flow, and computational fluid dynamics, as well as climate, including participation in developing community climate codes and management of the ARM Research Facility.

Multidisciplinary teams of domain and computer scientists and applied mathematicians have long been an elemental part of the research process at the Lab. For example, as part of developing NWChem, PNNL pioneered engaging teams of computational scientists to create a molecular modeling capability that dramatically advances the state-of-the-art through the development of scalable predictive methods for excitation and correlated phenomena and directly ties to experiments at DOE light sources. This same integrative, co-design-based approach now is being employed to develop advanced computational models at multiple length and time scales for the power grid, high energy physics, materials science, and climate, to name only a few. Moreover, PNNL has been a significant contributor to various DOE Scientific Discovery through Advanced Computing (SciDAC) projects. These teams continue to adapt to the changing computing landscape through efforts such as the Exascale Computing Project, which includes developing NWChemEx as well as Exascale power grid applications.

Internal LDRD investments have focused on bringing together interdisciplinary teams of data scientists, computer scientists, applied mathematicians, applied statisticians, and domain scientists to work on a wide range of DOE-relevant problems in microbiology, soil science, climate sciences, materials, renewable energy, and nonproliferation. Recently, these investments have focused on the development of domain-aware machine learning methods that can be applied to a wide range of DOE problems. PNNL-developed codes, such as NWChem, are also heavily used on DOE's Leadership Computing Facility systems and at the National Energy Research Scientific Computing Center.

Staff members are housed primarily in CSF, ISB1, ISB2, Environmental Technology Building (ETB), EMSL, and Math buildings. This capability leverages support from PNNL's applied mathematics and advanced computer science, visualization, and data core capabilities, and receives support from programs in ASCR, BES, BER, EM, and EERE.

Health: Scholarly Output trend is stable (Rank 4). Recruiting and retention is an area of focus for management; portfolio, infrastructure, and equipment are good.

Applied Mathematics

PNNL is a leader in applied mathematics and statistics, using mathematical models to predict the behavior of dynamic, complex systems and quantify associated uncertainty to accelerate scientific discovery. Our researchers develop novel mathematical methods for predictive modeling, uncertainty quantification, risk and decision analysis, machine learning, complex information modeling, data analytics, decision and control systems. A strength at PNNL is the seamless integration of applied mathematics and domain expertise to make major impacts in national problems such as the reliability and security of national critical infrastructures.

PNNL has broad expertise in multiscale mathematics, including dimension reduction, mesoscale Lagrangian particle methods, and hybrid methods for coupling multi-physics models operating at different scales. Building on our strength in multiscale modeling, PNNL is developing capabilities in domain-aware machine learning, as well as physics-informed methods for parameter estimation and uncertainty quantification as a part of several projects funded by ASCR, BER, and FE. These techniques focus on solutions for nonlinear and high-dimensional systems and include surrogate and multi-fidelity modeling for both forward prediction and inverse models. PNNL is developing operational models focused on resource utilization and risk assessment via simulation, optimization, and mathematical programming. In addition, PNNL is growing capabilities in distributed and hierarchical decision systems, reinforcement learning, verifiable machine learning based control, and concurrent system and control design for safety-critical system.

PNNL is pursuing innovative research in the analysis and integration of complex, high-dimensional data. PNNL mathematicians are advancing methods in computational topology, hypergraph theory, and applied category theory. We use these methods to build novel representations of tabular, relational, and time-series data, aimed at synthesizing quantitative and qualitative information with complex, multi-way dependencies. Applications include sensor fusion, anomaly detection, and visualization of complex data for critical problems in cybersecurity, computational biology, geolocation, and open-source data analysis. PNNL is also designing extreme-scale machine learning and data mining algorithms, including several supervised learning algorithms (*e.g.*, deep learning, support vector machine), unsupervised learning algorithms (*e.g.*, auto-encoders, spectral clustering), and physics-informed learning machines (PhILMs—methods where physics laws are used in addition to data to train deep learning algorithms). In addition, PNNL is developing strategies to generate interpretable models using one or more integrated mathematical or statistical techniques—such as machine learning, signature discovery, and game theory—to enable domain scientists to generate novel hypotheses in both static and streaming applications. Most of the research in data sciences is currently funded by DoD and NNSA.

PNNL also has an emerging capability in the applications of discrete mathematical techniques to a range of problems in the DOE mission space. PNNL uses these capabilities to solve crosscutting problems of national interest. PNNL is heavily invested in solving issues related to large-scale graph analysis (*e.g.*, data fusion), time evolution of discrete structures, and the development of network invariants and their applications. PNNL applied mathematics researchers are located in ISB1, ISB2, BSF/CSF, ETB, 3860, and our Seattle offices.

Health: Scholarly Output trend is stable (Rank 1). A majority of the staff (74 percent) have been at the Lab less than five years, bringing new vitality to this core capability. Portfolio, infrastructure, and equipment are good.

Cyber and Information Sciences

The Laboratory improves the security and reliability of critical networks and infrastructures through advanced sensing, analysis, and defense, as well as through identifying emerging threats from signatures extracted from diverse data sources, and detecting, responding, and recovering from incidents. This includes novel information sharing methods and the development and implementation of analytic techniques to extract value from data. Research staff are internationally recognized in cyber resiliency theory (encompassing both information and operational technology), cyber analytics, graph theory, machine learning, text and multimedia analytics, statistics, and emerging techniques for human-machine teaming.

PNNL's cybersecurity portfolio is based on decades of expertise in developing and deploying novel cybersecurity sensors for wide-scale enterprise network monitoring and situational awareness, including operation of the Cooperative Protection Program for DOE complex cyber defense and the CRISP, a voluntary information sharing and threat intelligence program for critical infrastructures. PNNL has developed unique expertise in the scientific and mathematical foundations of cybersecurity, including leadership in biologically inspired cybersecurity, multiscale graph methods for active cyber defense, critical infrastructure resiliency analysis and modeling, vulnerability assessment, and integrated cyber and physical security. An emerging area of focus is in consequence prediction to model the cascading effects of disruptions across linked cyber and physical systems. PNNL's expertise focuses on applications for critical infrastructures and industrial control systems, with particular emphasis on the power grid. PNNL has also developed a research-to-operations model for cybersecurity in which its cybersecurity research staff and internal cybersecurity operations staff partner closely to evaluate and deploy PNNL-developed analytic and security solutions on PNNL's internal network, as well as use PNNL's operational expertise to inspire the next generation of cybersecurity technologies.

PNNL's information science expertise is in areas of data acquisition, management, and storage systems (*e.g.*, experimental design, data workflow, provenance, and quality assurance); analytics and algorithms (*e.g.*, streaming and graph analytics and scalable machine learning); and decision support (*e.g.*, user experience, real-time analysis, and model/algorithm steering in response to user input). PNNL places special emphasis on developing next generation techniques for analysis and visualization of unstructured data from streaming heterogeneous sources, including new approaches for human-machine teaming to improve analytic quality and efficiency. PNNL has also developed a world-class deep learning capability that applies emerging machine learning techniques to accelerate discovery across all of PNNL's missions.

Major computing resources that support this capability include PIC resources, including the Constance cluster; real-time operating system and scalability testbeds; and the CyberNET and PowerNET virtual enterprise testbeds to simulate real-world cyber activity and improve cybersecurity for industrial control systems. In addition, facilities such as the Cyber Security Operations Center, the EIOC, the Visualization and Interaction Studio, and the Electricity Infrastructure Cyber Security/Resilience Center support this capability. External collaborations include industry, academic, and governmental partners from across the nation and around the world. Primary sponsors for PNNL's cyber and information sciences research include ASCR, OE, DoD, and DHS.

Health: Scholarly Output trend is improving (Rank 1). Demand in this core capability is extremely strong. This demand, coupled with strong private sector demand for relevant hot skills and associated high compensation levels, makes this core capability one of three in which staffing shortfalls are significant and being addressed through intensive recruiting and cross-training. There is insufficient federally owned office and laboratory space for research in data exploitation workflow and provenance in the extreme-scale science, energy, and security domains. PNNL plans to renovate unutilized space on the PNNL Richland Campus to support this need.

Decision Science and Analysis

PNNL maintains strong capabilities in modeling, analyzing, communicating, and mitigating crosscutting impacts at the interface between science, technology, policy, and society. Working collaboratively with scientists and engineers across the Laboratory and with external partner organizations, our experts continue to develop and implement innovative, holistic solutions to complex decision problems on the front lines of the nation's energy, environment, and national security challenges.

PNNL's staff expertise is focused in the areas of decision science, risk analysis, economics, systems engineering, decision support systems, policy analysis, social and behavioral science, statistics, and safety analysis. This capability enables the development and application of cutting-edge decision and risk analysis; safety, impact, and risk assessments; making decisions under uncertainty; alternatives analysis; strategic process/systems improvements; and decision support under resource constraints. Additional modeling and analysis capabilities include socioeconomic modeling, market and policy analysis, techno-economic modeling and analysis, regional/national energy simulation, and cost-benefit analysis and uncertainty analytics. The team's breadth and depth of decision and risk analysis expertise fosters flexibility in assembling dynamic, multidisciplinary teams to develop science-based strategies for minimizing risks to individuals or the public, program life cycles, facility designs and operations, and the environment at the local, state, regional, national, and global levels.

Staff that support this capability at the Laboratory are located in several locations in Richland, including ISB1, ISB2, the Engineering and Analysis Building, the Math Building, and the National Security Building, as well as the PNNL offices in Portland, Oregon and Seattle, Washington. They are recognized in the areas of nuclear and alternative energy, operational safety review and risk assessment; technology field testing, evaluation, and performance assessment; programmatic risk assessment; geo-spatial decision analytics and visualization; nuclear proliferation risk modeling; knowledge management and data reuse; multi-organizational collaboration decision support; distributed decision making for power grid reliability; energy policy and regulatory development\deployment; appliance and commercial equipment energy efficiency codes and standards; and feasibility analyses of technology, siting, policy, and tax structures for energy technology deployment. Leadership in safety assessment, probabilistic risk assessment methodology development and application, environmental impact assessment, and analyses and feasibility assessments for nuclear, geothermal, hydropower, and other sustainable energy technologies, such as hydrogen-powered vehicles, are specific strengths. Current stakeholders that primarily utilize our capabilities include DOE (EERE, OE, EM, FE, and NE), NNSA, DHS, DoD, EPA, BPA, and NRC.

Health: Scholarly Output trend is stable (Rank 4) with strong impact metrics (*i.e.*, ranked 1st in publication in top journals and 3rd in citation count). Staff, portfolio, and equipment are good.

Climate Change Science and Atmospheric Science

PNNL has extensive experience and strengths in measuring, modeling, and understanding the complex interactions among human and natural systems, from molecular to global scales, with expertise spanning the full range of disciplines and tools required to understand atmospheric processes and predict the evolution of the earth's climate system. This core capability includes activities ranging from laboratory and field measurements to multiscale numerical simulations to integrated analyses of climate impacts and response options. PNNL has domain expertise in atmospheric aerosol chemistry, cloud physics and cloud-aerosol-precipitation interactions, boundary layer meteorology, land-atmosphere interactions, hydrology, biogeochemistry, ecosystem science, integrated assessment, impacts analysis, and a wide range of measurement systems and modeling activities relevant to these disciplines. We leverage expertise from related core capabilities, including chemical and molecular sciences; biological systems science; earth system science and engineering; decision science and analysis; power systems and electrical engineering; advanced computer science, visualization, and data; and user facilities and advanced instrumentation.

PNNL's climate change and atmospheric science research focuses on improving our basic understanding of and ability to project changes in the earth system and related human systems, and on developing the measurements and data-driven modeling frameworks needed to do so. Key facilities include the Atmospheric Measurements Laboratory, ARM Research Facility, ARM Aerial Facility, EMSL, MSL, and Joint Global Change Research Institute (a partnership between PNNL and the University of Maryland focused on understanding the interactions among climate, natural resources, energy production and use, economic activity, and the environment). These facilities house a wide range of world-class equipment, such as a flow-through environmental chamber, and wind energy lidar buoys. The G-1 research aircraft was retired after its return from the DOE ARM CACTI field study. The process of finding a replacement aircraft is continuing. PNNL has followed the CD process (DOE O 413); and has received CD-2/3 approval for the purchase of a new research aircraft that will provide a state-of-the-art research platform. PNNL is also a leading developer of atmospheric, climate, land surface, and integrated human-earth system models, including the Global Change Assessment Model, the Weather Research and Forecasting model, DUSTRAN (DUST TRANsport), and the Energy Exascale Earth System Model (E3SM), as well as in integrating modeling and observational systems across disciplines to yield new insights into the evolution of the coupled human-environment system.

PNNL's capability includes programs in atmospheric-process research, regional and global earth system modeling, integrated multi-sector multiscale modeling, atmospheric wind energy research, and the advanced computational infrastructure and research needed to perform large-scale data analysis and numerical modeling to develop a more robust understanding of how extreme events and long-term stresses influence our energy systems and national security. Increasingly, these activities are being integrated and connected with other research areas and programs. This core capability is funded by programs in BER, ASCR, EERE (wind and water power technologies), FE (carbon dioxide storage), NASA, EPA, and National Oceanic and Atmospheric Administration (NOAA).

Health: Scholarly Output trend is improving (Rank 1). Staff, portfolio, and equipment are good; minor office space shortages are being addressed.

Earth Systems Sciences and Engineering

PNNL's earth systems science and engineering capability researches the impacts of energy production, storage, and use on valued environmental resources and functions; develops and deploys technologies to mitigate the impacts of past, current, and future energy production systems; and develops and deploys technologies that improve the performance of energy generation and minerals extraction from surface waters. This capability spans terrestrial, aquatic, and coastal ocean systems, both biological and abiotic. Applications of our expertise include Arctic and deep-ocean oil and gas, hydropower, wind power, marine and hydrokinetic generation, algal biomass production, nuclear energy, and legacy waste.

PNNL has scientists and engineers in a variety of fields, including aquatic and terrestrial ecosystems science, oceanography, biogeochemistry, hydrology, environmental engineering, and microbiology, with domain expertise in molecular-to-field-scale biogeochemistry, laboratory-to-field-scale hydrology, multiphase flow modeling, integrated (*e.g.*, biogeochemical, physical, and ecological) aquatic modeling, aquatic acoustics and tracking technologies, ecosystem-level adaptive management, biofouling/bio-corrosion, climate-simulating culturing of algae and higher plants, minerals extraction from seawater, ecosystems modeling and restoration, human health and environmental risk assessment, and environmental systems technology development and deployment.

PNNL is home to the only marine research facility in the DOE complex, the MSL in Sequim, Washington. MSL's coastal location and facilities enable studies of anthropogenic impacts on marine species and systems; a controlled study area for development and testing of marine energy systems; biogeochemical, ecotoxicological, and biotechnology investigations with ambient seawater; and a platform for development and testing of autonomous and *in situ* marine technologies. In addition, PNNL's distinctive Aquatics Research Laboratory supports fisheries research focused on sustainable hydropower operations and development. Advanced environmental monitors and ecological sensors for conventional hydropower, wind, marine, and hydrokinetic renewable energy systems are developed and tested at PNNL's Bio-Acoustics and Flow Laboratory (LSL 2). The advanced experimental and instrument capabilities of EMSL are also used to advance research in this area, with a focus in molecular-scale biogeochemistry and proteomics.

PNNL conducts research at the bench, pilot, and field-scale, integrated with advanced modeling and simulation, to provide the technical underpinnings, scientific approaches, and technological advancements to support breakthrough solutions, improve system knowledge, and champion new protocols that are protective of human health and the environment. The earth systems science and engineering capability is funded through DOE programs in BER, BES, EM, NE, EERE, as well as NRC, EPA, DHS, BPA, Department of Interior, NOAA, and the U.S. Army Corps of Engineers.

Health: Scholarly Output trend is stable (Rank 1). This core capability benefits from strong partnerships (10 incoming and five outgoing Joint Appointments). Minor space shortages are being addressed. PNNL is also planning renovations to building infrastructure and laboratory space at the MSL.

Environmental Subsurface Science

PNNL's environmental subsurface science capability focuses on developing and applying knowledge of fundamental biogeochemical reactions, thermodynamics, and mass transfer processes to the prediction and assessment of natural processes and engineered systems. PNNL provides DOE with domain expertise in molecular-through-field-scale biogeochemistry, reactive transport modeling, lab-to-field-scale geohydrology, multiphase flow and geomechanical modeling, computational geochemistry, subsurface technology development and deployment, advanced geophysical monitoring, isotopic analytical capabilities, and high temperature and pressure geochemistry. Potential applications include enhanced oil recovery systems, the design and operation of carbon sequestration reservoirs and enhanced geothermal systems (EGS), technology development for nuclear waste repositories, and remediation of contaminant plumes.

For EM, PNNL applies an integrated experimental and modeling approach to resolve technical issues necessary to inform decisions for environmental remediation, waste management, and closure. PNNL has teamed with other laboratories to develop the Advanced Simulation Capability, a state-of-the-art scientific approach that uses integrated toolsets for understanding and predicting contaminant fate and transport in natural and engineered systems. PNNL leads the Deep Vadose Zone-Applied Field Research initiative, providing the technical basis to quantify, mitigate, and monitor natural and post-remediation contaminant discharge from the vadose zone to groundwater. Outcomes include advanced prediction, characterization, remediation, and monitoring approaches for addressing residual soil and groundwater contamination at DOE facilities, as well as the protection of regional water resources and aquatic ecosystems.

This capability is also applied to numerous energy and water challenges, including sustainable energy generation, production, and use. This capability is essential to addressing the FE mission associated with ensuring readiness of technologies needed to support commercial scale deployment of geologic CO_2 storage for CCUS. In addition to participating on multiple Regional Carbon Sequestration Partnerships and CarbonSAFE projects, PNNL has key roles in FE's National Risk Assessment Partnership and in the EGS Collab project funded by the Geothermal Technologies Office (GTO). PNNL led the Wallula project, the world's first supercritical CO_2 injection demonstration into basalt formations, completing a 1,000 ton injection into the Grande Ronde basalt formation. Through its BER-funded SFA, PNNL is leading research in molecular and microscopic electron transfer processes, pore-scale reactive transport and upscaling, and field-scale microbial ecology and biogeochemistry. Staff members support programs funded by BER, BES, EM, FE, EERE (GTO), NRC, NNSA, DHS, EPA, NASA, and DoD, and have numerous active collaborations with other national laboratories and universities nationwide. Staff and capabilities are located across the PNNL campus in Richland and Sequim facilities, including EMSL, LSL 1, LSL 2, ISB2, ETB, and MSL.

Health: Scholarly Output trend is improving (Rank 4). Over one-third of the staff have been at the lab >25 years and leadership is actively recruiting and developing new leaders as many staff approach retirement. Portfolio, infrastructure, and equipment are all good.

Biological Systems Science

Through PNNL's biological systems science core capability, the Lab is developing a mechanistic understanding of complex multicellular systems and their response to perturbation to enable improved predictions of the impacts of environmental change, energy production, and emerging technologies on ecosystem sustainability and human health.

PNNL has made significant contributions in deciphering mechanisms of microbial community metabolic interactions and dynamics, understanding multiscale terrestrial biogeochemistry, predicting contaminant behavior and microbial ecology of the subsurface, quantifying the effects of renewable energy devices on aquatic ecosystems, and applying a systems biology approach to plant, microbial, and algal systems relevant to DOE’s missions in science, energy, and environment. PNNL's Soil Microbiome SFA aims to achieve a systems-level understanding of the soil microbiome's phenotypic response to changing moisture through spatially explicit examination of the molecular and ecological interactions occurring within and between members of microbial consortia. In addition, the Microbiomes in Transition (MinT) LDRD investment leverages the strengths within this core capability (biological and bioprocess engineering and earth systems science and engineering) to understand the metabolic activities of complex microbial communities and how metagenomes translate to the function of a microbial community, as well as to illuminate the microbiome’s role in plant, animal, and human health as well as biogeochemical cycling. PNNL’s expertise in fungal biology has generated an in-depth understanding of the biological processes underlying efficient fungal bioprocesses that produce fuels and other chemicals. In addition, PNNL is providing insight into the development of medical countermeasures and early diagnostics, characterizing emerging pathogens, and advancing human exposure assessment to improve health and biodefense.

In combination with other core capabilities, including chemical and molecular sciences; environmental subsurface science; advanced computer science, visualization, and data; applied mathematics; and large-scale user facilities/advanced instrumentation, this core capability delivers expertise in microbial ecology, microbiome science, fungal biology and biotechnology, pathogen biology and biological threat prediction, systems toxicology, plant science, biochemistry and structural biology, trace chemical analysis, biomolecular separations, advanced *in situ* and dynamic imaging, computational biology and biophysics, and signature discovery through data analytics. PNNL’s integrative ’omics capabilities, widely used by the BER programs (*e.g.*, the phenotypic response of the soil microbiome to environmental perturbations), leverage this broad suite of expertise to provide unprecedented molecular to mesoscale resolution of the structure and activity of biological systems.

This capability is funded through programs in BER, ASCR, BES, EERE, EM, DHS’s Science and Technology, DoD, NIH, NASA, and the EPA. Key facilities supporting this capability include BSF; CSF; the Bioproducts, Sciences, and Engineering Laboratory (WSUBSEL); MSL; the Aquatic Research Laboratory; Life Sciences Laboratory 1; the Microbial Cell Dynamics Laboratory; and EMSL. PNNL partners with the JGI to provide large-scale genome sequencing and analysis for DOE missions. EMSL and JGI now issue an annual joint call for user projects focused on synergistic use of capabilities at both facilities, targeting collaborative science projects in biogeochemistry, carbon cycling, and biofuels.

Health: Scholarly Output trend is stable (Rank 3). Infrastructure and equipment are good; capital equipment purchase (X-ray Nanotomography) is scheduled for FY 2019. Portfolio is growing again after loss of some BER funding a few years ago.

Biological and Bioprocess Engineering

Leveraging capability in biological and bioprocess engineering, PNNL is developing technologies and processes to convert biomass and waste materials into fuels and chemicals that will reduce the United States’ dependence on petroleum. Biomass sources include lignocellulosic materials (e.g., corn stover and wood wastes) and other waste materials (*e.g.*, water treatment plant wastes and other industrial wastes), as well as fungi and algae. This capability is strengthened through collaboration with Laboratory expertise in catalysis and reaction engineering; separations, process engineering, and flowsheet development; materials science; and techno-economic modeling. Research spans from a fundamental understanding of the molecular interactions involved in conversion processes to pilot-scale operations that demonstrate process technologies, paving the way for technology transfer to industry for commercial application.

PNNL's biologists, chemists, and chemical engineers specialize in fungal processing, catalysis and reaction engineering, algae growth and processing, separations, process engineering, techno-economic and life cycle analyses, and resource assessments. PNNL's technical areas of expertise include fast pyrolysis for converting biomass to bio-oil, hydrothermal liquefaction for conversion of wet materials to products, hydrotreating of biocrude and bio-oils to fuels, conversion of biomass-generated alcohols to jet fuels, and conversion of intermediates to chemical products. PNNL houses unique indoor, climate-controlled raceway ponds that can cultivate microalgae strains under conditions that simulate outdoor ponds at any geographic location in the world. The capability also includes a unique Biomass Assessment tool that can quantify potential fuel production from microalgae and waste feedstocks.

This capability maintains a significant IP portfolio, providing a pathway for technology commercialization. The PNNL team has seven distinguished inventors, each with 14 or more awarded U.S. patents, for a total of 76 bio-based U.S. patents since the year 2000. Most recently, a PNNL-developed alcohol-to-jet process was licensed to LanzaTech to enable the production of jet fuel from alcohol derived from industry flue gases. The jet fuel has been certified by the American Society for Testing and Materials (ASTM) for commercial use, and the first transatlantic flight utilizing a waste-gas derived jet fuel was flown by Virgin Atlantic in October 2018. PNNL provides leadership in biological and bioprocess engineering to the EERE Bioenergy Technologies Office, EM, academia, and industry. Industrial partners include companies such as Archer Daniels Midland, Genifuel, and LanzaTech.

Health: Scholarly Output trend is stable (Rank 2). Recent senior technical retirements are being addressed through recruitment. Portfolio and infrastructure are good.

Power Systems and Electrical Engineering

PNNL has internationally recognized capabilities spanning the entire electric power grid. PNNL staff have deep expertise in conventional and variable generation of electricity, the grid's transmission and distribution networks, reliability and resilience, smart grid and intelligent systems, distributed energy resources, market systems, and energy demand. PNNL develops innovative solutions to addressing emerging challenges facing today's power industry, by better planning, operating, and controlling of modern power grids for enhanced resilience and reliability. Primary supporting disciplines include power system, electrical, and control engineering; computational science; cybersecurity; data analysis; and mechanical engineering. With a focus on system-level issues, PNNL is the national leader in defining the inherently resilient power grid of the 21st century, delivering innovative tools to enable unparalleled grid performance (resilience, reliability, security, transparency, efficiency, and sustainability) and new control and architecture paradigms spanning future demand and supply for unprecedented consumer engagement.

Key research areas include grid architecture, transmission and distribution system reliability and control analysis, power system protection, advanced grid data applications, computing and visual analytics, renewable integration, energy storage, distribution system modeling, and grid cybersecurity. PNNL's expertise in grid simulation and analytics enables high-performance grid monitoring and control at unprecedented speed, from minutes to sub-seconds. For over a decade, PNNL has led the world in the development and application of transactive systems that combine economics and controls to enable distributed optimization and integration of distributed energy resources, including responsive loads, batteries, and renewable resources. PNNL's expertise in advanced control theory, application, and testbeds supports advances in the development of new, distributed controls for the electric power system. PNNL's leadership in phasor measurement technologies supports broader national deployment, enabling unprecedented grid visibility and enhanced situational awareness. PNNL's one-of-a-kind, utility-grade control center infrastructure supports research in grid visibility, control, and resiliency, with the largest national repository of grid data and models to inform research.

This research is made possible with the use of the EIOC, Interoperability Laboratory, Power Electronics Laboratory, and the Electricity Infrastructure Cyber Security/Resilience Center in the Systems Engineering Building (SEB). These laboratories and facilities support world-class commercial tools, as well as PNNL-developed tools, including the following: the GridLAB-D™ open-source simulation and analysis tool for designing and operating power distribution systems, the GridAPPS-D open-source platform for advanced distribution system planning and operations application development, the GridPACK open-source package for parallelizing power grid simulations, the VOLTTRON™ open-source software platform enabling smart appliances, the R&D 100 Award winning Dynamic Contingency Analysis Tool (DCAT) for enabling power grid cascading failure analysis, and tools for assessing power grid ramping capabilities with increased variable generation. These capabilities are supported by sponsors in OE, EERE (transportation technologies, hydrogen storage, building technologies, and fuel cell technology), CESER, ARPA-E, DHS, ASCR, DoD, the U.S. Department of State, and private industry.

Health: Scholarly Output trend is improving (Rank 1) with strong impact metrics (*i.e.*, ranked 1st in publications in top journals and 2nd in citation count). Demand in this core capability is extremely strong. This demand, coupled with strong private sector demand for relevant hot skills, makes this core capability one of three in which staffing shortfalls are being addressed through intensive recruiting and active focus on retention.

Systems Engineering and Integration

PNNL is internationally recognized for systems engineering and integration through the implementation of technology in real-world complex systems focusing on smart and robust energy and nuclear and radiological security. This core capability has solved some of the most challenging national problems by defining and interpreting complex technical requirements and translating them into fieldable solutions that address economic, social, policy, and engineering considerations. Using a structured approach to understand complex systems throughout their life cycle, PNNL applies its domain knowledge and experience in engineered systems simulation and modeling; system architecture and design; test, evaluation, and optimization; technology assessment, integration, and deployment; policy assessment and economic evaluation; and regulatory analysis, risk assessment, and decision support. This allows our staff to effectively take early-stage research through the development and technology maturation processes and to deploy technical solutions that address our sponsor's most critical challenges.

PNNL applies a graded approach to our systems engineering discipline that enables us to deliver solutions in a highly efficient, effective way. PNNL is known worldwide for effectively field-deploying international nuclear materials safeguards, nuclear and radiological security, and complex radiation detection systems. PNNL is also known for leadership in integrated building energy technologies, including advancing solid-state lighting, building control, and building-grid integration technology. Further, PNNL is recognized nationally for the rigorous analyses that support building energy code development and enable DOE to fulfill statutory requirements related to appliance standards. Lastly, PNNL is widely known for advancing national power grid reliability and smart grid technology, and conducting large-scale technology demonstrations. Staff members are housed in facilities that include SEB, the Electrical Infrastructure Operations Center, System Engineering Facility, 2400 Stevens, Engineering Development Laboratory, APEL, Radiation Detection Laboratory, and the Large Detector Test Facilities.

The Systems Engineering and Integration capability is funded through programs in BES (design and operation facilities), BER, HEP, NP, EERE (buildings and transportation), EM (waste processing and nuclear materials disposition), OE (infrastructure security and energy restoration), FE (carbon and co-sequestration), NNSA (nonproliferation and safeguards), DHS (radiation portal monitoring and critical infrastructure and analysis), NRC, EPA, and DoD.

Health: Scholarly Output trend is stable (Rank 1 tie) with strong impact metrics (i.e., ranked 1st in publications in top journals and 3rd in citation count). Staff, portfolio, infrastructure, and equipment are all good.

Chemical Engineering

PNNL's chemical engineering capabilities translate scientific discovery into innovative, first-of-a-kind processes to solve tough energy and environmental challenges for DOE and other stakeholders. PNNL develops materials, unit operations, and chemical processes at scales ranging from molecular interactions to engineering-scale experiments, through full-scale demonstrations that can be transferred to the sponsor or to industry for commercialization. PNNL has chemical engineers, mechanical engineers, and chemists specializing in disciplines including catalysis and reaction engineering, gas and liquid phase separations, heat exchange, process intensification, fluid dynamics and mixing, thermal-mechanical modeling, flowsheet development and modeling, and techno-economic analyses. Other distinctive areas of expertise include radioactive and non-radioactive nuclear waste treatment (from milligram to ton-scale), encompassing slurry transport and mixing, glass melting, advanced rheology, and fluid dynamics for complex multiphase systems.

PNNL applies chemical engineering capabilities to a broad array of challenges with demonstrated success, including the development and commercialization of NOx reduction units for automobile emissions control, the development and application of software to predict the thermal and structural performance of spent nuclear fuel storage and transportation systems, the development of novel heat pumps and building systems to increase energy efficiency, and the invention and development of micro-technology-based reactors and separations systems for applications such as fuel cells and solar natural gas reforming. Current research focus areas include biomass and fossil fuel conversion to fuels and chemicals, as well as subsequent fuel upgrading, nuclear waste processing and immobilization research, and cost-effective startup and operation of the Hanford Waste Treatment Plant.

This core capability supports sponsor-funded research by the Office of Science (BES), as well as DOE's Applied Energy Offices, including EM, EERE (VTO, BETO, GTO, SETO, and FCTO), FE, NE, NNSA, and ARPA-E. PNNL's chemical engineering capability is also leveraged in support of research funded by DHS and DoD.

Health: Scholarly Output trend is improving (Rank 4) with strong impact metrics (*i.e.*, ranked 3rd in citation count and publications in top journals). High hazard biofuels research currently conducted in high bay space on south campus (PDL-W) requires relocation to north campus. PNNL is planning a new federally owned facility located in a higher hazard zone supporting experimental test stands.

Nuclear Engineering

PNNL has expertise in complex irradiation systems that support materials science, tritium production, advanced fuel modeling, and reactor production analysis. Research staff members have a broad and deep technical skill set across the full spectrum of nuclear engineering disciplines, including reactor physics, mechanical design, thermal-mechanical analysis, fluid dynamics, heat transfer criticality safety, nondestructive evaluation, and robotics, as well as materials science and microscopy. PNNL applies these skills in radiological facilities (*e.g.*, the RPL) to characterize and understand irradiation effects on materials through post-irradiation examination and to make precise measurements and analyses that enable nuclear archeological assessments. In addition, PNNL has experimental testing capabilities that enable the design, development, and fabrication of advanced, accident-tolerant fuel for commercial reactors and low-enrichment fuel for research reactors, as well as the design, modeling, fabrication, and deployment of complex irradiation tests to evaluate nuclear materials.

PNNL is specifically recognized for the development of the Graphite Isotope Ratio Method, which is the world's most accurate estimation tool for graphite reactor operational history, and has a deep expertise in proliferant plutonium production, from reactor irradiation to plutonium metal. This year, a significant effort went into the Plutonium Verification Team that maintains a capability to verify nuclear facility production. PNNL is the design authority for tritium production targets, and this year addressed significant quality control concerns that could impact tritium supply. The combination of thermal, nuclear, and structural skills is also used to evaluate spent nuclear fuel storage and transportation options. PNNL is currently testing high burn up spent nuclear fuel to ensure the continued safe dry storage at nuclear power plants across the nation.

A wide range of sponsors rely on PNNL's nuclear engineering capability. These include BES to understand the benefits of modeling interfacial dynamics in radioactive environments and materials. The NRC relies on PNNL expertise to evaluate and confirm the thermal performance of nuclear systems as well as develop of new techniques for nondestructive evaluation to extend the life of existing reactors. This strong knowledge base and expertise in the commercial nuclear industry enables the design of targets for isotope production and fuel performance modeling to develop or evaluate fuels for use in NRC-regulated commercial or research reactors. PNNL's nuclear engineering capabilities also support DOE-NE's missions and objectives including the Versatile Test Reactor program based on our historical expertise with the fast reactors. NNSA's Defense Programs rely on nuclear engineering to understand the production of materials for the nuclear deterrent, most notably tritium. NNSA's Defense Nuclear Nonproliferation supports the understanding of future reactors and their impact on nuclear proliferation.

Health: Scholarly Output trend is stable (Rank 3) with strong impact metrics (*i.e.*, ranked 3rd in citation count and 3rd in collaboration nationally).

User Facilities/Advanced Instrumentation

Environmental Molecular Sciences Laboratory

As one of BER's national scientific user facilities, EMSL leads molecular-level discoveries for BER and DOE that translate to predictive understanding and accelerated solutions for national energy and environmental challenges. Our vision is to lead the scientific community toward a predictive understanding of molecular processes controlling the flux of materials that underpin biological and ecosystem functions.

Research in EMSL focuses around two science areas—biological sciences and environmental sciences. Within each of these thematic areas, EMSL scientists partner with users from around the world to explore critical questions in BER relevant science. The Biological Sciences Area focuses on biological "machines" and processes in and among microbes (archaea, bacteria, and algae), fungi, and plants. Research focuses on improving the mechanistic understanding of how genetic information is translated into processes across temporal, spatial, and organizational scales—molecules, organisms, consortia, multispecies communities, and ecosystems. This helps advance the accurate metabolic reconstructions and predictive models needed to understand nutrient flux in the environment and improve strategies for designing plants, fungi, and microbes for biofuels and bio-based products. The Environmental Sciences Area focuses on mechanistic and predictive understanding of fundamental physiochemical, ecological, hydrological, biogeochemical, plant, and microbial processes in above and below ground terrestrial and subsurface ecosystems, the atmosphere, their interfaces, and their interactions from molecular- to ecosystem-scale. EMSL provides the experimental, computational, and simulation expertise to investigate the cycling, transformation, and transport of critical biogeochemical elements (*e.g.*, C, N, S, P, Mn, Fe, and Ca), contaminants, and atmospheric aerosols. Coupled experiment and model approaches will accelerate mechanistic understanding of soil-microbe-plant-atmosphere processes and their interdependencies across molecular, plot, atmospheric, and ecosystem scales, and ultimately inform models of land-atmosphere interactions at larger scales. Through the integration of field, laboratory, and computational approaches, EMSL users gain new knowledge of molecular-scale phenomena that can be parameterized, scaled, and integrated into models designed to understand complex biological and environmental systems across many spatial and temporal scales.

PNNL is recognized for its ability to conceive, design, build, operate, and manage world-class scientific user facilities, and is known internationally for its advanced instrumentation designed to accelerate scientific discovery and innovation. As an example, PNNL demonstrated this ability with the development, design, construction, and deployment of the 21T Fourier-Transform Ion Cyclotron Resonance (FTICR) MS. As new capabilities are developed, special calls for first science applications promote rapid and effective utilization of these new tools. EMSL is active in leveraging its capabilities with other DOE user facilities to maximize the scientific community's ability to address critical challenges in biology, environment, and energy. As an example, EMSL and JGI sponsor joint user calls through BER's FICUS Initiative. The EMSL-JGI FICUS calls have been used to maximize DOE's genomic/transcriptomic and other 'omic capabilities, as well as EMSL's chemical and physical measurements for breakthroughs in systems biology. EMSL continues to explore other mechanisms to maximize the value and reach of the facility by partnering with other user facilities via the FICUS Initiative, such as ARM (described below) and BES funded light sources. EMSL also collaborates with other user facilities through the new Society for Science at User Research Facilities. This capability is funded by BER.

ARM Research Facility

The world's premier ground-based observatory for atmospheric science research, the ARM Research Facility, is a DOE user facility that provides a global network of instrumented fixed, mobile, and aerial observatories for obtaining cloud and aerosol measurements, as well as precipitation, solar and thermal radiation, surface heat and moisture, and meteorological conditions. ARM observatories are deployed to diverse meteorological regimes around the world where there are critical science questions and deficiencies in global-scale models. Fixed-location sites are located in the United States Southern Great Plains, the North Slope of Alaska, and Graciosa Island in the Eastern North Atlantic. Diverse data sets are being incorporated into integrated products for evaluating high-resolution atmospheric-process models and large-scale earth system models, such as the DOE National Center for Atmospheric Research Community Earth System Model and the DOE E3SM Model.

To accelerate model development and associated atmospheric-process studies, ARM is working to bridge the scale gap between ARM observations and global earth system models by expanding capabilities at ARM observatories. The first test of this new strategy has been at the U.S. Southern Great Plains site, where ARM has developed a framework that combines high-resolution model simulations with ARM observations. The ARM observations provide three-dimensional constraints to the model as well as a test of model output. The combination of the ARM observations with the high-resolution model output and associated diagnostics provides a more complete representation of the ARM site domain, enabling broader use of the data by the scientific community. ARM is in the process of planning at which site and for what set of science issues this observation-modeling framework will be applied next.

ARM continues to deploy mobile facilities and the ARM Aerial Facility as approved through the user proposal process. FY 2020 will represent a strong focus on the Arctic, as both mobile facilities will be deployed for Arctic experiments, while ARM continues to operate two sites on the North Slope of Alaska. The first mobile facility will be deployed to coastal Norway for a study of the cloud systems formed over the north Atlantic during cold-air outbreaks. The second mobile facility will be deployed on the German icebreaker, Polarstern, for a major international campaign in which observations will be taken for a year as the icebreaker drifts with the ice around the Arctic ocean.

The ARM Aerial Facility is undergoing a period of change as the G-1 aircraft, which has served ARM since 2010, has been retired and the process of procuring a replacement aircraft is underway. To replace the aircraft, PNNL is following the CD process (DOE O 413); we have received approval for CD-0, CD-1, and CD-3. The Air-ARM Project Team is now proceeding with plans for the aircraft acquisition and modification for research. In addition, the team, in conjunction with the Port of Pasco and other regional partners, has obtained new hangar space to support the new aircraft as well as a mid-size UAS.

PNNL leads the development of UAS capabilities within ARM. PNNL has procured a very capable mid-size UAS that can carry payloads of up to 100 pounds as high as 18,000 feet for periods of up to eight hours. This mid-size UAS is being used to study aerosols at the ARM Southern Great Plains site, where it is providing information about vertical profiles and spatial variability of aerosol properties.

PNNL is responsible for the overall technical direction of the ARM Facility's scientific infrastructure through leadership of a collaboration among nine DOE laboratories. PNNL has lead responsibility for a variety of facility components, including the management and operation of the ARM Aerial Facility and related operations, technical leadership for various instruments and data product development processes, and communications. This capability is funded by BER.

Health: The G-1 Replacement aircraft has CD-2/3 approval and has received full capital funding. The aircraft Request for Proposal pre-purchase inspection contract/aircraft modifications statement of work is in progress. A new ARM hanger to be constructed in late 2019 will consolidate space and will improve storage conditions. Shortages in high bay space and field test sites will be needed to execute our programs; these are being addressed. Staff and portfolio are good.

Major Initiative	Core Capabilities
Reinventing Catalysis	Chemical and Molecular Sciences Condensed Matter Physics and Materials Sciences Computational Science Advanced Computer Science, Visualization & Data Applied Materials Science and Engineering Chemical Engineering Applied Mathematics User Facilities
Understanding Multiscale Earth System Processes and Dynamics	Earth Systems Science and Engineering Climate Change & Atmospheric Science Biological Systems Science Environmental Subsurface Science Biological & Bioprocess Engineering Computational Science Advanced Computer Science, Visualization & Data Applied Mathematics User Facilities
Mastering Nuclear Materials Processing	Nuclear & Radiochemistry Chemical and Molecular Sciences Condensed Matter Physics and Materials Sciences Nuclear Engineering Chemical Engineering Applied Materials Science and Engineering

	Computational Science Computer Science, Visualization & Data Computational & Mathematical Sciences Applied Mathematics
Accelerating Scientific Discovery through Extreme-Scale Data Analytics and Simulation	Advanced Computer Science, Visualization & Data Applied Mathematics Computational Science Advanced Computer Science, Visualization & Data Systems Engineering & Integration Power Systems & Electrical Engineering User Facilities
Realizing a Secure, Flexible, and Resilient Electric Power System	Power Systems & Electrical Engineering Systems Engineering & Integration Cyber & Information Sciences Chemical and Molecular Sciences Chemical Engineering Condensed Matter Physics and Materials Sciences Computational Science Advanced Computer Science, Visualization & Data Decision Science & Analysis Applied Materials Science and Engineering Applied Mathematics
Delivering Cyber-Resilient Critical Infrastructure	Cyber & Information Sciences Decision Science & Analysis Advanced Computer Science, Visualization & Data Computational Science Applied Mathematics Power Systems & Electrical Engineering Systems Engineering & Integration
Enabling Chemical and Materials Discovery through Quantum Information Sciences	Chemical and Molecular Sciences Condensed Matter Physics and Materials Sciences Computational Science Advanced Computer Science, Visualization & Data Applied Materials Science and Engineering Chemical Engineering Applied Mathematics

Table: Core Capabilities Support to Major Initiatives

Science Strategy for the Future

PNNL draws on signature capabilities in chemistry, earth sciences, and data analytics to advance scientific discovery and create solutions for the nation's toughest challenges in energy resiliency and national security. To support current and future DOE missions, we are focusing on six major initiatives:

1. Reinventing Chemical Catalysis – We will apply inspiration from biological systems to develop catalysts and chemical pathways that create useful products from waste carbon and nitrogen and advance grid-scale energy storage.
2. Understanding Multiscale Earth System Processes and Dynamics – We will build the science basis for understanding coupled processes in earth systems to improve the predictive capability and utility of DOE's earth system models.
3. Accelerating Scientific Discovery through Extreme-Scale Data Analytics and Simulation – We will apply domain-aware machine learning and data analytics methods to derive new scientific insights from our unique earth system, grid, and cyber data sets.
4. Realizing a Secure, Flexible, and Resilient Electric Power System – We will develop and deploy the next generation of real-time grid situational tools and grid-scale energy storage technologies to create a more secure, flexible, and resilient electric power system.

5. Delivering Cyber-Resilient Critical Infrastructure – We will develop the tools, techniques, and procedures necessary to enable autonomic cyber defense of critical infrastructures, using our experience in grid operations as a foundation.
6. Mastering Nuclear Materials Processing – We will advance our scientific understanding of nuclear materials processing to strengthen the ability of the United States to produce nuclear materials and counter their proliferation by our competitors and adversaries.

We are exploring a seventh major initiative in quantum information science, in partnership with Microsoft and the University of Washington (UW), with the aim to be the first to design new chemical conversion catalysts using quantum computing.

Infrastructure

Overview of Site Facilities and Infrastructure

PNNL is based in southeastern Washington State, in the City of Richland, with buildings on the Laboratory's main campus and on the Hanford Site. PNNL also conducts operations at the MSL in Sequim, Washington. The PNNL campus master plan is available at https://www.pnnl.gov/sites/default/files/media/file/2017CampusMasterPlan.pdf. Specifically, PNNL consists of the following:

- 25 DOE-owned [10 by Office of Environmental Management (EM) and 15 by SC] buildings (927,222 gsf) and 21 OSFs on 454 acres
- 21 Battelle Memorial Institute (BMI)-owned buildings (419,968 gsf) and 25 OSFs on 326 acres, including 117 acres in Sequim (65 acres of land and 52 acres of tidelands)
- 31 buildings from third-party leases and agreements (973,350 gsf)

As part of the PNNL contract, Battelle provides DOE with exclusive use of the Battelle-owned buildings for PNNL purposes. Battelle buildings comprise 18 percent of PNNL's laboratory space (square feet) and are provided to the government at cost. DOE and Battelle have reached a contractual agreement to transfer the Battelle-owned buildings in Richland and Sequim, WA to DOE on or before the end of FY 2022.

PNNL's non-federally owned space is evaluated for operational efficiency, consolidation, and/or reduction opportunities. In FY 2018, PNNL renewed five leased buildings. In FY 2019, PNNL is planning to sign one new lease (beneficial occupancy in FY 2019), renew two leases, and exit one leased building ≥ 10,000 square feet. We are not disposing of any DOE land via lease, sale, or gift within the planning horizon. PNNL recently completed successful lease negotiations for five buildings on the PNNL Richland Campus, accounting for ~340,000 gross square feet. This negotiation resulted in an overall cost savings over the next 15 years of approximately $14M.

The utility and distribution systems that serve PNNL's Richland campus, the MSL, and PNNL-operated buildings in the Hanford 300 Area are provided by various suppliers. The water and sewer infrastructure in the Hanford 300 Area is owned by DOE and managed by PNNL; it currently has an overall asset condition of adequate. Water, sewer, and electric service in the PNNL Richland Campus and the Hanford 300 Area are provided by the City of Richland. The septic system and water distribution system at the MSL are owned by BMI and currently have an overall asset condition of adequate. Natural gas for both the Hanford 300 Area and PNNL Richland Campus is provided by Cascade Natural Gas. There is no centralized gas utility system at the MSL. All utilities consumed by PNNL have the necessary capacity to meet the current DOE mission. We are implementing an infrastructure strategy that will enable us to maintain the ability to deliver safe and reliable capacity, and address systems that are nearing end-of-life (*e.g.*, 300 Area systems). The service providers for the various utility infrastructure and distribution systems include EM contractors, Battelle as PNNL's operating contractor, the City of Richland, and Clallam County PUD.

As a result of an electrical short circuit study of the BMI buildings, it was determined that 54 pieces of electrical equipment (electrical panels and circuit breakers) have an ampere interrupting capacity that exceeds required limits. PNNL is accelerating the effort to address these issues by replacing all identified equipment.

The FY 2018 condition and utilization assessment designated all 25 (927,222 gsf) federally owned, active, operating buildings as adequate relative to mission. All buildings were designated as utilized; none were designated underutilized or unutilized. The assessment also designated 50 of the 52 (1,280,091 gsf) non-federal, active, operating buildings as adequate relative to mission; two (113,227 gsf) were designated as substandard and none were designated as inadequate. Of the 52 non-federal buildings, 51 (1,393,318 gsf) were designated as utilized, one (BIL; 17,621 gsf) was designated as unutilized, and none were designated as underutilized. Actions to resolve the unutilized and/or substandard buildings are described in the Campus Strategy.

PNNL's current deferred maintenance for all federal buildings (SC and EM) stands at $8.5M, and the overall condition index is 97. The transfer of non-federal (BMI) buildings to DOE will increase PNNL's overall deferred maintenance and replacement plant value. These buildings also have a low deferred maintenance balance related to their replacement value. Because of this, PNNL's overall condition index is not expected to change.

Campus Strategy

PNNL's campus strategy is aligned with PNNL's major initiatives and key programs. PNNL continues to plan its investments consistent with two objectives:

Objective 1 – Mission Aligned: support mission alignment and critical programs/initiatives and strengthen the core capabilities and ensure a mission-ready environment.

Objective 2 – Optimize Functionality, Reliability, Utilization, and Operating Costs: modernize and sustain facilities and infrastructure by delivering safe and reliable capacity.

PNNL balances our intentions for long-term value with near-term benefit to our Office of Science steward. Campus investments will promote a mission-aligned, functional, reliable, fully utilized campus. These efforts will be executed through reasonable and achievable planning, investment opportunities, and operational resources.

Successful execution of the campus strategy includes investments in four key categories:

- Campus Continuity – Federalize the core campus (transition Battelle buildings to DOE-SC ownership through accelerated depreciation and remediation activities)
- Mission Alignment – Construct new federally owned facilities while fostering collaboration
- Utilization & Safety – Optimize utilization and maximize public safety through construction of new federally owned facilities and renovation of existing space
- Sustain and Maintain – Provide the most mission-ready campus in the DOE complex by investing in existing facilities and infrastructure

The figure below shows PNNL's campus strategy site map at the end of FY 2030, with increased federal ownership (DOE-SC) of buildings and land. PNNL will continue to invest significant internal funds to support facilities and infrastructure, such as renovating/repurposing existing underutilized facilities and supporting the exits of multiple third-party leased facilities. PNNL is currently executing the SLI ESC project, with a total project cost of $93M for a 138,000 gsf to 145,000 gsf building. PNNL is in the planning stages for a new OE-funded facility (GSL) to consolidate and enhance the energy storage research capability. In addition to new construction SLI projects, PNNL will request $2.5M in SLI-general plant project (GPP) investments to provide updates to the PNNL Richland Campus security and emergency notification systems. PNNL also will pursue other direct-funded projects to support our campus strategy.

Our investment plans and actions for delivering a mission-ready campus, aligned with our campus strategy objectives, are summarized below. The plans and actions are based on our annual evaluation of current space utilization, condition assessments, core capability heath (as determined by the PNNL core capability management process), and mission projections. Investments by core capability are shown in the table below.

Possible funding for the campus strategy includes lab overhead/institutional general plant project (IGPP), direct sponsor funding, and SLI line item/GPP investments.

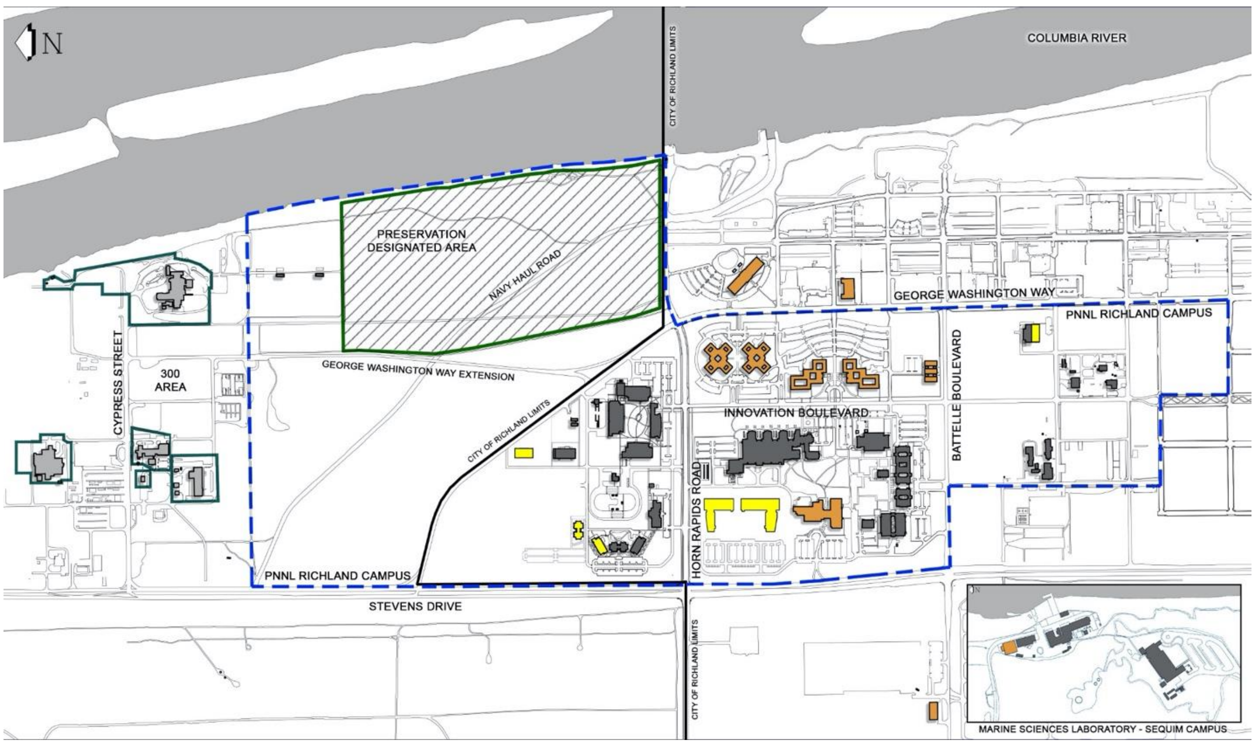


Figure: PNNL 10-year campus strategy site map at FY 2030 showing land ownership, PNNL Richland Campus area, and proposed and notional new construction; the inset shows MSL in Sequim, Washington

Objective 1 – Mission Aligned

Projects on the Planning Horizon:

The ESC Mission Need Statement described a science capability gap in chemical and molecular science exacerbated by an inability to integrate chemical conversion programs due to insufficient quantities of space at PNNL in the proper configuration and adjacency. PNNL is constructing a $90M SLI funded facility to close these gaps and support discovery science. This project has received CD 2/3 authorization and will provide an estimated 52 laboratories, 200 workstations, and collaboration space. This facility is scheduled to be completed in FY 2021.

In support of the PNNL' s Mastering Nuclear Materials Processing major initiative and our Engineering core capabilities, we are investing to maintain mission-ready facilities.

- **3420 Radiochemistry Ventilation:** This project is currently underway in the Radiation Detection Laboratory. This will modify building ventilation to support wet radiochemistry research. This $3.2M IGPP-funded project is anticipated to be complete in FY 2020.
- PNNL has initiated multiple IGPP-funded renovations to the RPL, a mission-unique Hazard Category II nuclear facility.
  - **325RPL Safeguards:** Implementing a project to increase the accountable nuclear material inventory limits to facilitate research and reduce the risk of exceeding the existing limit. This $3.6M IGPP-funded project is anticipated to be complete by FY 2020.
  - **325RPL Glove Box Functionality Improvements:** Replacing non-functional glove boxes and modernizing lab spaces. This $1.6M IGPP-funded project is anticipated to be complete by FY 2020.
  - **RPL Acid Degraded Fume Hoods:** Replacing fume hoods to avoid potential failures in the ventilation system. This project is anticipated to be complete by FY 2021.
  - **RPL Glove Box Replacement:** Replacing a non-functional glove box. This project is anticipated to be complete by FY 2020.
  - **Future Funding:** Replacing other facility and infrastructure systems that have reached the end of their useful life, including critical fire riser lines.

The following projects will support the exit of a third-party leased facility (56,000 gsf), generating savings of $1.2M to $1.5M annually. Additionally, these projects will support the conversion of all remaining substandard space on the PNNL Richland Campus to *adequate.*

- Repurpose Vivarium in Life Sciences Laboratory 2 (LSL 2) in support of Applied Process Engineering Laboratory (APEL) exits.
  - **Labs 421-436**: Converting unusable LSL 2 lab vivarium space into ventilation-intensive general purpose wet laboratory spaces. This $2.3M IGPP-funded project is expected to be complete in FY 2019.
  - **Labs 404–424**: Converting unusable LSL 2 lab vivarium space into ventilation-intensive general purpose wet laboratory spaces. This $2.4M IGPP-funded project is expected to be complete in FY 2022.
- **General Purpose High Bay**: PNNL will construct a general purpose high bay laboratory to address insufficient federally owned high bay space for experimental test stands and capabilities for bioenergy technologies research in higher hazard processes. This $7M to $9M IGPP-funded project is expected to be complete in FY 2025.
- **Repurpose Vivarium (331)**: Converting unusable Life Sciences Laboratory 1 (331) vivarium space into ventilation-intensive and general purpose wet laboratory spaces and improving utilization. This $1.7M IGPP-funded project is expected to be complete in FY 2027.

PNNL will align and optimize enhanced security facilities, in support of nuclear engineering on the PNNL campus. Initially, PNNL will remodel and expand the only unutilized facility on the PNNL Richland Campus. This $12M to $15M IGPP-funded project, to be initiated in FY 2020, will provide an institutional savings of $1.2M to $1.6M annually by consolidating enhanced security facility space onto the PNNL Richland Campus, allowing for the exit of a third-party leased facility. Additionally, PNNL is considering the need for a direct-funded facility that would provide laboratory space to support sensitive and secure research and related support staff and equipment. This effort would allow for redundant secure operations on the PNNL Richland Campus, which could include appropriately located laboratory work while maintaining an enhanced security posture.

PNNL proposes to accelerate the development of next generation grid-scale energy storage to enhance grid flexibility and resilience through efforts to be housed in a new OE-funded GSL that complements applied materials science and engineering and existing battery development at PNNL. This estimated

$60M–$70M direct-funded facility, to be completed in FY 2023, would consolidate over $26M of existing and new equipment and research across 25 laboratories into one integrated facility that will enable DOE to independently test and validate the next generation grid energy storage technologies under realistic grid operating conditions. PNNL, Battelle, and the state of Washington are exploring opportunities to provide ~$35M in new capability investments into the instrumentation in support of this initiative.

Potential Projects:

With the near-term federalization of the MSL in Sequim, WA, PNNL is exploring possible future investments at MSL to better enable field- and laboratory-based research, instrumentation development, and testing, as well as to create collaboration and demonstration areas. Investments would focus on capabilities in support of terrestrial-aquatic interface science, ecosystem science, coastal biogeochemistry, integrated coastal modeling, marine biotechnology, marine policy, and systems engineering. MSL focused investments would strengthen DOE's only facility dedicated to marine science while supporting research in the areas of energy and national security that requires coastal environments.

PNNL's vision is to pursue QIS**,** leveraging partnerships with universities and industry to collaborate in the fields of applied materials science and engineering, computational sciences, and applied mathematics, where PNNL will synthesize, test, and evaluate atomically precise materials. This will help address a grand-challenge in quantum computing. PNNL is well suited to this scientific mission and will include the need to provide appropriate lab space for research and industry collaboration/partnerships in our campus strategy. PNNL would directly support DOE-SC's priority focused on the development of quantum computing.

Objective 2 – Optimize Functionality, Reliability, Utilization, and Operating Costs

Projects on the Planning Horizon:

PNNL will continue to invest in the necessary maintenance, repair, and renewal to sustain our building and infrastructure assets in a mission-ready condition; provide the physical environment that meets current and emerging research needs required to deliver vital mission impacts in energy resiliency and national security; optimize campus functionality, reliability, and utilization; and improve research operations while maintaining or reducing operating costs. Our action and investment plan includes the following.

- Executing the DOE and Battelle contractual agreement to transfer the Battelle-owned Richland and Sequim, WA facilities to DOE-SC on or before the end of FY 2022. DOE and Battelle have also agreed that DOE has the right to acquire or lease Battelle-owned land in Richland and Sequim, Washington, and DOE has agreed to fully exercise this right on or before the end of FY 2035, subject to the availability of funds. This agreement could result in DOE acquiring 21 Battelle-owned buildings and approximately 347 acres in Richland and Sequim, Washington. In FY 2018, the Pacific Northwest Site Office (PNSO) and Battelle successfully transferred the NW Parcel (20.79 acres) from Battelle to DOE-SC ownership to site the ESC facility. In FY 2019, the transition of three additional parcels is expected to be finalized. The remaining parcels will be transferred to DOE-SC ownership, based on funding availability, prior to 2022.
- Completing a building restoration and remediation program to retire DOE-SC's current liability associated with the historical use of radiological and other materials in Battelle-owned buildings. Demolition of the Research Technology Laboratory complex (10 buildings), which has known contamination, began in FY 2018, with scheduled completion in FY 2019. Upon completion of the Research Technology Laboratory complex, including the unrestricted release, this program will be completed.

- Replacing the existing **programmatically leased hangar** (Port of Pasco) for the ARM Aerial Facility with a new, leased hangar. The new hangar would house the G-1's replacement and a mid-size UAS. This action resolves the Port of Pasco's current substandard condition.
- LSL 2 Exhaust Stack Upgrade: Resolving LSL 2's exhaust issues that expose workers to building exhaust plumes resulting in limited roof access and additional building outages. This $2M IGPP-funded project is expected to be complete in FY 2019.
- **Campus Infrastructure Upgrades:** In an effort to assure a mission-ready campus for the future, PNNL is planning to pursue the following investment opportunities to maintain the PNNL Richland Campus and the 300 Area into the future.
    - The Campus-Wide Safety System project will modernize PNNL's campus security/emergency notification system by replacing dated technology and addressing existing campus security camera system gaps. PNNL will deploy this campus communication/awareness detection system in support of active shooter and campus-wide notification events. This $2.5M–$5M SLI-GPP funded project is proposed to be funded in FY 2020.
    - 300 Area key infrastructure upgrades: PNNL operates four facilities that are strategically placed on the Hanford 300 Area. Much of the infrastructure supporting these facilities is beyond its useful life (65 years old) and requires significant investment to support PNNL use to FY 2046 and beyond. This request will address needs to replace existing heating, ventilation, and air conditioning (HVAC) and water distribution systems supporting the four buildings in the Hanford 300 Area. PNNL is proposing multiple IGPP projects totaling an estimated $7M to $9M over the 10-year planning horizon.
    - Steam to Hydronics: PNNL is planning two separate steam to hydronics conversion projects totaling an estimated $12M to $15M to replace failing heating and cooling infrastructure while attaining institutional energy savings and, where feasible, increasing the use of renewable energy sources. These are initially being proposed as a Bonneville Power Administration (BPA) Utility Energy Services Contract funded project. If this is not successful, these projects would be pursued as IGPP funded projects over the 10-year planning horizon.
- **Biological Sciences Facility (BSF) Increased Ventilation Capacity:** PNNL is planning an institutional investment to increase ventilation capacity in the BSF to create general purpose ventilation-intensive wet labs. This would allow for the installation of additional fume hoods as needed. This $1.5M IGPP-funded project is currently planned to be complete in FY 2026.

Potential Projects:

- **MSL1:** PNNL plans to modernize the MSL1 facility. Even though the building as a whole has an overall asset condition of *adequate*, the current condition of some of the equipment and infrastructure is *substandard*. PNNL plans to improve substandard electrical capacity, vertical clearance, temperature control, exterior research areas, and lighting to improve functionality to assure mission readiness. This $3M IGPP-funded project is expected to be complete by FY 2024.
- **Campus Sidewalks and Parking Addition:** To assure a mission-ready campus, PNNL is planning to make continual investments in the PNNL Richland Campus sidewalks and parking areas. This investment will refresh campus infrastructure to support pedestrian transportation across the PNNL Richland Campus.
- Fostering a **strategic partnership** with the City of Richland to modernize adjacent roadways, pedestrian travel, and emergency response infrastructure. In conjunction, to support the strategic objective of Campus Continuity, PNNL plans to make future investments in pedestrian circulation and parking that align with the campus master plan. This will improve travel times and employee safety, resulting in research efficiencies.

- PNNL is considering reconfiguring existing space to create additional workstations to support our current and future staff needs.

Primary Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
Chemical & Molecular Science **Condensed Matter Physics & Materials Science**	Current	Insufficient ventilation-intensive space for catalysis synthesis and collaboration; lack of environmental controls for state-of-the-art *in situ* characterization; limited space to integrate experimental capabilities; limited collaboration space for "point of research" work.	Limits ability to transform: Chemical energy conversion rates and selectivity at lower temperatures; and, ability to predict and design catalytic processes.	SC SLI investment in wet, ventilation-intensive labs and characterization tool labs (ESC) to advance understanding and control of catalytic processes.
Nuclear & Radiochemistry	Current	Insufficient ventilation-intensive wet space, specifically radiochemistry labs.	Limits simultaneous achievement of DOE's Security Systems mission while conducting research efficiently and attracting and retaining top researchers.	Invest overhead/IGPP (underway) to correct insufficient ventilation supporting Radiation Detection Laboratory space.
		Insufficient infrastructure in Radiochemistry Processing Laboratory to support operations with special nuclear materials to understand how material structures and properties evolve in radioactive environments.	Limits efficiency and increases cost to conduct research within current limits.	Invest overhead/IGPP (underway) to provide sufficient and secure infrastructure in the Radiochemistry Processing Laboratory to support efficient research operations using special nuclear material.
		Inadequate glove box and acid digestion hood functionality in Radiochemistry Processing Laboratory to understand how material structures and properties evolve in radioactive environments.	Limits efficiency and increases cost to conduct research within capacity.	Invest overhead/IGPP (underway) in Radiochemistry Processing Laboratory to replace non-functional glove boxes, acid degraded hoods and duct work.
Cyber and Information Sciences & Nuclear Engineering	Current	Insufficient federally owned lab and office space for research in data exploitation, workflow, and provenance at extreme scales for science, energy, and security domains; and, to protect critical U.S. cyber-enabled systems. Response challenges to multiple simultaneous events.	Increased life cycle operating costs from: continued reliance on non-federal-owned buildings; surplus ventilation-intensive (vivarium) space; and, responding to multiple simultaneous events.	Invest overhead/IGPP to repurpose surplus ventilation-intensive (vivarium) space to office and general dry lab space; Pursue direct funding to support a redundant centralized enhanced security facility.
Applied Materials	Future	Insufficient federally owned lab and office space for research in materials synthesis, performance	Continued reliance third-party space. Limited ability to maintain a U.S. leadership position in the	Procure other direct funding for a new energy storage facility (GSL) acquisition.

Primary Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
Science & Engineering		validation, and device fabrication and testing that can be scaled up and transferred to industry.	next generation of energy storage technologies.	
	Current	Insufficient federally owned lab and office space for research in materials synthesis, manufacturing, and device fabrication and testing that can be scaled up and transferred to industry.	Continued reliance on third-party space and continued retention of surplus federal space without conversion to needed space increases operational costs.	Invest overhead/IGPP to repurpose ventilation-intensive (vivarium) lab space in Life Sciences Laboratory 1 and 2 to ventilation-intensive general purpose wet lab space; relocate compatible work from non-federal facilities.
Chemical Engineering & Engineering & User Facilities Advanced Instrumentation	Future	Insufficient federally owned high bay space for experimental test stands and capabilities for bioenergy technologies research in higher hazard processes.	Continued reliance on third-party space and current higher hazard, thermochemical processes located in high bay space adjacent to residential and related commercial building developments.	Invest overhead/IGPP in a General Purpose High Bay Laboratory located in areas designated for higher risk work, to house experimental test stands and capabilities for bioenergy technologies and advanced instrumentation research.
Earth System Science and Engineering	Future	Substandard laboratory space.	Researcher effectiveness and pace of scientific innovation could be impacted by unplanned outages for emergent repairs thus increasing overall cost of research.	Invest overhead/IGPP in MSL1 200 wing to improve; electrical, ceiling clearances, temperature control, and lighting.
Multiple Core Capabilities	Current	Life Sciences Laboratory 2 stack design does not support current building codes; limits roof access and creates inefficient operations.	Worker exposure to building exhaust plumes, access to the roof is limited, creating additional building outages.	Invest overhead/IGPP to improve Life Sciences Laboratory 2 exhaust stack performance.
Enabling Infrastructure		Insufficient pedestrian circulation and parking lots on campus.	Inefficient pedestrian travel times continue to reduce research efficiency; discourages walking.	Invest internally to build campus sidewalks and parking consistent with campus master plan.

Primary Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
Multiple Core Capabilities **Enabling Infrastructure**	Future	End-of-life building systems and infrastructure to provide safe, secure, reliable space to deliver mission outcomes.	Researcher effectiveness and pace of scientific innovation could be impacted by unplanned outages for emergent repairs thus increasing overall cost of research.	Invest IGPP to renew utility water supply and HVAC systems. Invest IGPP to transition from steam to hydronics. Invest SLI-GPP in campus security and emergency notification systems.

Table: Current and future infrastructure gaps by core capability

Site Sustainability Plan Summary

Fundamental to the S&T outcomes that we deliver every day is our commitment to sustainability—a responsibility that we take seriously. Sustainability at PNNL encompasses environmental stewardship in our operations as well as how the Laboratory demonstrates social responsibility and advances economic prosperity—all in a manner that delivers lasting benefit to our sponsors, community, and nation

In FY 2018, we achieved several sustainability milestones, as highlighted below.

Utility Energy Services Contract

PNNL solicited interest from serving utilities and selected BPA to provide a customized Utility Energy Services Contract program based on their energy management services offerings, experience, and qualifications. Engineers from BPA began to evaluate both laboratory and office facilities at PNNL in FY 2017 and continued in FY 2018 to identify potential energy conservation measures for implementation. This partnership is expected to continue throughout 2019 until a project can be fully developed for implementation. Successful implementation of energy conservation measures is expected to significantly reduce energy intensity at PNNL.

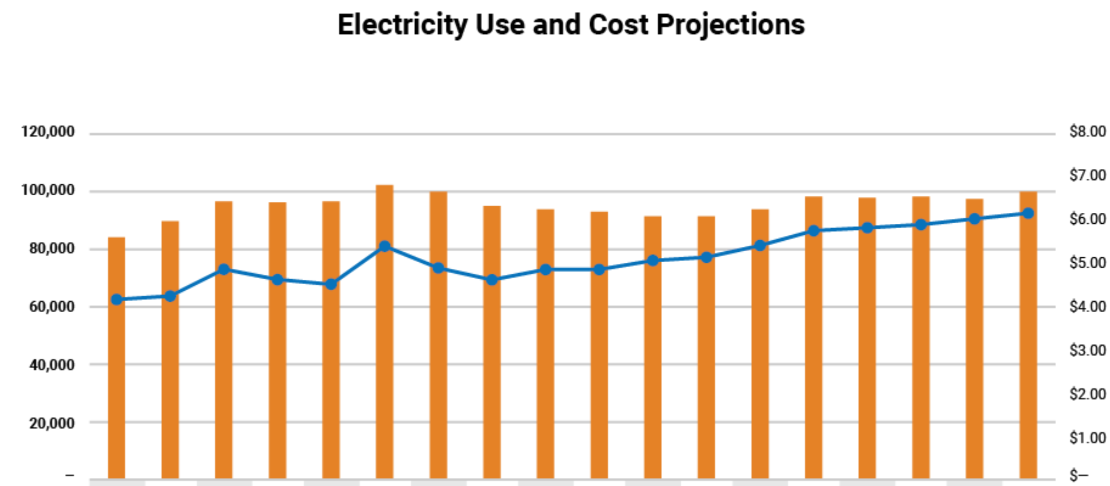
Guiding Principles for Sustainable Construction

In FY 2018, PNNL finished the certification process for the Lab's recently completed High Performance and Sustainable Building (HPSB), the 3860 Engineering and Analysis Building, using the Guiding Principles for Sustainable Construction. This was the second new facility at PNNL to use the Guiding Principles as a path toward HPSB status. The Engineering and Analysis Building included sustainable design elements, such as an HVAC system that uses advanced controls and incorporates energy recovery in both the heating and cooling season, low-flow plumbing fixtures, LED lighting, and water efficient landscaping. With the addition of this building, PNNL has over 60 percent of applicable buildings compliant with the Guiding Principles. PNNL is currently documenting HPSB certification on another new facility, the 3400 Building (Discovery Hall), a collaboration center on the PNNL campus designed to meet the Guiding Principles.

Clean and Renewable Energy

In FY 2018, PNNL procured enough renewable energy credits (RECs) so that combined with the on-site renewables, we offset 60% of its electrical use and 44% of its total electric and thermal energy. Thus, PNNL is exceeding both the FY 2018 renewable electric energy goal and the FY 2018 clean energy goal.

Aside from RECs, PNNL has several on-site solar arrays. The solar hot water heater installed at EMSL produces approximately 160,000 Btu/hr (peak output) and is dedicated to the lunchroom and associated restrooms, fulfilling the majority of that area's hot water needs. Several small solar photovoltaic (PV) arrays power various air and water monitoring stations throughout the campus; these have not been counted toward the goal. In addition, PNNL operates a 125 kW PV array at the EMSL building, which includes charging stations for electric fleet vehicles and is used for several R&D projects. A chart illustrating PNNL electricity usage and cost projections is shown in the figure below.



FY	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
MWH	84,167	89,608	96,663	96,304	96,453	102,136	100,030	95,012	93,799	92,968	91,259	91,473	93,678	98,295	97,686	97,973	97,377	99,577
$M	$4.17	$4.27	$4.87	$4.64	$4.52	$5.40	$4.88	$4.62	$4.87	$4.87	$5.07	$5.17	$5.43	$5.75	$5.84	$5.90	$6.04	$6.18

Figure: Energy usage and cost projections

PRINCETON PLASMA PHYSICS LABORATORY

Lab-at-a-Glance

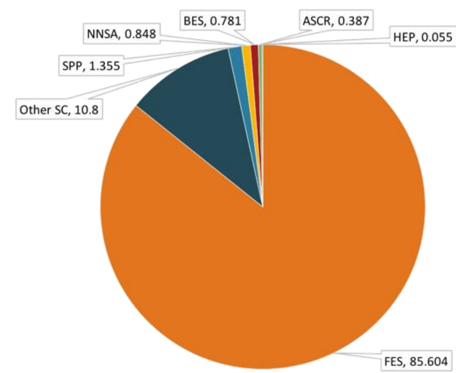
Location: Princeton, NJ
Type: Single-program Laboratory
Contractor: Princeton University
Site Office: Princeton Site Office
Website: www.pppl.gov

- **FY 2018 Lab Operating Costs:** $99.83 million
- **FY 2018 DOE/NNSA Costs:** $98.47 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $1.36 million

Physical Assets:
- 90.7 acres and 30 buildings
- 758,000 GSF in buildings
- Replacement Plant Value: $721 M

Human Capital:
- 447 Full Time Equivalent Employees (FTEs)
- 7 Joint Faculty
- 21 Postdoctoral Researchers
- 43 Graduate Student
- 292 Facility Users
- 50 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

The U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) is a collaborative, national center for fusion energy research. PPPL has two coupled missions: PPPL develops the scientific understanding of plasmas from nano- to astrophysical-scale and develops the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world. As a core part of Princeton University's culture, PPPL educates and inspires future generations to serve the national interest. PPPL's five core capabilities reflect its expertise and the role it plays in the DOE missions:

- Plasma and Fusion Energy Sciences
- Large Scale User Facilities/Advanced Instrumentation
- Mechanical Design and Engineering
- Power Systems and Electrical Engineering
- Systems Engineering and Integration

PPPL has been managed by Princeton University, a world-class teaching and research university, since 1951. For nearly seven decades, PPPL has been a world leader in magnetic confinement experiments; plasma science; fusion science; and engineering. PPPL is partnering in the ITER Project to prepare for U.S. participation in the first burning plasma. As the only DOE national laboratory dedicated to research in Fusion Energy Sciences, PPPL aspires to be the nation's premier design center for the realization and construction of future fusion concepts. The Laboratory contributes to the economic health and competitiveness of the U.S. by serving as a national leader in plasma theory and computation, plasma science, and technological innovation. Indeed, PPPL aims to drive the next wave of innovation in plasma technologies to maintain U.S. leadership in this critical area. At the end of FY 2018, PPPL's workforce was composed of 38 percent technical staff and 62 percent operation staff.

Core Capabilities

As a pioneer with decades of contributions to the U.S. and international fusion and plasma physics research communities, PPPL possesses core capabilities vital to the DOE Office of Science's mission to develop the knowledge base for fusion energy and both high- and low-temperature plasmas. These capabilities include 1) Plasma and Fusion Energy Sciences, 2) Large-Scale User Facilities/Advanced Instrumentation, 3) Mechanical Design and Engineering, 4) Power Systems and Electrical Engineering, and 5) Systems Engineering and Integration.

While the main focus of PPPL's capabilities is research for Fusion Energy Science (missions SC 17-20), they also support other important DOE missions and receive supplementary funding from Advanced Scientific Computing Research (mission areas SC 1, 3, 6), Basic Energy Sciences (mission area SC 7), High Energy Physics (mission area SC 25), and the National Nuclear Security Administration (NNSA).

Plasma and Fusion Energy Sciences

PPPL offers world-leading experimental and theoretical capabilities to explore the physical processes that take place within the high-temperature, high-pressure plasmas required for fusion energy. Areas of special strength include: the National Spherical Torus Experiment Upgrade (NSTX-U); the Lithium Tokamak Experiment - Beta (LTX-β); high-resolution techniques to measure plasma properties and processes at a wide range of spatial and temporal scales; powerful capabilities for plasma heating and current drive; capabilities for analysis of data from high-temperature plasmas used by experimental teams around the world; expertise in understanding, numerically modeling, and operating a wide range of magnetic confinement configurations including tokamaks and stellarators; world-leading basic plasma experimental facilities such as the Magnetic Reconnection Experiment (MRX) and the new FLARE facility; and premier analytic theory capabilities that are internationally recognized as a continuing source of seminal ideas and mathematical foundations for plasma physics and fusion energy science.

Synergistic to these core capabilities, the Laboratory also possesses world-leading computational capabilities to accelerate the understanding of the physics of high-temperature and burning plasmas (e.g., ITER) and to discover new approaches. This includes codes for modeling small-scale plasma turbulence and associated plasma transport, nonlinear extended magnetohydrodynamics of larger-scale plasma equilibria and motions, and wave-plasma interactions with plasma heating and the fusion-product induced instabilities possibly present in ITER. The Laboratory is developing advanced algorithms to enable efficient utilization of DOE-SC's leadership-class computing facilities for fusion research including its new Exascale computing initiatives. This allows PPPL to validate physics-based predictive models against existing experiments, to investigate innovations to successfully develop fusion energy, and to use the integrated models to guide future ITER operations and experiments.

PPPL offers significant expertise and capabilities in advancing the understanding of the interaction of plasmas with materials. PPPL, along with Princeton University's Engineering Department, has established two surface analysis laboratories to study fusion-relevant material issues. The Laboratory established a nano-laboratory to study low-temperature plasmas, their interaction with materials, and plasma synthesis of nano-materials of different types and compositions. PPPL also offers theoretical, computational, and laboratory capabilities in the realm of plasma astrophysics in areas such as plasma reconnection, the magneto-rotational instability, space weather, and high-energy-density plasma.

This core capability is the foundation for the Laboratory and is supported by all of our research funding, from DOE, other agencies, and SPP contracts.

Large Scale User Facilities/Advanced Instrumentation

PPPL has extensive capabilities in: plasma measurement, heating, and current-drive system design and construction; safe and environmentally benign facility operation including the use of tritium fuel; and specialized fusion confinement facility design and construction. These strengths, together with an enormously capable research complex for fusion research (shielded test cells, high-current power supplies, extensive cryogenic facilities, and high-speed broad-band network) support the operation of NSTX-U, LTX- β, MRX, FLARE, and smaller experiments, aid in the development and testing of components for ITER, and enable collaborations on major national and international fusion research facilities. PPPL is a partner with ORNL and Savannah River in the US ITER fabrication project, and specifically manages the U.S. role in ITER diagnostics and the ITER steady state electric network. These capabilities provide a flexible, capable platform for next-step U.S. fusion research facilities.

PPPL is internationally recognized as a pioneer in the development and implementation of fusion plasma diagnostics. It has provided diagnostics as well as the supporting expertise to many fusion programs around the world, often in collaboration with other U.S. institutions. The Laboratory's seminal contributions have been particularly strong in techniques to measure in detail the profile of the plasma parameters (density, temperature, current density, and rotation), fluctuation diagnostics to measure the underlying instabilities and turbulence responsible for plasma transport, and measurements of both the confined and lost alpha-particles produced by fusion reactions. PPPL has a long-standing, active collaboration program having provided diagnostics to fusion programs around the world (C-Mod, DIII-D, EAST, JET, JT-60U, KSTAR, LHD, and W7-X).

Previous technical failures on NSTX-U underscore PPPL's need to strengthen the Laboratory's core capabilities. A major reorganization of the top leadership of the Laboratory and of NSTX-U has taken place including the strategic acquisition of new senior experts in executive laboratory management, engineering management, project management, laboratory operations, and facility and infrastructure management. A new Laboratory Director and Deputy Director for Operations with demonstrated skills and experience have joined PPPL. The NSTX-U design, as well as PPPL procedures and processes, have been extensively reviewed by external committees to identify the root causes for the technical and operational failures. The reviews involved extensive expertise from across the DOE complex and international experts, and the reviews resulted in a comprehensive corrective action plan to improve the Laboratory's policies, procedures, and operational discipline, as described below. A corrective action plan and repair project are in progress to recover NSTX-U as a reliable user facility.

This core capability is primarily funded by the DOE Fusion Energy Sciences program. Recruitment and hiring in key areas such as mechanical engineering and systems engineering are being increased to meet the need to enhance the Laboratory's strengths while responding to the urgent need to respond to succession planning and attrition issues.

Mechanical Design and Engineering

PPPL is a fusion energy sciences leader in the confinement of high-temperature plasma using magnetic fields. The Laboratory offers demonstrated expertise in the design, analysis, and fabrication of large toroidal magnets, vacuum systems, and in-vessel components capable of withstanding the harsh operating conditions such as very high heat fluxes, large electromagnetic forces, and radiation fields. These engineering capabilities span a wide range of disciplines and are well integrated with other Laboratory capabilities. PPPL's engineers benefit from the challenges of designing and fabricating state-of-the-art components for experiments under construction such as ITER; from the exposure to a wide range of technological advancements via collaboration within and outside the U.S.; from the experience maintaining, modifying and operating on-site fusion experiments, such as NSTX-U and LTX-β, and astrophysics experiments, including MRX, FLARE, and MRI.

With the effort to return NSTX-U to operation, the Laboratory has implemented a more structured approach to engineering practices. The engineering management system has been overhauled, engineer design rigor has increased, systems engineering is being formally introduced and configuration management is being strengthened. Core procedures, revised in early 2018, have been further revised following feedback from the users to keep the increased rigor while making them easier to implement. Lessons learned from the design phase of NSTX-U Recovery indicate the need to promote iterative concept development and validation to increase analysis efficiency and reduce the cost and duration of a more rigorous design-by-analysis approach. This will be achieved by defining a design path, with gates to align the depth of the analysis with the level of maturity of the design. Opportunities for further improvement include the introduction of electronic workflows and investing in process mapping to quantify where best to invest to make the new process most efficient. As we enter the manufacturing phase of NSTX-U Recovery, we plan to modernize and develop cutting-edge mechanical shops and further integrate CAD and CAM into operations. This will improve our machining capabilities and enable us to reduce risk in the delivery of the project by providing prompt and flexible response to unpredictable and urgent requests.

PPPL is leading the design and procurement of the Low Field Side Reflectometer for ITER, a diagnostic system needed for first plasma. Additionally, the Laboratory maintains a strong engineering collaboration with DIII-D. PPPL designed and manufactured several systems for DIII-D including the launchers for electron cyclotron heating and neutral beam line components. A lead engineer, assigned to General Atomics, coordinates the PPPL work on neutral beam components, assists the local team in radio frequency and neutral beam projects, and in FY 2019 has coordinated the modification implemented in the Long-Term Outage of DIII-D. The lead engineer has also developed several plasma edge control devices including impurity granular injectors and powder droppers. These devices are now being installed or planned for installation in several fusion research experiments besides DIII-D including ASDEX Upgrade and W7-X in Germany, EAST in China, JET in the U.K., and KSTAR in South Korea.

Collaborations with laboratories and projects outside the U.S. expose PPPL engineers to the requirements of next-generation nuclear experiments and the complexity of superconducting devices. PPPL has provided trim coils and in-vessel components to W7-X and is working with ORNL on the design and manufacture of a continuous pellet injector. PPPL's engineering analysis staff is continually expanding its simulation capabilities. The study of fluid dynamics in magnetic fields is also applied to improve the understanding of nanomaterial production to support of the Laboratory for Low Temperature Plasma (LTP).

Power Systems and Electrical Engineering

PPPL offers both the physical infrastructure and the technical capabilities for meeting the extraordinary power system demands intrinsic to fusion energy research machines. The local utility is upgrading the grid in Central New Jersey, which also provides PPPL experimental power, from 138kV to 230kV. Consequently, a step-down transformer (230 kV to 138kV) will be installed at an off-site substation. While this introduces a new single point failure with a possible down time of two months, PPPL is working with the DOE and local utility to mitigate this risk by specifying requirements for current and future power needs to maximize reliability and availability. Installed capability at the Laboratory can provide peak powers of ~1000MW and transfer 4.5 GJ of stored energy to magnetic coil systems. This capability overlaps with the need to address issues of transmission grid efficiency, reliability, and integration of variable generation. The utility-scale power systems at the Laboratory include a 138kV grid interface, large rotating machines used for energy storage, a local 13.8kV AC distribution system, and complex AC/DC converter systems using various power electronics devices and topologies. The system has been used to perform high voltage tests on the prototype inner poloidal field magnets to qualify the design and the suppliers and will be used to test the production magnets.

Magnet systems designed by PPPL for use on its experimental devices include solenoidal and toroidal configurations operating at 10's of kV, up to 150kA, with 1000's of MJ of stored energy. Advanced digital control and protection systems on PPPL devices involve feedback loops derived from advanced plasma diagnostic sensors as well as power system voltages and currents. PPPL's engineering staff has deep understanding and experience in the design, fabrication, and operation of the diagnostic, control, and protection power systems, including proficiency in related design and simulation tools. These core capabilities are directly related to the development of new power systems and electrical engineering technologies for transmission grid modernization and renewables integration. In addition, the PPPL infrastructure could be utilized as a test bed for various advanced technologies such as energy storage, advanced reactive power compensation, and power flow control. The PPPL competency and power infrastructure as cited above exceed those at any other DOE laboratory and most, if not all, international laboratories.

Collaboration with other DOE labs could provide synergistic opportunities for technology development by engineering interaction and development of test facilities.

Systems Engineering and Integration

PPPL has the capability to produce whole-system design, fabrication, and operation of fusion, plasma, and large electromagnetic systems. Systems Engineering and Integration is applied at three levels in fusion research. First, systems studies are applied at the reactor studies/concept stage. Second, systems integration is used to prepare for and conduct the design, construction, operation, and modification of major fusion research experimental facilities. Third, systems simulations are used to improve the understanding of plasma operation and to control and protect large experiments.

The Laboratory provides leadership and key expertise in multi-lab integrated design teams. PPPL has provided the integrated engineering and physics system design studies of future U.S. and international facilities and programs including: the ARIES studies; the Fusion Nuclear Science Facility (FNSF) study, including liquid metals; K-DEMO (S. Korea); and CFETR (China). Systems simulation relies on PPPL personnel with the experience to provide the numerical modeling and optimization of systems including simultaneously elements of plasma physics, fluid dynamics, electromagnetics, electrical power, and thermal and structural engineering.

Systems integration was the subject of an in-depth review in response to the failures that halted NSTX-U operation in 2016. In FY 2017, the NSTX-U team has substantially improved requirement management with a new General Requirements Document that covers all project scope and System Requirements Documents. In FY 2018, a system engineer was dedicated to the NSTX-U Recovery project to formalize interface control documents and compliance matrices. The tools developed for NSTX-U are being applied to other systems and formulated in lab-wide procedures.

PPPL is a world leader in comprehensive tokamak simulations using TRANSP, which integrates many physics simulations and is being extended to include plasma control and power systems. PPPL has developed many-parameter, multi-physics advanced real-time control systems to optimize system performance while maintaining protection of the equipment. The NSTX-U Digital Coil Protection System combines the electrical and power systems controls of NSTX-U with mechanical performance models to provide combined electro-mechanical protection. This system was a reliable and valuable operational constraint during initial operations of NSTX-U; the same team that developed the NSTX-U real-time system is now collaborating on that of MAST-U. Such a system has been suggested to ITER and is of increasing necessity for the higher-value, higher-consequence protection of next-generation facilities.

Science Strategy for the Future

PPPL’s main focus is on developing fusion science and technology to produce a clean, abundant, and economical source of energy and to advance the frontiers of plasma science. The Laboratory pursues these goals through experiments and computer simulations of the behavior of plasma, hot electrically charged gas. Plasmas with sufficient temperature generate fusion reactions and thus plasma science is central to fusion research. The understanding of plasma and its related technologies also has a broad impact on many other scientific fields and applications that are central to U.S. economic health and competitiveness. These applications include plasma-material interactions and processing, astrophysics and space sciences, particle accelerators, and high-energy-density plasmas. Many industries, such as the microelectronics industry, are dependent on plasmas to synthesize and shape the materials in their products. These industries are seeking help to improve their existing processes and innovate new technologies and PPPL is strengthening its efforts to help these industries.

Three fusion-related initiatives prepare for participation in the ITER burning plasma experiment and advance innovations and understanding to reduce the scale and cost of future fusion energy systems. These initiatives are well-aligned with the two main recommendations of the recent National Academies of Sciences Report on a Strategic Plan for U.S. Burning Plasma Research (2018) for the U.S. to: 1) remain an ITER partner as the most cost-effective way to gain experience with a burning plasma, and 2) start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible cost. Initiatives in non-fusion plasma science and technology round out the Laboratory's strategy to maintain its breadth in plasma science and technology research areas important to the Nation. The following five strategic initiatives guide the evolution of the Laboratory's and DOE's program missions by targeting high-priority research needs over the next decade:

- Rebuild NSTX-U and advance the spherical tokamak as a compact fusion concept
- Develop predictive understanding, optimization, and control of burning plasmas for ITER operations
- Understand the plasma boundary composition and shape to optimize plasma confinement and exhaust of power and particles
- Understand the plasma universe from the lab to the cosmos
- Advance our understanding of plasma technologies for national security and industrial applications

Achieving the full success of these initiatives will require new infrastructure, in particular, the proposed Princeton Plasma Innovation Center (PPIC).

In pursuing its initiatives, the Laboratory will deploy not only its existing human and technical resources but will also leverage investments by DOE and Princeton University in new staff and infrastructure to sustain, extend, and diversify PPPL's core capabilities. These initiatives and their resulting activities are supported by Laboratory Directed Research and Development (LDRD) projects, the DOE, and/or other solicited agencies. Achieving the full success of these initiatives will require sustained effort and investment.

Infrastructure

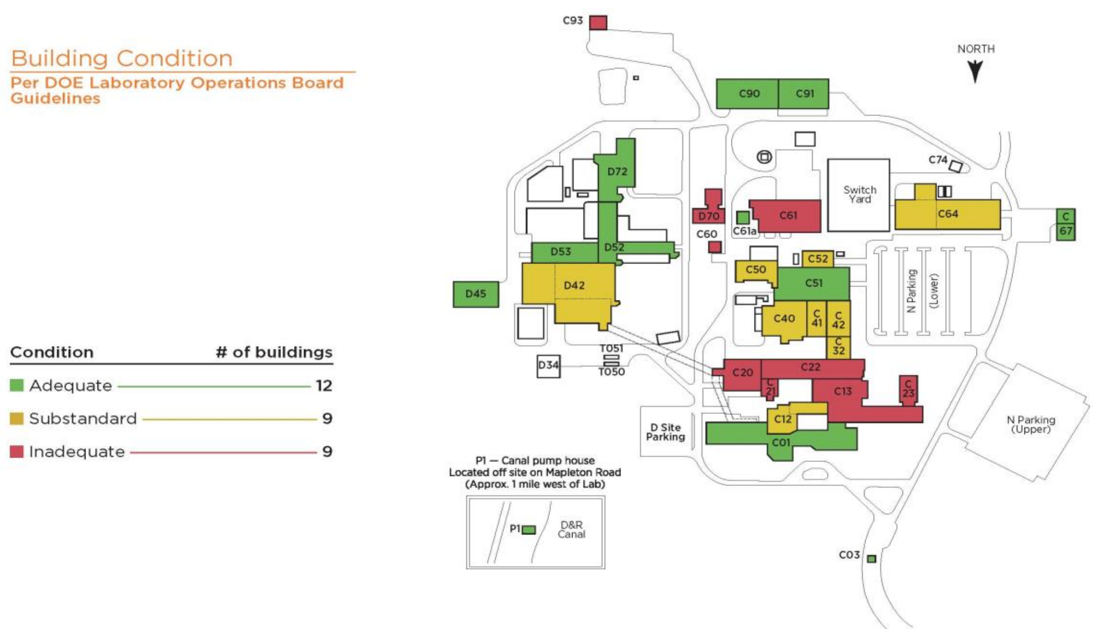
Overview of Site Facilities and Infrastructure

PPPL is located within the 1,750-acre Princeton University Forrestal Campus, in Plainsboro Township, New Jersey, that Princeton University has leased to DOE providing the land at virtually no cost to DOE going forward. The campus is punctuated by dense woods, brooks, and nearby streams; almost 500 surrounding acres remain in their natural state to protect and enhance the character of the campus. The Laboratory is conveniently located between Philadelphia and New York City.

The Laboratory utilizes 758k gross square feet (GSF) of the Princeton University Forrestal Campus, 30 Government-owned buildings and two trailers located at PPPL ("C" and "D" Sites), including one offsite (pump house). There are currently no leased buildings or facilities and no plans to enter into any external lease agreements. There were no real estate transactions during FY 2018 and none are currently planned. The leased trailer farm, employed as temporary office space during the Infrastructure Operational Improvements (IOI) Project and the Engineering Wing Renovation Project, were removed in February 2019 following completion of the latter project in October of 2018.

The major utility systems at PPPL are electric, natural gas, potable water, non-potable water, steam generation and distribution, chilled water, fuel storage, and D Site dewatering system, sanitary sewer system, fire alarm system and telecommunications. Primary 138 kilovolt (kV) power is provided by the local utility electric company. Ensuring the reliability of these utilities is essential to mission readiness and a key component of our infrastructure modernization strategy.

The annual condition assessments have identified 60 percent of PPPL's buildings as Substandard and Inadequate, as well as the need for more appropriate space types to safely support current work and research. The majority of the buildings on the PPPL campus are between 31-40 years old and 51-60 years old (depicted in blue and dark orange in the building age distribution that follows). The closeout of CD-04 for the IOI Project was in January. This completed the renovations to the C-Site MG Building, the LSB Annex, and converted the RESA Building into warehouse facilities. The project converted an additional 44,053 sq. ft. of space from Substandard to Adequate with a reduction in Deferred Maintenance for this total project of approximately $6.3 million for FY 2018. With the completion of the PPPL's IOI Project, there are nine buildings classified as Inadequate, nine as Substandard, and twelve as Adequate (depicted in the red, yellow, and green in the building condition charts that follow).



Infrastructure Data Summary

Total Building Assets	30
Total Building Assets Assessed	30
Total Area Assessed*	757,965 GSF
Total Other Structured Facilities (OSF)	26
Total OSF Assessed*	24
Total Deferred Maintenance 2018 ($)	$49,600,000
Total Repair Needs 2018 ($)	$138,700,000

*NSTX and TFTR experimental OSF assets (Asset Type: 3000's) and D-site office trailers not summarized as part of this infrastructure summary.

Core Capabilities: Plasma/Fusion and User Facilities/Advanced Instrumentation

Condition		Adequate	Substandard	Inadequate
	Buildings	12	9	9
Other Structures (OSFs)				
Condition		Adequate	Substandard	Inadequate
	OSFs	22	1	1

Campus Strategy

The Laboratory has developed a Campus Plan to focus on renovating or replacing critical core buildings and infrastructure needed to:

- Support all of the Laboratory's initiatives for the development of safe, clean, and plentiful fusion energy as well as plasma science and technology more broadly;
- Assure safe, efficient, and effective research operations;
- Transition aging infrastructure and buildings in order to support the current and future research needs and enhance the mission of the DOE and the Laboratory; and
- Remove the legacy tritium system.

PPPL leverages several funding sources to accomplish these objectives:

- PPPL Indirect
- DOE-SLI and DOE-SLI/GPP
- GPE
- DOE Safeguards and Security

The Laboratory's gap analysis informs the assessment of long-term infrastructure needs and priorities to establish mission readiness. The annual condition assessment allows for targeting infrastructure needs and priorities. The outcome of this effort is the Plan to address infrastructure improvements. The priorities are established, and the Laboratory makes strategic use of available funding opportunities to optimize implementation of these priorities through Science Laboratories Infrastructure (SLI), GPP, GPE and University support.

The Plan is to initiate large-scale, phased Science Laboratories Infrastructure (SLI)/GPP projects to modernize facilities through the replacement of aging laboratory and office spaces that have high levels of deferred maintenance. The objectives are aligned to fully support the NSTX-U recovery and operations, to address aging infrastructure needs, to upgrade outdated systems, and to provide modern, flexible laboratory space for small- to medium-sized experiments. A specific need for the Laboratory is space that can adequately and safely support the lithium testing activities necessary for current and upcoming research projects.

Long-term, execution of this Plan will provide space that facilitates collaboration, encourages the exchange of ideas, and provides room for growth of mission-specific programs within the existing campus property. The Plan addresses how real property assets will be used to support the mission of the Laboratory and DOE. Planning is developed in accordance with the DOE Order 430.1C, Real Property Asset Management, and as applicable, the Guiding Principles for Sustainable Federal Buildings. Planning analyses include integrating land use, maintenance, recapitalization, safety and security, and disposition plans into a comprehensive site-wide management plan.

The need for modern research spaces, office spaces, and flexible meeting spaces supporting “team drives,” real-time video conferencing, remote control room, and other tools for remote access that support the collaborative nature of the Laboratory’s research work have increased. A new space- planning initiative introduces new standards for workspaces, collaborative spaces for efficiencies and conversion of storage areas into offices, providing some near-term relief to the shortage of office/collaboration space.

An aggressive action plan was executed in FY 2017-18 to address long-term housekeeping issues and reclaim existing, underutilized space. As a result, more than 59,000 sq. ft. of existing laboratory space was converted for use. These reclaimed spaces will require replacement of aging infrastructure to provide usable, modern facilities capable of hosting research experiments. The Engineering Wing Upgrade project, completed in October 2018, provided more than 65 updated, higher-density workspaces, allowing engineering professionals to be co-located. This renovation converted the C-20 Building from Substandard to Adequate, a change in Overall Asset Condition that will be reflected in FY 2019 reporting. By the Fall of 2018, the renovated space was fully occupied. The continued and necessary growth of the Engineering staff means that further increases in capacity will be needed.

The Laboratory housekeeping efforts continued throughout FY 2018. Excess property, scrap, and waste generation rates are expected to return to normal operational levels in FY 2019 as the trailer clean-out, IOI Project, and lab-wide housekeeping efforts taper off. The following was accomplished in FY 2018:

- Excess property disposition in FY 2018 was 180 percent of the average for the previous five fiscal years;
- Scrap metal disposition in FY 2018 was 196 percent of FY 2016 and 374 percent of FY 2015 (over 298 tons in FY 2018);
- Electronics recycling in FY 2018 was 73 percent of FY 2016 and 155 percent of FY 2015; and
- Waste generation in FY 2018 was 164 percent of FY 2016 and 152 percent of FY 2015 (not including the IOI Project).

Collaboration with the University

As a critical partner of PPPL, Princeton University is supporting research infrastructure through cost sharing on FLARE and shared utilization of Princeton University’s High-Performance Computing Research Center (HPCRC) as of April 1, 2019. The HPCRC, a 47,000-square-foot sustainable building situated on Princeton’s Forrestal Campus, is the centerpiece of Princeton's innovative plan to provide robust computing resources to all faculty members, researchers, and students. The Laboratory is working with the University to assess the move of PPPL’s computing center infrastructure, currently located in the Laboratory’s Computer Center, to the HPCRC. A pilot, focused on high-performance computing, is ongoing and scheduled for completion in FY 2019. The pilot aims to answer questions about cost, feasibility, cyber security, system administration, data access and migration. Relocating PPPL’s computing center infrastructure into this facility can provide long-term efficiencies of scale and capability for PPPL, including expanding PPPL capability for Exascale-architecture computing and high-speed data access to ITER. And, a pilot study of cloud-based services as an additional option for meeting the projected demand for computing resources is being actively pursued. Further discussions with Fusion Energy Sciences (FES) and the Princeton Site Office (PSO) are required regarding cost, schedule, and implementation.

The Laboratory has collaborated with Princeton University to implement a number of solutions for systems and infrastructure challenges. These include, but are not limited to, utilizing the University's:

- Level 3 Multi-Factor Authentication for system access security;
- Learning Management System for training management;
- Maintenance management system; and
- Space management system.

PPPL is also exploring opportunities for sharing hardware and software licenses. These efforts continue to increase collaboration and decrease Laboratory indirect costs.

Infrastructure – Core Capability Gap Analysis

To assure mission readiness from an infrastructure viewpoint, PPPL performed a gap analysis. This effort focused on outlining infrastructure needs for mission initiatives and objectives and identifying elements and gaps to provide clear guidance for infrastructure planning. The core capabilities that are associated with each identified gap are noted in the table below.

Core Capabilities are:

1. Plasma and Fusion Energy Sciences
2. Large-Scale User Facilities/Advanced Instrumentation
3. Mechanical Design and Engineering
4. Power Systems and Electrical Engineering
5. Systems Engineering and Integration

Planning Objectives	Elements & Gaps	Core Capability
Fully Support NSTX-U Operations and Recovery (Top Priority)	Inadequate infrastructure and building systems that support critical needs in NSTX-U test cell areas (HVAC, controls, roofs).	1,2
Enable improved collaborations	Gap: Flexible meeting spaces and systems are needed to support team projects, real-time video conferencing, and other technology for remote access that supports the collaborative nature of the Laboratory's research.	1-5
Provide modern experimental and test laboratory with flexibility to accommodate the changing needs of modern research	Modern experimental and test lab space with flexibility, technology, and safety features to accommodate the changing needs of modern research: • Limited ability to accommodate even modest changes in the scientific program without significant lab modifications (small, old-style labs; limited infrastructure space; limited growth or additional capacity of systems).	1,2

	• Inability to accommodate new laboratory needs due to aging facilities and building systems such as, HVAC, electrical, and fire systems; • Needed space to safely conduct research involving lithium (or special materials).	
Optimize space utilization for staff, collaborators, researchers, students, visitors (short- & long-term) to facilitate collaboration of ideas	Sufficient and acceptable amount of basic space and functioning facility capabilities for existing occupants (short-term) and additional space (long-term): • Lack of optimal infrastructure to accommodate occupants and intended use for space; • Inability to locate appropriately "clustered" collaborators and mission focused teams with the scientific needs.	1-5
Remove legacy tritium systems and upgrade general campus infrastructure	• Disposal of legacy hardware and systems to eliminate risk and reduce operating costs; • Replacement of aging, general infrastructure to increase efficiency and reliability.	1-5

Infrastructure Renewal Plan:

Based on this gap analysis, the Laboratory has identified the infrastructure renewal priorities necessary to close the gaps and thereby support Mission Readiness going forward:

- Replacement of NSTX-U experimental and diagnostic spaces;
- Construction of the newly proposed Princeton Plasma Innovation Center (PPIC) to provide modern research spaces and offices, as well as collaboration and conferencing capabilities;
- Provide modern/updated, experimental and test laboratory space with flexibility to accommodate the changing needs of modern research through modernization of existing laboratory buildings; and
- Removal of legacy tritium systems.

In concert with the DOE's ""enterprise-wide investment in basic existing infrastructure," the following actions are planned to bridge gaps between the Mission Needs and the current conditions of the Laboratory:

1. Mission-enabling activities
- Construct the newly proposed PPIC to accommodate growth, collaboration space, seminar/conference space, research and innovation, offices, remote control room, outreach and welcome center for visitors
- Expand the space planning initiative to reorganize space utilization throughout the campus to co-locate collaborators and their associated scientific teams for both existing initiatives and future planned research activities and project populations
- Plan for the renovations of existing buildings to allow for continuation of current, addition of new, and expansion of other research projects, as well as their support areas (shops)

2. Utilities and Facilities modernization
- Update aging NSTX-U infrastructure that provides critical support of safe, operational conditions for research, which require:
    - HVAC instrumentation and control replacements

    - HVAC equipment replacements
    - D Site (Including Test Cell) roof replacements
- Update aging infrastructure in Laboratory and Laboratory-support buildings throughout campus, most of which are well past the end of useful life as corroborated by ongoing annual building condition assessments:
    - Building envelope (roofs, windows, HVAC, etc.) as evidence in the laboratory space identified for renovation to support new research activities (RF, CS, COB, ESAT Buildings)
    - Experimental space to provide a Liquid Metals Laboratory for research in Liquid Lithium Plasma facing walls
- Systems and tools to accommodate new technologies, work processes, and project management needs:
    - Accommodation of modern software and hardware solutions
- Electrical distribution system upgrades

Infrastructure Funding Needs

PPPL uses the Mission Readiness Process to prioritize the allocation of infrastructure funding, and a project documented ranking system for capital-funded improvements based on their risk and the benefit they provide to the Laboratory mission. This past year, data from both the Building Asset Assessment Program and equipment maintenance history data from the Computerized Maintenance Management System (CMMS), have been used to inform the infrastructure investment decision-making process.

The Laboratory's FY 2018 annual actual maintenance spend was $4.8 million, or 0.93 percent of the Non-Programmatic Replacement Plant Value (RPV). Given the corrective actions underway at the Laboratory requiring indirect resources in FY 2018 (Extent of Cause Review, Integrated Corrective Action Plan [ICAP]), the investment in maintenance and repair was less than 2 percent of the Laboratory's Replacement Plant Value. To support an increase in indirect maintenance effort in FY 2019, the Laboratory has increased maintenance spend budgets by almost $2 million to 1.25 percent of the 2018 RPV. PPPL's strategic plan directly focuses on maintenance and capital investments as the central element of the campus strategy. This plan is outlined in Enclosure 4. PPPL's campus strategy directly attacks the backlog of Repair Needs (RN) and Deferred Maintenance using the proposed projects as the essential measures to significantly reduce the Deferred Maintenance from its projected peak.

The Laboratory's cross-cut proposal for 2019-2030 includes the following key areas: repair core D Site building systems in support of NSTX-U, renovate buildings for small/medium experimental and test labs, evaluate and plan the need for new laboratory facilities, renovate office areas for team collaboration and better use of space, plan construction of a new research center, the Princeton Plasma Innovation Center (PPIC), and remove remaining contaminated tritium systems.

As listed in the Facility Information Management System (FIMS) FY 2018 report, the total RPV of all PPPL facilities and infrastructure was $721 million. The Non-Programmatic RPV was $516 million. The totalized PPPL campus asset utilization rating is greater than 90 percent, which is defined as "Over Utilized" by the Laboratory Operations Board (LOB) criteria.

Replacement of NSTX-U experimental and diagnostic spaces

Design for the replacement of antiquated HVAC instrumentation systems in D Site is in progress, supported by GPP funding (G254). The design phase for HVAC instrumentation and equipment upgrade is expected to go through FY 2019. Once completed, the Laboratory is requesting funding for the next phase that includes construction of the instrumentation phase, and the design and modernization of HVAC equipment as well as other critical peripheral systems in D Site. In addition, the roofing at D Site, which has experienced failures, is well past its useful life and warranty periods have expired. GPP funding support is planned for these roofs, which need replacement in the near future to minimize risk of leaks in the test cell before NSTX-U start-up. Design for the roof replacements is underway and construction is expected to start in the Fall.

Construction of the newly proposed PPIC to provide modern research spaces and offices, as well as collaboration and conferencing capabilities

Construction of a new research center, the Princeton Plasma Innovation Center (PPIC), is proposed to provide:

- Exascale and visualization capability leveraging DOE and PU investments in these areas;
- Remote Control room and Collaboration center for ITER, W7X, JT60SA, etc.;
- State-of-the-art laboratories to support low-temperature plasma experiments, microelectronics equipment, diagnostics, and materials analysis equipment;
- Modern seminar/conferencing, Science Education Labs and Community Outreach areas for students and visitors.

The project would improve efficiency, safety and, with the demolition of aging buildings totaling about 46,000 sq. ft., will also reduce Deferred Maintenance.

This state-of-the-art research center would be attractive and comfortable for occupants and would help attract and retain the world-class researchers and staff necessary for success in PPPL's mission.

Provide modern/updated, experimental and test laboratory space with flexibility to accommodate the changing needs of modern research through modernization of existing laboratory buildings

A systematic plan to improve existing aging laboratory infrastructure is being proposed to renovate small- to medium-sized laboratory space with the infrastructure and capability to support modern, flexible research needs. In order to meet our strategic mission goals, the Laboratory is in need of modern, general-purpose research space that can adapt and customize to the ever-changing mission needs. Renovation of the RF, CS, COB, ESAT, and PLT would accommodate new plans for small- and medium-sized experiments not suitable for the proposed PPIC. The projected need to provide a Liquid Lithium Laboratory would be a primary example of the type of lab that would be appropriate for one of these existing spaces after upgrades to infrastructure are completed. A specially designed laboratory to experiment with liquid flowing metals to study liquid lithium requires special construction and safety precautions. These laboratories would serve the future mission needs while being adaptable to accommodate and appeal to future generations of researchers. These extensive renovations are projected to eliminate ~$8 million in Deferred Maintenance when completed.

PPPL's core utility infrastructure is well positioned for the new construction. Renovation of existing space would include work to increase system and utility reliability and efficiency. A number of projects have been completed or are currently underway as a starting point in this long-term plan. Recently, PPPL completed both a chilled water and steam distribution upgrade project. Additionally, PPPL is targeted to complete an electrical power distribution upgrade by 2019. In reviewing the central utility plant capacity requirements to support the site and the proposed new construction.

PPPL has proposed a boiler equipment upgrade project (current GPP consideration). This infrastructure funding request is to execute a progressive renewal of buildings and campus infrastructure systems to provide:

- Reclamation and modernization of existing facilities to further support current and future research space required to meet the mission and vision of the Laboratory and the DOE. Modern, efficient, and flexible laboratory space with appropriate levels of infrastructure to adapt to fusion science and technology requirements.
- Co-location of similar needs of scientific approach to foster innovation, collaboration, and scientific engagement through both local and international means.
- Proper planning prior to and during this restoration and modernization period to integrate system redundancy and campus-wide backfeed-capable utility loops, and to employ smart building systems control to enhance efficiency and reliability, and to maximize value and minimize business disruptions.

Removal of legacy tritium systems

An important need is to remove and safely dispose of all remaining tritium hardware. The tritium systems at D Site date back to the 1980s and are no longer needed to support the program at PPPL. PPPL currently has ~1000 Ci of tritium remaining in the Tritium Systems, mostly as internal contamination. Princeton University commissioned an external assessment in May 2018, which concluded that the costs associated with maintaining and monitoring the current inventory, along with the risks of an unplanned loss of containment, will increase over time. In December of 2018, non-invasive characterization of the system began. Once complete, it will serve as a reference to develop a removal plan.

Excess Facilities

Currently, PPPL does not have any excess facilities. PPPL's Mod VI facility was vacated, demolished, and removed as part of the Infrastructure Operations Improvement (IOI) project in March 2018.

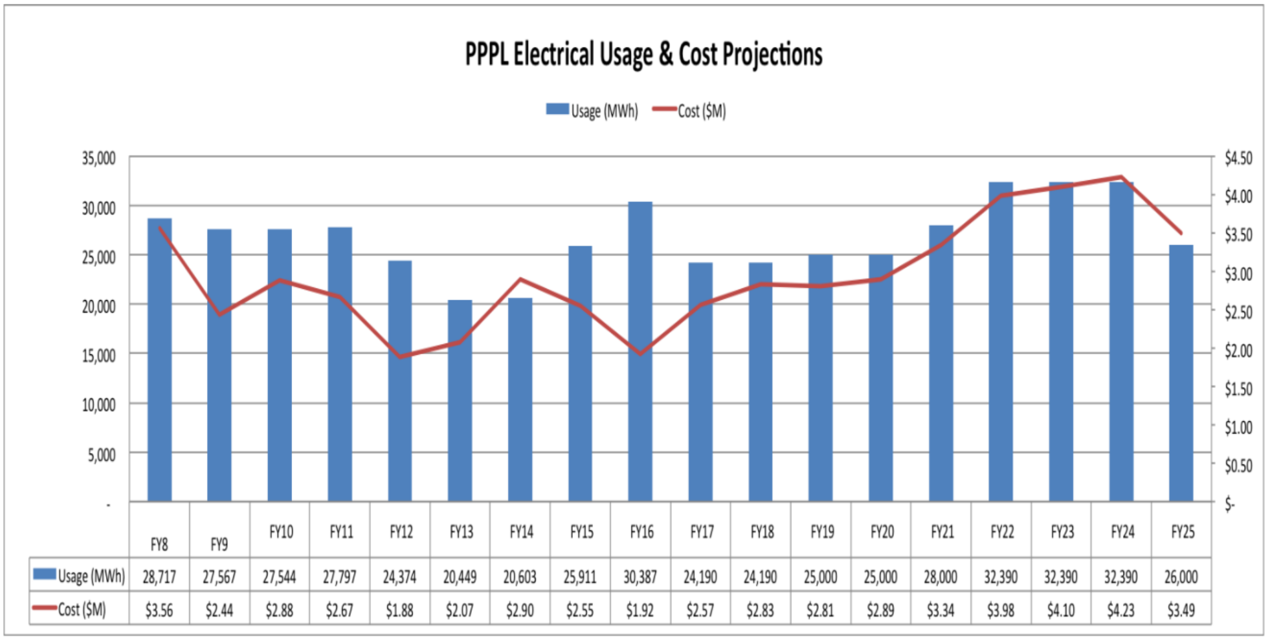
Site Sustainability Plan Summary

PPPL has institutionalized a comprehensive approach to fulfilling the requirements of Executive Order 13834, as well as applicable DOE Orders to advance the Department's energy, national security, and sustainability missions. The Laboratory's Sustainability Program includes the departmental sustainability goals of reducing greenhouse gas (GHG) emissions, improving energy and water efficiency, increasing the use of clean and renewable energy, reducing the environmental impact of our vehicle fleet, purchasing sustainable products, preventing pollution, diverting waste from landfills, and developing resilient infrastructure to combat the impacts of climate change.

PPPL's Scope 1 and 2 (GHG) emissions, which include direct site emissions, on-site fuel combustion, and purchased energy, in FY 2018 were 87 percent below FY 2008 baseline levels, primarily because there were no releases of sulfur hexafluoride (SF6) in FY 2018. Scope 3 GHG emissions (indirect emissions such as business travel, electricity transmission and distribution losses, and employee commuting) were approximately 14 percent below the FY 2008 baseline, representing the ongoing challenges to reducing business travel in support of our international collaborations. Renewable Energy Credit (REC) purchases are used to meet renewable energy goals and partially offset GHGs from experimental and facility energy use. We are also collaborating with international research partners to explore the applications of new proprietary SF6 alternatives in high-voltage systems.

Fleet petroleum use is down 70 percent from the 2005 baseline as a result of careful fleet management and the use of alternative fuels like E85 (85 percent ethanol) and B20 (20 percent biodiesel). Up to four (4) GSA-leased vehicles are scheduled for replacement in FY 2018 and FY 2019—a two-year program—subject to approval by GSA. Three of these vehicles have been replaced as of February 2019. These vehicle replacements will not change the total vehicle fleet size at the Laboratory.

While PPPL has not been successful in identifying lifecycle, cost-effective, on-site renewable energy projects, we continue to identify and evaluate a portfolio of smaller scale on-site renewable energy projects. These projects may be incorporated into ongoing energy efficiency efforts if they are cost-effective and as existing programmatic funding permits.



	FY8	FY9	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25
Usage (MWh)	28,717	27,567	27,544	27,797	24,374	20,449	20,603	25,911	30,387	24,190	24,190	25,000	25,000	28,000	32,390	32,390	32,390	26,000
Cost ($M)	$3.56	$2.44	$2.88	$2.67	$1.88	$2.07	$2.90	$2.55	$1.92	$2.57	$2.83	$2.81	$2.89	$3.34	$3.98	$4.10	$4.23	$3.49

Figure: Electrical Use and Projections

SLAC NATIONAL ACCELERATOR LABORATORY

Lab-at-a-Glance

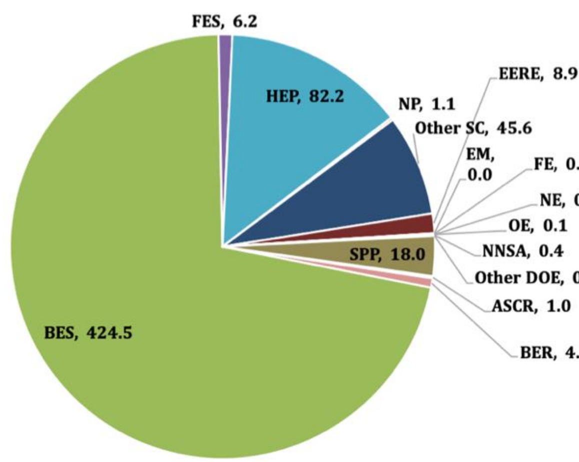
Location: Menlo Park, CA
Type: Multi-program Laboratory
Contractor: Stanford University
Site Office: SLAC Site Office
Website: www.slac.stanford.edu

- **FY 2018 Lab Operating Costs:** $592.9 million
- **FY 2018 DOE/NNSA Costs:** $574.9 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $18 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 3%
- **FY 2018 DHS Costs:** $0 million

Physical Assets:
- 426.3 acres and 150 buildings
- 1.7M GSF in buildings
- Replacement Plant Value: $2.8 B
- 1,170 GSF in 1 Excess Facilities
- 0 GSF in Leased Facilities

Human Capital:
- 1,602 Full Time Equivalent Employees (FTEs)
- 22 Joint Faculty
- 145 Postdoctoral Researchers
- 207 Graduate Student
- 120 Undergraduate Students
- 2,931 Facility Users
- 22 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

SLAC National Accelerator Laboratory is a vibrant multi-program laboratory whose mission is to explore how the universe works at the biggest, smallest, and fastest scales and invent powerful tools used by scientists around the globe. In support of the U.S. Department of Energy (DOE) mission in science and innovation, our research helps solve real-world problems and advances the interests of the nation. To date, four Nobel Prizes have been awarded for research done at SLAC.

SLAC is the world-leading laboratory in X-ray and ultrafast science due in large part to our X-ray user facilities: the Stanford Synchrotron Radiation Lightsource (SSRL), and the Linac Coherent Light Source (LCLS). LCLS is the world's first hard X-ray Free Electron Laser (XFEL) and a revolutionary tool for chemistry, materials sciences, biology, plasma physics, and matter in extreme conditions.

Since our founding in 1962, SLAC has made revolutionary discoveries that have established our leadership in high energy physics. SLAC continues to make major scientific contributions to understanding the physics of the universe, with international leadership in all five science drivers of the Particle Physics Project Prioritization Panel (P5), including probing the nature of dark energy with the Large Synoptic Survey Telescope (LSST).

With five decades of excellence in accelerator physics, SLAC is the leader in advanced accelerator concepts, such as plasma wakefield acceleration (PWFA), and drives the development of critical accelerator technologies with a broad range of applications.

As stewards of renowned user facilities, SLAC hosts, supports, and collaborates with more than 4,000 U.S. and international researchers, including many students, at SSRL, LCLS and Ultrafast Electron Diffraction (UED) facility, the Facility for Advanced Accelerator Experimental Tests (FACET), and the Stanford-SLAC facility for cryo-electron microscopy (cryo-EM), as well as in laboratory-hosted science programs.

Through continued diversification of our research programs, SLAC aims to strengthen our impact, specifically exploring applications of our core capabilities to support applied energy programs in the DOE and the missions of other federal agencies and expanding our collaborations with industry. To do this SLAC leverages our location in Silicon Valley and our strong relationship with Stanford University (Stanford).

Stanford manages the Laboratory for DOE, providing significant advantages in research, education, and operations. Stanford is home to and attracts some of the world's best and most innovative scientists. Together with Stanford, SLAC educates and develops the U.S. scientific workforce in key technological areas. SLAC jointly operates three institutes and two research centers with Stanford.

Core Capabilities

SLAC's mission is founded on unique user facilities, research capabilities, and scientific expertise and provides science and technology stewardship to the following six DOE core capabilities: Large-Scale User Facilities/Advanced Instrumentation, Condensed Matter Physics and Materials Science, Chemical and Molecular Science, Accelerator Science and Technology, Plasma and Fusion Energy Science, and Particle Physics.

Large-Scale User Facilities/Advanced Instrumentation

SLAC operates two DOE-SC user facilities (LCLS and SSRL), with a third one, FACET-II, expected to begin operation in 2019. The Laboratory also operates the joint DOE/NASA Fermi Large Area Telescope (LAT) mission and is a major partner in several particle physics and astrophysics (PPA) instrument projects.

Linac Coherent Light Source (LCLS): LCLS uses a 15 GeV linear electron accelerator to create X-ray pulses a billion times brighter than previously available at synchrotrons. Up to 120 pulses are delivered per second, each one lasting just quadrillionths of a second, or "femtoseconds"—a timescale at which the motion of atoms can be seen and tracked. LCLS takes X-ray snapshots of atoms and molecules at work, revealing fundamental processes in materials, technology, and living things. Its snapshots can be strung together into movies that show chemical reactions as they happen, or phase changes in materials. These movies allow scientists to study important proteins at room temperature, in some cases even while they are active.

LCLS features seven specialized instruments, each with a team of scientists and support staff, to conduct pioneering research and assist users with experiments. Each station is equipped with a suite of diagnostics to assist in gathering a wide range of data using various specialized techniques, from telltale signatures of electrons and ions to the intricate patterns left by crystallized samples probed by the X-ray laser. Up to a thousand unique scientists each year conduct groundbreaking experiments into the fundamental processes of chemistry, materials and energy science, biology, and technology at LCLS.

Ultrafast Electron Diffraction (UED) instrument (now integrated with LCLS user operations): SLAC has successfully realized the most advanced UED facility in the world with a 100-fs time resolution instrument. With the addition of a THz to mid-infrared pump source, the SLAC UED facility continues to make performance improvements that expand our ultrafast science capabilities. Single-shot UED capability has been developed and successfully deployed to the scientific community. Additional enhancements under development include liquid sample capabilities and a smaller probe with better temporal resolution and higher flux.

Stanford Synchrotron Radiation Lightsource (SSRL): SSRL is an X-ray synchrotron-based User Facility. The SSRL 3-GeV, high-brightness third-generation storage ring, upgraded in 2004, operates at 500 mA in top-off mode, with high reliability and low emittance. SSRL's extremely bright X-rays are a resource for researchers to study our world at the atomic and molecular level, leading to major advances in energy production, environmental remediation, nanotechnology, new materials, biology, and medicine. SSRL provides unique educational experiences and serves as a vital training ground for future generations of scientists and engineers. SSRL operates 13 X-ray beamlines with 29 unique experimental stations that enable and support outstanding scientific research by a broad user community in a safe environment. SSRL operates approximately 9 months each year with a very high reliability — delivering more than 97 percent of scheduled X-ray beam time.

SSRL has an active accelerator research and development program aimed at improving the performance and reliability of the accelerator complex, including emittance improvements to 6 nm-rad and the development of short pulse operation in the few ps range. In addition, SSRL is increasing its number of undulator beam lines in strategic areas including expansion of high-throughput characterization and *in situ* and *operando* studies of materials synthesis, growth, and assembly, as well as multimodal methods for time-resolved catalyst characterization to meet the needs of academic, national laboratory, and industrial users. The new beamlines will form additional bridges to LCLS, as will the addition of the undulator BL12-1 targeting micro-beam macromolecular crystallography, which will form a structural biology gateway between SSRL and LCLS and enable the multi-modal imaging integration with the cryo-electron microscopy (cryo-EM) facility at SLAC.

Facility for Advanced Accelerator Experimental Tests (FACET): See “Accelerator Science and Technology” core capability below.

Particle Physics and Astrophysics Facilities and Instruments: See “Particle Physics” core capability below.

Advanced instrumentation: SLAC is an international leader in the development of advanced instrumentation and computational tools to serve the needs of our current and future X-ray and particle physics experiments.

Data management systems: SLAC has long-standing, significant expertise and capability in managing very large experimental datasets and actively developing strategies for data acquisition (DAQ) and data management for LCLS-II and for future opportunities with LSST, ATLAS, DUNE, Cryo-EM, and UED. Integration of detector and control electronics, data systems, computational science, and algorithm development is critical to the success of these future flagship facilities and benefits from strong ties to relevant departments at Stanford. Applications include integrated X-ray beamlines and instrumentation for photon science experiments, ultralow background experiments for direct dark matter detection, space-qualified electronic systems, and computational resources for automated and optimized data collection and analysis.

SLAC is at the international forefront in the development of the new concept, where the data from an experimental facility are streamed on-the-fly to a supercomputer for analysis. Such near-real-time interpretation will require computational intensities of unprecedented scales, coupled to a data-path of unprecedented bandwidth. The high repetition rate of LCLS will increase its data throughput by three orders of magnitude by 2025. LCLS users require an integration of data processing and scientific interpretation, both demanding intensive computational analyses. This analysis must be carried out quickly to allow for most efficient use of beam time. Achieving such turnaround on future, much larger, datasets using algorithms with higher fidelity than any facility can support today is the goal of the Data Analytics at the Exascale for Free Electron Lasers project (ExaFEL), led by SLAC in collaboration with LBL, LANL, and Stanford.

Sensors and detectors: SLAC is an international leader in the development of advanced sensors and detectors to serve the needs of our current and future X-ray and HEP experiments. The expertise includes thin silicon sensors for high speed applications; GaAs, Ge, CdZnTe, and thick silicon sensors for high energy, high radiation applications; custom integrated circuits for detectors for high-rate (KHz to MHz), low noise experiments; and cold liquid argon and liquid xenon based system-on-chip ASICs and 20-psec fast timing ASICs for LIDAR and LHC forward region signal acquisition. Additional expertise includes super-conducting devices such as Transition Edge

Sensors and SQUID readout circuits for energy sensitive experiments such as HEP Cosmic Background Experiments and FEL spectroscopy cameras.

Electronics: SLAC is an international leader in the development of advanced electronics to serve the needs of our current and future X-ray and HEP experiments. In addition to high performance analog, digital, and mixed signal printed circuit boards with Field Programmable Logic Arrays including hardware and firmware components, SLAC has been designing, building, and commissioning complete electronics systems for particle detection, signal processing, data acquisition, and online processing. Applications are low noise, high speed experiments including systems with Low-Level RF components.

Funding for this core capability primarily comes from DOE-BES and DOE-HEP. Other sources include DOE-BER, DOE- FES, LDRD investments and Strategic Partnership Projects (SPP) from the NIH. SLAC's efforts support the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23, 24, 25, 26). ExaFEL is supported by the Exascale Computing Project (SC 17, 20), a joint project of DOE-SC and DOE-NNSA, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation's exascale computing imperative.

Chemical and Molecular Sciences

The history of condensed matter physics and materials science at SLAC has been tied to the development of SSRL as one of the first synchrotron light sources to address electronic and structural properties of matter. Over the last decade, the Materials Science Division (SIMES) has developed a strong program in materials science pursuing frontier issues in the assembly and design of materials, their collective quantum dynamics, and their ability to transform energy. A strong focus is on engineering novel collective properties through nanoassembly low-dimensional materials and interfaces, resplendent with opportunities to study mission-relevant Grand Challenge problems. The program focuses on key scientific problems that can be addressed using SLAC's X-ray user facilities, and complements them with world-class materials synthesis, characterization, and theory activities. These efforts involve partnerships between SLAC, Stanford, and industry researchers.

The three focus areas – quantum materials, ultrafast science, and energy storage materials – each address DOE's missions in science, energy, and security. Through SIMES, SLAC provides a strong coupling to initiatives at Stanford, such as the Global Climate and Energy Project and the Precourt Institute for Energy. In addition, SIMES is dedicated to outreach activities for energy science education and training, helping to develop the next generation of talent.

The research programs couple directly to current and future LCLS and SSRL science. Scientists from SIMES have been engaged with SSRL and LCLS in developing and using beamlines and have provided leadership to realize the ultrafast materials science strategy. Many SIMES PIs are key users of SLAC's light sources and the UED facility, allowing them to pursue important scientific lines of inquiry identified in several recent Basic Research Needs workshops and roundtable reports. Many of these scientists have contributed important content on quantum materials, synthesis and tool science, ultrafast science, and quantum computing to DOE-BES reports, helping to set a scientific agenda in cooperation with DOE-BES.

Materials science will continue to represent important scientific targets both in the greater area of quantum materials, interfaces, and energy materials as well as for SLAC's X-ray user facilities at SSRL and LCLS. With the advent of next-generation X-ray facilities such as LCLS-II, a golden age of scattering and spectroscopy is emerging with unprecedented opportunities for studies at nano to microscopic length scales and femto- to picosecond time scales. Advanced scattering, spectroscopy, and microscopy will play a pivotal role in detailed explorations of the electronic, geometric, and excited state properties of crystals, surfaces, interfaces, and complex nanoscale assemblies of atoms and molecules, and how this physics evolves with temperature, pressure, electric and magnetic fields, or other externally controlled parameters. This exploration is not only of intrinsic scientific interest, but also essential for designing new materials with properties tailored for energy and other technological applications, on which the economic well-being and the energy security of the nation will continue to depend in the future.

Funding for this core capability comes from DOE-BES, with related support from Energy Efficiency and Renewable Energy (DOE-EERE) and LDRD investments and serves the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23).

Chemical and Molecular Science

Research in chemical and molecular science is a significant core capability of SLAC. The research program in this area focuses around two themes: fundamental understanding of chemical catalysis and research at the frontier of ultrafast chemical science. Both catalysis and ultrafast chemical science benefit greatly from the proximity to and expertise associated with SSRL and LCLS. Both programs, developed over the past decade, have achieved broad recognition for their quality and innovation, as well as for their distinctive profiles within the broader American scientific enterprise.

Chemical catalysis: Research into the fundamental aspects of chemical transformation through catalysis is a scientific frontier and important field for energy transformation, storage, and management. The SLAC program differentiates itself from other DOE supported catalysis activities through our world-leading use of theory to provide a quantitative and predictive understanding of key problems in catalysis under realistic reaction conditions. Over several years, SLAC has developed a theoretical description of surface reactivity and heterogeneous catalysis, electrocatalysis, and photocatalysis. Within this program of predictive fundamental theory, we have expanded complementary experimental expertise in catalyst synthesis, characterization, and testing. Catalyst characterization at SSRL facilities is an integral component in catalyst. Our approach to advance chemical catalysis is supported by strong involvement of Stanford faculty, bringing together expertise in catalyst synthesis, characterization, and testing through SUNCAT. The SUNCAT program also provides the fundamental basis for the SLAC involvement in the Joint Center for Artificial Photosynthesis, where SLAC integrates theory and experiment to achieve a mechanistic understanding of electrochemical CO_2 reduction and to devise new catalysts for this process.

Ultrafast chemical science: This focus area concerns chemical transformation and dynamics at atto- to picosecond time scales. By measuring and modeling change on these ultrafast time scales, we can understand fundamental processes of electronic and nuclear motion on their intrinsic time scales. Collaboration between SLAC's ultrafast science research program and LCLS has enhanced the impact and success of both this activity and LCLS. The research program further benefits from strong interactions with Stanford, including the joint PULSE Institute. In terms of its scope, depth, and experimental capabilities, the SLAC ultrafast chemical science program is unique within the U.S., although comprehensive programs are being rapidly developed elsewhere in the world, particularly in conjunction with new XFEL facilities opening abroad.

The experimental capabilities provided by LCLS and LCLS-II are complemented by extensive laboratory capabilities, including high-harmonic generation for time-resolved ultraviolet and soft X-ray spectroscopy, that permit access to dynamics occurring down to femto- and attosecond time scales. In addition, extensive use is made of SLAC's UED instrument for probing chemical dynamics. We are currently applying these diverse methods to study of non-Born-Oppenheimer dynamics, strong-field laser-matter interactions, solution phase photochemical dynamics, nonlinear X-ray optics, and, most recently, time-resolved studies of reduced dimensional systems. The experimental efforts are coupled to a strong theory program on excited state molecular dynamics, which is supported by advanced computational capabilities.

Funding for this core capability comes from DOE-BES (SC 2, 21, 22, 23). Selected LDRD investments are supporting scientific discovery and innovation.

Accelerator Science and Technology

SLAC is the premier electron accelerator laboratory in the U.S. and one of the top accelerator laboratories worldwide. Our research in accelerator science and technology continues to lead to innovations in accelerators internationally. These technologies enable the development of bright, coherent X-ray light sources – both free-electron lasers and storage ring light sources – and in UED and Ultrafast Electron Microscopy (UEM), thereby strengthening SLAC's core capabilities in materials science, chemical and molecular science, and plasma and fusion science. In conjunction with Stanford, SLAC maintains a renowned accelerator education program – one of only a few in the U.S. Accelerator Science and Technology at SLAC encompasses the following broad areas:

FEL R&D: LCLS is the world's first operational hard X-ray Free Electron Laser (XFEL), with a highly successful R&D program that brings new capabilities to the user community on a continuing basis. The goal of the XFEL R&D program is complete control of spectral and temporal X-ray properties to drive the discovery potential of LCLS and all its future upgrades. The program includes X-ray seeding for transform-limited pulses; high-power FEL generation by bunch compression and undulator tapering; generation and measurement of sub-fs X-ray pulses; generation of multiple colors and pulses; ultrafast techniques, diagnostics, and optics; and technology development. The R&D program recently implemented a new bunch compression mode for high-peak-power XFEL pulses, pushing the existing record by a factor of three. This mode benefits many fields, including non-linear X-ray spectroscopy, diffraction, and imaging.

The LCLS-II project uses high-repetition-rate SC accelerator technology. In contrast to the pulsed SC European XFEL, LCLS-II will operate in a highly stable, 1-megahertz (MHz), CW mode. Providing high-brightness electron beams at the undulator is a key component for generating hard X-rays for LCLS-II-HE. High brightness beams are also critical for future experiments in UED/UEM and even plasma wakefield acceleration (PWFA). SLAC has recently launched a comprehensive program in high-brightness beams for future accelerator applications, which includes detailed start-to-end simulations to solve collective effects that degrade beam emittance. The program is developing CW SRF electron sources and plasma-based sources. This work is critical for the success of future X-ray experiments, UED/UEM, and even future colliders.

Advanced acceleration and RF acceleration R&D: SLAC plays an internationally unique role in the development of beam-driven PWFA. For SLAC to maintain our leadership in this increasingly competitive field, FACET-II – the follow-on facility to FACET – is under development. FACET-II will be the only facility in the world capable of providing 10-GeV electron and positron beams in support of accelerator science R&D, with the primary focus on investigating key R&D challenges of PWFA-based positron- electron colliders and fifth-generation light sources. SLAC's capability in RF accelerator technology is tapped by federal agencies, industry, and labs around the world. Within the DOE laboratory system, only SLAC has the integrated capability to conceive, design, prototype, and test RF power sources. The foci of our source R&D efforts are game-changing reduction in source cost, efficiency improvement, and extending frequency reach to the THz regime. SLAC's systematic investigation of the limits of RF acceleration in high-vacuum metallic structures has been extended to THz frequencies and broadened in scope to study topologies to improve efficiency.

Accelerator test facilities: SLAC test facilities also include:

- The low-energy Accelerator Structure Test Area (ASTA) facility, a small bunker and test stands equipped with multiple high-power RF sources, flexible laser, and excellent temperature stabilization (ASTA allowed efficient development of our UED capability);
- The medium-energy Next Linear Collider Test Accelerator (NLCTA), which provides critical support for vital R&D programs, including SC-RF gun studies for LCLS and LCLS-II, high- gradient structure testing, and novel THz accelerator R&D supporting an existing Early Career Award; and
- The higher-energy End Station Test Beam (ESTB), which plays an important national role for detector R&D by providing capabilities unique in the U.S. for small-scale experiment development, deployment, and execution.

Educating the next generation of accelerator physics leaders: The science and engineering challenges associated with realizing ambitious programs at state-of-the-art facilities enhances the renowned SLAC-Stanford accelerator education program. The exciting research opportunities enabled by the unique set of accelerators and test facilities at SLAC provide an environment in which graduate students and postdocs can get the requisite hands-on experience to further their careers.

In its more than 25-year history, the SLAC-Stanford accelerator science education program has produced more than 60 PhDs in accelerator physics; 32 from Stanford and approximately 28 from other U.S. universities and international institutions. Ten of the 28 total awardees of the annual American Physical Society thesis award in beam physics completed their graduate research at SLAC. Today the program features 14 graduate students in accelerator physics and engineering and five Stanford faculty.

Funding for this core capability comes from DOE-BES, DOE-HEP, SPP customers, and Laboratory Directed Research and Development (LDRD) investments. The core capability supports the DOE-SC mission in scientific discovery and innovation (SC 2, 22, 23, 24, 25, 26).

Plasma and Fusion Energy Science

The SLAC program in plasma and fusion energy sciences is driven by a broad-based vision to exploit the unparalleled capabilities that arise from the unique combination of high-power lasers with LCLS. This program marks the beginning of a new era of precision in HED science by probing the ultrafast changes of matter in extreme conditions. Fusion science research drives new technology developments in 100-Hz repetition rate and high-power petawatt-class lasers and develops the physics of energetic phenomena and radiation sources important for astrophysics and technical applications.

Our research programs in plasma and fusion energy sciences lie at the scientific frontier and focus on high-pressure and high-temperature plasmas. LCLS X-rays characterize warm dense matter states with an accuracy that can support or refute competing theoretical models. These studies provide critical experimental tests of physics models that are important for the design of full-scale fusion experiments and provide understanding of structural, transport, and radiation physics properties of fusion plasmas. These programs advance fusion experiments at SLAC.

Another major research area is the development of particle acceleration in plasmas with high-power, short-pulse lasers. Our experimental efforts are coupled to a theory program that uses 3-D particle-in-cell modeling of HED plasmas. It can resolve the femtosecond time scales and sub-micrometer spatial scales for exploration of advanced particle acceleration, ultrafast X-ray probes, and laser-produced fusion neutrons. Our calculations result in new understanding of radiation sources and predict Weibel-mediated collision-less shocks and magnetized shocks that can lead to very high particle energies relevant to the physics mechanisms for explaining the origin of cosmic rays.

The HED program has initiated a new theory group funded by a DOE-FES Early Career Award in theory. The program is expanding SLAC's footprint in the simulation of HED phenomena, thus exploring new scientific frontiers than will be accessed by our HED facilities.

We have demonstrated ultrafast pump-probe experiments on warm dense matter, achieving unprecedented precision. These experiments are enabled by investments in a diagnostics and technology program specifically aimed at achieving high-resolution measurements in space, time, and energy. We combine these capabilities with developments of cryogenic targets for high-repetition-rate studies of liquid hydrogen, deuterium, and other important materials for fusion research. In addition, the program has demonstrated novel probe techniques unique to ultrafast studies with X-ray lasers or UED.

We are developing a detailed plan that optimizes the layout and laser drivers of the Matter in Extreme Conditions (MEC) instrument to keep our world leadership role in this area. The upcoming LCLS-II facility motivates modifications of the Far Experimental Hall (FEH) to provide additional space suitable for a petawatt-class laser driver together with appropriate radiation shielding walls.

Funding for this core capability comes from DOE-FES and LDRD investments and serves the DOE-SC mission in scientific discovery and innovation (SC 2, 24).

Particle Physics

SLAC is world-leading in the exploration of the frontier of particle physics and cosmology with a comprehensive suite of underground, surface, and space-based experiments exploring the frontiers of particle physics and cosmology. This effort fully aligns with the science drivers described in the 2014 Particle Physics Project Prioritization Panel (P5) report as the most compelling lines of inquiry showing great promise for discovery over the next decade. Priorities are driven by the pursuit of high-impact science questions, as identified in collaboration with our world-renowned theory effort and unique contributions to the successful construction of detectors and facilities through our core world-leading instrumentation capabilities.

SLAC possesses core expertise in large-scale camera design, building, testing and project management that will allow us to deliver the LSST Camera, and in superconducting (SC) detector and readout design and fabrication for microwaves that have led to the world-leading limits on inflation in the BICEP cosmic microwave background (CMB) program. Together, these capabilities form the basis of our goal to lead and build the CMB Stage 4 project. The ultimate experiment in this field, CMB-S4, will build on BICEP and other pathfinder experiments to provide definitive measurements of the universe’s first light with a broad science scope that includes Inflation, neutrino mass, CMB lensing, and cluster cosmology. SLAC’s unique expertise in SC device design and fabrication and the large-scale integrated focal plane assembly from LSST, along with plans to build suitable microfabrication facilities to allow large-scale production of SC devices, underpin both our CMB-S4 plans and new systems for X-ray applications.

The ATLAS experiment at the LHC is exploring TeV mass scales and beyond for elucidating the properties of the Higgs and discovering new particles and interactions, two of the P5 science drivers. For the High Luminosity-LHC (HL-LHC) project, SLAC leads the assembly of the Inner Tracker pixel detector system, as well as studies of pile-up and jet reconstruction. SLAC has assumed a major role in the construction of the silicon inner tracker, which is the most important detector subsystem in the planned HL-LHC upgrades. We have the infrastructure and expertise in several key areas, including 3-D and CMOS pixels, strip detectors, and high-speed data transmission and readout. SLAC will assemble the U.S. pixel staves using a newly commissioned precision mounting and optical survey Coordinate Measurement Machine in our Building 33 clean room.

SLAC's two major neutrino programs, the EXO program to search for neutrinoless double beta decay (NDBD) and the DUNE program to study neutrino oscillations, are powered by an expanded expertise in liquid noble Time Projection Chambers (TPC), associated high-speed readout and purification systems, and ML analysis reconstruction techniques. With world-leading NDBD limits and the first observation of the related two-neutrino process, SLAC and Stanford are well-positioned to build on the success of 200-kg Enriched Xenon Observatory LXe TPC to better determine the mass-scale of neutrinos and whether they are their own antiparticle. SLAC is well positioned to play a leading role in the next NDBD program, established as a high priority by the Nuclear Science Advisory Committee (NSAC). Here, one of the leading candidate technologies is the multi-ton "next" experiment, nEXO, which follows the EXO-200 prototype lead by SLAC. SLAC’s effort in the accelerator-based, long-baseline neutrino oscillation and charge conjugation parity violation program provides critical expertise in various areas for the Deep Underground Neutrino Experiment (DUNE). SLAC instrumentation is a leading candidate for the cold electronics systems for DUNE. More recent efforts exploit our core expertise in liquid noble detector design to play the lead role in the design of the near detector, for which we are building a liquid argon (LAr) TPC Stage 2 prototype for the pixelated readout of the Argon-Cube technology. This work builds directly on our investment in the liquid noble test platform in operation since 2014 for the LZ project, which will also provide capabilities for nEXO development. This core expertise enables key roles in nEXO and DUNE, and position SLAC to become a leading center for neutrino science.

Funding for this core capability comes from DOE-HEP and DOE-NP, as well as SPP from NSF and NASA, and LDRD investments. SLAC's efforts serve the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23, 24, 25, 26, 29).

Science Strategy for the Future

At the center of SLAC's scientific vision is solving the most challenging problems in chemistry, materials sciences, and biology by fully exploiting the potential of the ultrashort, ultrabright pulses of coherent X-rays produced by LCLS. Our vision also focuses on the physics of the universe, specifically the search for dark matter and dark energy and probing the fundamental nature of the neutrino; as well as driving the frontier of advanced accelerator science and technologies.

Through diverse research programs, SLAC aims to solve the nation's critical scientific and technological challenges in energy, environment, health, and national security. We leverage our location in Silicon Valley and our strong relationship with Stanford to increase the impact of our work.

Infrastructure

Overview of Site Facilities and Infrastructure

The SLAC site is located on 426 acres of Stanford land, leased to DOE, located in unincorporated San Mateo County on the San Francisco Peninsula. Our Laboratory is a mixture of original 1960's era facilities and utility systems with newer facilities supporting current and future generations of science.

The land lease agreement with Stanford has been in place since 1962 and was renewed in 2010 for 33 years. The agreement identifies three areas, totaling 25 acres, which can be returned to Stanford in three separate phases. Stanford has not identified a timeline for the "take back" of these areas; however, this information is important for land use planning.

SLAC maintains 264 buildings, other structures and facilities (OSFs), and trailers. Majority of the square footage consist of buildings; however, approximately one-fourth of our total square footage resides in OSFs that are underground tunnels and unique experimental facilities, the largest of which is the 2-mile-long accelerator housing located 25 feet below grade that houses the linac. Other OSFs include a variety of supporting infrastructure, including 48 miles of distribution lines for our various utility systems.

SLAC's major utility systems include electric, chilled and hot water, domestic and fire water, storm sewer, sanitary sewer, natural gas, fire alarm, telecommunications, compressed air, and beginning in 2019, a major cryogenic generation and distribution system. Our primary source of power is provided by a 230-kilovolt (kV) 5.4-mile-long transmission line owned by DOE. A secondary 60-kV transmission line provides an alternate power source from Pacific Gas and Electric Company (PG&E). Reliability of these utility systems through infrastructure modernization is a vital component of our site-wide strategy.

Most of our facilities' portfolio is in "adequate" condition. However, a portion of our mission critical utilities infrastructure is still in "substandard" or "inadequate" condition due to its age and needs infrastructure revitalization. Our review of Facilities Information Management System (FIMS) FY 2018 year-end data validates that we have taken actions to ensure data integrity and implementation of our strategy to reduce deferred maintenance. In the past year, we retired $4.1 million in deferred maintenance, mainly as a result of improvements to our electrical substations, demonstrating our focus on prioritized investments and ongoing efforts to improve the quality of our infrastructure.

We are committed to stewardship of our infrastructure by providing operational reliability, collaborative spaces, and modernized facilities. Our campus strategy outlines our approach to identifying and reducing risks and maintaining mission ready facilities as our Laboratory grows and existing infrastructure matures.

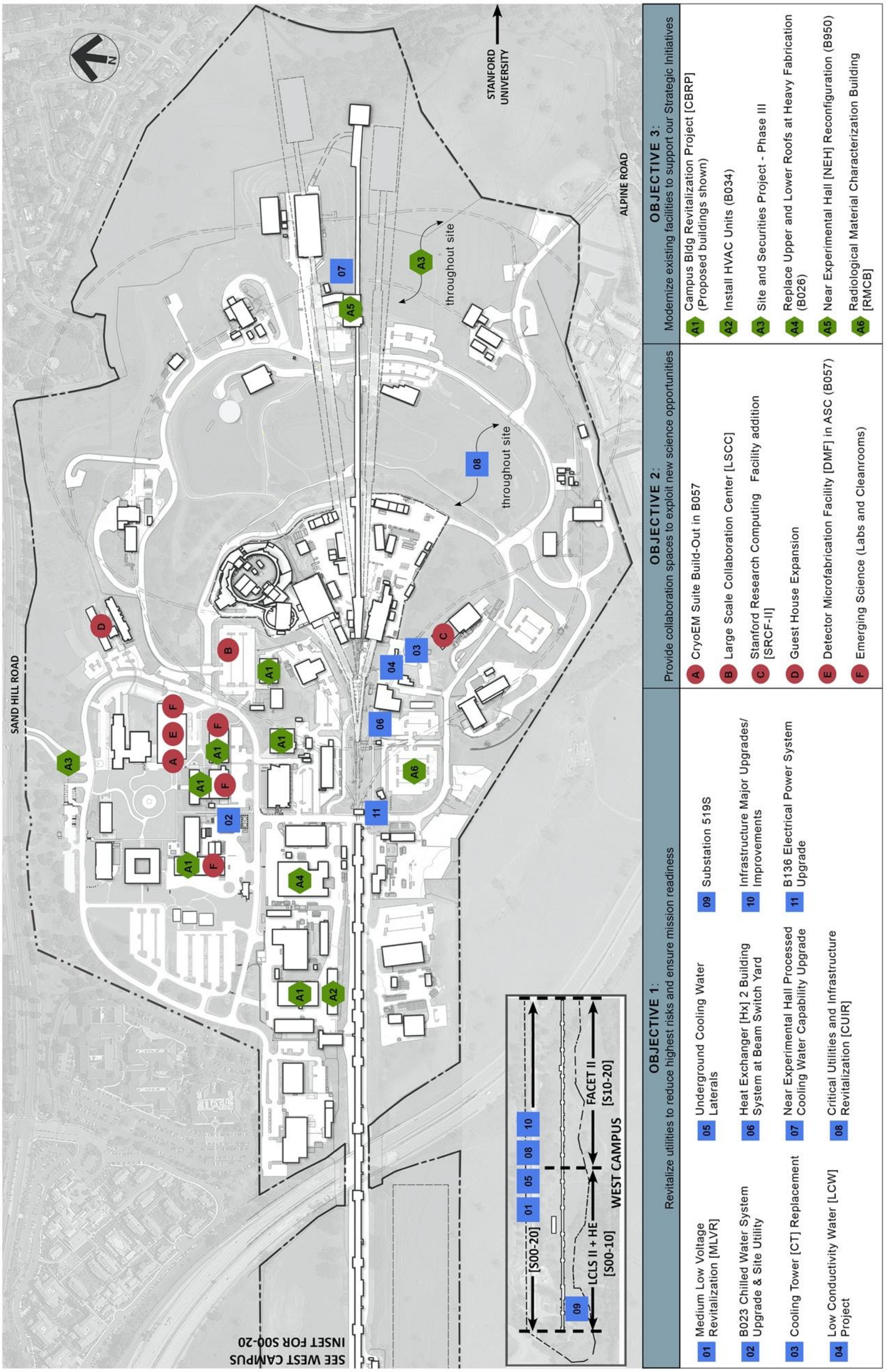


Figure: SLAC's Planned Facility & Infrastructure Investments

Campus Strategy

SLAC's campus strategy has three primary objectives to achieve the infrastructure vision:

1. Revitalize utilities to reduce highest risks and ensure mission readiness;
2. Provide collaboration spaces to exploit new science opportunities; and
3. Modernize existing facilities to support our Strategic Initiatives.

The SLAC Infrastructure Vision shows how we are supporting the science mission through campus planning of buildings, utilities, and other infrastructure. It is essential that SLAC maintains "Mission-ready facilities and infrastructure that ensure excellence in mission delivery and provides adequate and modernized space to support growth and collaboration" to support our Strategic Initiatives and to advance our DOE Core Capabilities.

The figure 'SLAC's Planned Facility & Infrastructure Investments' located on the previous page illustrates planned projects across the site. The illustration depicts how each project meets one of three campus strategy objectives for one unified infrastructure vision. The following sections articulate how we are currently executing our campus strategy and our highest priorities for the future.

Revitalize Utilities to Reduce Highest Risks and Ensure Mission Readiness

In recent years, we have made substantial progress in operational reliability, reducing operational risks and creating an environment of effective and efficient infrastructure operations. We have aligned our infrastructure investments with our science mission and prioritized them accordingly while maximizing our return on investment. Notable recent activities include improvements of electrical substations and switchgear along the linac through two SLI general plan projects (GPP): FY 2016 K-Subs and FY 2017 Medium Low Voltage Revitalization (MLVR). Both projects improve operational reliability to support the existing linac and the new superconducting linac.

In 2017, SLAC's institutional risk assessment and assurance process identified a potential critical electrical liability and fire risk to the Laboratory and neighboring community. The DOE-owned 230-kV, 5.3-mile transmission lines that bring power to SLAC traverse difficult terrain, complicating detailed inspection, maintenance, and vegetation management. SLAC hired experts to conduct aerial and ground inspections of the transmission line to check for deterioration, accurately map, and provide a plan to address potential vegetation risks. Power line vegetation management arborists removed vegetation according to the plan in 1Q FY 2019. A long-term maintenance strategy, including inspections, vegetation removal, and documentation is currently under development. Additionally, SLAC is working with PG&E to install remote engineering controls to improve electrical fault protection in FY 2020.

As part of our operations, we have performed comprehensive inspections and assessments, identified electrical maintenance concerns, and implemented several maintenance and repair actions. We implemented a revised electrical maintenance plan with a key feature of providing mitigation measures and training to protect personnel against hazards. As a result, since 2016, there have been zero electrical faults caused by a lack of maintenance. Planned implementation of state-of-the-art technologies will provide further optimization of operations and maintenance.

With improvements in electrical infrastructure, the next highest operational reliability risk is our cooling water systems. SLI-GPP projects are now underway for Low Conductivity Water (LCW) systems and Cooling Towers (CT). The LCW project provides reliable, right-sized, and reconfigured LCW systems with the ability to isolate lines for maintenance, thereby minimizing disruption to multiple science programs. The CT Project provides a cooling tower replacement enabling localized cooling for critical loads for the Beam Switch Yard to SSRL, LCLS experimental halls, and research yard end stations. Combined, these two projects will retire $4.6 million in repair needs, of which $2.2 million is deferred maintenance. SLAC IGPP is also being used to replace corroded 50-year-old water valves and cooling water laterals along the linac over the course of the next three years.

The next major category contributing to operational risks is our underground utilities: sanitary sewer, storm drains and piping, domestic water/fire protection, and lift stations. Most of this degraded infrastructure is past its service life and in some cases, deterioration has reduced building service capabilities.

As we plan for revitalization of our utility infrastructure to ensure mission readiness, the focus is on a SLI-Line Item (LI) request for a utility infrastructure investment project, the Critical Utilities Infrastructure Revitalization (CUIR), $189M (FY 2021-FY 2025). The primary objective of this project is to close infrastructure gaps to support multi-program science missions as technologies, instruments, experimental parameters, sensitivities, and complexity associated with evolving science demand increases required reliability, resiliency, and service levels in electrical, mechanical, and civil systems.

The CUIR project addresses degraded infrastructure with critical repairs, replacements, and modernization of underground water/fire protection, sanitary sewer, storm drain, and electrical systems site-wide, as confirmed by specialized assessments and inspections. It also extends utilities to facilities that now require more robust utility service. The project provides two 12-kV feeders and switch installation along the linac, replaces electrical feeders throughout the site, and modernizes switching equipment to provide an electrical grid that minimizes science disruptions caused by power fluctuations and faults. This outcome is necessary to address electrical reliability and redundancy requirements supporting LCLS, Cryoplant, and FACET-II. This project also installs a Supervisory Control and Data Acquisition (SCADA) system for power monitoring of electrical infrastructure for DOE-BES, DOE-HEP, DOE-BER, DOE-FES, ASCR, and NP science programs. Additional electrical improvements include replacement of the linac's Motor Control Centers (MCC), Variable Voltage Substation (VVS), low-voltage breakers, and K-Substation's low-voltage breakers, collectively reducing the risk of beam downtime. In addition to underground infrastructure and electrical work, this project addresses vital cooling water system revitalization with increased capacity to support multiple programs. Two new 5-megawatt cooling towers, cooling system controls, and tower piping connecting to the existing underground cooling tower water infrastructure are also included. The timely delivery of this project is essential for current and future success of our science programs.

Provide Collaborative Spaces to Exploit New Science Opportunities

Over the last two years, SLAC has been working on a campus vision that fosters collaboration by logically assembling research groups amongst the various sciences to maximize our human capital potential. Key to this collaboration is workplace design and the physical locations of people and workspaces. The SLI-LI Photon Sciences Laboratory Building (PSLB) project provided an interior fit-out of the first and second floors of the ASC, a building shell donated by Stanford. Stanford retains ownership of the third floor. The first and second floors of the ASC opened in April 2019 and will initially house metrology and calibration laboratories, laser laboratories, an optics nanofabrication facility, and two SLAC-Stanford joint institutes: PULSE and SIMES. SLAC will fund the fit-out of the Cryo-EM Center (in conjunction with NIH), slated for June 2019. Future options include space for a microfabrication detector clean room to build detectors for quantum science and physics of the universe programs. This laboratory facility not only advances our campus vision but also furthers DOE's goals for sustainability by achieving LEED Platinum certification, expected in FY 2020.

The Large-Scale Collaboration Center (LSCC), $62 Million (FY 2020-FY 2024) is the next logical step in our campus vision. While the ASC delivered primarily laboratory spaces, the LSCC supports current and future science by providing a modern research collaboration facility for large-scale data science, visualization, ML, and user interaction. Extremely large data rates (e.g. terabytes per second) generated from detectors at LCLS (DOE-BES), LSST (DOE-HEP), FACET-II (DOE-HEP), SSRL (DOE-BES), Cryo-EM (DOE-BER, DOE-BES, NIH), NP and ASCR will drive our need for data analytics, visualization, ML, and complex simulation codes using high-performance computing. LSCC will enable collaborations that will catalyze advancements with use of new imaging tools and software.

The LSCC is a new building to co-locate approximately 100 to 150 personnel for a robust cross-over between major programs to gain insight, innovation, and co-development. SLAC will impact and leverage a wide range of large-scale programs by co-locating teams of x-ray scientists, instrument scientists, computer scientists, and visiting users who develop critical algorithms and data analysis techniques. Early examples of a cross-functional approach have already produced strong results in the ability to interpret complex images in a wide variety of situations through the application of ML and other artificial intelligence methodologies. Synergies will be realized across all major DOE-sponsored programs at SLAC with a broad spectrum of researchers in materials science, chemical science, cosmology, computational support, artificial intelligence and ML, exascale applications, and private partnerships.

As demonstrated by the PSLB/ASC (DOE/Stanford) example and other recent projects around the Laboratory, Stanford has been an important contributor of infrastructure by providing essential projects that create a great work environment at SLAC. In partnership with our Laboratory, Stanford is expected to begin conceptual design for a second phase of the existing SRCF called SRCF-II which is a key part of SLAC's computing infrastructure strategy. Stanford will conduct a feasibility study for the Stanford Guest House expansion. Both these projects will provide additional assets to support the Laboratory's growth.

The Stanford Research Computing Facility addition "SRCF-II" ($52 Million) is an approximate 9,700 square foot, 3 MW proposed expansion to the existing SRCF. Both SRCF and SRCF-II would provide the Stanford and SLAC research community with computing facilities designed specifically to host high-performance computing equipment. The scientific computing resources in this state-of-the-art facility is planned to use 40 percent less energy per square foot than the national average. Stanford is completing a feasibility study and is evaluating a path forward.

The Guest House Expansion ($38 Million) is an approximate 47,000 square foot, 120-room addition to the existing Guest House. The project also includes interior gathering areas, conference areas, and other guest amenities. This would provide a much-needed asset to the Laboratory and our science programs as we continue to grow and need resources to host visiting scientists.

Modernize Existing Facilities to Support our Laboratory Goals

A holistic approach to our campus vision must also evaluate the strengths and opportunities of our existing assets. Modernization of existing facilities already in an optimal location is good stewardship of DOE resources and reduces deferred maintenance. Complete demolition of obsolete facilities and construction of new facilities is also important to the campus vision. As new facilities open for operations and existing facilities are modernized, access to SLAC also becomes a critical component for a holistic campus vision.

Over the last decade, SLI-LI as well as our IGPP and our indirect funding has supported the modernization of our site. SLI-LI supported the conversion of an underutilized warehouse and renovations of old office space to provide modern administrative spaces to support various mission support functions. More recently, Laboratory Indirect has supported the replacement of roofs, construction of laboratory space, and upgrades to the manways and stairways at the linac. Currently our indirect funding supports upgrades to heating, ventilation, and air conditioning (HVAC) units and roofs on mission-critical facilities. The next phase of modernization focuses on major renovations of some of our most critical "substandard" aging laboratory and office buildings. Consistent with good stewardship, investments in modernizing existing facilities are focused on mission-critical facilities. As we modernize the overall site, further improvements to access controls and operational equipment in several buildings to protect DOE assets in the central campus area and around the site become even more critical.

The Campus Building Renovation Project (CBRP), $96 Million (FY 2022-FY 2025) will be a SLI-LI modernization project to update aging laboratory and office spaces in buildings around our Science Quad for programs supporting our existing multi-program missions. This modernization will involve 83,000 to 125,000 gross square feet of existing space. This project renovates buildings that house infrastructure to support the full lifecycle of the Laboratory's accelerator systems; engineering and scientific talent in particle and X-ray detector systems, sensors, ASICs, and electronics for a broad range of advanced applications. Renovations of substandard office and laboratory spaces will provide more workspaces per square foot and help meet sustainability requirements. Recent assessments identified additional requirements for this project, specifically end-of-life roofs and building utility infrastructure. Mechanical utilities, HVAC units, roofing systems, and electrical systems will be replaced and upgraded to comply with current codes, enhance sustainability, and reduce deferred maintenance. Currently document deferred maintenance for this project is approximately $4.1 million; however, this data is obsolete and updated condition assessments are scheduled for these facilities in 2019 and 2020. It is anticipated that deferred maintenance value for these facilities will increase substantially.

The Site Security and Access Improvements, $8 Million (FY 2020-FY 2021), with proposed funding by DOE Safeguards & Security Program, would represent the final phase of security projects at SLAC that have spanned the past decade. It will complete the protection of DOE assets and enhancement of science collaboration across our Laboratory. The project will replace the existing main entrance Gate House with a modern Guard House and security dispatch center, reconfigure SLAC's main entrance at Sand Hill Road, modernize to improve safety for our security officers and efficiency in access badge verification, as well as adding radiation portal monitoring capability at SLAC's two external gates to reduce the risk of inadvertent off-site transport of activated materials. This project will also retrofit the remaining 31 buildings and 12 accelerator tunnels with entry control points using card key access. Providing modern access control directly on buildings will improve property and personnel security by providing site lockdown capability for active threat situations and complying with DOE Design Basis Threat requirements. This will also substantially reduce the accelerator access area, converting the area around PEP Ring Road into a general access area.

Asset Management

DOE relies on FIMS extensively for making management decisions as they relate to condition, use, mission, status, maintenance, operations, and disposition of real property. Complete and accurate information on real property assets is critical to DOE for managing facilities and satisfying external reporting requirements such as the Federal Real Property Profile.

The following sections describe current efforts to ensure data quality in FIMS. To validate the data, we will rely on the data quality enforced through the annual DOE FIMS data validation conducted in close coordination with our Site Office.

Replacement Plant Value (RPV)

In the third quarter of FY 2017, we began to recalculate RPV using DOE models to reflect the uniqueness of our facilities and the higher costs associated with the San Francisco Bay Area. Because of this adjustment, RPV in the coming years will increase. The RPV reported in FY 2017 was $1.92 billion. The reported RPV in FY 2018 is $2.85 billion. The increase is a result of recalculating RPV for approximately 550,000 square feet of our underground tunnel facilities. To date, 40 percent of the facilities have been validated. We will continue to update about 25 assets each year until the remaining 150+ assets are updated. On a yearly basis, we will review updates and gain concurrence from DOE on the methodology, modified models, and factors used to adjust RPV.

DOE defines Maintenance Index (MI) as the product of Annual Actual Maintenance (AAM) as the numerator and RPV as the denominator. The RPV of SLAC's assets is $2.85B; however, for MI, we have calculated RPV as the sum of all our assets that are operational, including 3000 series assets because programmatic real property (linear and ring accelerators) have not been calculated into the RPV. The table below illustrates MI broken down by facility type. In FY 2018 AAM was focused on our top infrastructure priority, utilities, specifically OSF-Underground Distribution, with an associated MI of 2.3%. This strategy invests higher amounts to address the highest risks.

Maintenance Index by Facility Type on Operational Faculties (in $000)										
	Buildings		OSFs-Tunnels		OSFs-Underground Distribution		OSFs-All Others		Trailers	
AAM	$8,063	0.46%	$959	0.26%	$3,351	2.29%	$3,180	1.2%	$54	0.8%
RPV	$1,745,321		$374,379		$146,472		$265,007		$6,883	
Source: FIMS Year-End Data FY 2018										

Repair Needs (RN) and Deferred Maintenance (DM)

In recent years, we have taken an improved approach to ensure reliable FIMS and CAIS data which serves as the foundation of our infrastructure investment plan. Beginning in 2016, a collaboration of DOE-SC laboratories, under the Infrastructure/Mission Readiness Working Group, developed a process to better define Repair Needs (RN) and Deferred Maintenance (DM). Our utility "Stewards," who are the subject matter experts responsible for assessing systems, have used this methodology to validate the classification of deficiencies as either RN or DM. Their efforts have increased the accuracy of our documented infrastructure gaps.

The baselined DM increased from $28.4 million in FY 2016 to a more accurate $80.3 million in FY 2017. As a result of critical infrastructure improvements to substations for our linac Gallery and other indirect projects, we decreased DM to $76.2 million for FY 2018. Although DM remains high, the overall SLAC Facility Condition Index earns a "good" rating by industry standards. Assets identified as high risks are addressed through our campus strategy in our planned infrastructure investments. Investments in our electrical substations, cooling towers, and low conductivity water systems will further reduce our DM. The combination of planned maintenance activities, indirect investment, and the proposed projects discussed in Section 6.2 should result in a decrease of DM by about 40 percent compared to the current trendline through 2026. SLAC will constantly track new and retired DM to accurately monitor this key performance indicator.

FIMS Data Reconciliation with Geographic Information Systems (GIS)

Facilities and Operations is collaborating with our Metrology/GIS group to validate the overall inventory of facilities in FIMS. GIS provides a geospatial illustration of the data in FIMS, transforming data elements into visuals that are easier to analyze. This has proven to be an important tool in reconciling what is on the site as compared to what is documented in FIMS. This tool has also been extremely useful in validating the accuracy of linear assets that are often more difficult to access in a visual inspection. GIS is also used by our Space Planners, who document current utilization of space as moves are made throughout our site. The ability to capture space use by all our users supports important data elements in FIMS.

Site Sustainability Plan Summary

We are meeting the current targets on most of our DOE goals. Our strategy is to perform building assessments, prioritize opportunities based on life-cycle cost-effectiveness, and develop projects to optimize energy and water usage. We made excellent progress this past year:

- Optimized office building energy usage over the site-wide portfolio of 18 metered buildings, by employing the energy metering dashboard to achieve a 6 percent energy reduction compared with last year;
- Acquired EV charging stations via an NREL grant and used indirect funding to install 24 new chargers that support both personal and fleet vehicles at Buildings 41 and 950;
- Performed a feasibility assessment that includes detail cost and energy savings calculations for creating a multi-year strategy for certifying nine buildings to meet the DOE High Performance Sustainable Buildings (HPSB) goal in 2025;
- Completed LED lighting upgrades in line with HPSB assessments which reduce maintenance and energy cost by $40,000 annually;

- Improved site resiliency to wildfire risk by completing tree and vegetation trimming around electrical power transmission lines at high-risk areas.

Our next steps:

- Complete our EISA 4-year energy audits on remaining 14 of 51 buildings;
- Re-commission energy systems by mid-2020 on five buildings to maintain our HPSB certification;
- Increase building manager awareness of the energy metering tool to monitor building performance and control energy waste.

We will continue to innovate in the areas of efficiency. One example is in the controls for the Accelerator "power saving mode", a conservation measure employed when running lower energy electron beams to LCLS. Klystron modulators are powered down when not needed, potentially saving several megawatts over a 12-hour shift. Despite efficiencies, the nature of the higher energy science will result in us increasing energy and water consumption. Offsetting science-based emissions through Renewable Energy Credit (REC) purchases is not currently planned given the additional costs of these purchases.

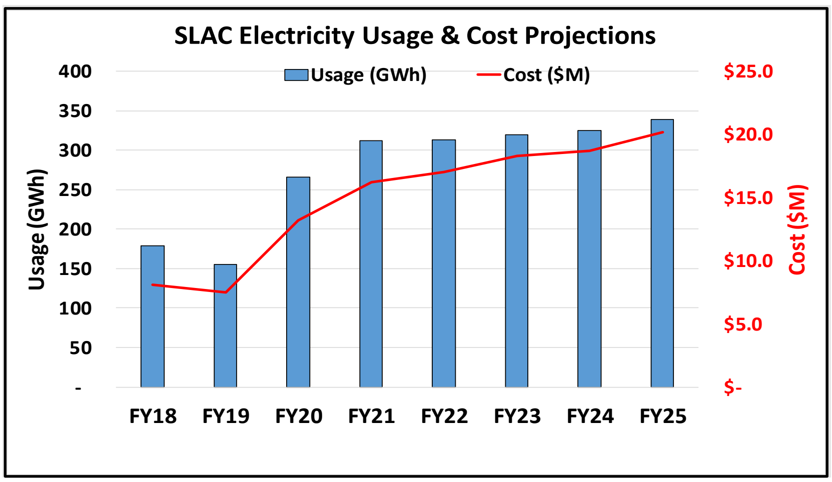


Figure: Electricity Usage & Cost Projections

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

Lab-at-a-Glance

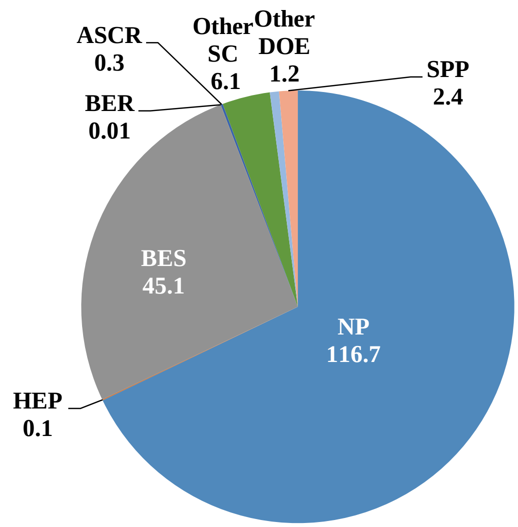
Location: Newport News, VA
Type: Single-program Laboratory
Contractor: Jefferson Science Associates, LLC
Site Office: Thomas Jefferson Site Office
Website: www.jlab.org

- **FY 2018 Lab Operating Costs:** $172 million
- **FY 2018 DOE/NNSA Costs:** $169.6 million
- **FY 2018 SPP (Non-DOE/Non-DHS) Costs:** $2.4 million
- **FY 2018 SPP as % Total Lab Operating Costs:** 1.4%
- **FY 2018 DHS Costs:** $0 million

Physical Assets:
- 169 acres and 69 buildings
- 883,000 GSF in buildings
- Replacement Plant Value: $480 M
- 0 GSF in Excess Facilities
- 66,289 GSF in Leased Facilities

Human Capital:
- 693 Full Time Equivalent Employees (FTEs)
- 28 Joint Faculty
- 33 Postdoctoral Researchers
- 42 Graduate Student
- 20 Undergraduate Students
- 1,630 Facility Users
- 1,491 Visiting Scientists

FY 2018 Costs by Funding Source ($M)



Mission and Overview

The Thomas Jefferson National Accelerator Facility (TJNAF), located in Newport News, Virginia, is a laboratory operated by Jefferson Science Associates, LLC, for the Department of Energy's (DOE) Office of Science (SC). The primary mission of the laboratory is to explore the fundamental nature of confined states of quarks and gluons, including the nucleons that comprise the mass of the visible universe. TJNAF also is a world-leader in the development of the superconducting radiofrequency (SRF) technology utilized for the Continuous Electron Beam Accelerator Facility (CEBAF). This technology is the basis for an increasing array of applications at TJNAF, other DOE labs, and in the international scientific community. The expertise developed in building and operating CEBAF and its experimental equipment has facilitated an upgrade that doubled the maximum beam energy (to 12 GeV (billion electron volts)) and provided a unique facility for nuclear physics research that will ensure continued world leadership in this field for decades. TJNAF's current core capabilities are: Nuclear Physics; Accelerator Science and Technology; and Large-Scale User Facilities/Advanced Instrumentation.

The lab supports an international scientific user community of 1,630 researchers whose work has resulted in scientific data from 188 full and 33 partial experiments (including 10 full and 23 partial in the 12 GeV era), 453 Physics Letters and Physical Review Letters publications and 1,550 publications in other refereed journals to-date at the end of fiscal year (FY) 2018. Collectively, there have been more than 163,000 citations for work done at TJNAF.

Research at TJNAF and CEBAF also typically contributes to thesis research material for about one-third of all U.S. PhDs awarded annually in Nuclear Physics (22 in FY 2018; 630 to-date; and 212 more in progress). The lab's outstanding science education programs for K-12 students, undergraduates and teachers build critical knowledge and skills in the physical sciences that are needed to solve many of the nation's future challenges.

Core Capabilities

Large-Scale User Facilities/Advanced Instrumentation

TJNAF is a unique world-leading user facility for studies of the structure of nuclear and hadronic matter using continuous beams of high-energy, polarized electrons. The completion of the 12 GeV Upgrade project enables many outstanding new scientific opportunities. The 2015 NSAC (Nuclear Science Advisory Committee) Long Range Plan clearly stated that its highest priority was to capitalize on this investment: “With the imminent completion of the CEBAF 12 GeV upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.”

The Continuous Electron Beam Accelerator Facility (CEBAF) electron beam can be simultaneously delivered to the experimental halls at different energies. With the completion of the 12 GeV Upgrade the beam energy can be up to 12 GeV, converted to 9 GeV photons for experimental Hall D, and up to 11 GeV to Halls A, B and C. Each experimental hall is instrumented with specialized experimental equipment designed to exploit the CEBAF beam. The detector and data acquisition capabilities at TJNAF, when coupled with the high-energy electron beams, provide the highest luminosity (10^{39}/eN/cm^2/s) capability in the world. The TJNAF staff designs, constructs and operates the complete set of equipment to enable this world-class experimental nuclear physics program. With more than 1,600 users annually, of which roughly two-thirds are domestic, TJNAF supports what is generally considered the largest nuclear physics user community in the world.

The CEBAF science program spans a broad range of topics in modern nuclear physics. Recent lattice QCD (Quantum Chromodynamics) calculations predict the existence of new exotic hybrid mesons that can be discovered with the new 12 GeV experiments and elucidate the nature of confinement. New phenomenological tools have been developed that produce multidimensional images of hadrons with great promise to reveal the dynamics of the key underlying degrees of freedom – a new science program termed Nuclear Femtography. A surprising connection between the role of nucleon-nucleon interactions and the quark structure of many nucleon systems discovered at TJNAF earlier, needs to be understood. Development of measurements of exceptionally small parity-violating asymmetries with high precision has enabled major advances in hadronic structure, the structure of heavy nuclei (through measurement of the neutron distribution radius), and precision tests of the standard model of particle physics, including a measurement of the electron’s weak charge.

A comprehensive theoretical effort provides leadership across nuclear physics by pulling together state-of-the art theoretical, phenomenological and computational approaches, including effective field theory techniques, QCD global analyses, and non-perturbative Lattice QCD calculations. TJNAF deploys cost-optimized High Performance Computing for Lattice QCD calculations as a national facility for the U.S. lattice gauge theory community that complements DOE’s investment in leadership-class computing. Computational techniques in Lattice QCD now promise to provide insightful and quantitative predictions that can be meaningfully confronted with and elucidated by forthcoming experimental data. Those techniques also promise to calculate the structure of hadrons that are hard, if not impossible, to do scattering experiments with.

Excellent synergy exists between the TJNAF experimental and theoretical programs. The Joint Physics Analysis Center (JPAC) develops theoretical and phenomenological understanding of production and decays of hadron resonances, which helps bridge the analyses and interpretation of experimental data from TJNAF with the results of Lattice QCD calculations. TJNAF scientists are heavily engaged in the community effort and its phenomenological studies to help develop the strong science case and unique detection capabilities for a future Electron-Ion Collider (EIC). TJNAF has consolidated its efforts in the development of the science program by forming an Electron Ion Collider Center (EIC[2]). Seminars, visiting fellows, and workshops will be among the components of this new center.

Accelerator Science and Technology

TJNAF has world-leading capabilities in technologies required for superconducting linacs – notably, as follows:

- Complete concept-to-delivery of superconducting linear accelerators and associated technologies
- State-of-the-art SRF fabrication and assembly capabilities
- Unrivaled design, commissioning and operations experience in large cryogenic plants
- World-leading polarized electron injector capabilities
- Low-level RF and controls
- Accelerator and large-scale control systems

These world-leading capabilities are evidenced by the production of more than 100 cryomodules produced and in continuous operation today. The ability to deliver large projects on time and on budget is evidenced by our involvement in major superconducting projects for SRF and cryogenics, including SNS, LCLS-II – for which TJNAF is responsible for construction of half of the superconducting cryomodules, as well as the two cryogenic refrigerators, and the FRIB helium refrigerator.

Construction of the Upgraded Injector Test Facility (UITF) at building 58 is nearly complete. The UITF provides a means to test important devices for CEBAF, like the new SRF "booster" cryomodule and the HDIce polarized target for Hall B. It is a testbed to evaluate new accelerator technologies, like Nb_3Sn-coated accelerating cavities operating at 4K, and potential accelerator applications, like wastewater treatment with electron beams. And although providing only low-energy electron beams (< 10 MeV), the UITF could be used to conduct the PAC-approved bubble chamber astrophysics experiment to study photodisintegration of oxygen.

In addition, TJNAF has pioneered Energy Recovery Linac (ERL) concepts and technologies, holds the record for recirculated beam power (1.4 MW), and has been a world leader in high-power free electron lasers based on ERL technology. TJNAF, through its Center for Advanced Studies of Accelerators, possesses world-leading capabilities in beam dynamics' aspects of linear accelerators, energy-recovery linacs, free-electron lasers, and colliders.

Electron Ion Collider (EIC) Design: The Accelerator Division, in partnership with the Physics Division and collaborators at other national laboratories, has been developing a design concept for a Jefferson Lab Electron Ion Collider (JLEIC). A design report for JLEIC was published in 2012, to respond to the energy and luminosity requirements of the EIC physics White Paper. The JLEIC design team, composed of TJNAF personnel and strategic national and international collaborators, is developing a pre-Conceptual Design Report (pre-CDR) in FY 2018 and FY 2019, with a CDR to follow in FY 2020. Design and R&D efforts in support of the CDR phase are consistent with the critical-decision timeline for the EIC project and with the requirements for DOE Order 413.3.

Large Scale User Facilities/Advanced Instrumentation

Experimental Nuclear Physics (funded by DOE SC – Nuclear Physics)

TJNAF is the world's leading user facility for studies of the quark structure of matter using continuous beams of high-energy, polarized electrons. CEBAF is housed in a seven-eighths mile racetrack and was built to deliver precise electron beams to three experimental end stations or halls. The electron beam can be converted into a precise photon beam for delivery to a fourth experimental Hall D. Accelerator instrumentation is installed to deliver beams to all four halls simultaneously.

CEBAF provides a set of unique experimental capabilities unmatched in the world, as follows:

- Highest energy electron probes of nuclear matter
- Highest average current

- Highest polarization
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Highest-intensity tagged photon beam at 9 GeV for exotic meson searches
- Unprecedented stability and control of beam properties under helicity reversal for high-precision parity violation studies

Hall D is dedicated to the operation of a hermetic large-acceptance detector for photon-beam experiments, known as GlueX. Hall A houses two high-resolution magnetic spectrometers of some 100 feet in length and a plethora of auxiliary detector systems, including the large-acceptance Super BigBite Spectrometer. Hall B is home of the CEBAF large-acceptance spectrometer (CLAS12) with multiple detector systems and some 100,000 readout channels. Hall C boasts two roughly 80-foot-long, high-momentum magnetic spectrometers that allow for precision scattering experiments and has housed many unique large-installation experiments. Maintenance, operations and improvements of the accelerator beam enclosure and beam quality, and the cavernous experimental halls and the multiple devices in them, are conducted by the TJNAF staff to facilitate user experiments. Important capabilities related to the experimental program include state-of-the-art particle detection systems, high-power cryogenic targets, polarized targets, high-speed readout electronics and advanced data acquisition technology.

CEBAF Operations (funded by DOE SC – Nuclear Physics)

As mentioned above, CEBAF has been recently upgraded to provide an electron beam with energy up to 12 GeV, a factor three over the original 4 GeV CEBAF design. In addition to the increase in beam energy, the maximum number of simultaneous experiments that CEBAF can support increased this year from three to four, with the completion of a four-laser injector upgrade. With the completion of the 12 GeV Upgrade, TJNAF will continue to be the world's premier experimental QCD facility.

With 418 installed SRF cavities, CEBAF operations represent a significant fraction of the worldwide SRF performance data set. Some of the CEBAF SRF cavities have been operating for more than 20 years. The CEBAF data set and operational experience is a valued resource for new or existing SRF-based accelerators. TJNAF has the ability to conceive and design large accelerator facilities, building upon 6 GeV CEBAF operations and augmented with the ongoing 12 GeV Upgrade.

Accelerator Technology (funded by DOE SC – Nuclear Physics, Basic Energy Sciences, High Energy Physics, DOD ONR, Commonwealth of Virginia, and Industry)

The ability to use the TJNAF Low Energy Recirculator Facility (LERF) as an accelerator R&D test bed for Energy Recovery Linacs and techniques required to establish cooling of proton/ion beams, for example, provides a mutually beneficial cross-fertilization between the TJNAF LERF and Nuclear Physics. The LERF vault has recently been configured to enable higher throughput of cryomodule testing for LCLS-II. In addition, the LERF is supporting an R&D program to develop an accelerator-based concept to make Cu-67.

As a result of the development, construction and operation of CEBAF, TJNAF has developed world-leading expertise in superconducting RF linear accelerators, high-intensity electron sources, beam dynamics and instrumentation, and other related technologies. These capabilities have been leveraged to develop new technologies relevant to other disciplines beyond nuclear physics, as well as applications to areas of national security.

TJNAF is applying its accelerator technology to collaborate with four other national laboratories to realize the Linac Coherent Light Source II, at the Stanford Linear Accelerator Center (LCLS-II at SLAC). TJNAF is responsible for construction of half of the superconducting cryomodules as well as the two cryogenic refrigerators. An upgrade is already underway to double the energy of LCLS-II from 4 to 8 GeV and extend the X-ray energy limit from 5 keV to 12.8 keV. TJNAF will build 10 cryomodules for the LCLS-II HE project.

TJNAF has been selected to produce cryomodules for the Spallation Neutron Source Proton Power Upgrade (SNS PPU). The scope of the project is to build seven new high beta cryomodules to increase the SNS linac beam energy.

Cryogenics (funded by DOE SC – Nuclear Physics)

Over the last two decades, TJNAF has developed a unique capability in large-scale cryogenic system design and operation that is a critical resource for the U.S. national laboratory complex. The TJNAF cryogenics group has been instrumental in the design of many construction projects requiring large-scale cryogenics: SLAC (LCLS-II), Michigan State University (FRIB), Oak Ridge National Lab (SNS), TJNAF (12 GeV Upgrade), and NASA (James Webb Space Telescope), as well as improving the cryogenic efficiency of existing systems (Brookhaven National Laboratory). In the process, many inventions have been patented, and one has been licensed by Linde (one of two companies that build cryogenic systems) for worldwide applications on new and existing cryogenic plants. This work has also resulted in many master's theses, to ensure the continuity of this expertise in the coming decades.

The group is presently responsible for designing, specifying, procuring and commissioning the two CHLs for LCLS-II, based on the successful CHL2 design for the 12 GeV Upgrade and designs developed for FRIB. The FRIB refrigerator installation is nearing completion along with TJNAF's scope of work supporting the project. Significant CEBAF upgrades in progress include design and in-house fabrication of a replacement 2K cold box for CEBAF operations using the latest cold compressor technology. Additionally, work has begun to modify and install a surplus SSC refrigerator, ESR2, to support future CEBAF end station operations.

Science Strategy for the Future

The TJNAF science strategy for the future has a strong foundation based on the advancement of the U.S. nuclear physics program (as embodied in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan) and the support of Office of Science accelerator projects utilizing TJNAF's expertise in Superconducting RF and cryogenics technologies. TJNAF has developed the FY 2019 Laboratory Agenda to delineate major initiatives associated with strategic objectives in Science and Technology as well as Operations. The Agenda was constructed around a set of four Strategic Outcomes that deliver on the mission of the laboratory, and three of these Strategic Outcomes are related to TJNAF's science and technology activities.

Infrastructure

Overview of Site Facilities and Infrastructure

Thomas Jefferson National Accelerator Facility is located on a 169-acre DOE-owned federal reservation within the City of Newport News in southeast Virginia. Adjacent to the federal reservation is the Virginia Associated Research Campus (VARC), a five-acre parcel owned by the Commonwealth of Virginia and leased by SURA, the managing member of the JSA joint venture, which sub-leases five acres to DOE for use by TJNAF. Also adjacent to the federal reservation is an 11-acre parcel owned by Newport News that contains the Applied Research Center (ARC), within which JSA leases additional office and lab space. SURA owns 37 acres adjacent to the TJNAF site, where it operates a 42-room Residence Facility at no cost to DOE.

The TJNAF complex consists of 68 DOE-owned buildings comprising 882,990 square feet (SF) of office, shop, technical, and storage space. JSA leases an additional 37,643 SF of office and shop space from the Commonwealth of Virginia in the VARC and 11,097 SF of office and lab space from the City of Newport News in the ARC. JSA also leases 17,549 SF of storage space in two offsite storage warehouses within 12 miles of TJNAF. These areas are gross, usable space as summarized in the table below.

The TJNAF complex provides office and workspace for approximately 760 JSA contractor, JSA, and federal government employees along with a transient population of 1,600 users and visiting scientists. Facility space is well utilized with a current asset utilization index of 98.6%. Distribution of space by use is summarized in the table below.

Type of Use	Total Square Feet, Usable Space, Owned and Leased
Technical and Laboratory	258,768 (39%)
High Bay	150,198 (23%)
Office	101,420 (16%)
Storage	92,847 (14%)
Common	54,579 (8%)
TOTAL	657,812 (100%)

Table: Distribution of Usable Space by Type of Use

The condition of TJNAF facilities is generally good. Of the 74 DOE-owned or -leased buildings, 65 are rated adequate, eight substandard, and one inadequate. There are no longer any office trailers on site. Of the 36 other structures and facilities (including OSF 3000 series assets) assessed, 33 were rated adequate and three substandard. A total of 2,009 SF of space is currently rated as underutilized. These spaces will be fully utilized once capital funds are received and construction is complete. There are currently no excess facilities at the Lab and none are expected within the next ten years. There are 49 shipping containers representing 15,160 SF of storage space in use at TJNAF. TJNAF plans to remove four of these containers by the end of FY 2019.

Condition		Mission-Unique Facilities		Non-Mission-Unique Facilities		Other Structures and Facilities	
		Number	SF	Number	SF	Number	SF
Rating	Adequate	36	339,976	29	360,697	33	N/A
	Substandard	0	0	8	259,221	3	N/A
	Inadequate	0	0	1	6,638	0	N/A
	TOTAL	36	339,976	38	626,556	36	N/A
Utilization	Underutilized	2	3,240	0	0	0	N/A
	Excess	0	0	0	0	0	N/A

Table: TJNAF Facility Rating and Utilization Assessment

TJNAF is entirely dependent on public utility service. JSA sources power from Dominion Virginia Power at an average rate of $0.06/kWh and water from Newport News at an average rate of $3.69/HCF and disposes of wastewater through the Hampton Roads Sanitary District at an average rate of $8.77/HCF. Utility service meets mission requirements although occasional, unplanned commercial-power outages periodically disrupt accelerator operation.

The TJNAF Land Use Plan is maintained on the TJNAF website. The only real-estate action planned for FY 2020 is an extension of the lease of 11,097 SF of office and lab space in Applied Research Center (ARC). The ARC is owned by the Newport News Economic Development Authority and sits immediately adjacent to TJNAF. JSA is currently working with Newport News to transition operations and maintenance responsibility for the entire ARC to the City before the start of FY 2020. However, the city has been reluctant to engage in definitive operations and maintenance transfer discussions due to ongoing discussions about an eventual transition of the ARC to the DOE. This is one option currently being evaluated under the CEBAF Renovation and Expansion (CRE) project which received CD0 as an SLI initiative at the end of FY 2018.

Campus Strategy

The S&T strategy described in this plan dictates the campus investment plan. Working with the Chief Research Officer, the facilities planning team reviews the capabilities of the current infrastructure against the S&T strategy to identify current and projected gaps. TJNAF then performs an analysis of alternatives (AOA) to select the optimum solutions to close the gaps between mission needs and infrastructure capability. The selection of solution and time phasing is driven by mission priority and constrained by the projected levels of indirect, GPP and SLI program funding.

This plan reflects the heightened urgency to improve infrastructure reliability given the recent trend of increasingly disruptive failures impacting experimental schedules. Accelerator reliability is the product of the joint availability of all component systems (cavities, magnets, controls, infrastructure, and so forth). To meet the CEBAF 85% availability goal, the Accelerator Division has allocated to facilities infrastructure an availability requirement of >98%, which translates to <107 hours of total downtime over a 32-week experimental period.

The recent failure history suggests continued substantial improvement in infrastructure reliability is needed to reach this availability requirement. Electrical distribution issues remain the greatest cause of impact to accelerator operations and the area of major concentration. In the third quarter of 2018, Facilities Operations and Maintenance performed Preventative Maintenance (PM) on 46 15 kV transformers. The tests included oil tests and electrical tests. Of the 46 transformers serviced, 17 transformers either failed or had less than satisfactory test results. Transformers failing the test were repaired or replaced. Transformers with less than satisfactory test results are currently being monitored and tracked.

Belt-driven rack fans cooling the RF power supply racks have been in service since the original accelerator start-up and are failing at an increasing rate with parts obsolescence making it extremely difficult to maintain. An alternate design is being evaluated with plans for replacement in 2020. Heat detection in the tunnel failed due to higher radiation levels during 12 GeV beam operations. A project is underway to replace the current system with a more robust heat detection wire system capable of withstanding higher radiation levels.

Presented in the table below is the correlation between S&T mission requirements, required infrastructure capability, current shortfall in this capability, and optimum solution.

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
Accelerator Science and Technology (SC01)	Provide LHe to the Test Lab to enable the development, production and testing of SRF components and cryomodules, both for use by TJNAF in CEBAF and under WFO projects for other labs.	The Cryogenics Test Facility (CTF) has experienced heavy utilization due to the CEBAF upgrade and large WFO projects. Approximately $4M of system components have reached end-of-life and others require upgrading to maintain adequate capacity for projected workload.	Complete the **Cryogenics Test Facility (CTF) Upgrade.** Need date is FY 2021 or sooner if practical.
	Provide sufficient storage space for material and tooling needed to design, produce and test SRF components and systems.	18,000 SF of technical storage is leased in warehouse space remote from TJNAF. This introduces additional labor and time requirements to control and access this high-value material.	Construct a 15,000 SF **Equipment Storage Building** to relieve the demand for remote, off-site leased storage for SRF components, tooling, and work in process. Need date is FY 2022 or sooner if practical.

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
	Low Energy Recirculator Facility (LERF) for R&D on magnetized high-current beams, characterization of materials using low-energy positrons, and production of medical isotopes	Mechanical systems are at end of service life and electrical systems are at or past capacity. Finishes are well worn and need to be renewed.	Execute a **LERF Renovation** to ensure the facility can meet its planned operational use. Need date is FY 2027 or sooner if practical.
Large Scale User Facilities/R&D Facilities/Advanced Instrumentation (SC16)	Central Helium Liquefier (CHL) capable of supplying CEBAF with 9400W of 2K cooling and 22 g/s of LHe at >85% reliability	Two plants, CHL1 and 2, must operate to meet the 2K cooling requirements, but CHL1 is unable to meet the up-time requirements due to an aging cold box.	Complete the **CHL1 2K Cold Box Replacement**. Need is immediate and project is underway as a FY 2017 SLI-GPP project scheduled for completion in 2021.
	Provide 10,152 SF of suitable office and workspace for Cryogenics Engineering staff adjacent to CHL plant.	Current facility is substandard due to aging mechanical systems and worn finishes. Office space is over utilized due to expanding cryogenics staffing.	**Cryogenics Engineering Office Renovation (Building 89)** replaces worn systems and finishes and increases office space capacity. Project is under construction with expected completion in January 2020.
	45,000 SF of environmentally controlled high bay and technical space to support SRF production, cryogenics fabrication, and equipment assembly and staging for four experimental halls operating at 32 weeks/year.	High bay space in the Test Lab and TED buildings is heavily over utilized. Overcrowding increases the safety risk to staff and visiting scientists. Off-site space is currently being leased to meet the demand.	Build a **Large Scale Assembly & Testing (LSAT)** facility near the CEBAF experimental halls to provide an additional 45,000 SF of environmentally controlled high bay and work space. Need date is FY 2022 with desired completion by FY 2025.
Nuclear Physics (SC20)	End station refrigeration capable of supplying Halls A, B, and C with 4000W of 4K cooling and 40 g/s of LHe at >85% reliability	Current End Station Refrigerator serving Halls A, B, and C only has 1500W of 4K cooling and 11 g/s of LHe, has been operating nearly continuously for 20 years and is near end-of-life.	Complete installation of the SSC Cold Box to activate **End Station Refrigerator 2 (ESR2)**. This will close the capability gap and provide a long-term solution to meet the experiment plan. Need date is immediate.

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
	Up to 210,000 SF of office and collaborative space that meets DOE high-performance, sustainable building standards to house staff, students and visiting users	CEBAF Center (127,000 SF) is over utilized and substandard due to aging mechanical systems that require immediate replacement. An additional 45,000 SF of office space is leased in adjacent buildings at disadvantageous rates.	**CEBAF Center Renovation and Expansion (CRE),** possibly including the acquisition of the ARC, renovates CEBAF Center and provides an additional 82K-144K SF of space. The project consolidates staff and vacates leased space. Need date is FY 2021 with desired completion by FY 2024.
	The Experimental Equipment Lab (EEL) provides 54,800 SF of technical and lab space for physics, engineering, and facilities staff and is integral to our campus plan.	The EEL mechanical systems are at the end of their service life. Portions of the building need to be brought within code. Exterior cladding is approaching the end of its serviceable life and requires replacement within the next 8-10 years to maintain effective use of this facility.	The **LSAT** project provides a midlife renovation of the EEL facility. Completion of the proposed LSAT project also provides an opportunity to consolidate facilities operations functions from buildings 13 and 19 into the EEL. Need date is FY 2022 or sooner if practical.
Support Facilities and Infrastructure (SC25)	Provide adequate cooling water for the Test Lab, Computer Center, and CEBAF with >98% availability.	Existing Central Utility Plant (CUP) receives power from only one of three primary distribution sources at the TJNAF campus. This introduces a single-point failure that limits CUP reliability and complicates downtime planning for maintenance.	**Central Utility Plant (CUP) Power Diversity** adds a connection to the 40MVA substation to eliminate the single-point failure mode by relying on only the 22 MVA substation. Expect completion in 2019.
	Suitable access roads and parking to meet safety and regulatory requirements	Continued expansion of the TJNAF campus as outlined in this plan along with development of property immediately surrounding TJNAF requires expansion and alteration of campus access and parking to support vehicle loads and maintain compliance with safety and regulatory requirements.	Site-wide **Road, Parking, and Sidewalk Improvements** rebuild existing roads and resolve impacts created by both on-site and adjacent off-site construction. Need to align solution with selected option for this project. Need date is FY 2019 with desired completion by FY 2022.

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
	To meet DOE sustainability goals for 2025, TJNAF must reduce potable water consumption by 36% relative to 2007 baseline.	Must reduce potable water consumption from current intensity of 63.5 gal/GSF to 41 gal/GSF.	**Cooling Tower Reuse Water** project develops a 40 Mgal/year alternate water source for use in cooling towers. Project would direct and treat water from off-site retention ponds for use in cooling towers. Need date is FY 2021.
	Main entrance sign appropriate for a DOE national laboratory and adequate wayfinding signage to safely direct users and visitors	Existing entrance sign was designed and built when TJNAF was first opened and no longer reflects the scope and capabilities of the site or its important technology anchor role in the community	The **Main Entrance and Site Signage** project will replace the main entrance sign and provide needed wayfinding signage across the site. The site circulation plan will be impacted with the CRE project. Need to align solution with selected option for this project. Need date is FY 2024 or sooner if practical.
	Provide 1,900 gal/hr of chilled water to cool R&D equipment in the Test Lab, EEL, CEBAF Center, and Accelerator service buildings.	Existing Test Lab chilled water system uses cooling fluid that will be no longer available after FY 2030 requiring replacement prior to this date	**Test Lab Chiller Replacement** includes replacing the existing chillers with a new chiller to be installed in the Central Utility Plant (CUP). Need date is FY 2025.
	Provide 165,000 SF of outside storage to accommodate large experimental assemblies, support structures, and equipment for future experiments and operations	Current laydown space is scattered in multiple locations around site. Stored material in some of these sites is visible from off site and creates an eyesore. Another 100,000 SF of existing laydown area will be lost due to future building construction.	The **Laydown Area Expansion** roughly doubles an existing, centrally located storage area which is not visible from off site. Consolidation will improve material management and provide an opportunity to eliminate unneeded material. Need date is FY 2025 or sooner if practical.
	Provide an isolated and secure facility to calibrate radiological instruments and house rad waste processing equipment and work in process	Campus growth is encroaching on the existing calibration lab and making it more susceptible to storm water flooding. Further, rad waste processing equipment and work in process are currently located in part of the Equipment Storage	Construct a new **RadCon Calibration Lab and Waste Processing** work center in a more remote area adjacent to the Central Material Storage Area (CMSA). Need date is FY 2026 or sooner if practical

Core Capability (SC-X)	Infrastructure Requirement	Current Shortfall	Optimum Solution and Need Date
		Building assigned to Physics Division.	
	Suitable potable water distribution to reliably meet need for 120 Mgal. per year use	Portions of the water system exceed 50 years and have experienced severe corrosion. The site lacks a full water loop with isolation valves to allow for normal maintenance without severely affecting operations.	The **Potable Water Improvements** project replaces aging sections of piping and provides for completion of the site water distribution loop with adequate isolation valves for system operations and maintenance. Need date is FY 2029 or sooner if practical.
	Suitable sanitary sewer system to meet the service needs of the site	Portions of the system have insufficient slope and have experienced breaks or surface water infiltration. The capacity is marginal to meet future needs.	The **Sanitary Sewer Improvements** project will correct existing deficiencies and add additional capacity to meet expected growth requirements. Need date is FY 2029 or sooner if practical.
	Suitable stormwater management infrastructure to meet regulatory requirements	Continued expansion of the TJNAF campus as outlined in this plan along with development of property immediately surrounding TJNAF requires expansion and alteration of stormwater management structures to meet regulatory requirements and reduce flooding impacts of major rain events.	**Stormwater Improvements** will enhance existing stormwater conveyance structures and increase on-site stormwater retention to meet regulatory requirements and minimize flooding impact to our structures. Need date is FY 2030.

Table: Campus Strategy Reflecting Realistic Solutions to Address Infrastructure-Capability Shortfalls to Meet TJNAF S&T Strategic Objectives

The gaps identified above can be closed using a combination of SLI, SLI-GPP, and NP-GPP funding of $157M. In addition to providing essential capabilities for mission performance, these investments will eliminate $5.2M of deferred maintenance.

The primary focus of our facilities operations and maintenance program is to increase the mean time between failure of facility systems through accelerated replacement of end-of-life systems and adding redundancy for critical systems to eliminate downtime from single-point failures. Similarly, when failures occur TJNAF will reduce the mean time to repair by making sure sufficient stock of critical spares is on hand to immediately restore operation rather than accept lengthy downtimes to source replacements.

The most recent TJNAF Asset Condition Index is 0.99. However, this could drop over time if Facilities Operations and Maintenance funding continues to be limited to 1.5% of replacement value. Recent construction of new facilities through SLI and GPP has reduced the deferred maintenance value, decreasing from $8.6M to $6.5M. Over the next few years, deferred maintenance is expected to decrease as JSA increases facility maintenance spending to 2% of RPV along with the capital spending.

Site Sustainability Plan Summary

The table below shows Sustainability Project funding for planned actions to meet DOE Sustainability goals.

Category	FY 2018 Actual	FY 2019 Planned/ Request	FY 2020 Projected
Sustainability Projects	0	161,000	161,000
Sustainability Activities other than projects	0	0	0
SPO Funded Projects (SPO funding portion only)	0	43,600	0
Site Contribution to SPO Funded Project	0	195,400	0
ESPC/UESC Contract Payments	0	0	0
Renewable Energy Credits (REC) Purchase Costs	18,900	21,000	23,000
Total	18,900	421,000	184,000

Table: Summary of Sustainability Project Funding ($k)

The lab received a 2018 Federal Energy and Water Management Award in the Lab and Data Center category for energy and water cost savings, optimized energy and water use, and/or the use of advanced and distributed energy technologies under the Computer Center Modernization project achieving a PUE of 1.3.

JSA decided against awarding a UESC project totaling about $3.48M addressing lighting, domestic water conservation, Ultra-Pure Water Reuse, and mechanical upgrades, due to operation risk. These elements are being implemented separately by the Lab as part of operations and maintenance efforts or incorporated into planned recapitalization projects. This approach is expected to reduce the risk while delivering the same or better outcome at a lower cost. The Sustainability Program Office is partially funding the Ultra-Pure Water Reuse project scheduled for completion this year.

All but one sustainability target was met this year. The sustainability objective expected to be below the FY 2018 interim target is water intensity (interim FY 2018 target -22% relative to 2007 baseline).

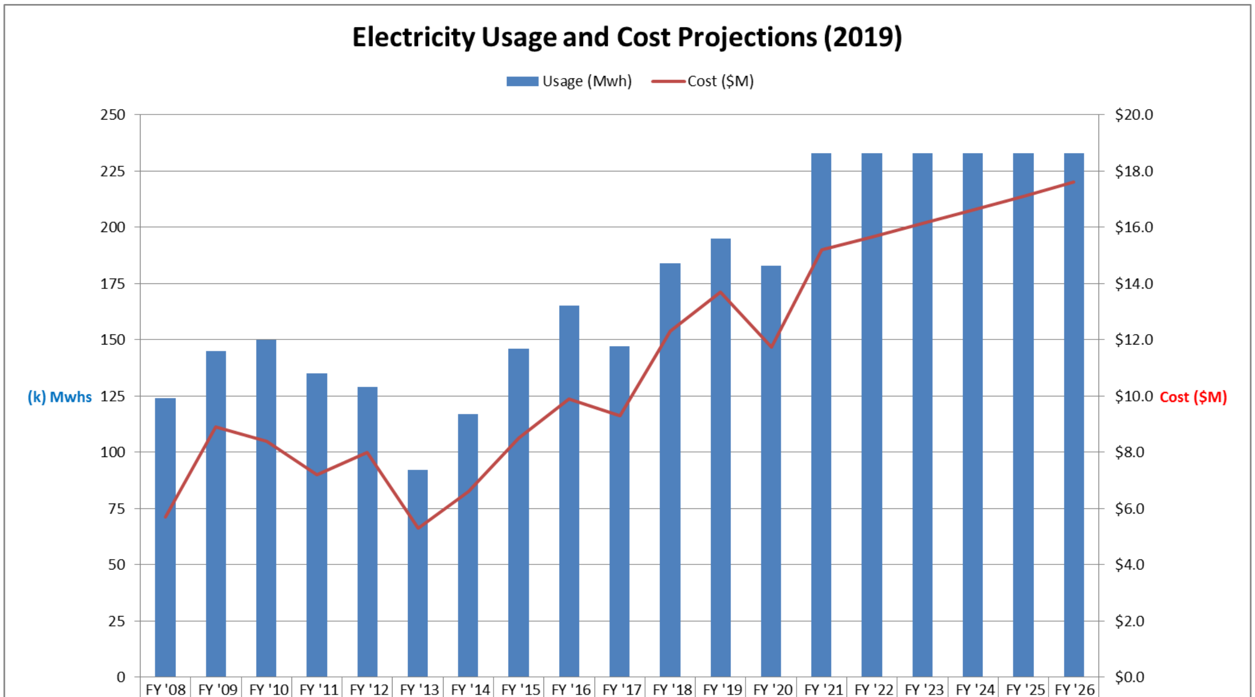
Projects and strategies to achieve future interim targets goal categories have been identified and incorporated into building renovation plans. Energy intensity (BTU/GSF) should realize significant reduction through high-efficiency lighting upgrade in subject buildings. Reduction of domestic water consumption strategies are included in building renovation plans.

The building level energy and water reductions will also contribute to achievement of High-Performance Sustainability Building (HBSB) compliance for several additional facilities. To date, the laboratory has exceeded the minimum 15% (by GSF) compliance requirement for HPSB's. Domestic and industrial water reduction projects will contribute to achievement of future interim water intensity targets. Future alternative water strategies are under consideration to achieve a -36% reduction in water intensity (gallons per GSF) by FY 2025.

A previously completed climate change vulnerability assessment identified potential negative site impacts from flooding due to major storm events. Flood protection initiatives have been implemented to protect below-grade facilities from potential future flooding.

Electricity Usage and Cost Projections

Figure 1 shows TJNAF's historical electricity usage in (k) Megawatt Hours and costs (actual year $M), and future projected electricity usage and costs. Projections are based on scheduled operations for FY 2019 of 32 weeks and FY 2020 of 26 weeks including low-energy summer runs both years. From FY 2021 forward, 34 weeks of operations are projected for each year.



	FY '08	FY '09	FY '10	FY '11	FY '12	FY '13	FY '14	FY '15	FY '16	FY '17	FY '18	FY '19	FY '20	FY '21	FY '22	FY '23	FY '24	FY '25	FY '26
Usage (Mwh)	124	145	150	135	129	92	117	146	165	147	184	195	183	233	233	233	233	233	233
Cost ($M)	$5.7	$8.9	$8.4	$7.2	$8.0	$5.3	$6.6	$8.5	$9.9	$9.3	$12.3	$13.7	$11.8	$15.2	$15.7	$16.1	$16.6	$17.1	$17.6

Figure: Electricity Usage and Cost Projections

APPENDIX 1
SCIENCE AND ENERGY CORE CAPABILITIES

The Programs reporting to the Under Secretary for Science and the Under Secretary for Energy have together identified twenty four categories of core capabilities that comprise the scientific and technological foundation of its national laboratories. There are three criteria to define core capabilities. They must:

- Encompass a substantial combination of facilities and/or teams of people and/or equipment;
- Have a unique and/or world-leading component; and
- Be relevant to a discussion of DOE/NNSA/DHS missions.

Below is a table of the core capabilities that have been affirmed by DOE at each of the thirteen Science and Energy national laboratories. The following pages give a detailed definition of what each core capability encompasses.

Figure: Distribution of Core Capabilities across the Science Laboratories

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF
1	Accelerator Science and Technology		✓	✓	✓	✓	✓			✓	✓
2	Advanced Computer Science, Visualization, and Data		✓	✓	✓	✓	✓	✓			
3	Applied Materials Science and Engineering	✓	✓	✓		✓	✓	✓			
4	Applied Mathematics		✓			✓	✓	✓			
5	Biological and Bioprocess Engineering		✓			✓	✓	✓			
6	Biological Systems Science			✓		✓	✓	✓			
7	Chemical and Molecular Science	✓	✓	✓		✓	✓	✓		✓	
8	Chemical Engineering		✓	✓		✓	✓	✓			
9	Climate Change Science and Atmospheric Science		✓	✓		✓	✓	✓			
10	Computational Science		✓	E		✓	✓	✓			
11	Condensed Matter Physics and Materials Science	✓	✓	✓		✓	✓	✓		✓	
12	Cyber and Information Sciences		✓			✓	✓	✓			
13	Decision Science and Analysis		✓			✓	✓	✓			
14	Earth Systems Science and Engineering					✓	✓	✓			
15	Environmental Subsurface Science					✓	✓	✓			

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF
16	Large Scale User Facilities/Advanced Instrumentation		✓	✓	✓	✓	✓	✓	✓	✓	✓
17	Mechanical Design and Engineering					✓	✓		✓		
18	Nuclear and Radio Chemistry		✓	✓		✓	✓	✓			
19	Nuclear Engineering		✓				✓	✓			
20	Nuclear Physics		✓	✓		✓	✓				✓
21	Particle Physics		✓	✓	✓	✓				✓	
22	Plasma and Fusion Energy Science					**E**	✓		✓	✓	
23	Power Systems and Electrical Engineering					✓	✓	✓	✓		
24	Systems Engineering and Integration		✓	✓		✓	✓	✓	✓		

✓ **=** DOE Endorse Core Capability **E** = Emerging Core Capability

1. **Accelerator Science and Technology:** The ability to conduct experimental, computational, and theoretical research on the physics of particle beams and to develop technologies to accelerate, characterize, and manipulate particle beams in accelerators and storage rings. The research seeks to achieve fundamental understanding beyond current accelerator and detector science and technologies to develop new concepts and systems for the design of advanced scientific user facilities.

2. **Advanced Computer Science, Visualization, and Data:** The ability to have a widely recognized role in advances in all applications in computational science and engineering. A core capability in these areas would involve expertise in areas such as programming languages, high-performance computing tools, peta- to exa-scale scientific data management and scientific visualization, distributed computing infrastructure, programming models for novel computer architectures, and automatic tuning for improving code performance, with unique and/or world-leading components in one or more of these areas. The capability requires access to (note: these resources do not need to be co-located) a high-end computational facility with the resources to test and develop new tools, libraries, languages, etc. In addition, linkages to application teams in computational science and/or engineering of interest to the Department of Energy and/or other Federal agencies would be beneficial to promptly address needs and requirements of those teams.

3. **Applied Materials Science & Engineering:** The ability to conduct theoretical, experimental, and computational research to understand and characterize materials with focus on the design, synthesis, scale-up, prediction and measurement of structure/property relationships, the role of defects in controlling properties, the performance of materials in hostile environments to include mechanical behavior and long-term environmental stability, and the large-scale production of new materials with specific properties. The strong linkages with molecular science, engineering, and environmental science provides a basis for the development of materials that improve the efficiency, economy, cost-effectiveness, environmental acceptability, and safety in energy generation, conversion, transmission, and end-use technologies and systems. Primary supporting disciplines and field include materials synthesis, characterization, and processing; chemical and electrochemistry, combinatorial chemistry, surface science, catalysis, analytical and molecular science; and computation science.

4. **Applied Mathematics:** The ability to support basic research in the development of the mathematical models, computational algorithms and analytical techniques needed to enable science and engineering-based solutions of national problems in energy, the environment and national security, often through the application of high-performance computing. Laboratory capabilities in this area would involve expertise in such areas as linear algebra and nonlinear solvers, discretization and meshing, multi-scale mathematics, discrete mathematics, optimization, complex systems, emergent phenomena, and applied analysis methods including but not limited to analysis of large-scale data, uncertainty quantification, and error analysis.

5. **Biological and Bioprocess Engineering:** Applies understanding of complex biological systems and phenomena to design, prototype, test and validate processes components, technologies and systems relevant to (1) bioenergy production, (2) environmental contaminants processing, and (3) global carbon cycling and biosequestration. Primary supporting disciplines include chemical engineering, agricultural science, fermentation science, materials science and engineering, and systems science.

6. **Biological Systems Science:** The ability to address critical scientific questions in understanding complex biological systems via the integration of laboratory-specific research facilities, instrumentation and/or leadership-class computational systems, and individuals with expertise in biological systems research and related disciplines to advance DOE missions in energy, climate, and the environment. This unique combination of tools and people is the foundation for research of scale and breadth unmatched by other facilities world-wide, for example, on research that employs systems and synthetic biology and computational modeling approaches enabled by genome sequencing and functional characterization of microbes, plants, and biological communities relevant to (1) bioenergy production, (2) carbon/nutrient cycling in terrestrial environments and (3) microbial biogeochemical controls on contaminant transport and biosequestration at DOE sites. Primary supporting disciplines include systems biology, plant biology, microbiology, biochemistry, biophysics and computational science.

7. **Chemical and Molecular Science:** The ability to conduct experimental, theoretical, and computational research to fundamentally understand chemical change and energy flow in molecular systems that provide a basis for the development of new processes for the generation, storage, and use of energy and for mitigation of the environmental impacts of energy use. Areas of research include atomic, molecular and optical sciences; gas-phase chemical physics; condensed phase and interfacial molecular science; solar photochemistry; photosynthetic systems; physical biosciences; catalysis science; separations and analytical science; actinide chemistry; and geosciences.

8. **Chemical Engineering:** The ability to conduct applied chemical research that spans multiple scales from the molecular to macroscopic and from picoseconds to years. Chemical engineering translates scientific discovery into transformational solutions for advanced energy systems and other U.S. needs related to environment, security, and national competitiveness. The strong linkages between molecular, biological, and materials sciences, engineering science, and separations, catalysis and other chemical conversions provide a basis for the development of chemical processes that improve the efficiency, economy, competitiveness, environmental acceptability, and safety in energy generation, conversion, and utilization. A core capability in chemical engineering would underpin R&D in various areas such as nanomanufacturing, process intensification, biomass utilization, radiochemical processing, dielectric materials, advanced conducting materials, high-efficiency clean combustion, and would generate innovative solutions in alternative energy systems, carbon management, energy-intensive industrial processing, nuclear fuel cycle development, and waste and environmental management.

9. **Climate Change Sciences and Atmospheric Science:** The ability to apply knowledge of atmospheric, oceanic, terrestrial, ecological, hydrological, and cryospheric processes, that combine with human activities and anthropogenic emissions, in order to understand and predict climate change and different patterns of meteorological conditions, with a particular focus on (1) understanding and describing the causes, impacts, and predictability of climate change via the integration of laboratory-specific research facilities, instrumentation and/or leadership-class computational systems, and individuals with expertise in future climate change research and related disciplines. This unique combination of tools and people is the foundation for research of scale and breadth unmatched by other facilities, world-wide, for example, on (1) atmospheric-process research and modeling, including clouds, aerosols, and the terrestrial carbon cycle; (2) climate change modeling at global to regional scales; (3) research on the effects of climate change on ecosystems; (4) integrated analyses of climate change, from causes to impacts changes, including impacts on energy production, use, and other human systems; (5) understanding and predicting future extreme

weather as the climate evolves, that in turn introduces risk and vulnerability to energy and related infrastructures; (6) understanding the carbon cycle, with focus on the interdependence of a changing climate and terrestrial ecosystems, and (7) predict the influences of terrain and atmospheric processes and systems on the availability, behavior, and quality of energy resource and operations.

10. **Computational Science:** The ability to connect applied mathematics and computer science with research in scientific disciplines (e.g., biological sciences, chemistry, materials, physics, etc.). A core capability in this area involves expertise in applied mathematics, computer science and in scientific domains with a proven record of effectively and efficiently utilizing high performance computing resources to obtain significant results in areas of science and/or engineering of interest to the Department of Energy and/or other Federal agencies. The individual strengths in applied mathematics, computer science and in scientific domains in concert with the strength of the synergy between them is the critical element of this core capability.

11. **Condensed Matter Physics and Materials Science:** The ability to conduct experimental, theoretical, and computational research to fundamentally understand condensed matter physics and materials sciences that provide a basis for the development of materials that improve the efficiency, economy, environmental acceptability, and safety in energy generation, conversion, transmission, and utilization. Areas of research include experimental and theoretical condensed matter physics, x-ray and neutron scattering, electron and scanning probe microscopies, ultrafast materials science, physical and mechanical behavior of materials, radiation effects in materials, materials chemistry, and bimolecular materials.

12. **Cyber and Information Sciences:** The disciplines, technologies, and practices designed to protect, analyze, and disseminate information from electronic sources, including computer systems, computer networks, and sensor networks. A core competency in this area would involve recognized expertise in one or more of the following topics: cyber security, information assurance, information analytics, knowledge representation, and information theory, control systems design and engineering, embedded systems, reverse engineering, and advanced hacking techniques. This core competency would be applied to: the protection of information systems and data from theft or attack; the collection, classification, analysis, and sharing of disparate data; and the creation of knowledge from heterogeneous information sources; securing control systems integrated into critical infrastructure; and increasing security, reliability, and resilience of automated processes and systems.

13. **Decision Science and Analysis:** Derives knowledge and insights from measured and modeled data sets to further the understanding of and tradeoffs among resource and technology options, to identify and quantify the risks and impacts of current and emerging technologies on environmental systems, and to assess the impact of market dynamics, human behavior and regulations, policies or institutional practices on the development and uptake of technology. Primary supporting disciplines include engineering, environmental science, applied math, finance, business, social and political science, and market and behavioral economics. This capability provides credible and objective information to support DOE and others to support strategic planning and program direction, policy formulation and implementation, efforts to remove market barriers to deployment and engagement with stakeholders.

14. **Earth Systems Science and Engineering:** The ability to understand environmental and ecological systems, processes, and interrelationships to predict, assess, and mitigate the impacts of past, current, and future energy production, transmission, distribution, and use on subsurface, terrestrial, coastal, and marine

environments. Knowledge is used to develop technologies that minimize emissions and/or control technologies that protect these environments.

15. **Environmental Subsurface Science:** The ability to understand and predict the physical, chemical, and biological structure and function of subsurface environments to enable systems-level environmental prediction and decision support related to the sustainable development of subsurface resources, environmentally-responsible use of the subsurface for storage, and effective, mitigation of the impacts of environmental contamination from past nuclear weapons production and provide a scientific basis for the long-term stewardship of nuclear waste disposal via the integration of laboratory-specific research facilities, instrumentation and/or leadership-class computational systems, and multidisciplinary teams of individuals with expertise in environmental subsurface science and related disciplines in microbial ecology and biogeochemistry. This unique combination of tools and expertise is the foundation for research on (1) linking research across scales from the molecular to field scale, (2) integration of advanced computer models into the research and (3) multidisciplinary, iterative experimentation to understand and nutrient cycling and contaminant transport in complex subsurface environments. This ability can contribute to mitigating the impacts of environmental contamination from past nuclear weapons production and provide a scientific basis for the long-term stewardship of nuclear waste disposal, as well as understanding subsurface environments and their role in the functioning of terrestrial ecosystems.

16. **Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation:** The ability to conceive, design, construct and operate leading-edge specialty research facilities available to universities, industry, and national laboratories customers to conduct groundbreaking research and development activities and/or 'at scale' testing and demonstration of technology. This includes the ability to manage effectively construction of $100 million or greater one-of-a-kind scientific facilities, and to host hundreds to thousands of U.S. and international users in addition to carrying out world-class research at the facility itself. The ability to conceive, design, build, operate and use first-in-class technical instruments intended for a particular research purpose, often requiring the material expertise of multiple scientific disciplines. Instrumentation that can be created by a small number of individuals or that would sit on a laboratory bench-top is not considered part of this core capability.

17. **Mechanical Design and Engineering:** Applies the principles of physics, mechanics, and materials science to analyze, design, test, validate, and enable operation of advanced engineered systems, machines and tools. Includes equipment used to move or extract energy bearing materials (e.g., oil, gas, coal) or from moving fluids (e.g., water, wind, steam), as well as equipment used to convert energy to useful services (e.g., mobility, home heating and cooling, robotics, imaging devices, etc.) or to manufacture products. Primary supporting disciplines include physics, materials science, aerospace engineering, mechanical engineering, chemical engineering, electrical engineering and computational science.

18. **Nuclear and Radio Chemistry:** The ability to use a broad range of facilities, instrumentation, equipment and, often, interdisciplinary teams that apply the knowledge, data, methods, and techniques of nuclear chemistry, mechanical engineering, chemical engineering to missions of the Departments of Energy and Homeland Security. The elements of this capability are often brought together in unique combinations with those of other disciplines to address high priority needs such as new and improved nuclear systems; radioisotope production and advanced instrumentation for nuclear medicine; development of methods and

systems to assure nonproliferation and combat terrorism; and environmental studies, monitoring, and remediation.

19. **Nuclear Engineering:** The ability to use a broad range of facilities, instrumentation, equipment and, often, interdisciplinary teams that apply the knowledge, data, methods, and techniques of nuclear engineering, mechanical engineering, nuclear reactor physics, measurable science and risk assessment to missions of the Departments of Energy and Homeland Security. The elements of this capability are often brought together in unique combinations with those of other disciplines to address high priority needs such as new and improved energy sources and systems; advanced instrumentation for nuclear systems; accelerator science and technology; and development of methods and systems to assure nonproliferation and combat terrorism.

20. **Nuclear Physics:** The ability to carry out experimental and theoretical research to provide new insights and advance our knowledge on the nature of matter and energy. This includes the design, operation and analysis of experiments to establish the basic properties of hadrons, atomic nuclei, and other particles, and the development of models and theories to understand these properties and behaviors in terms of the fundamental forces of nature.

21. **Particle Physics:** The ability to carry out experimental and theoretical research to provide new insights and advance our knowledge on the nature of matter and energy, and the basic nature of space and time itself. This includes the design, operation and analysis of experiments to discover the elementary constituents of matter and energy and probe the interactions between them and the development of models and theories to understand their properties and behaviors.

22. **Plasma and Fusion Energy Sciences:** The ability to conduct world-leading plasma research that can range from low-temperature to high temperature/high pressure plasmas. This ability can be in operation of the state-of-the-art experimental fusion facilities to carry out world-leading research on the fundamental physics of plasmas, in theory and computations, which is critical to the full understanding of the plasma phenomena being studied or to enable technologies that allow experiments to reach and in many cases exceed their performance goals.

23. **Power Systems and Electrical Engineering:** Applies understanding of electromagnetic phenomena to design and engineer circuitry, electrical and electronic devices and equipment, sensors, instruments and control systems to address the efficiency and reliability of power transmission and distribution systems, and the interface of the grid with variable generation and modern loads. Primary supporting disciplines include electrical engineering, power systems engineering, computational science, and materials synthesis, characterization and processing.

24. **Systems Engineering and Integration:** The ability to solve problems holistically from the concept and design phase to ultimate deliverable and completion phase, by synthesizing multiple disciplines, and to develop and implement optimal solutions. The ability to develop solutions that address issues of national energy and environmental security. Areas of application of this capability include development of programs in energy supply, storage, transportation, and efficiency; and deployment of novel solutions to materials and sensor problems in fields of interest to the Department of Energy and/or the Department of Homeland Security.

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