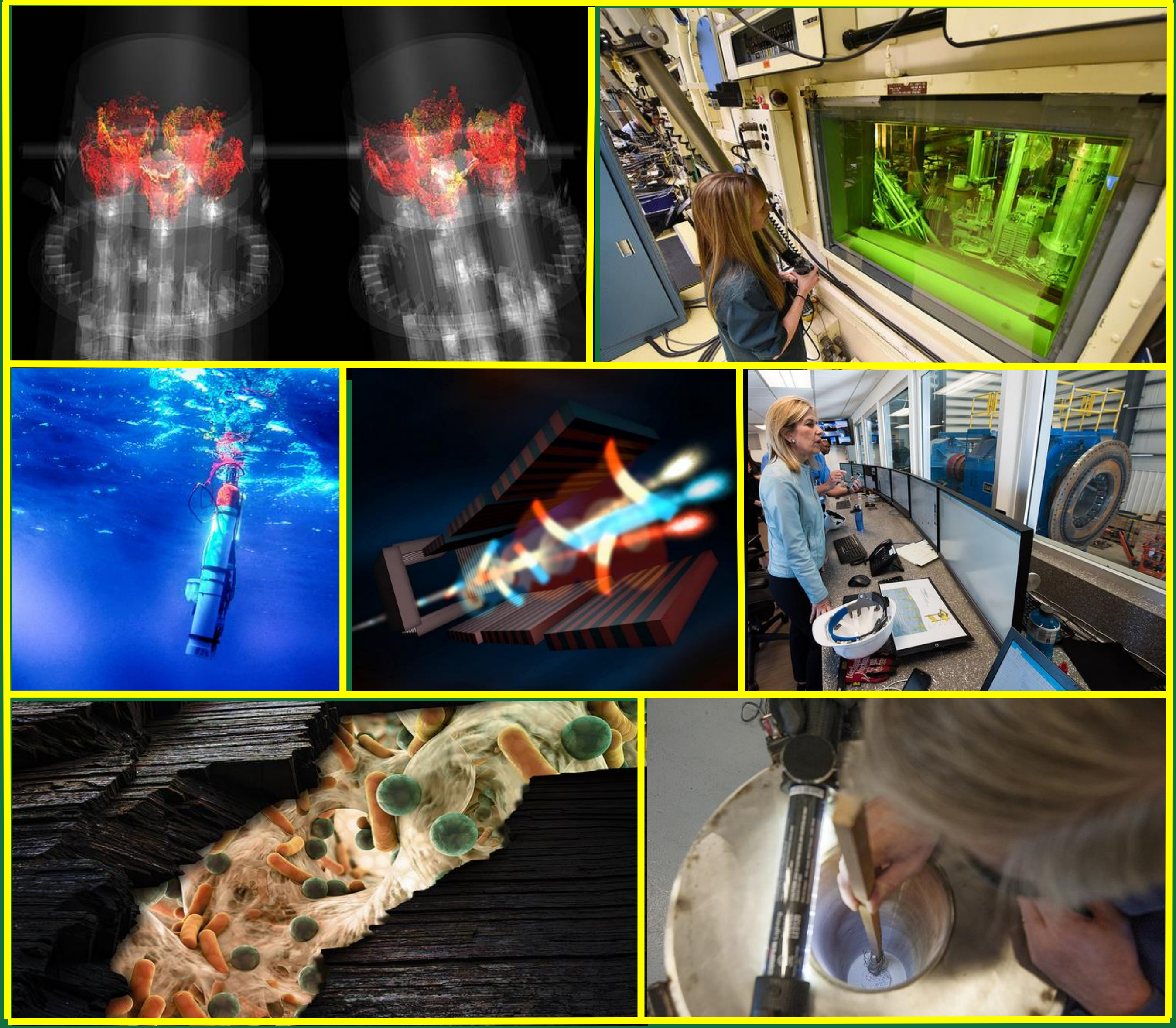
U.S. DEPARTMENT OF ENERGY

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

FY 2016



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Introduction

The Department of Energy (DOE) is responsible for the effective stewardship of 17 national laboratories, of those thirteen focus on discovery science and applied enegy technologies. They are stewarded by the Offices of Science, Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy. 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 the challenges established in the President's American Competitive Initiative (ACI) and the Advanced Energy Initiative (AEI).

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 30,000 facility users and more than 7,000 visiting scientists in Fiscal Year (FY) 2015, 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 thirteen national laboratories for the period FY 2016-2025.

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[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. Appendix 2 provides a listing of the DOE missions.

Ames Laboratory

1. Mission and Overview

Ames Laboratory creates materials, inspires minds to solve problems, and addresses global challenges.

Removing toxic lead from the environment by inventing lead-free solder, converting crops more efficiently to biodiesel by designing a hybrid catalyst, and innovating a new class of materials with remarkable optical properties by creating unique metamaterials are just a few examples of Ames Laboratory's materials that are impacting our world. We tightly couple theory, computation and experiments to design new materials; synthesis and fabrication of those materials with innovative AMES developed techniques; and characterization and testing at our new Sensitive Instrument Facility with world-class characterization equipment. Since our founding in 1947, AMES culture of interdisciplinary science allows us to seamlessly design, synthesize, and characterize new materials for DOE's Office of Science, Energy Efficiency and Renewable Energy, Fossil Energy, and Advanced Research Project Agency—Energy. Through Strategic Partnership Projects, AMES conducts research for and provides materials to the Department of Defense and U.S. industry. We are one of the top DOE national laboratories in converting science into licensed technologies.

Our belief in and dedication to our mission naturally inspires our 138 scientists and engineers and 122 support staff. Our mission extends to inspiring minds of undergraduate and graduate students. Educating future scientists and engineers is a key part of our mission; 3,081 Masters and Ph.D. degrees have been awarded to students from Iowa State University, our contractor, based on their AMES research.

2. Lab-at-a-Glance

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

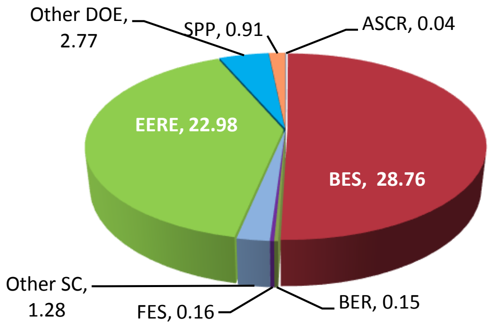
Physical Assets:

- 10 acres and 13 buildings
- 340,968 GSF in buildings
- Replacement Plant Value: $88.6 million
- 0 GSF in 0 Excess Facilities
- 0 GSF in Leased Facilities

Human Capital:

- 309 Full Time Equivalent Employees (FTEs)
- 73 Joint Faculty
- 43 Postdoctoral Researchers
- 45 Undergraduate Students
- 59 Graduate Students
- 0 Facility Users
- 84 Visiting Scientists

FY 2015 Funding by Source: *(Cost Data in $M):*



FY 2015 Lab Operating Costs (excluding Recovery Act): $57.0 million
FY 2015 DOE/NNSA Costs: $56.1 million
FY 2015 SPP (Non-DOE/Non-DHS) Costs: $0.9 million
FY 2015 SPP as % Total Lab Operating Costs: 1.6%
FY 2015 DHS Costs: $0.0 million

We have addressed global challenges by, for example, conducting pioneering research that enables part-per-trillion detection of elements and molecules, and the mapping of the human genome. Today, we are addressing the global challenge of critical materials as we lead the Critical Materials Energy Innovation Hub. And we are tackling the 100-year old technology of compressed vapor refrigeration to improve significantly efficiency and reliability, and to remove greenhouse gases from the environment through the CaloriCool^{TM} consortium.

Building on our core capabilities, AMES' vision is to lead the interdisciplinary science of accelerating the design, discovery, and fundamental understanding of advanced energy and chemical conversion materials through technical innovation and excellence in safety, operations, quality, and diversity.

3. Core Capabilities

Three core capabilities identified by DOE's Office of Science provide the foundation for the science and engineering research at Ames Laboratory. Each core capability 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. We are focused on clean energy foundational research and development, building on our unique strengths and core capabilities. New fundamental discoveries in the core areas of *Condensed Matter Physics and Materials Science,* and *Chemical and Molecular Science,* enable successes in *Applied Material Science and Engineering*.

Our core capabilities support DOE's strategic objectives to

- Deliver scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.
- Advance the goals and objectives of the President's *Climate Action Plan* by supporting prudent development, deployment, and efficient use of "*all of the above*" energy resources that create new jobs and industries.
- Support a more economically competitive, environmentally responsible, secure, and resilient U.S. energy infrastructure.

Our core capabilities also support DOE's Office of Science Mission: *"… delivery of scientific discoveries and major scientific tools to transform our understanding of nature and to advance the energy, economic, and national security of the United States."*

Inherent in all research at Ames Laboratory is the education and mentoring of the next generation of leading scientists and engineers in these core areas. Masters and Ph.D. students are engaged in cutting-edge, mission-relevant research, and undergraduate students are afforded in-depth research experiences. In addition, Ames Laboratory effectively uses DOE-sponsored educational programs in conjunction with our contractor, Iowa State University, to provide research opportunities for a diverse student population from around our nation.

Condensed Matter Physics and Materials Science

Ames Laboratory is recognized worldwide for its leading, collaborative research in the theory, design, synthesis, processing, and characterization of innovative, energy-relevant materials. Exceptional strengths in this core capability include rare-earth metals and alloys, photonic-band-gap materials, metamaterials, magnetic materials, high-temperature superconductors, correlated electron and topological materials, critical materials, and biomaterials.

AMES also is internationally recognized for its ability to grow high-quality samples of unusual materials.

Our scientific mission is aided by comprehensive, world-leading synthesis capabilities including the Materials Preparation Center (MPC), which prepares, purifies, fabricates, and characterizes materials in support of our research programs, for our sister national laboratories, and for research and development programs at universities and companies throughout the world. DOE's synchrotron and neutron source user facilities strongly benefit from the capabilities of the MPC to synthesize the highest purity and quality materials in both single crystal and polycrystalline form. The MPC also capitalizes on DOE's investments in basic and applied research to address scientific and technical challenges to scaling these new materials for use in manufacturing with a current focus on design and synthesis of powder metals for additive manufacturing.

To study these materials, AMES' condensed matter physics and materials science teams develop cutting-edge characterization techniques (e.g., solid-state nuclear magnetic resonance (SS-NMR) methods and new techniques for studying materials under pressure at DOE's X-ray and neutron scattering user facilities). These tools, combined with high-resolution electron probes and microscopes for *in situ* characterization, enable discoveries of new materials with enhanced functionalities. Recent world-leading examples include laser-enhanced angle-resolved photoemission spectroscopy (ARPES) with high-resolution for active states near the electronic chemical potential in correlated-electron and topologically materials, and microwave-enhanced dynamical nuclear polarization NMR for unprecedented, game-changing sensitivity for local characterization in solid-state materials. Cutting-edge characterization tools are exceptionally sensitive to vibrations and stray electromagnetic signals, and require strict environmental control. Our new Sensitive Instrument Facility, completed in FY 2015 and fully operational in FY 2016, provides the necessary environment for, and now houses, state-of-the-art characterization tools.

Ames Laboratory is pushing the limits of computational methods such as quantum Monte-Carlo simulations, electronic structure calculations, and classical and quantum molecular-dynamics simulations by developing 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.

Ames Laboratory continues to develop the fundamental science of rare-earth materials. This basic science provides the foundation for the Critical Materials Institute (CMI), a DOE Energy Innovation Hub.

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

Chemical and Molecular Science

Interdisciplinary research teams at Ames Laboratory develop and apply theoretical, computational, and experimental methods to study catalysts, chemical reactivity, energy conversion, metal and alloy surface dynamics, and biomimetic processes. World-leading research is conducted at the interface between homogeneous and heterogeneous catalysis enabling the design of new catalysts that combine the best characteristics of both. Ames Laboratory improves the understanding of chemical processes for energy and security decision-making, and molecular design by utilizing and developing new simulation and modeling techniques.

Ames Laboratory enables discoveries in the chemical and molecular sciences through the development of techniques to characterize a broad range of materials at time and length scales never before possible. Our techniques are used in applications ranging from bioenergy to bioremediation to national security. Particular strengths include fine spatial chemical analysis and optical imaging within, for example, plants, polymers, solar energy conversion materials, and porous catalysts. Ames Laboratory is internationally recognized for developing and advancing solid-state nuclear magnetic resonance, optical spectroscopies, mass spectrometry, and single molecule spectroscopies. A recent example includes developing a method that enables the detection of oxygen using solid-state NMR. Oxygen is one of the most ubiquitous elements in chemistry and materials science, yet one of the most elusive elements for spectroscopic investigation by NMR. Less than four of every 10,000 oxygen nuclei are ^{17}O, the only NMR-active isotope of oxygen. These developments in enhanced sensitivity through the use of *dynamic nuclear polarization* (DNP) solid-state NMR may facilitate new widespread investigations of the structure and dynamics in a variety of oxygen-containing materials, including catalysts and nanoparticles, in particular at surfaces and interfaces with low concentrations of oxygen.

This core capability provides the strong foundation needed for the discovery of new, advanced catalysts and the development of energy efficient processes for bio-, photo-, and thermal catalytic conversions of biorenewable feedstocks.

Major Sources of Funding: Office of Science.

Applied Materials Science and Engineering

The application of knowledge derived from fundamental experimental, computational, and theoretical research to invent, design, and synthesize new materials with specific energy- and environment-relevant functionalities is a well-known strength of the Laboratory. AMES 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 a new material for more efficient electrical transmission wires.

AMES is world-renowned for developing materials that improve energy efficiency and conversion and reduce environmental impact. Understanding and advances made from basic science through Basic Energy Sciences (BES) funded investigations in extraordinarily response materials have impacted a variety of applied areas, such as sensors or cooling technologies with caloric materials, which are thermodynamically responsive but need better response and control. Our advanced powder processing capabilities lead the world in providing unprecedented control over particle size and voiding, a key for rapid and low-loss additive manufacturing and scaling of nanocrystalline to bulk material while retaining the fine-scale microstructural features responsible for enhanced properties and performance. Key powder technology was initially licensed to a start-up company *Iowa Powder Atomization Technologies (IPAT)*, a winner of DOE's 2012 America' s Next Top Energy Innovator challenge. IPAT was purchased in 2014 by Praxair, who announced in August 2015 that it would "*begin marketing fine, spherical titanium powder for use in 3-D printing by additive manufacturers*". Our work is impactful particularly in the development of new catalysts, ultra-hard materials, low-friction materials, magnetic alloys, high-temperature superconductors, powder processing, and lightweight, high-strength materials responsive to energy and environmental concerns. These novel materials exhibiting superior functionalities enable advanced sensors, improved thermal management strategies and energy harvesting opportunities for both national defense and consumer use.

This core capability is further strengthened by the *Critical Materials Institute (cmi.ameslab.gov)*, 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. Our 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. Because of its mission and work on solving critical problems in the area, the CMI has many industrial partners.

This core capability is also strengthened by the new research consortium led by Ames Laboratory called Caloricool^{TM}. Caloricool^{TM} is part of DOE's Energy Materials Network. This consortium seeks to improve refrigeration efficiency by discovering better materials, performing rapid testing, and facilitating adoption into commercial use.

AMES accelerates manufacturing via an integrated, virtual engineering design environment *VE-Suite (www.VESuite.org)*. This package is open-source software that links models, process simulations, data and real-time graphics to permit 3-D, real-time engineering design of complex systems, like next-generation power plants, efficient cars, and video games. Two spin-off companies, *Praxik (www.praxik.com)* and *AgSolver (www.agsolver.com)*, were created in 2013 to deploy interactive, visually based, decision-making environments based on this software.

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.

4. Science Strategy for the Future/Major Initiatives

Science-based discovery, design, development, and deployment of new material innovations are needed to increase the pace of clean energy technology adoption, and to enhance our nation's energy security. AMES will accelerate clean energy technology innovation through advances in foundational, computer-assisted design of materials—ideas are established theoretically, tested by simulations, verified through synthesis and characterization, and realized by innovative processing methods. This fully integrated strategy enhances our established leadership in computational algorithm development, material design, synthesis, and characterization expertise, strengthens our core capabilities, and addresses key gaps in our nation's scientific understanding and design of new clean energy relevant materials.

Ames Laboratory has extensive expertise in developing theory and computational methods to accelerate materials discovery and design, upon which our initiatives build. We strive to develop simulation tools that are generalized such that the cross-fertilization of ideas from one problem to another in an entirely different area is possible through the common link of the mathematical formulation. AMES has the Nation's most comprehensive facilities for advanced materials synthesis to enable discoveries of new energy production and conversion materials. We have exceptional strengths in metal purification, alloy synthesis, single-crystal growth, structured material and chemical synthesis, and powder production, and the ability to scale up with innovative materials processing. AMES couples advanced characterization techniques—enhanced in FY 2016 with the completion of the Sensitive Instrument Facility and the addition of three new state-of-the-art electron beam instruments—with our synthesis and computational materials science to elucidate underlying material properties and design desirable material response. Analytical instrumentation development and implementation are key strengths of AMES and central to our science strategy.

Ames Laboratory's agility in the invention, synthesis, and characterization of new materials is facilitated by coordinated scientific collaborations and by our approach of *integrating Materials Technology, Engineering, Education, and Research* (*i-MatTER*).

All three major initiatives stem from the Laboratory's leadership in *Chemical and Molecular Science*, in *Condensed Matter Physics and Materials Science*, , and in *Applied Materials Science and Engineering* and focus either on filling a compelling scientific gap within a core capability or for bridging a scientific gap between core capabilities. Each initiative brings together the multidisciplinary expertise of our outstanding scientists and engineers to address DOE mission objectives. The outcome of each initiative is to meet the clear need to provide the scientific community with new fundamental understandings of materials characteristics, and efficient and effective tools for materials discover and design.

Laboratory Directed Research and Development (LDRD) projects play a critical role in our science and technology strategy. LDRD projects are pursued in forefront areas of basic and applied science and technology that support the DOE mission, enrich Laboratory core capabilities, generally advance the knowledge and technology base, and have the potential to generate follow-on funding, particularly from DOE offices and programs.

The objectives of our LDRD portfolio are to enhance the Laboratory's ability to achieve its mission by enabling selected critical projects for which no other source of funds is available. LDRD funds are used: (1) to foster innovation and creativity from the scientific and technical staff by supporting their pursuit of novel, forefront science and technology research ideas, new concepts, and high-risk/high-reward research and development projects; (2) to develop, recruit, and retain the researchers needed to maintain and enhance the scientific, engineering, and technical vitality and capabilities of the Laboratory; (3) to exploit the technical potential of the Laboratory for the benefit of the nation; and (4) to enable the Laboratory's R&D planning by supporting its mission and strategic plans, as described in its Strategic and Lab Plans.

The LDRD program provides support for *Strategic Initiatives*, *Novel Projects, and Exceptional Opportunities*. *Strategic Initiatives* are proposals that address at least one of the strategic goals or an area of potential growth within AMES' Strategic Initiatives and Core Capabilities. *Novel Projects* are a balance of basic, applied, single-investigator, and multidisciplinary projects in new areas or directions, not necessarily in direct support of our initiatives. *Exceptional Opportunities* is an integral part of the pursuit of capabilities in a strategic area that enhances human and physical resources to support that area. This component consists of projects that do not fit neatly into the other two or that can arise outside the normal fiscal-year schedule, e.g., strategic hires, collaborations with external institutions where a superior expertise resides, or projects offering exceptional R&D opportunities for AMES. The director retains the option to identify and support these exceptional projects.

5. 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 where 13 DOE-owned buildings reside (340,968 gross square feet, GSF). There are four research buildings, an administrative building, and eight support buildings on the campus.

In 2014, the Laboratory began construction on the Sensitive Instrument Facility (SIF), which is a 13,304 GSF structure to house state-of-the-art transmission electron microscopes and other sensitive electronic equipment. A new land-lease between DOE and the Iowa Board of Regents was approved to locate the SIF at ISU's Applied Science Complex, Northwest of the main campus. The building was completed in the Fall of 2015.

The three older research buildings (Wilhelm, Spedding, Metals Development) on the main campus are 50-60 years old; they have good structural integrity but they were designed for research needs of the mid to late 1900s. These three buildings were all rated "substandard" in the 2014 DOE Laboratory Operations Board (LOB) infrastructure survey. The remaining DOE-owned buildings were rated as "adequate". The Laboratory also utilizes ISU space for research and support. In 2015, the Laboratory leased 34,851 net usable square feet (NUSF) of university space. Co-location of staff resulted in ISU leasing 26,096 NUSF of Ames Laboratory space. Ames Laboratory has no utility generating plants; the Laboratory receives its utilities from Iowa State University and the City of Ames.

The four main research buildings are for general use and support research for all three of our core capabilities: (1) condensed matter physics and materials science, (2) chemical and molecular science, and (3) applied materials science and engineering. Our workforce includes approximately 750 people who work at Ames Laboratory as staff, students, or associates.

Harley Wilhelm Hall
(1949)

Spedding Hall
(1953)

Metals Development Building
(1961)

Technical & Administrative Services
Facility (1995)

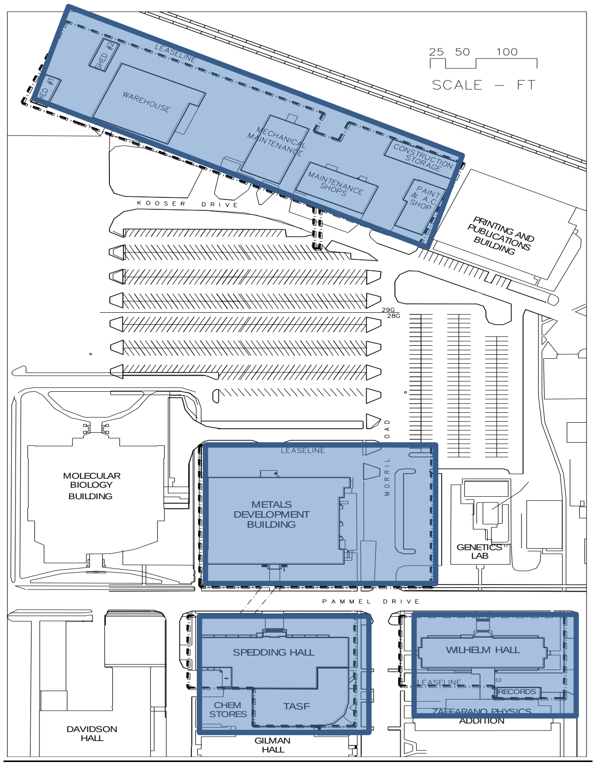
Sensitive Instrument Facility-SIF
(2015)

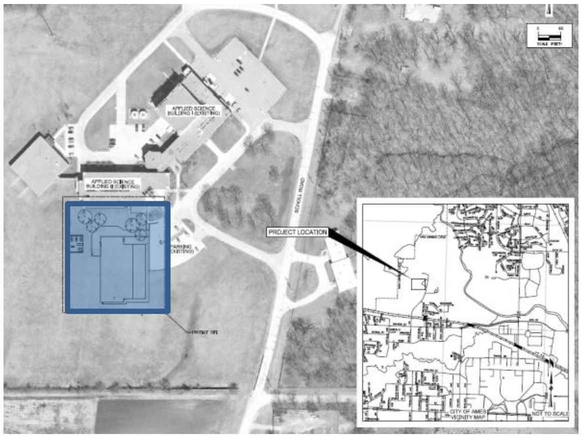
Shop Buildings and Warehouse
(1964-1991)

Ames Laboratory Complex
10 acres of land leased from ISU, where 13 DOE-owned buildings reside

Asset	Facility Use	Gross Square Feet (GSF)	Year Built	Overall Rating	Poor Condition Space (SF)
Campus Warehouse	General Storage	16,506	1966	Adequate	
Construction Storage Shed	General Storage	4,440	1967	Adequate	4,163
Maintenance Shops Building	Maintenance Shops, General	7,503	1967	Adequate	
Mechanical Maintenance Building	Maintenance Shops, General	8,540	1964	Adequate	
Metals Development Building (MD)	Laboratory, General	69,663	1961	Sub-standard	9,007
Paint and Air Conditioning Building	Maintenance Shops, General	4,998	1968	Adequate	4,083
Records Storage Facility	General Storage	1,689	1948	Adequate	
Shed 1	General Storage	1,461	1990	Adequate	
Shed 2	General Storage	1,702	1991		
Spedding Hall (SPH)	Laboratory, General	107,630	1953	Sub-standard	9,279
Technical and Administrative Services Facility (TASF)	Office	46,991	1995	Adequate	
Harley Wilhelm Hall (HWH)	Laboratory, General	56,541	1949	Sub-standard	14,561
Sensitive Instrument Facility (SIF)	Laboratory, General	13,304	2015	Adequate	
TOTAL		340,968			41,093

Campus Strategy





Site Map: Ames Laboratory Main Campus located on Iowa State University's Main Campus

Site Map: Ames Laboratory Sensitive Instrument Facility Located at Iowa State University, Applied Sciences Complex

Our guiding principles for ensuring the facilities of Ames Laboratory are mission ready are to provide:

- Modern facilities and infrastructure to support our core capabilities
- A safe and secure work environment
- Productive workspaces
- Good stewardship of our national, DOE and contractor resources

Guided by these principles, our mission supports basic research in the discovery, design and development of energy-relevant applications; research to attain foundational advances in the science of solid-state NMR; advances in catalysis and energy as well as transferring these technological breakthroughs to the public via our Critical Materials Institute and our strategic partnership projects program.

To bring our campus up to the standards of the guiding principles and enhance Ames Laboratory's ability to provide quality research, we have developed the following strategy:

- Support a new scientific computing building
- Modernize the existing campus
- Provide mission-enabling spaces
- Extend the life of existing buildings and infrastructure

Figure 4: Site Map of the Ames Laboratory Sensitive Instrument Facility, located at Iowa State University's Applied Sciences Complex

Current Gaps

Our four research buildings provide space that supports all of our core capabilities, and can be generally adapted to meet core capability needs. Each building has a mixture of wet and dry lab, office, and conference spaces. Metals Development has high bay space currently utilized by the Facilities and Engineering Services machine shop that could be repurposed for research activities. During our mission readiness process several gaps kept recurring for all three of our older research buildings.

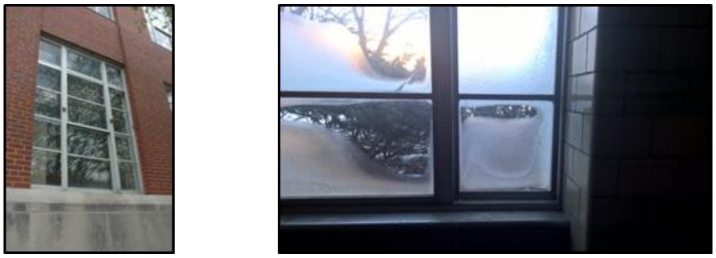
<u>Electrical power</u> was identified as a critical gap at the Laboratory. This includes the current electrical supply infrastructure and its capacity. There are components to the distribution system that are original and need to be replaced. In addition, capacity has been reached on many floors as new electrical devices are added to our research toolset. Basic Energy Science-General Plant Project (BES-GPP) dollars have been used over the last two years to address the immediate needs of 4160V switchgear replacement for the complex, and the 120/208V electrical distribution upgrades in Spedding Hall. Additional resources are needed to upgrade the electrical distribution systems in Wilhelm Hall and Metals Development. The Laboratory needs to add distribution panels to each floor of these two research buildings to provide the power capacity needed now and in the future.

4160V Switch (Old)

4160V Switch
Installed in 2015

Spedding Hall—New 120/208V Electrical Distribution System (In-progress)

<u>Building improvements</u> are needed that will improve the research—for example, new windows in Spedding Hall will improve the research spaces' ability to provide an environment conducive for today's research; cutting down on drafts, dust, fumes and other contaminants that infiltrate the building. An updated HVAC system is needed in Metals Development to replace the system original to the building built in 1961. Roofs continue to be a problem area for the Laboratory. The roof in the worst condition (TASF) was replaced in FY 2016 utilizing maintenance and general services dollars. The three older research buildings also need new roofs. The built-up roofs on these buildings are 20-30 years old and all have active leaks. The leaks damage the buildings, raise potential for mold, and pose a risk to expensive research equipment. The three older research buildings also need tuckpointing to extend the lives of their exteriors.



Spedding Windows

Spedding Roof

Spedding Exterior Condition

TASF Roof-EPDM Rock Ballasted (Old)

TASF Roof-PVC Wind Ballasted/Vented (New 2015)

Another big gap is the condition of the research labs themselves. The 2014 LOB infrastructure survey identified 41,000 square feet of space in the older buildings as being in poor condition. Many of these labs have fixtures that date back to the original construction, cabinets that are rusted and hard to operate, work surfaces pocked from chemical exposure, asbestos that needs to be removed, and the lighting updated. The condition of these spaces is detrimental to morale and is a barrier to recruiting and retention. In FY 2015 the Laboratory invested overhead dollars to renovate 1,500 square feet of the lab space in poor condition. Another 3,000 square feet of lab space is scheduled to be renovated in FY 2016 and FY 2017. Our capacity to renovate space with overhead dollars is approximately 1,500 square feet per year. With 36,500 square feet of poor condition lab space remaining, it would take the Laboratory 25 years to bring the spaces up to standard.

Laboratory (Poor Condition)

Laboratory (Renovated-2014)

Electronic access control is another gap that should be addressed within the next 5 years. Starting under the American Recovery and Reinvestment Act (ARRA), the Laboratory began a project to convert its door access from physical keys to electronic proximity card readers. Once the ARRA funds were exhausted, the Laboratory allocated some GPP funds to continue to make progress in the conversion. All of the exterior doors, the property protection areas for the site, and the interior doors for two buildings were completed. This system gives the operations staff a greater amount of control of different access situations and helps to provide better safety, security and accountability for room use. However, most of the interior doors in Spedding Hall and Metals Development are still key access only, and need to be converted to proximity card access.

Facilities and infrastructure for computational sciences were identified as other critical gaps. Ames Laboratory mission requirements have placed tremendous strain on the available computational resources and space. The Laboratory's strong and evolving Office of Science, Basic Energy Sciences research coupled with our leadership role in the CMI and CaloriCool™ (part of the EERE Energy Materials Network) and supporting roles in several other research endeavors have strained the Laboratory's physical infrastructure and computational resources. We are currently at maximum power utilization in our buildings and are using valuable experimental laboratories and office space to house clusters and servers.

Ames Laboratory requires high performance computing to execute its mission to create materials and energy solutions. The increased focus on using computing resources to support the BES mission as well as growth in complementary efforts are creating need for more staff, more space, and more computational resources.

The Ames Laboratory core expertise is in the discovery, design, synthesis, processing, and characterization of new materials with novel properties for new energy technologies. The resources needed to support this mission have moved from solely bench-top science to experiments guided by computational modeling and simulations as enabled by advances in computer capabilities and speed. Ames Laboratory has world-class theory groups for materials and chemistry research that develop novel theories, algorithms, and computational models to support our scientific breakthroughs. As needed, scientists successfully compete for time on leadership class computers at ORNL, LBNL and ANL to run their codes, such as Gordon and Windus in 2015 and 2016 (200 million processor-hours per year). However, the gap is growing between what the Ames Laboratory researchers need on-site and what is available on-site. Currently, our researchers are hindered by the infrastructure limits on space, power, and cooling for HPC needs. Local high-performance computing (HPC) systems allow quicker model code development, debugging, and scale up for use at leadership computing facility and also necessary local computation for programs that are inefficient for running on leadership computers.

In addition to scientific computing facilities, Ames Laboratory needs additional office and laboratory space for computational sciences application, collaborative space, and data analytics/visualization. The growth encountered by the Laboratory has put a great deal of pressure on existing buildings. The Laboratory continues to identify space that can be reclaimed for renovation and reuse. Another impact is the growth experienced by the contractor, ISU. Their enrollment has grown over 10,000 students in recent years creating need for more classrooms, more staff, more offices and laboratories, more housing, and improved infrastructure. ISU has started a process to tear down old buildings and replace them with new ones. However, this means displacing people from the old buildings into temporary space until the new buildings can be completed. The Laboratory still works with the university to accommodate small staff changes. However, Ames Laboratory's growth cannot be completely accommodated by ISU.

The Laboratory also needs a large auditorium to allow for collaborative space and meetings accommodating increased staff and research needs. As partnering becomes more the norm, larger meetings become a necessity and the Laboratory has a difficult time hosting meetings of 150 people or more. A larger auditorium can be equipped to handle large group meetings, large training sessions, all-hands meetings and important events where dignitaries or the public are involved. It would also allow the Laboratory to host events where the public could be invited to improve community outreach.

Specific gaps include:

- Sufficient space, electrical infrastructure, and cooling infrastructure to support current and needed additional mid-level High-Performance Computing (HPC) clusters and servers
- Dedicated energy-efficient, combined scientific computing space
- Sufficient office space and a large auditorium to support the growing research mission and our core capabilities

Recent progress:

- Devoted significant resources to reclaim and remodel any under-utilized space. However, now there is little under-utilized space remaining.
- Evaluated possible ways to address electrical power and cooling needs in current space.
- Determined maximum additional load on infrastructure to support new computer clusters.

Despite our attempts to address the gaps, we feel at this point the only path forward to ensure our mission readiness is with a new facility. Therefore, to address the gaps the Laboratory is proposing to build a new facility combining dedicated scientific computing space, offices, research laboratories, and a large auditorium to support the growing research mission at the Laboratory supported by vibrant computational and computational sciences efforts.

Computational Sciences and Computing Facility: Ames Laboratory is requesting an SLI line item project beginning in FY 2018 to build a new Scientific Computing Building (estimated at < $25,000K and 30,500 gsf). As noted, the Laboratory is currently out of space and power in the main computer room and the research buildings were not designed for this type of environment. The research buildings were built from 1949 to 1960 and were not designed for modern computing. The Laboratory has research computers scattered throughout the research buildings where additional power and cooling had to be installed to accommodate the computers. This has led to a very inefficient operation and has converted valuable research space away from its intended use.

A new scientific computing facility would address expanding computer needs, reduce energy consumption, improve heat management, consolidate cluster management, and free up laboratory space in the older research buildings currently housing computers. Clusters currently are 70 Teraflops cumulative (or ~35M processor-hours/year), which are in continuous operation at 85-99% of peak performance, and completely saturated. Hence, the Laboratory in 2016 (estimated to fully accommodate current FWP requirements) is in need of a ~1 Petaflop cumulative (heterogeneous) computing environment designed around the needs of scientific models, with growth to 3 petaflops in 5 years. Currently, for those applications that do not require leadership class facilities, each FWP prioritizes applications, slowing the integrated computationally guided design and characterization, which is a hallmark of Ames Laboratory's research.

Without a new facility, new computers will have to be installed in laboratory buildings not designed for computing and with insufficient power to support them. Converting existing laboratory space to house new computers cannot be done efficiently. It fragments the computing and networking resources, it over-taxes utility capacity, it does not allow for energy efficient features such as heat recovery, it is inefficient to manage, and diverts valuable laboratory space away from its designed function. Having multiple computer rooms scattered throughout the facilities requires an excess of UPS and HVAC infrastructure because spare capacity and redundancy have to be built into each location.

The Laboratory has worked with a local data center provider to develop some conceptual ideas for the computational science facility to meet our space and data center needs. The company is examining a new concept that they call the "spine" design. The data center portion of the building is built around a central service corridor with utilities and networking on one side and the computing facility on the other. When needed, additional computing space and support are accommodated by adding a new section to the "spine." This holds the initial costs down and allows the Laboratory to match its facility needs to its computing needs. This also is responsive to the uncertainty of state-of-the-art computing when we purchase the equipment. If our needs are based on today's technology the building can be built to accommodate that equipment. If we have the opportunity to utilize the new technology being currently developed within DOE, such as massively parallel cell-phone CPU/GPU sets, we can adjust the building size accordingly.

Advantages associated with this option include the flexible design of the data center and the ability to add computing space when needed, the ability to utilize waste heat generated by the computers to heat the building in the winter time, the ability to add office space to accommodate growth, the ability to add an auditorium to improve collaboration and communication between the Laboratory, its customers and partners, and better control over funding and time schedules for starting and completing the project.

Scientific Computing Facility—Street View

Scientific Computing Facility—Rear View—showing a long "spine" allows allowing for future expansion

Another option we are exploring is a combined data center partnering Ames Laboratory with three state agencies that have all expressed a need for data center space. Iowa State University is the principal partner. The Director and COO have both been involved with developing this option and, as we understand, the Governor of the State of Iowa has written a letter of support to the Secretary of Energy. Advantages to this solution include the reduction of risk associated with major repairs and overall operating costs. The Laboratory would have three partners to share repairs and operating costs, and each partner would pay for power needed to run their respective computers. We could also share operators to reduce labor costs. Disadvantages include the need to accurately predict the future of computing equipment and the foot print needed since expansion would be more difficult, location would not be adjacent to the current Laboratory campus making access more difficult, security features in the shared facility would have to be enhanced since there would be multiple tenants and the Laboratory would have to find another solution to address our needs for laboratory, office, and auditorium space. There is also a great deal of uncertainty when the State of Iowa legislature will fund this option, if they fund it at all.

Electrical Systems Upgrades: The Laboratory started the electrical systems upgrade using the FY 2014 allotment of BES-GPP funds ($600K) and some of the FY 2015 BES-GPP funds ($400K) to complete the first and second phases. The Laboratory is requesting $2,000K under the Science Laboratory

Infrastructure-General Plant Project (SLI-GPP) funding for FY 2017 to complete Phase 3 of the electrical system upgrades (Harley Wilhelm Hall and Metals Development electrical distribution systems). Continuing the upgrade under BES-GPP would require phasing the project over 4 years, which would raise the risk of a major failure.

Building Improvements: As the buildings continue to age, their many systems need to be replaced in order to extend the life of the building. Some of these projects are primarily maintenance in nature and will be handled under maintenance and general services funded through overhead. These include new roofs ($1,300K over 7 years), and tuckpointing ($900K over 5 years). Other projects, capital in nature, have been included in the funding request of this plan. They include: replacement of the Spedding Hall windows ($1,000K), and replacement of the HVAC system in Metals Development ($1,000K). We have included these projects as BES-GPP funding requests scheduled as shown on Laboratory Investments Table. Though these are of high importance, they are lower priority than the electrical upgrades and the scientific computing building. Failure to invest in building improvements will contribute to the further deterioration of the buildings and accelerate their obsolescence.

Research Labs: We have included requests for SLI-GPP funds in this plan to renovate and improve research space. Our capacity to renovate space with overhead dollars is only 1,500 square feet per year. The level of SLI-GPP funding requested in conjunction with continued investment of overhead dollars will allow for an orderly upgrade of poor space within the next 10 years. We have requested SLI-GPP ($1,000K to $2,000K per year) from FY 2019 to FY 2027 to upgrade the laboratories and research areas in poor condition. These projects are critical to improve the ability of the Laboratory to support modern science, improve morale and attract quality scientists. Failure to invest in the research labs will erode our ability to perform research in those spaces, keep key personnel, and to attract new staff.

Electronic Access Control: This new project will complete the conversion of all interior doors to electronic access for Spedding Hall and Metals Development. The estimated cost to complete this project is $3,000K. The Laboratory is requesting SLI-GPP funding to complete this project in FY 2018 (Spedding Hall: $2,000K) and FY 2019 (Metals Development: $1,000K). After the conversion is complete, we will have the opportunity to tie the system to our training management system. This will make sure employees have completed the appropriate training before they have access to the work areas. This project will also improve our ability to quickly lock-down our facility in case of a security issue.

Building Maintenance and Repair: The maintenance program consists of activities necessary to keep the existing inventory of facilities in good working order and extend their service lives. This work is funded using overhead. 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 that it will need to continue to operate in the older buildings over the 10-year window of this plan. Historically AMES has invested approximately 2.0% 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 that they will continue to meet the needs of research activities. Maintenance and repair expenditures need to increase so that aging components can be replaced and deferred maintenance can be reduced. For this reason, the Laboratory increased maintenance and repair funding to approximately 2.8% of RPV in FY 2016, and plan to sustain this level for the next 5 years.

The two most critical of the gaps listed at the Laboratory are the need for scientific computing facilities and the aging electrical systems. Building improvements, research labs condition, electronic access control, and building maintenance and repair are the next gaps that need to be addressed over the next 10 years. To fill these gaps, the Laboratory is requesting to sustain funding levels of $1,000K per year in GPP-BES, and $2,000K per year in GPP-SLI over the 10-year duration of this plan. The Laboratory is also requesting the new Scientific Computing Building as a $25,000K line item project starting in FY 2018.

Table 3: Laboratory Investments

Objectives	
	1. Support a sensitive instrument facility
	2. Support a modern computational facility
	3. Modernize the existing campus
	4. Provide mission enabling space renovations
	5. Extend life of existing facilities

Project	Total	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Funds
Sensitive Instrument Facility	8.9	1.2	7.7												GPP-BES
Computational Facility	15.0					15.0									SLI
Upgrade SPH Windows	0.6					0.6									GPP-SLI
Upgrade Electrical Systems-Phase 1	0.6	0.3	0.3												GPP-BES
Upgrade Electrical Systems-Phase 2	0.4		0.4												GPP-BES
Upgrade Electrical Systems-Phase 3	2.2				2.2										GPP-SLI
Upgrade HVAC in SPH-Phase 7	0.4	0.2	0.2												GPP-BES
Sustainability Co-Funding (SPOFOA)	0.3		0.2	0.1											GPP-BES
Upgrade HVAC in MD	1.3							1.3							GPP-SLI
Upgrade MD Freight Elevator	0.5									0.5					GPP-SLI
Upgrade Access Control	3.3				3.3										GPP-S&S
Improve Energy & Water Conservation	0.5										0.5				GPP-BES
Upgrade Sprinklers in Maint Shops	0.2											0.2			GPP-BES
Improve Handicap Access to Bldgs	0.3												0.3		GPP-BES
BES Mission Readiness Renovations	5.5			0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.1	0.4	0.3	0.6	GPP-BES
Additional Mission Enabling Space Renovations	9.8				1.1	0.8	0.9	1.2	1.1	0.9	0.9	0.9	0.9	1.1	GPP-SLI
Total (GPP)	49.8	1.7	8.8	0.6	7.2	17.0	1.5	3.1	1.7	2.0	1.5	1.5	1.5	1.7	
Core Program (Maint & Repair)	25.7	1.7	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	OH
Replace Roofs (TASF,MD,HWH,SPH)	1.3			0.2		0.6		0.2		0.3					OH
Repair Bldg Exteriors (SPH,HWH,MD)	0.9				0.3		0.3		0.3						OH
Remove Excess Equipment from MD	0.1			0.1											OH
Lab Space Maintenance & Repair	2.7	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	OH
Total (OH)	30.7	2.0	1.9	2.3	2.3	2.7	2.4	2.4	2.5	2.6	2.3	2.4	2.4	2.5	
Total Investment (GPP+OH)	80.5	3.7	10.7	2.9	9.5	19.7	3.9	5.5	4.2	4.6	3.8	3.9	3.9	4.2	
Deferred Maintenance Trend		1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	

Argonne National Laboratory

1. Mission and Overview

Argonne National Laboratory creates knowledge and delivers science-driven innovation that advances American prosperity and security. To further the missions of the Department of Energy and other federal agencies, Argonne's globally recognized scientists and engineers leverage the Laboratory's unique pairing of world-class user facilities and an integrated computational science community.
Through its broad-based capabilities in the basic and applied sciences and engineering, the Laboratory meets key national needs in science and technology by providing:

- Ground-breaking discovery science that transforms understanding of physical, chemical, mathematical, and biological phenomena
- Innovative, internationally recognized solutions to critical challenges in energy, transportation, infrastructure, and security
- An unmatched portfolio of integrated, on-site experimental and computational capabilities used by both Argonne staff and researchers from around the world, including the:

-Advanced Photon Source
-Argonne Leadership Computing Facility
-Center for Nanoscale Materials
-Argonne Tandem-Linac Accelerator System

Multidisciplinary partnerships, both internally and externally, are a cornerstone of Argonne's research and development enterprise, exemplified by collaborations such as the Joint Center for Energy Storage Research, the Center for Electrochemical Energy Science, and the Midwest Integrated Center for Computational Materials.

1. 2. Lab-at-a-Glance

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

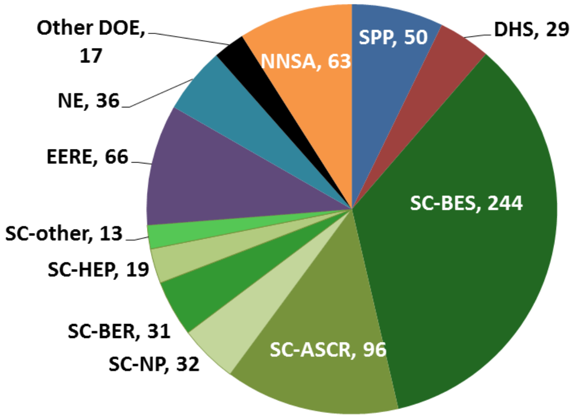
Physical Assets:

- 1,517 acres and 157 buildings
- 5.0M GSF in buildings
- Replacement Plant Value: $3.11B
- 50,779 GSF in 15 excess facilities
- 339,673 GSF in leased facilities

Human Capital:

- 3,298 Full Time Equivalent Employees (FTEs)
- 248 Joint faculty
- 315 Postdoctoral Researchers
- 250 Undergraduate Students
- 207 Graduate Students
- 7,186 Facility Users
- 1,362 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



FY 2015 Lab Operating Costs (excluding Recovery Act): $734.1M
FY 2015 DOE/NNSA Costs: $617.4M
FY 2015 SPP (Non-DOE/Non-DHS) Costs: $88.1M
FY 2015 SPP as % Total Lab Operating Costs: 12%
FY 2015 DHS Costs: $28.6M
ARRA Costed from DOE Sources in FY 2015: $0.3M

Argonne leverages its Chicago-area location through joint research institutes with Northwestern University and The University of Chicago and through partnerships within the Chicago area's rich "innovation ecosystem" that accelerate the transition of Laboratory technology to the marketplace. The University of Chicago has managed Argonne since its founding in 1946, guiding the growth of an internationally renowned institution for 70 years.

3. Core Capabilities

Argonne National Laboratory's 18 core capabilities together form a powerful asset to meet key national needs for scientific and technological leadership. These broad-based capabilities in basic and applied science and engineering constitute the foundation for Argonne's interdisciplinary major initiatives and enable the Laboratory to deliver:

- Ground-breaking discovery science that advances understanding of nature and our universe
- Innovative solutions to critical challenges in energy, infrastructure, and security
- Unique, integrated experimental and computational capabilities

To advance the missions of the Department of Energy, Department of Homeland Security, and other federal agencies,[2] Argonne's globally recognized scientists and engineers leverage the Laboratory's unique pairing of world-class user facilities and an integrated computational science community:

- Argonne operates large-scale facilities – accelerators, leadership computing systems, nanoscience research facilities, and atmospheric radiation measurement networks – that are integral to work by scientists and engineers both inside and outside the Laboratory (Sec. 3.1)
- Through accelerator science and engineering, Argonne develops concepts for next-generation accelerators; existing accelerators are central to much of the Laboratory's highly regarded nuclear and particle physics research (Sec. 3.2)
- Argonne's leadership computing facilities are both supported and leveraged by staff capabilities in computer science, computational science, and applied mathematics (Sec. 3.3)
- The Laboratory's facility and computational strengths support the work of an exceptional staff with expertise in four broad areas of research and development:
    - Chemistry and materials (Sec. 3.4)
    - Biology and environment (Sec. 3.5)
    - Nuclear energy (Sec. 3.6)
    - Cybersecurity, decision making, and integrated systems (Sec. 3.7)

Large-Scale User Facilities/Advanced Instrumentation

Argonne is a leader in the design, construction, and operation of world-class scientific user facilities, with four internationally renowned user facilities on Argonne's Illinois site: the Advanced Photon Source (APS), the Argonne Tandem-Linac Accelerator System (ATLAS), the Argonne Leadership Computing Facility (ALCF), and the Center for Nanoscale Materials (CNM). More than 500 Argonne staff members operate these facilities, which together served over 7,100 users in FY15. Effective management of large facility-user programs and synergistic, cross-discipline collaboration across facilities are hallmarks of Argonne's

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[2] Throughout Sec. 3 of this plan, in the "Mission relevance and funding" listing of sponsors, organizations are listed in alphabetical order, based on sponsor acronym.

approach to user facility operation. In addition, Argonne operates one component of the DOE/SC-BER Atmospheric Radiation Measurement Climate Research Facility, the Southern Great Plains (ARM-SGP) site in Oklahoma.

APS, funded primarily by DOE/SC-BES, 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 time scales, including time-resolved studies of dynamics for *in situ* and *in operando* scattering and spectroscopy experiments, studies of shock physics, x-ray interrogation of electron and lattice excitations, and real-time studies of evolving systems. Argonne is currently planning for the installation of a multi-bend achromat storage-ring lattice as part of the APS Upgrade project, which will increase x-ray brightness and coherent flux by two to three orders of magnitude.

ATLAS, funded by DOE/SC-NP, is a superconducting linear accelerator and the only DOE user facility for low-energy nuclear research. It provides heavy ions in the energy domain best suited to study the properties of the nucleus. ATLAS offers a unique capability, the Californium Rare Ion Breeder Upgrade (CARIBU), which provides both stopped rare isotopes and reaccelerated beams of these exotic nuclei. CARIBU beams are requested in roughly half of all user proposals for experiments at ATLAS. Additional ATLAS attributes are detailed in the description of Argonne's core capability in nuclear physics.

ALCF, funded by DOE/SC-ASCR, operates an IBM Blue Gene/Q system (ALCF-2, named Mira), one of the world's largest supercomputers dedicated to open science, and is preparing to deploy a Cray XC class system in late 2016 (ALCF-Lithium) and an Intel/Cray Shasta system in 2018 (ALCF-3). The ALCF provides petascale computing capabilities that enable the computational science and engineering community to run the largest and most complex scientific applications. It also hosts the Joint Laboratory for System Evaluation (JLSE), which gives Argonne and its collaborators access to the latest production and prototype computing resources. ALCF staff expertise will be critical to meeting the major technology and design challenges of exascale computing and the management of very large data sets.

CNM, funded by DOE/SC-BES, provides expertise, instruments and infrastructure for interdisciplinary nanoscience and nanotechnology research, to address grand challenges in energy and new materials development at the nanoscale. Work at the CNM focuses on the synthesis, characterization, fabrication, and science of hierarchical nanomaterials. This facility provides a unique suite of near-field-scanning-probe, photonics, and x-ray nano-imaging tools, including an x-ray nanoprobe beamline at the APS, an electron microscopy center, and a world-class nanofabrication facility. The CNM partnership with APS continues to grow, with new jointly operated instrumentation at the APS, collaboration on novel nanofabricated x-ray optics, and multimodal imaging initiatives leveraging the expertise of both facilities.

ARM-SGP, funded by DOE/SC-BER, is the world's largest and most extensive climate research field site. It was the first ARM field measurement site and has been collecting data since 1992. Its instruments are arrayed across 55,000 square miles in north-central Oklahoma, with a heavily instrumented central facility on 160 acres near Lamont. The facility provides data used by scientists worldwide to improve the representation of clouds and radiation in models used for climate research.

Mission relevance and funding

This core 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. Current sponsors include DOE/NNSA; DOE/OE; DOE/SC-ASCR, -BER, -BES, and -NP; industry, NIH, and NSF.

Accelerator and Physics Capabilities

Argonne is a global leader in accelerator science and technology, with a team of nearly 200 staff with an exceptional breadth of expertise. Facilities that are key to this capability include the APS, ATLAS, and the Argonne Wakefield Accelerator (AWA). Other elements in Argonne's unique suite of tools for accelerator science and technology include an extensive superconducting radio-frequency-cavity infrastructure and a wide range of test beams and test stands.

Argonne scientists and engineers are internationally recognized for their expertise in:

- Modeling, design, and operation of photon sources; electron accelerators and storage rings; free electron laser seeding and oscillators; superconducting undulators; beam diagnostics, stability and feedback; and vacuum system engineering − the APS Upgrade is exploiting these capabilities to develop the world's leading fourth-generation hard x-ray light source
- Creation, acceleration, and manipulation of high-intensity stable and rare-isotope ion beams, including the development of superconducting radio-frequency (SRF) cavity systems for accelerating low-velocity ions − this expertise supports nuclear physics research at ATLAS and other DOE accelerators
- 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 that combines the world's highest electron bunch charge produced by a photocathode gun with a state-of-the-art linear accelerator and beam instrumentation
  - Argonne also has significant associated expertise in areas vital to future colliders, including high-power radio frequency sources, generation and preservation of high-brightness beams, collective beam instabilities, and positron production
- State-of-the-art accelerator computation: Argonne's advanced accelerator modeling code "elegant" is used by researchers at more than 200 institutions worldwide
- Development of EPICS software tools and applications for distributed control systems for accelerators

Because of these capabilities, Argonne also is a key partner in development and construction of DOE-supported facilities elsewhere, including the Linac Coherent Light Source-II (LCLS-II) at the SLAC National Accelerator Laboratory, the Facility for Rare Isotope Beams at Michigan State University, the Proton Improvement Plan II project at the Fermi National Accelerator Laboratory (Fermilab), and the Electron-Ion Collider (EIC) being considered by DOE. These build upon previous successful partnerships that resulted in substantial Argonne contributions to the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory and the original LCLS.

Mission relevance and funding

This core capability supports the DOE-SC mission to enhance the capabilities of its current accelerators and drive development of next-generation facilities. Current sponsors include DOE/NNSA and DOE/SC-BES, -HEP, and -NP.

Nuclear Physics

Argonne's theoretical and experimental nuclear physics research provides world leadership in nuclear structure, nuclear astrophysics, fundamental interactions, medium energy physics and, more broadly, in nuclear instrumentation, accelerator development, and selected applications. Key to Argonne's work is ATLAS, which provides stable and radioactive ion beams at energies up to about 20 megaelectron-volts/nucleon.

Argonne staff and visiting scientists use ATLAS to highlight aspects of nuclear structure that vary strongly with the proton-to-neutron ratio and are not readily apparent in stable nuclei, investigate reactions far from stability as the basis of astrophysical processes generating the chemical elements, and test nature's fundamental symmetries.

The Laboratory's physicists are leaders in seeking a deeper understanding of the underlying strong force and its foundation in quantum chromodynamics as it applies to protons and neutrons (e.g., how quarks and gluons assemble into various forms of matter) and to the strongly coupled nuclear many-body system. They design, construct, and operate detectors at the Thomas Jefferson National Accelerator facility (TJNAF) and Fermilab to carry out these investigations. Argonne staff members lead Fermilab's SeaQuest experiment and are principal investigators for about 30% of all approved experiments in TJNAF's 12-gigaelectron-volt program. At Argonne, they probe the baryon asymmetry of the universe using an electric dipole moment measurement of radium-225.

Argonne's experimental programs in nuclear physics are supported by its work in accelerator science and technology as well as by widely recognized theory efforts that leverage the ALCF and the Laboratory's capabilities in advanced computer science, visualization and data. Argonne physicists are leaders in Monte Carlo nuclear structure calculations and parameter-free predictions of hadron properties in continuum-quantum chromodynamics.

Additional applications include characterization of spent nuclear fuel for reactor design using accelerator mass spectrometry; production techniques for medical radioisotopes; and radio-krypton and radio-argon dating with atom traps for geophysical, oceanography, and fundamental research. The development of a national center for radio-krypton and radio-argon dating at Argonne is under consideration.

Multiple upgrades have kept ATLAS at the forefront of discovery, providing capabilities that include:

- Superconducting radio-frequency structures with world-leading fields, providing total accelerating voltages in excess of 17 megavolts
- High-purity ion beams of radioactive isotopes not available anywhere else in the world, from CARIBU, which efficiently delivers the beams at energies relevant for nuclear structure and astrophysics research and makes the species of interest directly available for experiments or provides them for subsequent re-acceleration through ATLAS
- State-of-the-art instrumentation such as Gammasphere (the national gamma-ray facility), HELIOS (a helical orbit spectrometer), the Canadian Penning Trap mass spectrometer, ion and atom traps, and a fragment mass analyzer

Further upgrades to ATLAS are underway, including a gas-filled spectrometer, an in-flight radioactive ion separator, and projects to more than double the intensity of re-accelerated CARIBU beams and deliver stable heavy ions with tens of particle micro-ampere intensities. To address high demand from the user community for ATLAS beam time, a concept for a multi-user capability is being developed where two beams of different species and energies would be delivered at the same time.

Mission relevance and funding

This core capability supports the DOE-SC nuclear physics mission. Current sponsors include DOE/SC-BES, -HEP, and -NP; IAEA; NSF; and universities in the U.S. and abroad.

Particle Physics

Argonne's particle physics research advances understanding of the properties and interactions of the particles making up the universe and the underlying symmetries of nature. This work, which has a track record of many significant contributions and leadership roles, is distinguished by the use of cross-disciplinary research teams to develop transformational instrumentation technologies and to leverage computational science and high-performance computing.

Argonne's efforts in particle theory include Higgs production, as well as beyond-the-standard-model predictions. The most precise theoretical simulation of vector bosons plus jet process yet performed is carried out using the ALCF: these very detailed, compute-intensive calculations are essential to compare data to theory and look for forms of new physics. Argonne also is leading the testing and calibration of the magnetic field mapping facility for the Muon g-2 and Muon-to-Electron (Mu2e) experiments being built at Fermilab.

The Laboratory's cosmological theory and computation group collaborates closely with the ALCF as well as other DOE laboratories, and plays a leadership role in the national strategy for extracting science from cosmological surveys. Argonne has become a leader in extreme-scale, high-resolution cosmological simulations by developing the HACC cosmological simulation framework, along with its data analysis library CosmoTools. Simulations run at the ALCF and other DOE leadership computing facilities are used to produce precise predictions and synthetic sky maps that closely correlate to actual observations.

Argonne has pioneered the development of new, large-area photo-detectors with picosecond timing resolution (LAPPD) and has produced evaluation LAPPD detectors that are now being tested at laboratories and institutes in the U.S. and overseas. Future efforts are directed toward bringing LAPPD-type detectors to industrial production through a Small Business Innovation Research award to INCOM, Inc.

The development of large detector systems to study particle interactions is another leadership area for Argonne, supported by worldwide collaborations. Of note are the Laboratory's design, construction, and commissioning of the large tile calorimeter for the ATLAS (A Toroidal LHC Apparatus) Experiment at the Large Hadron Collider (LHC) at CERN, as well as prototyping of the NOvA detector for neutrino interactions and development of new instrumentation for astrophysics experiments. Argonne also is leading construction of the third-generation South Pole Telescope experiment to measure cosmic microwave background radiation, based on the Laboratory's unique capabilities to fabricate transition edge sensor array detectors.

Argonne is a leader in advancing work at the LHC ATLAS detector through the development of state-of-the-art trigger hardware and software, creation of meta-databases, and first-of-a-kind simulation of LHC particle collisions using the ALCF. This work already has delivered a significant fraction of currently needed simulated events to LHC ATLAS, and has enabled publication of results from the LHC ATLAS Experiment that would not otherwise have been possible.

Mission relevance and funding

This core capability supports the DOE/SC-HEP mission and is well aligned with priorities defined by the DOE Particle Physics Project Prioritization Panel that recommended a strategic plan for U.S. high energy physics in 2014. Current sponsors include DOE/SC-ASCR, DOE/SC-HEP, and NASA.

Scientific Computing Capabilities

Argonne is widely recognized for broad-ranging foundational research in mathematical modeling, analysis, and algorithm development, implemented in scalable software for execution on the world's largest computing systems. Unique Argonne facilities and capabilities supporting this work include ALCF, the Joint Laboratory for System Evaluation (operated by ALCF and the mathematics and computer science division), the Laboratory Computing Resource Center (Argonne's internal supercomputing facility), and many of the Laboratory's networking and storage capabilities, including site-wide access to Globus Online.

Argonne excels in the scalable solution of partial differential equations (PDEs). For example:

- The Nek5000 and NekCEM software packages employ the spectral element method to efficiently solve problems in computational fluid dynamics and computational electromagnetics
- The PETSc software library provides scalable linear solvers, nonlinear solvers, and time integration methods for solving discretized PDEs; it is used by hundreds of scientific applications
- Argonne has new capabilities for implicit-explicit time integration, nested and hierarchical solvers for increased scalability and improved support for multiphysics applications, and algorithmic innovations to

improve performance on computer architectures that are latency-dominated and memory-bandwidth-starved

- The Laboratory also is developing advanced solution-transfer and problem-coupling algorithms to address multiphysics and multiscale applications

Through world-class research in optimization, game theory, uncertainty quantification, and control, Argonne develops new models, algorithms, and software to tackle ubiquitous design and decision problems:

- Argonne's derivative-free optimization algorithms, which can exploit problem structure, are used in applications ranging from calibrating energy density functions in nuclear physics, to minimizing vehicle emissions, to improving load balance and tuning performance using compiler-based code transformation
- Mixed-integer nonlinear optimization algorithms implemented in Argonne's MINOTAUR software library enable solution of challenging optimization problems with both discrete and continuous parameters
- Scalable algorithms for the solution of large-scale PDE-constrained and stochastic optimization are implemented in Argonne's TAO and PIPS software packages, which bring together advanced algorithms, sophisticated implementations, and leadership computing to enable solution of optimization problems with billions of variables and constraints

Argonne's best-in-class research in automatic differentiation supports optimization, uncertainty quantification, and nonlinear PDE solvers through efficient computation of derivatives. Advances in automatic differentiation theory and technique are encapsulated in Argonne's OpenAD/F, ADIC, and Rapsodia tools. Argonne continues to examine the role of communication in adjoint-based derivative computations, an important consideration for derivative computation on leadership computers, and the linearization of nonsmooth functions, important for applications in materials science and data analysis. The Laboratory also is a leader in effectively formatting data analysis problems as linear algebra or optimization problems.

Mission relevance and funding

This core capability supports the DOE/SC mission to develop and deploy high-performance and leadership computing resources for science discovery. Current sponsors include DOE/OE; DOE/SC-ASCR, -BER, -BES, and -FES; NIH; and NSF.

1.1 Advanced computer science, visualization, and data

Capability

Argonne is a leader in multiple efforts critical to achieving exascale computing capabilities. In particular, the Laboratory's computer science staff is recognized for expertise in exascale operating systems and runtime software, programming models, data storage and input/output, distributed systems, workflows, visualization, and data analysis.

Unique Argonne facilities and capabilities supporting this work include ALCF, the Joint Laboratory for System Evaluation, the Laboratory Computing Resource Center, and many of Argonne's networking and storage capabilities, including site-wide access to Globus Online. Argonne software is also deployed and tested at the National Energy Research Scientific Computing Center at Lawrence Berkeley National Laboratory and at the Oak Ridge Leadership Computing Facility.

Production supercomputer systems worldwide use Argonne's innovative research software tools, including MPICH, a high-performance, portable implementation of the Message Passing Interface (MPI) standard for parallel programming; Darshan, a scalable high-performance computing input/output characterization tool; and Globus Online, a cloud-based reliable file-transfer infrastructure for science.

In exascale computer science, the Argo project is highly regarded for its development of operating system and runtime software for exascale systems. Argonne's expertise in resilience covers multi-level checkpoint/restart, signal-analysis-based failure prediction, domino-free fault-tolerant protocols, and use of data analytics to detect silent data corruption. Argonne is also heavily involved in developing DOE's research plan for exascale computing, while maintaining multiple partnerships with researchers in Japan and Europe.

Argonne is tackling the "big data" challenge by developing new techniques and tools for storing, transferring, accessing, visualizing, and analyzing extremely large datasets. Flagship projects include Triton, a novel, highly resilient, self-repairing distributed storage system; GLEAN and DIY, software libraries for *in situ* analysis and visualization; and RAMSES, a suite of end-to-end performance models and tools for science workflows.

The Laboratory's unique tools for visualization, analysis, and workflows are also key to advancing computer science. For example, Argonne's Swift is a task-based parallel scripting language, compiler, and runtime system that is being used in many fields to run millions of tasks per second as soon as their inputs are available, reducing the need for complex parallel programming. In addition, Argonne is a leader in the application of cloud computing for science; this includes NIMBUS, an open source toolkit for turning computing clusters into infrastructure-as-a-service clouds for science, and the platform supporting the DOE Systems Biology Knowledgebase (KBase) services.

Argonne has begun to leverage its expertise in system software, distributed computing, and cloud computing to expand into the 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 these sensors in Chicago.

In a variety of projects, the Laboratory is working to provide better data analysis capabilities and tools to APS users, including infrastructure and services for data transfer from APS to ALCF and for real-time data analysis as well as new parallel algorithms and software for ptychographic imaging.

Mission relevance and funding

This core capability supports the DOE/SC-ASCR mission to develop and deploy high-performance and leadership computing resources for science discovery. Current sponsors include DOE/NNSA; DOE/OE; DOE/SC-ASCR, -BER, -BES, and -FES; NIH; and NSF. Much of this funding supports co-design activities and interdisciplinary research partnerships with scientists in various application areas.

1.2 Computational science

Capability

Computational science is a cornerstone of Argonne's research and development enterprise, with applications to critical problems in chemistry, climate, combustion, cosmology, engineering, materials science, microbial and environmental biology, nuclear reactor design, physics, and x-ray science. Argonne's computational science ecosystem integrates over 350 scientists and engineers in interdisciplinary project teams with embedded applied mathematicians and computer scientists.

These teams leverage the ALCF and Laboratory Computing Resource Center to deliver breakthrough results that span the spectrum of Argonne's core capabilities and major initiatives in science and technology:

- Scientists and engineers develop the basic mathematical structure of their research problem, applied mathematicians formulate the problem in reasonable and tractable ways, and computer scientists provide the solution methodologies
- Working with formally appointed points of contact for data and computation in each Argonne research directorate, ALCF staff members proactively connect computational science groups to the Laboratory's computing facilities, allocating machine time and assisting in development of proposals to DOE's

Innovative and Novel Computational Impact on Theory and Experiment (INCITE) and ASCR Leadership Computing Challenge (ALCC) programs

- Computational science teams collaborate with industry and academia in projects such as the Virtual Engine Research Institute and Fuels Initiative (VERIFI) and in multi-institution centers such as the Joint Center for Energy Storage Research (JCESR), the Center for Hierarchical Materials Design (CHiMaD) at Northwestern University, and the Midwest Integrated Center for Computational Materials (MICCoM)

Examples of the global impact and leadership of Argonne's computational science capability span multiple disciplines and include:

- One of the world's largest high-resolution cosmological simulations (HACC)
- Innovative modeling of nuclear reactors (Nek5000, UNIC, OpenMC)
- Groundbreaking efforts in analysis, integration and comparison of microbial genomes and environmental genomic datasets (KBase, ModelSEED, and PATRIC)
- De facto world-standard bioinformatics tools (RAST and MG-RAST)
- Theoretical and computational chemical dynamics for understanding combustion
- Algorithms and toolkits for analysis of large datasets from APS and the Large Hadron Collider
- Codes for additional applications: ACME (climate), elegant (accelerator simulation), TomoPy (x-ray tomographic analysis), and Green's Function Monte Carlo (properties of nuclei)
- Leadership in identifying and proposing applications for exascale computing

Mission relevance and funding

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

1.3 Chemistry and Materials Capabilities

Argonne is internationally known for work in the synthesis, characterization, and control of molecules and chemical processes, with a focus on energy production and use. The Laboratory is a leader in artificial photosynthesis; catalysis; combustion; interfacial geochemistry; heavy-element and separations chemistries; ultrafast phenomena; atomic, molecular, and optical science; and energy conversion and storage.

APS-based experiments, which include the use of atomic-scale resolution probes, are an integral aspect of this work, and APS-U improvements will enable further advances in understanding of excited states in molecular energy transduction, *in operando* studies of catalysis, and *in situ* and real-time studies of reactions at solid-liquid interfaces. Synthesis is also an essential component of most of the research activities in chemical and molecular sciences, and Argonne has developed high-throughput facilities to increase the speed of synthesizing and testing organic molecules, inorganic chemical platforms, and mesoscale assemblies.

These strengths collectively provide a foundation for Argonne's advanced battery research programs and leadership of JCESR. Argonne's battery research leverages both the APS and ALCF and continues to produce breakthroughs in understanding of complex solid-state and interfacial chemical interactions relevant to battery electrodes and electrolytes.

Argonne's catalysis research targets small molecule activation to enable use of varied fuel sources, investigates reactivity *in situ* and in real time, and identifies new synthetic routes for directed catalysts. Theoretical, experimental, and computational chemists collaborate in groundbreaking studies of electronic structures, and use a unique set of *in situ* APS tools to study catalysis under realistic operating conditions.

Other research strengths include the study of fundamental mechanisms for solar-driven water-splitting-to-fuels chemistry in natural and artificial photosynthesis. Argonne's cross-cutting approach combines synthesis with advanced physical techniques to uncover physical-chemical concepts needed to design artificial photosynthetic systems that replicate the sustainability and sophistication of carbon and nitrogen fixation chemistries in photosynthesis, but far exceed nature's limitations for solar energy conversion efficiency. Argonne has demonstrated the opportunity to combine chemical synthesis with biological synthesis to create biomimetic hybrids with combined chemical and photosynthetic functionalities. This approach links to the Laboratory's capability in biological and bioprocess engineering, and establishes a first-principles, physical-chemical approach for achieving photosynthetic systems with enhanced solar conversion efficiencies.

Argonne pushes the frontiers of combustion chemistry through a strong theoretical and experimental program in gas-phase chemical physics combined with predictive modeling. Experimental facilities for this work include several unique instruments for studies of high-temperature kinetics and dynamics.

Argonne's research is advancing understanding of x-ray interactions with atoms, molecules, and clusters, via work undertaken at APS, LCLS, and other light sources. Strengths in this area include the use of high-repetition-rate lasers and x-ray spectroscopy to explore and control the photo-induced dynamics of solvated molecules. Theorists and computational scientists work together to better understand x-ray radiation damage in complex systems, a matter of foundational importance for the APS-U.

Interfacial science at Argonne leverages the unique capabilities of the APS to understand molecular-scale controls over structure and reactivity at liquid-solid interfaces in systems ranging from geological materials to energy storage systems. These activities resulted in the Center for Electrochemical Energy Science, a DOE/SC Energy Frontier Research Center, led by Argonne with external partners, that seeks to understand and control reactivity at oxide-electrolyte interfaces relevant to lithium-ion batteries.

Mission relevance and funding

This core capability supports missions across all of DOE and other agencies that fund research and development in combustion, energy production and storage, new fuels, and solar energy, geological sequestration, and quantum control of atomic and molecular systems. Current sponsors include DOD and DOE/SC-BES.

1.4 Chemical engineering

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 and energy conversion. The Laboratory is internationally recognized for its lithium-ion battery work that integrates basic research, applied R&D, engineering, and battery testing.

Argonne provides a unique, integrated suite of capabilities within the DOE complex: applied materials science and engineering; basic materials R&D; and the ability to scale materials to a pre-pilot level, incorporate materials in commercial-grade cells and run them through multiple tests, and then analyze the materials down to the molecular scale. This set of engineering capabilities is accessible to external organizations that are developing battery materials and chemistries.

The Laboratory's battery programs rely on a unique suite of supporting facilities, notably the Cell Analysis, Modeling and Prototyping (CAMP) facility, Electrochemical Analysis and Diagnostics Laboratory (EADL), and High-Throughput Research (HTR) Laboratory. The first of these, the CAMP facility, is used to design, fabricate, and engineer advanced batteries using pilot-scale equipment in a dry room, with expert staff creating prototype electrodes and cell systems. It was the first facility of its type at a national laboratory or university. CAMP-manufactured cells enable realistic, consistent, and timely evaluation of candidate chemistries in a close-to-realistic industrial format.

The EADL provides battery developers with reliable, independent, and unbiased performance evaluation of cells, modules, and battery packs. It also houses the Battery Post-Test Facility, which is one of the few in the world that allows diagnostic analysis of battery components after use to identify mechanisms that limit battery life. The HTR Laboratory provides a set of robotic tools and reactor systems for rapid, highly automated, and parallel approaches to chemical synthesis and materials development. This facility accelerates discovery and optimization of new materials for catalysis, energy storage, fuel cells, solar energy, and nanoscale chemistry.

In addition to its leadership in battery R&D, Argonne is internationally recognized for its work in development and demonstration of fuel cell technology. This multidisciplinary effort is developing advanced membranes, electrodes, and electro catalysts that reduce the cost and improve the durability of fuel cells based on both solid oxide and polymer electrolyte membrane technologies.

Mission relevance and funding

This core capability supports the missions of DOE and other agencies to advance energy storage and fuel cell science and engineering. Current sponsors include DOD, DOE/EERE, industry, and the Small Business Innovation Research program.

1.5 Condensed matter physics and materials science

Argonne's internationally recognized research in this area advances understanding of the foundational principles that link materials complexity to function, tailors this functionality for applications, and designs and creates new materials. The Laboratory's leadership is grounded in integration of the APS, CNM, and ALCF with diverse expertise in basic and applied research in materials, chemistry, nanoscience, computing, and biology. This integration is particularly important for bridging the gap between the nano-scale and macro-scale, thereby harnessing the true promise of quantum and molecular engineering. This is reflected in Argonne's strategic planning for this core capability, which emphasizes defects and interfaces, quantum and spin coherent matter, soft matter and hybrid materials, and electrochemical phenomena and clusters.

Argonne's portfolio of capabilities includes the use of coherent and diffuse x-ray and neutron scattering, Lorentz microscopy, and scanning tunneling probes; these capabilities are applied in world-class research programs in vortex physics, spintronics, single-crystal and thin-film synthesis, and electrochemistry, with a strong emphasis on *in situ* characterization coupled to modeling and simulation. The Laboratory's materials focus includes superconducting and magnetic materials, quantum metamaterials, ferroelectrics, ionic and electronic conductors, metal and metal oxide nanoparticles, bio-nanoparticle hybrids, nanocarbons, granular and soft matter, and catalytic materials.

Complementing this unique suite of capabilities are:

- The strengths of the University of Chicago-Argonne Institute for Molecular Engineering (IME) in computational materials science, soft and bio-inspired materials, and quantum engineering
- The work of the new, Argonne-based MICCoM, which brings investigators from the Laboratory and five universities together to develop and disseminate computational tools for simulating and predicting properties of functional materials for energy conversion processes
- Argonne's roles in JCESR, a DOE/SC Energy Innovation Hub, and three DOE/SC Energy Frontier Research Centers: Argonne-Northwestern Solar Energy Research Center, Center for Emergent Superconductivity, and Center for Electrochemical Energy Science

Argonne's world-class nanomaterials capabilities in synthesis and in optical, x-ray, electron beam, and near-field characterization, based at the CNM, are a pivotal resource. The CNM not only serves more than 500 users annually but it has a research mission to create functional hybrid nanomaterials and tailor nanoscale interactions to address grand challenges in energy and information conversion and transport. CNM's unique characterization approaches include atomic-scale probes such as the synchrotron x-ray scanning tunneling microscope (SX-STM) at the hard x-ray nanoprobe (HXN) facility, laser-coupled STM, transmission electron microscopy, and *in situ* structure-function correlations at the nanoscale performed at the APS.

A hallmark of Argonne's condensed matter physics and materials science research is a strong coupling of simulations at ALCF with state-of-the-art experiments in laboratories, at the APS and CNM, and at off-site DOE/SC-BES facilities including the SNS and LCLS. Looking to the future, the planned APS and ALCF upgrades will provide critical new experimental tools to accelerate the Laboratory's materials breakthroughs, and the Materials Design Laboratory will enhance the laboratory capabilities and interdisciplinary synergies that have been realized with the adjacent Energy Sciences Building and its Materials for Energy Module.

Mission relevance and funding

This core capability supports DOE missions in multiple areas, including materials for energy applications, condensed matter physics, scattering and instrumentation science, materials discovery and synthesis, soft matter research, and energy-efficient computing paradigms. Current sponsors include DOD, DOE/EERE, DOE/SC-BES, and industry.

1.6 Applied materials science and engineering

Argonne applies its internationally recognized expertise in materials development and synthesis to drive advances in clean energy science and manufacturing processes. This work leverages a unique combination of resources: applied and basic science teams from across the Laboratory; materials characterization at the APS and CNM; computational science using the ALCF; one-of-a-kind facilities for materials synthesis, fabrication, and testing; and polyelectrolyte science and polymer synthesis expertise from the IME.

The Laboratory's applied materials science and engineering has produced more-efficient batteries, new solar panel designs, high-performance sponges for oil absorption, and high-performance lubricants. Ongoing work has shown promise for more-efficient nuclear fuel reprocessing, lighter-weight transportation alloys, and higher-performance superconducting materials for use in detectors, accelerators, energy transmission, and energy storage. Additionally, two newly formed collaborative centers, Nano Design Works (NDW) and the Argonne Collaborative Center for Energy Storage Science (ACCESS), are facilitating maturation of those novel materials and deployment to industry. Argonne also partners with industry in a number of innovative manufacturing institutes, including PowerAmerica, DMDII, and NextFlex.

Argonne is a leader in creating innovative materials and developing scalable processes to produce those materials and apply them. For example, the Laboratory develops thin films and nanostructured materials, using both atomic layer deposition and enhanced vapor deposition, and extends those technologies to applications ranging from high-performance catalysts for the chemical industry to more-efficient solar cells and solid-state lighting, based on abundant materials such as titanium dioxide, zinc oxide, and copper sulfide. In other work, Argonne develops ultracapacitor materials for transportation applications and membrane materials and systems for gas- and liquid-phase separation, for applications such as hydrogen production, carbon dioxide separation, biofuels processing, and water treatment and reuse.

The 10,000-square-foot Materials Engineering Research Facility is a unique state-of-the-art research center that is central to Argonne's applied materials capabilities. This facility enables development of manufacturing processes for producing advanced materials in sufficient quantities for industrial testing, thereby bridging the gap between bench-scale science and industrial evaluation. Looking forward, the APS-U will enable real-time interrogation of scalable process technologies and thus shorten the time to deployment of novel, efficient approaches to materials production.

Argonne's nuclear materials work is focused on reactor safety and fuel reprocessing, and uses experiments and modeling to:

- Understand the performance of nuclear fuel and reactor materials under prototypic irradiation and coolant chemistry conditions for both normal and accident scenarios
- Develop chemical methods and systems for reprocessing conventional and advanced reactor fuels

Mission relevance and funding

This core capability supports the missions of DOE and other federal and private-sector organizations in the areas of energy efficiency, renewable energy, energy storage, and environmental stewardship. Current sponsors include DOE/EERE, DOE/NE, DOE/NNSA, DOE/SC-BES, industry; and NRC.

1.7 Biology and Environment Capabilities

Argonne's bioprocess research identifies fundamental mechanisms for biological energy capture and conversion. This work investigates those mechanisms at the molecular level, and uses the results to develop first-principles bioengineering approaches to meet technology challenges in energy, environment, and carbon sequestration. The Laboratory is pioneering new approaches to biological and bioprocess engineering that combine synthetic biology and synthetic chemistry to create bio-materials with tuned, collaborative functionalities.

This capability is anchored by a suite of unique facilities available at Argonne. The CNM provides a rich array of tools for imaging and manipulating genomes, cells, and processes over multiple scales. APS synchrotron technology is applied to determine the crystallographic structure of biological macromolecules by x-ray diffraction. Capabilities include bionanoprobe and micro-diffraction tools, and two facilities that use APS beamlines: the Argonne Structural Biology Center and the National Institute of General Medical Sciences and National Cancer Institute Structural Biology Facility. In all, 17 APS beamlines are largely dedicated to biological sample analysis, more than at any other synchrotron in the world, and the planned APS upgrade will significantly enhance capabilities to probe biological materials. These tools are complemented by the world-class Advanced Protein Characterization Facility, which can produce and characterize tens of thousands of unique proteins each year, including their kinetic and thermodynamic properties.

Examples of Argonne's leadership and unique capabilities in this field include:

- International leadership in integration of hybrid nanoparticles with biological molecules for sensing and cell metabolism
- R&D 100 awards for technologies expressing membrane proteins and extending x-ray crystallography to microcrystals
- Unique, directed molecular evolution approach for natural photosynthetic systems spanning femtoseconds to hours
- Unique expertise in protein design for robust catalysis and modulation of functionality

In recent advances in biological and bioprocess engineering, Argonne has demonstrated the abilities to engineer microbes for biofuels and bioproducts production and to engineer energy-converting proteins with radically altered function. This creates a capability to design microbes and microbial communities for energy-water research and provides a synthetic biology capability to link with the Laboratory's capabilities in bio-hybrid research programs in chemistry and materials.

Mission relevance and funding

This core capability supports the missions of DOE and other entities that seek to better understand plants and microbes to engineer them for bioenergy, carbon storage, and bioremediation. Current sponsors include DOE/EERE, DOE/SC-BES, industry, and NIH.

1.8 Climate change sciences and atmospheric science

Through collection and analysis of environmental samples, and advanced simulation modeling, Argonne research advances understanding of complex atmospheric and related soil processes, from the molecular level to the global level. Argonne's strength is the ability to develop models, methods, and data sets that bridge the gap between observations and computer simulations of the atmosphere. This work also takes advantage of the capabilities of the APS, where Argonne has pioneered the application of synchrotron technology to perform chemical and physical analyses of environmental samples such as soils, dust, and aerosols.

The Laboratory's atmospheric scientists are recognized internationally for their expertise in cloud aerosol processes and measurement techniques. To enhance that capability, Argonne recently expanded its early-career and post-doctoral research staff in this area, and is working to develop joint proposals with Brookhaven and other national laboratories. Argonne's atmospheric measurement capabilities range from remote sensing and surface meteorology instruments to instrumentation designed to quantify the land-atmosphere exchange of energy, water, and greenhouse gases:

- Since 1992, Argonne has operated the ARM-SGP site for DOE/SC/BER; data gathered there supports studies of the effects of aerosols, precipitation, surface flux, and clouds on the global climate
- Argonne scientists also have deep expertise in the development and worldwide deployment of mobile climate measurement facilities, including the ARM Mobile Facility-2, the first ocean-capable atmospheric radiation measurement facility, which traversed the Pacific to gather data on cloud transformations

Argonne's atmospheric modeling capabilities begin with regional-scale climate, air quality, and aerosol modeling and extend to global chemical transport models, general circulation models of the atmosphere, models of the biosphere, and coupled earth system models. A team of over 30 scientists applies ALCF and other Argonne high-performance computing capabilities in support of earth systems modeling and atmospheric sciences:

- The Laboratory contributes computational and science leadership to DOE's multi-laboratory Accelerated Climate Modeling for Energy (ACME) program
- Argonne meteorological experts have used the ALCF to simulate the North American climate for 1980-2090 at the most detailed resolution (12 km) ever achieved

The Laboratory's research also explores varied aerosol and soil phenomena that have the potential to drive climate change. Knowledge gained will be applied to improve climate models:

- Groundbreaking aerosols research has identified the importance of light-absorbing organic carbon (brown soot) in the earth's radiation budget and, through the use of the APS, determined the chemical changes that aerosols undergo as they cross the Atlantic
- Argonne is a world-recognized expert in arctic soils and soil structure, and is pioneering new methods for characterizing soil composition and decomposability; that knowledge is being applied to evaluate the potential for thawing Arctic permafrost to release carbon dioxide

Mission relevance and funding

This core capability supports the missions of DOE and other agencies with climate science initiatives. Current sponsors include DOD, DOE/SC-BER, DOI, and EPA.

1.9 Nuclear Energy Capabilities

Argonne is internationally recognized for its pioneering work in chemical separations, nuclear chemical engineering, and the materials science of actinides, radioisotopes, and the nuclear fuel cycle. A unique portfolio of research facilities enable this work, including:

- APS, ATLAS, and ALCF

- Electron microscopy tools
- Two co-located, purpose-built radiological facilities: a low-energy electron linear accelerator and a chemical separations system for radioisotope production and isolation
- Radiological laboratories that enable Argonne to develop and test advanced electrochemical and aqueous processes, to support development of innovative nuclear fuel cycle and safeguard technologies

Argonne's work in this area has produced significant new knowledge, from nano-scale to pilot-scale systems. Leading research contributions include:

- Insights into the structure-property relationships behind actinide chemistry and solvent extraction across a broad spectrum of energy-related areas
- World-leading approach to defining the critical ion-ion correlations that underpin effective syntheses of transuranic materials and drive actinide/fission-product separations
- Next-generation separations and safeguards technologies for future nuclear energy systems
- International leadership role in fuel cycle technology development and demonstration

Argonne also carries out world-leading actinide science that pioneers novel approaches to the synthesis, characterization, and modeling of transuranic complexes. Purpose-built radiological facilities are used to extend understanding of the chemistry of these man-made elements. Predictive bonding and energetics models are targeted, within the context of separations relevant to nuclear energy, by using Argonne computational facilities to interpret x-ray data made available through the APS.

In addition, Argonne is developing capabilities in accelerator-based medical radioisotope production, with associated separation and purification technologies. In this work, the Laboratory is exploring multiple approaches to produce molybdenum-99 (Mo-99) from low-enriched uranium, to reduce dependence on overseas sources of Mo-99, which is the parent nuclide for the vital gamma-ray-imaging medical isotope technetium-99m.

The Laboratory also supports sensor and detector research for national programs in border, cargo, and transportation security, as well as chemical, biological, radiological, and nuclear incident mitigation. Research 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 core 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 organizations.

1.10 Nuclear Engineering

Argonne pioneered nuclear energy systems and continues to work to advance those systems to provide an abundant, sustainable, safe, and secure energy source. The Laboratory's 300 member nuclear engineering team carries out R&D in nuclear energy, nuclear security and nonproliferation, and other applications of nuclear science and technology. This team is internationally recognized for groundbreaking research in both advanced nuclear energy technology and nuclear materials security. National and international collaboration with research and industrial partners is a hallmark of Argonne's approach to nuclear engineering R&D.

Nuclear engineering R&D leverages the Laboratory's strengths in materials science, nuclear and radio chemistry, nuclear physics, and computational science. Key facilities that support this work include APS; ALCF; ATLAS; Intermediate Voltage Electron Microscopy-Tandem Facility (IVEM), which has unique capabilities to image changes in materials during irradiation; and specialized engineering development laboratories for detailed studies of reactor components and separations flowsheets under prototypic conditions through the engineering scale. Using ALCF, Argonne pioneered the application of high-performance computing to nuclear-reactor analysis via the Center for Exascale Simulation of Advanced Reactors (CESAR).

Because of its history in and continued contributions to the development of nuclear power, Argonne is uniquely positioned to:

- Lead the assessment and conceptual development of innovative reactors operating with a variety of neutron energy spectra, coolant types, and fuel-cycle schemes
- Partner with industry and other national laboratories in development and commercialization of innovative nuclear systems
- Support U.S. engagement of other nations in cooperative research and assessments

Argonne plays a leadership role in U.S. efforts to develop and integrate innovative technologies to improve the performance, safety, and economics of future nuclear reactor and fuel cycle systems. In particular, the Laboratory is internationally recognized for technical leadership in developing fast-neutron reactors, which can use recycled fuel to better manage nuclear waste, use uranium more efficiently, and reduce the need for uranium enrichment. Argonne is also advancing the design, licensing, and construction of other new types of reactors, such as small modular reactors, and is partnering with the Korea Atomic Energy Research Institute to develop a sodium-cooled fast reactor.

The Laboratory also makes essential contributions toward sustaining the safe operation of existing light water reactors, addressing the challenges of used nuclear fuel and nuclear materials management. Argonne's capabilities to examine and characterize irradiated fuels and materials under diverse service conditions are essential for confirming reactor safety and providing a sound technical basis for regulation of existing plant operations and industry initiatives to optimize power generation, increase fuel burnup, and extend plant lifetimes.

Argonne is the U.S. leader in international efforts to reduce nuclear proliferation and security risks. The scope of work in this area includes conversion of research reactors to low-enrichment fuels, technology export control, and risk and vulnerability assessments. This leadership was demonstrated in the Laboratory's technical work in support of the Joint Comprehensive Plan of Action agreed upon by the United States and Iran in 2015: Argonne contributed to the redesign of the Arak heavy-water reactor and provided reactor physics and thermal-hydraulic analyses to support a tactic for inventory control of fresh low-enriched uranium.

Mission relevance and funding

This core capability supports the missions of DOE and other organizations to develop advanced nuclear energy systems and enhance the security of nuclear technology applications worldwide. Current sponsors include DOE/NE, DOE/NNSA, NRC, the nuclear power industry, and overseas organizations.

1.11 Cybersecurity, Decision Making, and Integrated Systems Capabilities

Argonne is a nationally recognized leader in defending computer networks against cyber threats: the Laboratory conducts research into new cybersecurity approaches, performs analyses, identifies methods to enhance operational due diligence, provides tools, and manages enterprise-class programs. More than 50 staff members are dedicated to the cybersecurity mission. Key Argonne capabilities include:

- Cybersecurity research in data analysis, energy resiliency, intelligent log analysis, authentication, infrastructure risk assessment, moving target defense, vehicle security, power grid cyber susceptibility, and technologies to increase resilience and improve national security
- Design of tools for evaluating the resiliency, interdependency, and defenses of computer systems that operate critical infrastructure, as well as the consequences of attacks on those systems
- Creation of regional cyber resiliency plans, including incident response and recovery

- Development of techniques for offensive cybersecurity programs, including penetration testing and nation-state threat analysis
- Conduct of both quick-turnaround and long-term assessments of cyber threats, vulnerabilities, consequences, and dependencies, including regional and national cascading dependencies and impacts: these assessments address topics such as cloud infrastructure, industrial control systems, the electric grid, emerging technologies, internet of things, the Darknet, internet infrastructure, water and wastewater treatment plants, and ports, locks and dams

Facilities that support this core capability include enterprise data centers that host a multi-agency secure private cloud and state-of-the-art facilities for analyzing the cyber-security of vehicles.

In addition, Argonne developed and maintains the DOE Cyber Federated Model, a highly regarded tool that is used by DOE, other federal agencies, the energy sector, and selected commercial partners. This model provides automated, real-time sharing of cyber threat indicators among participating organizations, and enables machine-speed mitigation of cyber threats.

Mission relevance and funding

This core capability supports the missions of DOE and other federal agencies that are charged with assuring the resilience of federal information systems and cyber infrastructure. Current sponsors include DHS (multiple entities), DOD, DOE/IN, DOE/NNSA, DOE/OCIO, DOE/OE, NERC, and NSA; Argonne's DHS sponsors include CS&C, FEMA, FPS, I&A, IP, OCIA, PSCD, and TSA.

1.12 Decision science and analysis

Argonne combines its rich expertise in systems and decision analysis with computer simulation to bring science to inform government decision-making. With over 200 staff members working in decision science and analysis, the Laboratory is internationally recognized for addressing pressing national challenges through innovative applications of agent-based modeling, complex adaptive system modeling, system dynamics, complex network analysis, and life-cycle analysis.

For nearly 40 years, Argonne has successfully applied decision science and judgment science to evaluate options over multiple objectives in uncertain, large-scale environments and to identify optimal actions. Much of this work is carried out in collaboration with the private sector.

Facilities that support this work include an immersive decision visualization studio and the ALCF; leadership computing has notably been applied to the analysis of social and behavioral systems, including predictive modeling of the spread of infectious disease in urban areas and the mitigating effects of interventions.

Argonne has provided national and international leadership in:

- Application of novel agent-based modeling approaches to electric power system behavior, market acceptance of advanced technology and the resulting impact on the power grid, and homeland security systems
- Development of bottom-up approaches to understanding supply chains and market dynamics for critical materials for the national stockpile and for clean energy technologies
- Evaluation of alternatives for interdependencies and resilience of lifeline infrastructures
- Analysis of social dynamics applied to energy and national security issues
- Analysis of the energy and environmental impacts of vehicle and fuel technologies

Through this work, the Laboratory contributes a wealth of credible and objective information to support federal agencies in decisions regarding technology choice, policymaking, planning, resource allocation, market engagement, and national security. The breadth of Argonne's expertise in this area positions the Laboratory to support decisions regarding emerging topics of national importance, such as the energy-water nexus. This core capability strongly leverages the tools developed in Argonne's work in systems engineering and integration as well as its work in cyber and information sciences.

Mission relevance and funding

This core capability supports the missions of DOE and other federal agencies that are charged with developing defensible, cost-effective decisions and policies in complex and uncertain environments. Current sponsors include DHS, DOD, DOE/EERE, DOE/EPSA, DOE/NE, NGA, NIH, and NSF.

1.13 Systems engineering and integration

Argonne's capstone R&D programs are supported by crosscutting systems capabilities that strongly leverage basic research and major scientific user facilities. The Laboratory is widely recognized for leadership in developing experimental facilities and analytical tools to advance understanding of transportation, infrastructure, urban, communications, and other large-scale systems. These facilities and tools support Argonne's core capability in decision science and analysis.

Argonne applies its world-renowned transportation systems engineering capabilities to identify efficiencies that reduce greenhouse gas emissions. Specialized resources used in this work include:

- Experimental facilities:
    - APS, used to study fuel injector spray dynamics and combustion chemistry in automotive engines
    - Advanced Powertrain Research Facility, used to evaluate vehicle propulsion systems
    - Engine Research Facility, used to study in-cylinder combustion and emissions under operating conditions
    - Electric Vehicle (EV) − Smart Grid Interoperability Center at Argonne, with sister facilities in Italy and the Netherlands operated by the European Commission's Joint Research Centre (JRC), used for research to facilitate transatlantic interoperability between EVs and the charging infrastructure and, ultimately, smart-grid integration
- Transportation Research and Analysis Computing Center (TRACC), which provides high-performance computing resources for transportation modeling and planning, computational fluid dynamics research for applications such as vehicle aerodynamics, and computational structural mechanics research
- Software tools including:
    - Autonomie, a powertrain simulation tool used by the automotive industry and researchers worldwide for vehicle energy predictions
    - VERIFI's experimentally validated three-dimensional computational fluid dynamics model of engine combustion that runs at the ALCF
    - GREET model of the greenhouse-gas impacts of vehicle and fuel technologies
    - POLARIS model of the traffic flows that result from individual travelers' choices

The Laboratory's expertise in vehicle energy consumption and emissions is leveraged for global benefit through Argonne's ongoing collaborations with Chinese universities and industry via the U.S.-China Clean Energy Research Center's Clean Vehicles Consortium.

Argonne is nationally recognized for development of methods to help solve security, risk, resiliency, and interdependency problems facing lifeline infrastructures; this work focuses on disruptive natural and man-made events. In complementary work, the joint Argonne / University of Chicago Urban Center for Computation and Data provides resources and tools to address the global challenges created by rapid urbanization and aging cities. Additionally, as part of the DOE Grid Modernization Laboratory Consortium and in partnership with industry, Argonne is developing analytical and modeling tools, including advanced computational algorithms, to drive improvements in the U.S. electrical infrastructure.

Notable methods and tools that support Argonne's analyses of varied large-scale systems include geospatial analysis and agent-based modeling. The Laboratory is a leader in geospatial analytics, with applications ranging from understanding the distribution of carbon reservoirs in Arctic permafrost, to monitoring infrastructure vulnerabilities, to supporting environmentally sound development of energy resources. This expertise is grounded in geographical information systems, high-performance computing, and deep domain knowledge in biology, ecology, hydrology, economics, engineering, remote sensing, environmental statistics, and risk analyses. In addition, Argonne's crosscutting agent-based modeling capability is world renowned for its effectiveness in simulating the social and behavioral systems that drive outcomes ranging from the spread of disease to market acceptance of new technology. As part of this work, Argonne has developed the Repast modeling toolkit, which is widely used world-wide to build agent-based models.

Mission relevance and funding

This core capability supports the missions of DOE and other federal agencies to address issues of national significance in energy, environmental, and infrastructure security. Current sponsors include DHS; DOD; DOE/EERE; DOE/EPSA; DOE/OE; DOE/SC-ASCR, -BER, and -BES; DOS; DOT; and industry.

4. Science Strategy for the Future

Argonne's strategy for the future is customer focused and grounded in core science and user facilities. The Laboratory integrates its scientific and engineering capabilities to overcome critical challenges across the spectrum from basic research to the transition of technology to market. Convening partnerships – at the regional, national, and international levels – is a cornerstone of Argonne's strategy. This strategy is executed both through transformational projects that are underway today and through major initiatives to build crucial new mission capabilities.

The Laboratory's top-priority projects are:

- For the Advanced Photon Source Upgrade (APS-U), achieve CD-3b approval in 2016 and hold a CD-2 readiness review in 2017
- For Argonne Leadership Computing Facility (ALCF), deploy the ALCF-Lithium computing system in 2016 and the ALCF-3 system in 2018
- For the Joint Center for Energy Storage Research (JCESR), deliver world-leading energy storage science that meets the Center's goals and define a strategy for JCESR-2

Argonne is investing discretionary resources in a portfolio of major initiatives[3] to significantly advance its capabilities in discovery science, scientific facilities, and innovation in energy technology and national security. These initiatives, which support the missions of a diverse set of DOE offices, other federal agencies, and private-sector entities,[4] have wide-ranging goals:

- Deliver powerful new experimental capabilities that enable solutions to grand-challenge problems in science and engineering by:
    - Designing and operating transformational hard x-ray light sources

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[3] The goals of the systems science initiative described in Argonne's 2015 Laboratory Plan are now being pursued within the major initiatives described in this year's Plan.

[4] Throughout Sec. 4 of this plan, organizations whose missions are supported by particular initiatives are listed in alphabetical order, based on sponsor acronym.

  - Leveraging cosmological observations to understand fundamental physical properties
- Develop new classes of hardware and software for leadership computing by:
  - Creating robust software for data-intensive, exascale computing applications
  - Designing alternative, neuromorphic computing architectures
- Create new chemistries and materials, both biological and non-biological, that enable diverse applications, particularly in the energy sector
- Improve understanding of the natural world by:
  - Reimagining climate measurement to enable high-resolution modeling of climate and earth systems
  - Characterizing proteins' functions *en masse*, to identify microbial processes that drive the global carbon cycle
- Advance the nation's goals in energy efficiency and security by:
  - Increasing the national and global impact of Argonne's energy storage research
  - Driving rapid development of advanced vehicles and transportation systems
  - Developing advanced nuclear reactor technologies and enabling secure use of nuclear energy
  - Revolutionizing the design and resiliency of future infrastructure systems

The Laboratory is also continuing its ArgonneNext initiative to enable superior science and technology through enhanced facilities, information systems, community and competitive advantage.

5. Infrastructure

Overview of Site Facilities and Infrastructure

Argonne is located on 1,517 acres, about 25 miles southwest of Chicago, in DuPage County, Illinois. The site includes 157 buildings totaling 4,966,048 gross square feet (SF).[5] The Laboratory's site, overseen by DOE/SC, accommodates about 12,800 persons yearly, including Argonne and DOE employees, contractors, facility users, visiting scientists, and students.

In addition to buildings operated by Argonne, the site includes the Howard T. Ricketts Regional Biocontainment Laboratory, operated by the University of Chicago; the Theory and Computing Sciences Building, a privately operated building in which Argonne leases about 240,000 SF; and Building 350 (the former New Brunswick Laboratory), currently operated by DOE.

The average age of the Argonne-operated facilities and infrastructure is 49 years, with more than 58% of the assets being more than 50 years old. Argonne facilities are roughly 90% occupied. The Laboratory's asset utilization index values related to use-specific measures exceed the DOE goals for the laboratory, warehouse, and housing use types. Excluding the accelerator facilities that are designated as "3000-series assets" by DOE, the current overall site-wide asset condition index (ACI) is 0.90 (adequate). The ACI is based on identified deferred maintenance as it relates to the estimated plant replacement value. The specific ACI for Argonne buildings, structures and trailers for each mission category is as follows:

- Mission-critical – ACI = 0.90 (adequate)
- Mission-dependent – ACI = 0.83 (fair)

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[5] The number of buildings reported has increased significantly from past years' Laboratory Plans as a result of a re-categorization of assets previously identified as Other Structures and Facilities, per new DOE Facility Information Management System guidance. This re-categorization also increased the average building age and decreased the ACI and the overall occupancy rate.

- Not-mission-dependent – ACI = 0.88 (fair)

No real estate actions – including new (or renewal) leases of 10,000 SF or more or disposals of DOE land via leasing, sale, or gift – were executed in FY15. For FY16, a 10,000 SF lease to SBA Towers, LLC, is planned to support a multi-provider cellular tower, which will significantly improve cellular service for Argonne employees and visitors as well as for members of neighboring communities.

Campus Strategy

To achieve its infrastructure vision, Argonne has developed a long-term plan to revitalize existing facilities and infrastructure to meet current and emerging mission needs. This includes complying with standards of environmental performance and safety, eliminating legacy waste and obsolete facilities, and optimizing operating and maintenance support. The Argonne physical site has few constraints to expanding the Laboratory's role in 21st century research, beyond the need for modern facilities and the elimination of outdated and unneeded buildings.

Argonne has developed a structured, 10-year site modernization plan. Needs identified in the plan are prioritized, with timing and sequencing of actions chosen to optimize the benefits and leverage the resources available for execution. The conceptual locations of proposed investments are summarized in Figure 6.1, with the details of the investment plan presented in Tables 6.1 and 6.2. The site modernization plan may be accessed through Argonne's website, www.anl.gov.

Four main objectives guide the campus strategy: support mission-critical programs, build replacement facilities and reuse/renovate existing facilities, address support infrastructure, and address legacy waste and excess facilities. These objectives are detailed below.

Argonne continues to commit internal resources to *support mission-critical programs* that have immediate infrastructure needs. Argonne has aligned upgrade projects for the Bldg. 528 Central Chilled Water Facility and Bldg. 551 Electrical Substation to meet site cooling and electrical capacity demands projected for the ALCF upgrades and the future Materials Design Laboratory (MDL). The APS-U project has identified multiple space requirements to meet project objectives: reuse of existing facilities will be pursued for most space types, but unique space for a magnet receiving, assembly, and staging (MRAS) building has been identified as a new leased-facility need. Additionally, new multi-user facilities, such as clean-room and dry-room spaces, will support multiple R&D objectives and core capabilities including particle physics, condensed matter physics and materials, and applied materials science and engineering.

To meet the objective of *building replacement facilities and reusing/renovating existing facilities,* Argonne is renovating and modernizing facilities in the 200 and 300 areas of the campus to meet current and future scientific laboratory facility needs through flexible design approaches. These efforts apply overhead investment to enable re-use of facilities that, although obsolete due to age, retain positive structural and space characteristics that promote modern scientific research. In parallel, new facilities such as the MDL, funded by the DOE/SC Scientific Laboratories Infrastructure (SLI) office, and the Energy Innovation Center, funded by the State of Illinois, are being designed and built to provide modern lab spaces and allow Argonne to vacate and ultimately demolish inadequate spaces.

Argonne continues to maintain a rigorous process to *address support infrastructure* conditions to prioritize and implement repairs and upgrades to meet reliability and redundancy goals. The Laboratory is committed to reducing the identified deferred maintenance backlog, with an ultimate target of achieving the DOE-established ACI goals for "mission critical" and "mission essential" facilities. Adequate funding of routine maintenance and the major repairs program is necessary to decrease deferred maintenance, along with significant contributions from Laboratory overhead funds and the DOE/SC-SLI office. Specific investments include DOE General Plant Project (GPP) funding for electrical reliability upgrades to the 138kV high voltage system in addition to water and sewer utility upgrades to improve substandard assets. Figure 6.2 summarizes these assets by condition as defined by the DOE Laboratory Operations Board (LOB). Longer-term plans to support full electrical infrastructure redundancy for the Argonne site, through external power upgrades and the construction of a secondary site power supply, are also identified as future DOE/SC-SLI line item projects.

Argonne remains committed to *addressing legacy waste and excess facilities***.** Removal of legacy waste and excess facilities is consistent with the DOE/SC goal of achieving an asset utilization index ratio of 1:1 for comparison of utilization-justified assets to current real property assets; it also supports complex-wide DOE requirements for overall footprint reductions via space banking. As of April 2016, Argonne's estimated unfunded, nonrecurring liability totaled $591 million, based on recent in-house evaluations of the remaining legacy facilities. The Laboratory's approach to designating facilities as excess, and prioritizing excess facilities for removal, is based on an evaluation of whether a facility:

- Has been, or over the next 10 years will be, replaced by new construction or vacated as a result of program consolidation
- Is an unlikely candidate for renovation due to contamination, infrastructure condition, or its general age/deterioration and/or
- Has potential negative impacts to the environment, employee safety, or the surrounding community

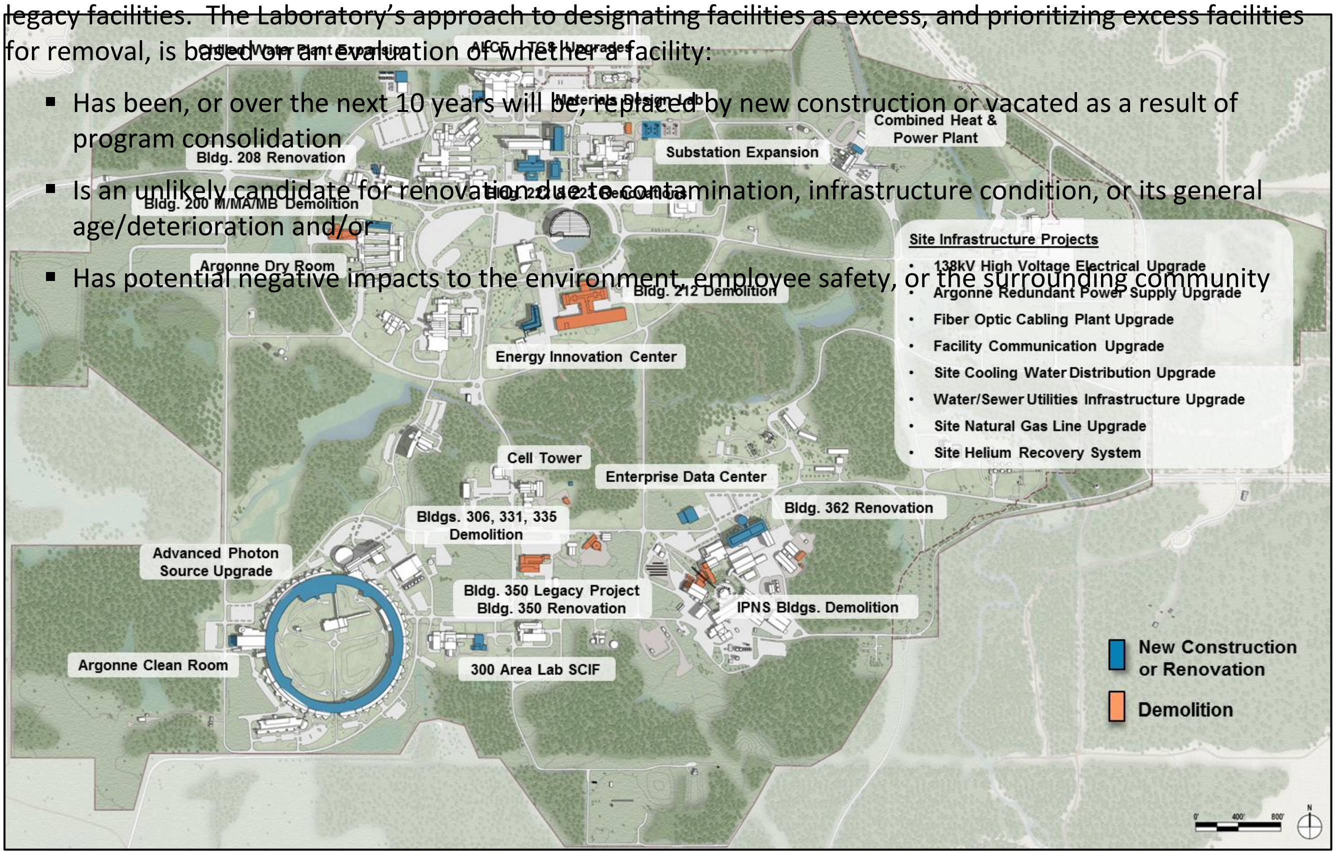


Figure 5.1 Ten-year campus infrastructure strategy

The Laboratory is aggressively consolidating radiological facilities and reducing inventories of radiological materials, while preserving the capability to perform mission-important activities. Partnering with DOE to identify stable funding is required for expeditious cleanup, material and waste disposition, and ultimate disposition of these facilities.

Argonne has requested DOE/EM funding to remove several contaminated facilities that are or will become inactive within this reporting period; however, due to federal budget constraints there is an increased risk of not receiving funding within the proposed time frame. This lack of timely funding significantly impacts Argonne's deferred maintenance projections. Figure 6.3 compares the projected deferred maintenance profile with and without DOE/EM-funded demolitions.

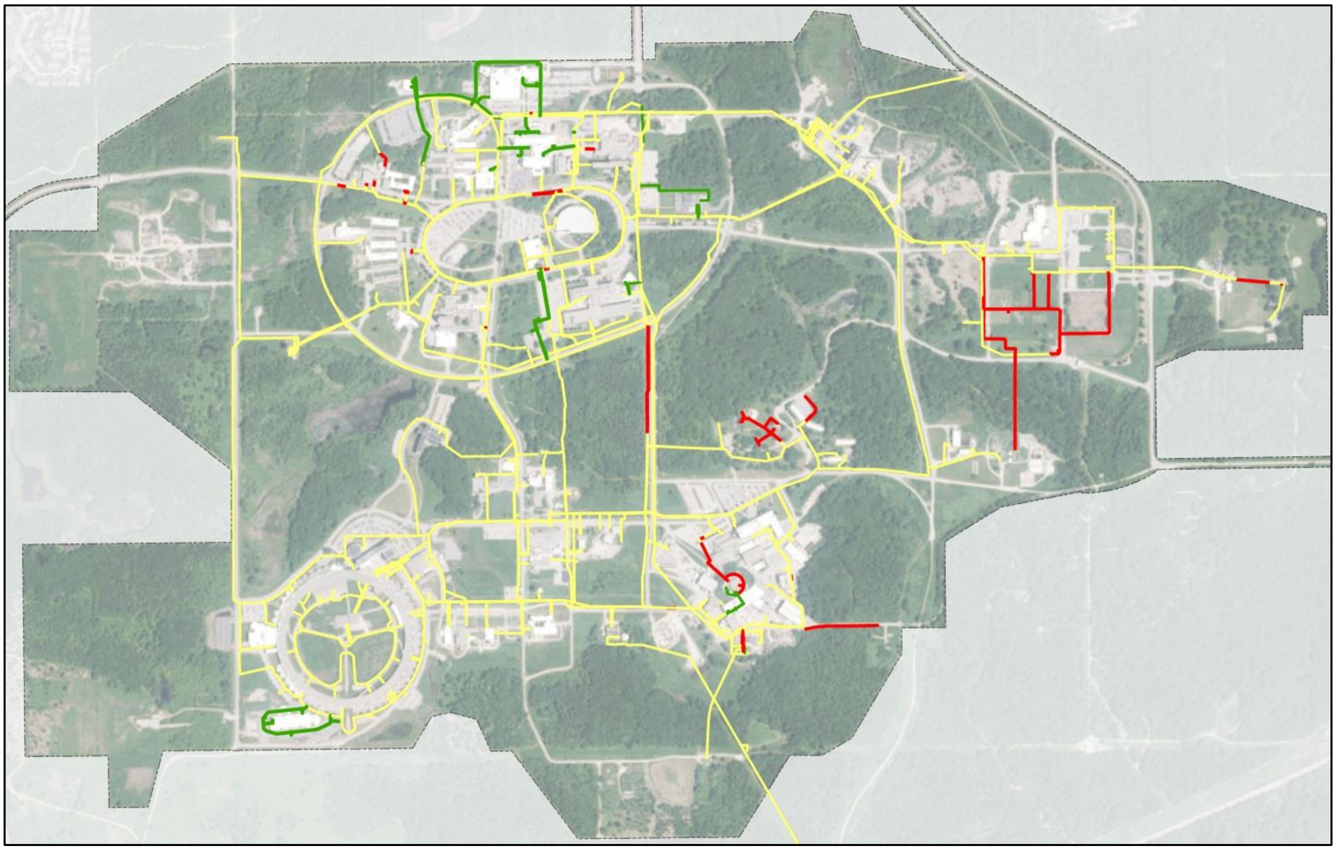


Figure 5.2 Water and sewer utilities condition summary

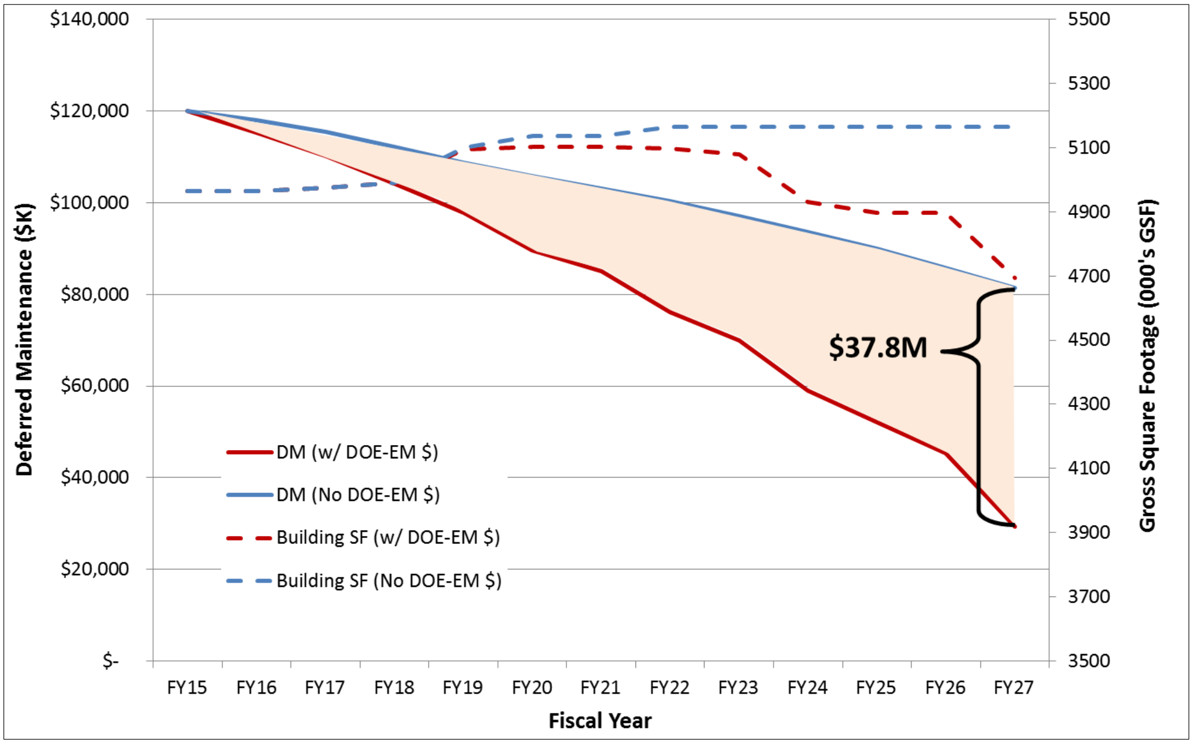


Figure 5.3 Impact of DOE/EM demolition funding on deferred maintenance projection

Table 5.4 Infrastructure gap and investment strategy by core capability

Core capability	Time frame	Infrastructure gap	Risk	Investment strategy
Accelerator science & technology	Today	Current labs and offices require modernization due to aging infrastructure and substandard conditions	Aging facilities will limit the ability for researchers to perform basic research and attract/maintain research talent	- Use major repair program investments to address prioritized rehabilitations to existing labs and offices (~$5M/yr OH – *Major Repair Program*)
	Future (10 years)	Significant enhancement (clean rooms, refrigeration, electrical power) required for superconducting radio-frequency (RF) facility	Without the necessary upgrades, superconducting RF operations will be limited and will prevent the advancement of R&D efforts	- Leverage investment in separate Argonne clean room facility adjacent to CNM *($9.3M IGPP – Argonne Clean Room)* - Address program-specific facility needs (i.e., reconfiguration or installation of specialized capabilities) through programmatic operating funds
Advanced computer science, visualization and data **Applied mathematics** **Computational science**	Today	Chilled water and electrical utility upgrades required to support new pre-exascale leadership computing equipment (e.g., ALCF-3)	Lacking adequate cooling supply or electrical capacity investments, the new equipment cannot be supported by existing infrastructure, severely impacting the ability to perform mission	- Since FY13, expanding chilled water plant and electrical substation aligned with 200 Area infrastructure investments *($9.3M IGPP – Central Chilled Water Plant Upgrade, $8.7M IGPP – 200 Area Substation Expansion)* - Install 138-kV line upgrade to support full electrical redundancy to TCS building/data center *($3.6M GPP – High Voltage Electrical Upgrade)*
	Future (10 years)	Data center space and cooling/electrical infrastructure required to support exascale leadership computing equipment	Without investments, Argonne will not be able to support exascale computing	- Begin Argonne redundant power supply upgrade in FY19 *($60M SLI – Argonne Redundant Power Supply Upgrade)* - Reconfigure ALCF-4 data center/utility room ($26.2M ASCR – *ALCF-4 – TCS Data Center Renovations and Build Out*)
Applied materials science & engineering **Systems engineering & integration**	Today	Current labs and offices require modernization due to aging infrastructure and substandard conditions	Aging facilities will limit the ability for researchers to perform basic research and attract/maintain research talent	- Renovate Bldg. 362 through a phased IGPP modernization program beginning in FY15 *($6M IGPP – Space Rehabilitation Program – Bldg. 362)*
		Lack of office space for new funded programs	Results in distributing researchers in multiple buildings, reducing collaboration and leveraging of resources	
	Future (10 years)	In-house space for computer clusters for scientific research requires expansion to meet increased IT needs	Limitations in networking and computing capacity will limit communications, analysis and scientific collaboration needed for distributed research teams	- Consolidate multiple business system and programmatic data centers into a centralized supported data center *($10M IGPP – Enterprise Data Center)*
		More clean/dry room space needed to fabricate and test prototype devices	Clean & dry room limitations will constrain progress in Argonne's advanced materials and manufacturing program	- Leverage investment in a separate Argonne clean room facility adjacent to CNM *($9.7M IGPP – Argonne Clean Room)* and Argonne dry room (*$3.0M IGPP – Argonne Dry Room)*

Table 6.1 Infrastructure gap and investment strategy by core capability (continued)

Core capability	Time frame	Infrastructure gap	Risk	Investment strategy
Biological & bioprocess engineering	Today	None	N/A	N/A
	Future (10 years)	High-throughput biology facilities to leverage protein function discovery	Generic high-throughput biological labs would support next-generation research at speeds that would close the gap from discovery to commercial markets	• Use existing Advance Protein Characterization Facility and repurpose labs as necessary
Chemical & molecular science **Chemical engineering** **Nuclear and radio chemistry**	Today	Modernization needed for radiological labs for heavy elements and separation science and applications in Bldgs. 200 and 205	Aging, outdated and/or deteriorating facilities will limit ability to perform modern 21st century science	• Relocate existing HESS programs to newly constructed radiological labs *($95M SLI – Materials Design Lab)* • Remove MA/MB Wings in FY18-19 *($21.6M DOE/EM – Bldg. 200 MA/MB Wing Demolition)*, then clean up and demolish vacated M-Wing in FY19-21 *($28.3M DOE/EM – Bldg. 200 M Wing Cleanup & Demolition)*
		Current dry room facilities are over capacity; additional spaces required to support growing research	Lack of dry room space significantly limits the ability of multiple initiatives related to energy storage, prototyping, and testing	• Renovate existing lab space for multi-programmatic users *($3M IGPP – Argonne Dry Room)* • Energy Innovation Center (EIC) *($35M AF State of Illinois – Energy Innovation Center)*
	Future (10 years)	In-house space for computer clusters for scientific research requires expansion to meet increased IT needs	Limitations in networking and computing capacity will limit communications, analysis and scientific collaboration needed for distributed research teams	• Consolidate multiple business systems and programmatic data centers into a centralized supported data center *($10M IGPP – Enterprise Data Center)*
Climate change science & atmospheric science	Today	None	N/A	N/A
	Future (10 years)	None	N/A	N/A
Condensed matter physics & materials	Today	Current labs require modernization to control temperature, humidity and electro-magnetic interference	Aging, outdated and/or deteriorating facilities will limit ability to perform 21st century science	• Relocate existing researchers and consolidate in new lab facilities *($95M SLI – Materials Design Lab)* • Renovate Bldg. 222 through phased IGPP program investments to complete the Argonne "Energy Quad" *($5M IGPP – Space Rehabilitation Program – Bldg. 222)*
	Future (10 years)	Adequate cleanroom capabilities required for sample preparation and research activities	Lack of clean space limits the ability for researchers to perform tasks related to meeting mission objectives	• Leverage investment in separate Argonne clean room facility adjacent to the CNM *($9.7M IGPP – Argonne Clean Room)*

Table 6.1 Infrastructure gap and investment strategy by core capability (continued)

Core capability	Time frame	Infrastructure gap	Risk	Investment strategy
Cyber & information sciences **Decision science & analysis**	Today	Shortage of lab and computing space that enables work for intelligence community (IC)	Insufficient SCIF space will result in inability to support growing demand for Argonne's work in multiple areas critical to the IC	• Build new SCIF space to support Argonne's increasing work for the IC *($8.6M IGPP – 300 Area SCIF)*
	Future (10 years)	Need space for infrastructure testing and modeling, including cyber testing that requires secured work spaces	Lack of available space would result in the inability to support key infrastructure system testing (e.g., 3D printing for modeling of "cyber city")	• Leverage existing vacant lab space for non-secure work in combination with use of SCIF space *($8.6M IGPP – 300 Area SCIF)*
Large-scale user facilities /advanced instrumentation	Today	Current need for increased laboratory, office, storage, and staging space	Inability to support space needs for staff and/or equipment will hinder the ability to perform research and achieve goals tied to core capability	• Lease space for APS-U magnet receiving and storage (MRAS) *($1M/year BES – APS-U MRAS Facility)* • Decommission and demolish IPNS equipment to enable reuse of existing high bay space *($6.3 GPP – D&D IPNS Monolith for reuse of Bldg. 375 High Bay and $6.9M GPP – D&D IPNS Linac for reuse of Bldg. 361 High Bay)*
		An upgrade to the APS storage ring is required to meet 21st century science objectives	Lack of an upgrade to the current storage ring would result in an inability to meet multiple research goals	• Under APS-U project, upgrade the current storage ring to meet research needs (*programmatic funds through DOE/BES)*
	Future (10 years)	Additional clean-room fabrication and assembly space needed for detector and optics R&D	Lack of additional clean space will significantly impair Argonne's ability to develop and deploy advanced optics and detectors that maximize science outcomes	• Leverage investment in a separate Argonne clean room facility adjacent to the CNM *($9.7M IGPP – Argonne Clean Room)*
Nuclear engineering	Today	Modern radiological laboratory facilities are needed in Bldg. 205	Upgraded facilities, if not provided or identified, will limit the ability of researchers to support the mission need	• Overhead investments will address prioritized repairs to existing labs and offices *($5M/yr OH – Major Repair Program)*
	Future (10 years)	Existing nuclear facilities (e.g., AGHCF) have transitioned to a de-inventory status	New or upgraded facilities and relocation are needed before complete shutdown and demolition of existing nuclear facilities	• Consolidate programmatic research into remaining facilities after renovation (*Out Year IGPP Investments*) • Remove abandoned IPNS buildings *($14.6M DOE/EM – D&D IPNS Bldgs. 379, 384, 389B, 390, 391, 399)* • Characterize, dismantle and de-inventory equipment to prepare to demolish Bldg. 212 FGH Wings *($66.4M DOE/EM – Bldg. 212 FGH Wings Cleanout and D&D)* and Bldg. 212 ABCDE Wings *($51.8M – Bldg. 212 ABCDE Wings Cleanout and D&D)* • Remove legacy nuclear waste support infrastructure *($28.6M DOE/EM – Bldg. 306 Cleanout and D&D and $43.1M DOE/EM – D&D Shell Rad Bldg. 331)*

Table 6.1 Infrastructure gap and investment strategy by core capability (continued)

Core capability	Time frame	Infrastructure gap	Risk	Investment strategy
Nuclear physics	Today	Current labs and offices require modernization due to aging infrastructure and substandard conditions; chilled water distribution restricting capacity available for equipment	Aging facilities will limit the ability for researchers to perform basic research, and limit programmatic equipment upgrades and synergies created through neighboring capabilities (e.g., ALCF)	• Use major repair program investments for prioritized rehabilitations to existing labs and offices *($5M/yr OH – Major Repair Program)* • Upgrade chilled water distribution system *($8.5M IGPP – Site Cooling Water Distribution Upgrade)*
		Relocation of the Californium Rare Ion Breeder Upgrade (CARIBU) transfer facility from Bldg. 212	CARIBU transfers currently using Alpha Gamma Hot Cell Facility (AGHCF) in Bldg. 212 must be relocated to maintain the source material which, if unavailable, would result in ATLAS being unable to produce its unique rare-isotope beams	• Renovate space in the 200 Area to allow for continued, safe CARIBU transfers to support ATLAS *($4.2M GPP – ALTAS CARIBU Facility Relocation/Renovation)* • Fully deactivate AGHCF through RH-TRU waste removal once CARIBU needs are met *($15.5M OH – RH Waste Removal (AGHCF, 331, 306))* • Clean out and demolish Bldg. 212 FGH Wings once AGHCF is deactivated ($*66.46M DOE/EM – Bldg. 212 FGH Wings Cleanout and D&D)*
	Future (10 years)	Ion source space west of ATLAS needed, as well as power and cooling infrastructure for ion separator	Lacking this investment, the ability of ATLAS to develop additional needed capabilities and follow its long-range plan will be significantly impacted	• Expand electrical substation and chilled water plant *($9.3M IGPP – Central Chilled Water Plant Expansion and $8.7M IGPP – 200 Area Electrical Substation Expansion)* • Meet individual program-specific facility needs (i.e., reconfiguration or installation of specialized capabilities) through programmatic operating funds
Particle physics	Today	Current labs and offices require modernization due to aging infrastructure and inadequate facilities to support initiatives	Inadequate and aging facilities will limit ability to perform basic research and develop advanced detector systems required to support multiple objectives	• Consolidate programmatic research from multiple buildings in the 300 Area to renovated space in 200 Area *($8.5M IGPP – Space Rehabilitation Program – Bldg. 223)*
		Additional clean fabrication and assembly laboratory space is required	Ability to perform assembly and fabrication activities will be significantly limited or result in significant waste as a result of increased number of non-compliant components due to contamination	• Leverage investment in separate Argonne clean room facility adjacent to the CNM *($9.3M IGPP – Argonne Clean Room)*
	Future (10 years)	None	N/A	N/A

Table 6.2 Laboratory facility and infrastructure investments ($M, activity/funding key below table)

Objective 1 - Support mission-critical programs

Objective 2 – Build replacement facilities and reuse/renovate existing facilities
Objective 3 – Address support infrastructure
Objective 4 – Address legacy waste and excess facilities

Project	Total	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	Activity type	Funding program
Central chilled water plant expansion	**9.3**	4.5	3.4												IGPP	OH
200-Area electrical substation expansion	**8.7**	2.3	3.5	1.0											IGPP	OH
ALCF-4: TCS data center renovations/ build out	**26.2**						2.2	24.0							LI	ASCR
Argonne redundant power supply upgrade	**60.0**					8.0	25.0	27.0							LI	SLI
ATLAS CARIBU facility relocation/renovation*	**4.2**						4.2								GPP	SLI
APS-U MRAS facility (leased)	**5.0**				1.0	1.0	1.0	1.0	1.0						LI	BES
High-voltage electrical upgrade project*	**3.6**		3.6												GPP	SLI
Argonne clean room	**9.4**	0.4	5.9	3.1											IGPP	OH
Energy Innovation Center	**35.0**				15.0	15.0									AF	--
Materials Design Laboratory	**95.0**	7.0	23.9	19.6	24.5	20.0									LI	SLI
Space rehabilitation program - Bldg. 362 (a)	**6.0**	2.0	1.8	2.2											IGPP	OH
Space rehabilitation program - Bldg. 223 (b)	**8.5**			0.5	2.5	3.5	2.0								IGPP	OH
Space rehabilitation program - Bldg. 222 (c)	**5.0**					2.0	3.0								IGPP	OH
Space rehabilitation program - Bldg. 208 (d)	**1.6**			1.6											IGPP	OH
Argonne dry room	**3.0**			0.5	2.5										IGPP	OH
Enterprise Data Center	**10.0**	0.5	6.0	3.5											IGPP	OH
Bldg. 350 legacy project	**45.1**			2.5	10.1	10.1	10.1	9.9							--	SLI
Bldg. 350 renovations	**9.9**				9.9										GPP	SLI
300-Area laboratory SCIF	**8.6**				4.6	4.0									IGPP	OH
Out-year IGPP investments	**107.5**						4.0	12.0	14.0	14.5	15.0	15.5	16.0	16.5	IGPP	OH
Fiber optic cabling plant upgrade - 200 area	**1.4**	1.4													IGPP	OH
Fiber optic cabling plant upgrade - E/W lab	**6.3**		0.3	1.5	1.5	1.5	1.5								IGPP	OH
Facility communication upgrade - copper to fiber	**3.0**	0.6		0.6	0.6	0.6	0.6								IGPP	OH
Site natural gas line upgrade	**1.5**	1.5													IGPP	OH
Bldg. 200/205 upgrade control systems	**1.0**	0.2	0.4	0.4											IGPP	OH
Site cooling water distribution upgrade	**8.5**				1.5	2.5	2.5	2.0							IGPP	OH
Water/sewer utilities infrastructure upgrade (e)*	**8.5**					8.5									GPP	SLI
Site helium recovery system	**1.8**	0.8	1.0												IGPP	OH
Bldg. 450 hardware controls upgrade	**0.8**				0.8										IGPP	OH
Operations maintenance & repair	**586.2**	46.6	43.1	44.0	44.0	44.5	44.5	45.0	45.0	45.5	45.5	46.0	46.0	46.5	--	OH
Major repair program	**94.8**	6.1	5.0	6.0	6.5	7.0	7.2	7.4	7.6	7.9	8.1	8.4	8.6	8.9	--	OH

Table 6.2 Laboratory Facility and Infrastructure Investments (continued)

Project	Total	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	Activity type	Funding program
Extent of condition - residual contamination cleanup	**3.1**	3.1													IF-EFD	OH
CH TRU waste removal (Bldgs. 331, 306, 205)	**10.0**		0.9	0.9	1.5	2.5	2.5	1.7							IF-EFD	OH
RH waste removal (AGHCF, Bldgs. 331 & 306)	**15.5**	3.8	3.3	3.3	2.7	0.6	0.6	0.6	0.6						IF-EFD	OH
Bldg. 264 demolition (f)	**0.1**	0.1													IF-EFD	OH
Consolidated space initiative	**9.0**		3.0	3.0	3.0										IF-EFD	OH
Multi-building preparation for DOE-EM demolition*	**10.0**			10.0											GPP	SLI
Bldg. 200 MA/MB Wing demolition (g)	**21.6**				11.9	9.7									DF-EFD	--
Bldg. 200 M Wing cleanup & Demolition (h)	**28.3**					2.8	19.8	5.7							DF-EFD	--
D&D IPNS (Bldgs. 379, 384, 385, 389B, 390, 391, 399) (i)	**14.6**							9.5	5.1						DF-EFD	--
D&D IPNS monolith for reuse of Bldg. 375 high bay*(j)	**6.3**					4.1	2.2								GPP	SLI
D&D IPNS LINAC for reuse of Bldg. 361 high bay*(k)	**6.9**					4.5	2.4								GPP	SLI
D&D shell rad Bldg. 331 (m)	**43.1**								4.3	19.4	19.4				DF-EFD	--
Bldg. 202 XY Wing cleanout and D&D (n)	**1.8**				1.8										IF-EFD	OH
Bldg. 306 cleanout and D&D (o)	**28.6**											18.0	10.6		DF-EFD	--
Bldg. 212 FGH Wings cleanout and D&D (p)	**66.4**						18.2	18.2	18.0	12.0					DF-EFD	--
Bldg. 212 ABCDE Wings cleanout and D&D (q)	**51.8**										12.9	12.9	26.0		DF-EFD	--

*Denotes infrastructure crosscut proposed project

FIMS ID key

- (a) FIMS ID: 123578 (Substandard to Adequate)
- (b) FIMS ID: 123520 (Substandard to Adequate)
- (c) FIMS ID: 123588 (Substandard to Adequate)
- (d) FIMS ID: 123712 (Substandard to Adequate)
- (e) FIMS ID: 123639 & 123651 (Substandard to Adequate)
- (f) FIMS ID: 123655 (Removal of Inadequate Asset)
- (g) FIMS ID: 123515 (Removal of Substandard Wing from Adequate Bldg.)
- (h) FIMS ID: 123515 (Removal of Substandard Wing from Adequate Bldg.)
- (i) FIMS IDs: 123672, 123590, 123589, 123598, 123597, 123596, 123595 (Removal of Substandard Assets)
- (j) FIMS ID: 123714 (Removal of Inadequate Asset)
- (k) FIMS ID: 123725 (Removal of Inadequate Asset)
- (m) FIMS ID: 123548 (Removal of Substandard Asset)
- (n) FIMS ID: 216309 (Removal of Inadequate Asset)
- (o) FIMS ID: 123565 (Removal of Substandard Asset)
- (p) FIMS ID: 123519 (Partial Removal of Substandard Asset)
- (q) FIMS ID: 123519 (Removal of Remaining Substandard Asset)

Key to activity types

AF – alternative financing
DF-EFD – direct funded – excess facilities disposition, decontamination and demolition
IF-EFD – indirect funded – excess facilities disposition, decontamination and demolition
GPP – DOE general plant project
IGPP – Argonne institutional general plant project
LI – Line item in federal budget

Key to funding programs

ASCR – DOE/SC Office of Advanced Scientific Computing Research
BES – DOE/SC Office of Basic Energy Sciences
OH – Argonne overhead
SLI – DOE/SC Scientific Laboratories Infrastructure

Brookhaven National Laboratory

1. Mission and Overview

Established in 1947, Brookhaven National Laboratory (BNL) originated as a nuclear science facility. Today, BNL is a multi-purpose Laboratory with a primary mission focus in the physical and energy sciences, and additional expertise in biological and climate sciences, in energy technologies and in national security. BNL brings strengths and capabilities to the Department of Energy (DOE) laboratory system to produce excellent science and advanced technologies, safely, securely, and environmentally responsibly, with the cooperation and involvement of the local, national, and scientific communities. With a long-standing expertise in accelerator science and technology (S&T), BNL conceptualizes, designs, builds, and operates major scientific facilities available to university, industry and government researchers, in support of its DOE mission. These facilities serve not only the basic research needs of the DOE, but they reflect BNL and DOE stewardship of national research infrastructure that is made available on a competitive basis to university, industry, and government researchers. The Relativistic Heavy Ion Collider (RHIC) complex, the National Synchrotron Light Source II (NSLS-II), the Center for Functional Nanomaterials (CFN), and the Accelerator Test Facility (ATF) account for the >2000 scientists/year served at BNL. In FY 2015, the CFN served 493 users, a record number. To date, seven Nobel Prizes have been awarded for discoveries made at the Laboratory.

BNL's strong partnerships with Stony Brook University (SBU), Battelle Memorial Institute, and the Core Universities* are important strategic assets in accomplishing the Lab's missions. Beyond their roles in Brookhaven Science Associates (BSA), which manages the Laboratory, Stony Brook and Battelle are key partners in all of BNL's strategic initiatives, from basic research to the commercial deployment of

2. Lab-at-a-Glance

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

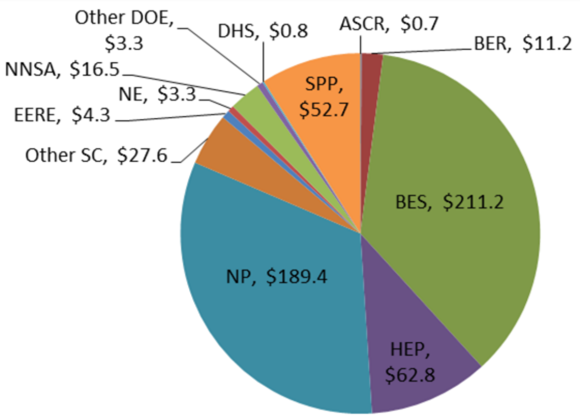
SC Physical Assets:

- 5,322 acres and 319 buildings
- 4.84M GSF in buildings
- Replacement Plant Value: $2.31B (for buildings)
- 57,520 GSF in 11 Excess Facilities
- No Leased Facilities

Human Capital:

- 2,671 Full Time Equivalent Employees (FTEs)
- 24 Joint faculty
- 133 Postdoctoral Researchers
- 256 Undergraduate Students
- 150 Graduate Students
- 2,041Facility Users
- 2,147 Visiting Scientists (guest researchers & remote users)

FY 2015 Funding by Source (Costs in $M):



FY 2015 Total Lab Operating Costs (excluding Recovery Act): $584M
Total DOE/NNSA Costs: $530M
SPP (Non-DOE/Non-DHS) Costs: $53M
SPP as % Total Lab Operating Costs: 9.0%
DHS Costs: $0.8M

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*Columbia, Cornell, Harvard, MIT, Princeton, and Yale technology, and figure prominently in BNL's energy research and development (R&D) strategy. They also underpin the Lab's growing partnership in the Northeast, especially with New York State (NYS).

3. Core Capabilities

Thirteen core technical capabilities underpin activities at Brookhaven National Laboratory**.** Each of these core capabilities 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 that includes 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 missions of DOE/Department of Homeland Security (DHS), as listed in Appendix A.

Accelerator Science and Technology

Summary**:** 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 and now including RHIC and NSLS-II. 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 National Synchrotron Light Source II (NSLS-II), the Laboratory began adopting high energy accelerator technology to achieve unprecedented brightness, integrating damping wigglers in a unique configuration. NSLS-II construction has now been completed and is operational.

BNL's development and implementation of stochastic cooling for high-energy bunched beams has enabled an earlier and much less costly completion of the RHIC-II luminosity upgrade, enhancing RHIC heavy-ion collision luminosities by approximately an order of magnitude. BNL's pioneering development of the acceleration of spin-polarized proton beams to high energy using Siberian snakes made RHIC the world's only polarized proton collider and allows for the unique exploration of the polarization of quarks and gluons inside the proton. The Lab's developing competencies in superconducting RF technology for high intensity beams, high-brightness high-energy Energy Recovery Linacs (ERL), and innovative electron cooling techniques, together with its established world-leadership in acceleration of spin-polarized beams to high energy, lay the groundwork for eRHIC, a future Electron-Ion Collider (EIC) using the RHIC facility. The ERL development is also relevant for possible future high power and high brightness X-ray Free Electron Lasers. World-leading expertise in designing and building high field magnets, including those using high temperature superconductor technology, is essential to upgrades of existing hadron colliders and to the possible construction of future circular colliders.

BNL operates the Accelerator Test Facility (ATF), a unique national user facility for beam physics experiments and technology demonstrations, which also provides training for the next generation of accelerator scientists in cutting-edge tests of advanced accelerator concepts. The ATF is the flagship facility of the DOE Office of High Energy Physics (OHEP)-funded Accelerator R&D Stewardship program. An upgrade of ATF (ATF II) is underway to provide expanded and more flexible capabilities to the user community, including that in Basis Energy Sciences.

A unique strength of the ATF is the interaction of high-power fast-pulsed lasers with high-brightness electron beams. The development of such lasers at long wavelengths (~10 μm) has led to recent breakthroughs in the generation of mono-energetic ion beams from laser bombardment of gas jets, with game-changing potential for radiotherapy. As part of the ATF II upgrade, the laser power will be increased to a world-leading 100 TW. Shorter-term collaboration with industry for improved ion beam therapy facilities is being driven by recent patents building on BNL expertise in developing synchrotrons and Fixed-Field Alternating Gradient (FFAG) accelerators for nuclear and particle physics projects.

BNL possesses strength as a world-class accelerator laboratory, which is the foundation of the Laboratory's and DOE's research programs. The Lab is pursuing stronger integration of the Accelerator Science and Technology (AST) effort to foster cross-fertilization between the accelerator R&D effort towards eRHIC and the advanced acceleration R&D at the ATF under the Nuclear and Particle Physics Directorate, and the high brightness photon R&D effort under the Energy and Photon Sciences Directorate. AST drives, both internally and externally, the projects currently envisioned to sustain the Laboratory. AST underscores the creativity, breadth, and flexibility of BNL's expertise in this area.

In order to extend BNL's strong tradition of creative accelerator design well into the eRHIC era, the joint BNL-Stony Brook University (SBU) Center for Accelerator Science and Education (CASE) was established. The mission of CASE is to educate and train the next generation of accelerator scientists and technologists, who will support the growing needs of BNL and the community at large. About ten Ph.D. students are currently engaged in accelerator research at BNL under the auspices of CASE.

The Office of Nuclear Physics (NP) [mission areas Office of Science (SC) 3, 32], the Office of Basic Energy Sciences (BES) [mission area SC 10], and OHEP [mission areas SC 24, 25, 26], as well as SBU and Laboratory Discretionary Funds are the primary sources of funding for the ongoing Accelerator Science and Technology efforts.

Advanced Computer Science, Visualization & Data

Summary: BNL has a long standing engagement in the research, development and operation of advanced computer science and data science methods, algorithms, tools and infrastructures. In the past, these capabilities were distributed across different directorates, divisions and groups. However, in 2015 BNL established the Computational Science Initiative (CSI), integrating its many outstanding computer science, applied mathematics and computational science experts under one umbrella – the newly formed CSI.

RHIC ushered in high throughput, data intensive computing as a capability at BNL 15 years ago, and ATLAS computing at BNL has built on that. The RHIC-ATLAS Computing Facility (RACF) today is a unified facility delivering leveraged, cost-effective computing to both RHIC (NP) and ATLAS (HEP). RACF provides ~90% of the computing capacity for PHENIX and STAR data analysis. The ATLAS Tier-1 facility is the largest of 11 Tier-1 centers worldwide and contributes 23% of the worldwide computing capacity to ATLAS data analysis at 99% service availability (12 month average). BNL's expertise in large scale data management has established the BNL ATLAS Center as the most important ATLAS data repository besides CERN: currently delivering ~200 TB/day to >100 data centers around the world. Together with the Physics Application Software group, these resources and capabilities make BNL today one of the largest Big Data / High Throughput Computing resources and expertise pools in U.S. science.

The purchase of the New York State-funded Blue Gene/L system (New York Blue) in 2007 (debuting as number 5 in the world) enabled the development of leading high performance computational science expertise at BNL, by bringing together computer scientists, applied mathematicians and domain scientists to advance numerical modeling for science. For example, the Lattice Quantum Chromodynamics (QCD) team developed a new high density QCD model that, boosted by New York Blue, was able to simulate 10 million times more complex systems than before. Climate scientists from BNL's Fast-physics System Testbed and Research (FASTER) project utilized the system to create a high resolution numerical model that enabled them to study cloud processes in more detail, in particular the dispersion bias, dispersion effects and aerosol-cloud interactions. Furthermore a new generation nuclear reactor model was developed in collaboration with researchers at Rensselaer Polytechnic Institute.

Today BNL has worldwide recognized computational science expertise in lattice QCD, materials and chemistry, as well as underpinning applied mathematics capabilities for example in highly scalable particle methods for multi-phase and multi-scale systems used in leading fusion, accelerator modeling and materials codes. The development of these numerical simulation codes is supported by CSI's Computational Science Laboratory. The resulting computational science capabilities are used for basic research, as well as in support of large scale experimental facilities, such as RHIC, ATLAS at the Large Hadron Collider (LHC), NSLS-II, and the Center for Functional Nanomaterials (CFN). The codes fulfill three principle functions: support the design of new facilities, plan experiments more effectively and help in the result interpretation. At present, Computational Scientists at BNL are preparing their codes for the upcoming exascale systems, utilizing the latest in programming models and numerical libraries to push the frontiers of scientific discovery. Apart from utilizing the latest computing architectures to their full potential, BNL scientists have also been instrumental in designing the next generation of computer systems, guiding industry with their in depth understanding of both hardware architectures and applications. The results of these collaborations are the 2004 QCD On a Chip (QCDOC) system and the subsequent IBM Blue Gene series. Today the same scientists are collaborating with Intel on their next generation chip design.

Under the leadership of the former Computational Science Center, BNL developed an initial capability in data analytics and underpinning software tools and technologies. This capability is now stewarded by the CSI's Computer Science and Mathematics Division (CSM) and represents CSI's most intense growth area. Research in this area focuses on the development of streaming, real time and *in situ* analysis, interpretation and decision making processes in large-scale experimental, observational, and computational discovery environments. CSI is taking a co-design approach that ranges from the system architecture to the application level. New appointments, such as Barbara Chapman, a world-leading expert in programming models, Peter Boyle, a key player in the development of the IBM Blue Gene series and outstanding computational scientist in the field of QCD, and Kerstin Kleese van Dam, an internationally recognized expert in data management, are strengthening the existing team. Today CSM supports research in fast I/O and data transfer, runtime systems, programming models and machine learning. Research results are translated by the CSI Center for Data Driven Discovery into novel tools and services for experimental facilities, such as the NSLS-II and CFN, and also the Office of Biological and Environment Research (BER) Systems Biology Knowledge Base (KBase), the electrical power grid, plant sciences, and climate science.

The primary sources of funding for this core capability come from OHEP [mission areas SC 21, 22, 24, 26], NP [mission areas SC 27, 3, 32], BES [mission areas SC 7-11], BER [mission areas SC 12, 13, 15, 16], and the Office of Advanced Scientific Computing (ASCR) [mission areas SC 4, 5, 6], as well as Advanced Research Projects Agency-Energy (ARPA-E) and Laboratory Discretionary Funds. Additional New York State funding is anticipated during this fiscal year***.***

Applied Materials Science and Engineering

Summary: BNL engages in a broad spectrum of activities related to energy storage, 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 is establishing new capabilities for nanoscale imaging using micro-electrochemical cells for X-ray and electron microscopy under *operando* conditions These capabilities are extensively used to understand complex active electrochemical interfaces, carry out research in high energy density cell technology, and to advance the goals of the Center for Mesoscale Transport Properties, an Energy Frontier Research Center (EFRC), led by Stony Brook University, in which BNL participates.

BNL also has capabilities to study materials in extreme environments. BNL has developed a specialized robot at NSLS-II for the rapid characterization of materials damaged by high-radiation environments, initially focusing on the large number of pressure-vessel steel samples stored at Idaho National Laboratory. BNL has also developed a unique end station cell for *in situ* characterization of reactor material under for high temperature and pressure.

The BNL Linac is used to support the development of new materials for advanced nuclear reactors. The 200 MeV proton beam of the Linac, the Brookhaven Linac Isotope Producer (BLIP) target facility, and the Tandem accelerators are used extensively for studies of radiation damage in materials for fast fission and fusion reactors and high-energy particle accelerator elements, such as pion production targets for neutrino experiments.

The primary sources of funding are: BES [mission areas SC 7-10], the Vehicle Technologies Program of the Office of Energy Efficiency and Renewable Energy (EERE) [mission area Energy Security (ES) 15], the Office of Nuclear Energy (NE) [mission areas NE 1, 4], and Laboratory Discretionary Funds.

Biological Systems Science

Summary: The goal of BNL's programs in biology is to develop a quantitative understanding of complex biological systems, relevant to the DOE mission with respect to energy and the environment. Expertise ranges from investigating structures of individual proteins, protein complexes, regulation of carbon fluxes from carbon capture, conversion within central metabolism and storage as reduced carbon compounds including lipids and biomass. In all cases, the objective is to create foundational knowledge that relates structure and function, so that desired manipulations, such as increasing growth rates, altering metabolic pathways to enable the accumulation of desired products, or environmental adaptation can be optimized. The tools used include structural biology in a wide variety of forms, molecular biology, physical biochemistry, biological imaging, which employ a close coupling of experiments with modeling and simulation.

BNL recently launched the Quantitative Plant Science Initiative (QPSI) to address the grand challenge of "enabling predictive biology." One key focus area will be on genomic dark space, i.e., to accelerate discovery of the large numbers of genes for which there is currently no knowledge of function. A key new capability, a genotype-to-phenotype discovery platform is under construction that will enable genome wide screening to define the roles of genes in core plant metabolism. Use of this new capability is key to developing the knowledge-base needed to model plant processes in order to identify strategies for manipulating living systems to accumulate feedstocks for fuels and other desired products. To enable this new capability, BNL is supporting three new scientific hires with expertise and focus in various aspects of biological systems science, i.e., with complementary expertise to the existing portfolio of physical biochemistry, thereby synergizing with the widely-recognized basic research capability in plant biochemistry, funded by BES, that has a strong focus on lipid production in plants. QPSI will benefit from interactions with, and shared technical expertise with this well-established group. The Biology Department has a history of securing support from application-oriented programs within DOE and private industry with the goal of transferring the results from model plant systems to potential feedstock crops to enable the production of bio-based products, including fuels and polymer feedstocks.

QPSI also leverages world-leading analytical capabilities coming online at NSLS-II during 2016, 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 (EM), and fluorescence resonance energy transfer, BNL will perform structural analysis on complex biological systems at scales ranging from angstroms to the whole plant level. BNL will also expand its capabilities for using transcriptomics, metabolomics, fluxomics and proteomics to develop and test detailed plant models so that prediction of behavior *in silico* can become a reality.

The bioinformatics and computational biology capability is an integral part of the BNL biological systems program. BNL researchers contribute to the Systems Biology Knowledgebase (KBase) development team (led by Argonne, Lawrence Berkeley, and Oak Ridge National Laboratories).

With the combination of strong existing programs in plant physical biochemistry and the emerging systems biology capability, BNL is in a strong position to build a capability in biosystems design. In summary, BNL is supplementing the existing plant biology, biochemistry, with programs in genome wide functional discovery, modeling, simulation, and computational expertise to position BNL in a prominent leadership position with regard to Quantitative Plant Science.

Funding comes from BES [mission area SC 10], the Office of Biological and Environmental Research [mission areas SC 12, 15], the National Institutes of Health (NIH), a Cooperative Research and Development Agreement (CRADA), and Laboratory Discretionary Funds.

Chemical and Molecular Science

Summary: In chemical and molecular sciences, BNL focuses on basic and applied research on catalytic chemistry for energy conversion processes and fundamental studies in chemical dynamics and radiation chemistry. Catalysis research builds on a synergistic approach that combines leadership in *operando* studies of powder catalysts, *in situ* studies of model nanocatalysts, and quantum chemical computation. *Operando* studies using synchrotron methods are now exploiting the world-leading capabilities at NSLS-II. New *in situ* imaging capabilities based on ambient pressure scanning tunneling microscopy and ambient pressure infrared reflection absorption spectroscopy are transforming the ability to characterize the catalytic active site and its interaction with reaction intermediates in model catalysts synthesized on nanostructured single crystals. These capabilities are being applied to important new energy conversion reactions, such as sustainable methanol synthesis from small molecules H_2 and CO_2. Electrocatalysis research also builds on world leadership in synthesis and characterization of nanostructured core-shell metal and metal oxide electrocatalysts to develop improved catalysts for fuel-cell reactions and electrolysis.

BNL's scientists are leaders in the development of advanced, time-resolved laser spectroscopy methods for characterization of molecular dynamics in gas and condensed phases, which are important in combustion processes, and for the study of molecule-surface interactions underlying catalytic and photocatalytic processes. These efforts combine leading experimental capabilities with computational methods in quantum molecular dynamics.

The radiation chemistry program benefits from the advanced pulse radiolysis capabilities at the Accelerator Center for Energy Research (ACER). Within ACER, the Laser Electron Accelerator Facility provides capabilities for ultrafast pulse radiolysis, a Van de Graaff accelerator supports kinetics studies on slower timescales, and two ^{60}C sources enable irradiation studies. ACER is developing time-resolved infrared spectroscopy as a unique chemically specific probe. Instrumental capabilities involve new quantum cascade laser sources and broadband step-scan Fourier transform infrared instrumentation that are transforming the ability to investigate chemical mechanisms using pulse radiolysis. This is enabling the investigation of chemical mechanisms in photocatalysis, radiation chemistry, and molecular charge transfer and transport.

Fundamental chemistry programs are funded by BES [mission areas SC 7-9, 11] and Laboratory Discretionary Funds, whereas applied fuel-cell electrocatalysis and battery-materials research is supported primarily by EERE's Hydrogen and Fuel Cells Program [mission area ES 3] and EERE's Vehicle Technologies Office [mission area ES 15], respectively.

Chemical Engineering

Summary: BNL has a small but emerging effort in applied chemical research that translates scientific discovery into deployable technologies. BNL has developed innovative catalysts that have 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.

The Synchrotron Catalysis Consortium (SCC), an open organization of current and future users of NSLS-II, will continue to offer opportunities for advanced characterization and testing of real-world catalysts to researchers from universities, industry, and other National Laboratories. New efforts under the Laboratory's *in situ* characterization theme will expand SCC efforts across multiple photon science and nanoscience capabilities to provide the foundation for an Integrated Center for Energy Sciences in catalysis.

These programs are funded by BES [mission area SC 7-9, 11], EERE Hydrogen and Fuel-cells Technologies program [ES 3] and through a CRADA with General Motors Corp.

Climate Change Sciences and Atmospheric Science

Summary: BNL's atmospheric science programs aims 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. 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 specialists, as well as by making contributions to the design and interpretation of ARM measurements. Climate scientists support the Accelerated Climate Modeling for Energy project through their expertise in component development and model validation.

BNL researchers, organized in the Terrestrial Ecosystem Science and Technology group, play a central role in both BER-funded Next Generation Ecosystem Experiments (NGEE) – NGEE-Arctic and NGEE-Tropics. Research is focused on improving the representation of ecosystem processes in Earth System Models and understanding what drives uncertainty in model structure and parameterization 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 [mission areas SC 6, 13, 15, 16] and Laboratory Discretionary Funds.

Condensed Matter Physics and Materials Science

Summary: BNL conducts world-leading research in Condensed Matter Physics and Materials Science focusing on new and improved complex, nanostructured, and correlated-electron materials for renewable energy, energy storage, and energy efficiency. This is accomplished through interdisciplinary and tightly coupled research programs in materials synthesis, including both single-crystal growth and thin-film growth by molecular beam epitaxy and pulsed laser deposition; advanced characterization using a range of experimental techniques, both lab and facility based, including scanning tunneling microscopy, photoemission, X-ray and neutron scattering, electron microscopy, and theoretical techniques focused on strongly correlated materials, from condensed-matter field theory to dynamical mean field theory. BNL is the lead institution in the Center for Emergent Superconductivity, an EFRC.

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 under development and will be completed shortly. OASIS will bring together in one instrument the ability to fabricate thin films and examine their properties *in situ* using both scanning tunneling microscopy and angle-resolved photoemission. New capabilities in X-ray scattering and angle-resolved photoemission are also being developed to exploit the opportunities afforded by NSLS-II.

BNL's ultrafast electron diffraction facility is being upgraded to considerably enhance the ability to explore non-equilibrium physics in strongly correlated materials. The upgraded facility will include an optical parametric amplifier and a double tilt sample stage. The optical parametric amplifier will allow the pumping of strongly correlated systems with different photon energies, so that it will be possible to probe degrees of freedom over a wide range of energies. The double tilt design of the sample stage will allow precise control over sample orientation, which will make it possible to separate the effects of different degrees of freedom on a single diffraction pattern. A strategic planning process, currently underway, will identify high scientific impact problems for the ultrafast electron diffraction facility and for OASIS, consistent with the scientific themes of the Department.

BNL has recently created a center for computational materials science formally called Center for Computational Design of Functional Strongly Correlated Materials and Theoretical Spectroscopy. This major initiative aims to develop a software suite that will enable its users to predict the properties of strongly correlated materials. The software is based on various flavors of dynamical mean-field theory with first-principles input. In addition to making the computer programs widely available to the scientific community, the goal is to establish BNL as the permanent home of the software, stimulate its use among NSLS-II users, and enhance the synergy with the larger Computational Science Initiative project.

BES [mission area SC 7-9, 11] and Laboratory Discretionary Funds are the primary sources of funding for the ongoing Condensed Matter Physics and Materials Science efforts.

Large-Scale User Facilities/Advanced Instrumentation

Summary: As a key part of its mission, BNL has developed and operates user facilities that individual institutions could not have afforded and would not have had the expertise to develop. In FY 2015, BNL served more than 2000 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 RACF and US ATLAS Analysis Support Center.

NSLS-II is completing its first year as a User Facility, with seven beamlines operational and available to users. Operations are routine at 250 mA in top-off mode. By the end of FY 2017, there will be 18 beamlines available in the General User program, with ~4000 hours of user operations at 300 mA as expected, with a goal of > 95% reliability. Ten additional beamlines are under development, and due to come into operations between FY 2018 and FY 2021.

The CFN, which is in its eighth year of operation, supports seven integrated, state-of-the-art facilities for synthesis of nanostructured materials by chemical and thin-film patterning methods; high-resolution characterization of materials and interfaces with advanced electron, optical, and X-ray probes; and understanding materials through theory and computational methods.

BNL envisions a future major upgrade of RHIC (eRHIC) that will attract a new generation of users interested in using high-energy electron-ion collisions to study cold nuclear matter at extreme gluon densities. BNL researchers and staff support the ARM Climate Research Facility and lead the External Data Center and ARM metadata management. Finally, ATF II will support a user facility in ultrafast electron diffraction.

BNL also makes important contributions to international facilities – the LHC, Daya Bay, and such future facilities as a Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) and Large Synoptic Survey Telescope (LSST), which is under construction. This core capability is strongly tied to those in *Accelerator Science and Technology*, *Advanced Computer Science, Visualization & Data*, and *Systems Engineering and Integration* [CC 1, 2, 13].

The Long Island Solar Farm (LISF) is creating the largest data set (solar insolation, weather, power, and power quality) for a utility-scale solar plan in the U.S. Such data represents a unique asset to study solar forecasting models and to assess the impact of large solar plants on grid operations.

The Northeast Solar Energy Research Center (NSERC) is a BNL facility to conduct field tests of innovative new solar and grid technologies. In collaboration with the Electric Power Research Institute, BNL is studying the synergistic performance and impacts of solar photovoltaic, such as LISF on transmission and distribution systems. NSERC will also allow the testing of renewable integration strategies, including the use of storage. This Center will reach-back to BNL's applied research efforts in materials and storage for grid applications, by providing analytical results illustrating the role that storage can play on the grid (see CC 3).

The Instrumentation Division supports projects and research programs at major scientific user facilities by conceptualizing, designing, and constructing state-of-the-art detectors, electronics, and optical instruments used in the experiments. BNL staff has designed and constructed or helped to construct instruments for use at RHIC, NSLS-II, Fermilab, LHC, LSST, the Spallation Neutron Source, the Los Alamos Neutron Scattering Center, the Linear Coherent Light Source, and other accelerator- and reactor-based facilities around the world. The Division is known for its leadership in noble liquid detector technology, low-noise 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. BNL has pioneered the application of diamond detectors for photon spectroscopy, and has wide experience with the construction of gamma ray spectrometers, neutron imaging and directional detectors, as well as long-range detection of special nuclear materials for national security applications.

The major sources of funding are: BES, NP, HEP, BER [mission areas SC 10, 16, 24, 25, 26, 3, 32], Case Western Reserve University, the Department of Commerce, the Department of Homeland Security (DHS) [mission area Homeland Security (HS): 2], the National Aeronautics and Space Administration (NASA), the National Nuclear Security Administration (NNSA) [mission area National Security (NS) 2], the New York State Energy Research and Development Authority (NYSERDA), the New York Structural Biology Center, NIH, and Laboratory Discretionary Funds.

Nuclear & Radio Chemistry

Summary: BNL's nuclear science programs span the range from medicine to national security. At the Brookhaven Linac Isotope Producer (BLIP), BNL plays a critical role in preparing radioisotopes for the nuclear medicine community and industry that are unavailable commercially. BLIP is one of the world's major sources of Sr-82, the parent of Rb-82. This short-lived positron emitter is Federal Drug Administration-approved and used routinely for assessment of cardiac function following a heart attack in more than 300,000 patients per year. This work continues BNL's long leadership tradition in radiotracer development.

To bolster BNL's leading role in developing and producing radioisotopes through the Medical Isotope Research and Production program, the Lab will increase the quantities of isotopes produced for cancer diagnostics and therapies. The strategic R&D vision focuses on developing radioisotopes or radioisotope pairs that combine both emission of imaging photons and alpha or beta particles for therapy. The highest priority, in collaboration with Los Alamos and Oak Ridge National Laboratories, is the development of an accelerator route to produce Ac-225, an alpha emitter with high potential for cancer therapy, especially for difficult diffuse cancers. Ac-225 has the ability to destroy cancer cells more precisely, without damaging healthy surrounding cells. However, its production has been costly and too limited to support clinical trials based on the isotope. Those shortages of Ac-225 could be significantly lessened by this research. Using high-energy proton beams to irradiate thorium targets at BLIP, BNL researchers demonstrated that the current annual supply of Ac-225 can potentially be produced in a week. A Linac beam current upgrade and the installation of a beam raster at BLIP have enhanced its capability. BLIP also supports an active program of radiation damage studies of interest to Fermilab, the Facility for Rare Isotope Beams, and LHC and for future high power accelerators. A doubling of the Linac beam current for radioisotope production and addition of a second beamline and target station for BLIP are also under consideration in the future.

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 established a CRADA with a commercial partner interested in building such next-generation centers.

BNL has leading expertise in the application of ionizing radiation for the diagnosis and treatment of cancer. The effects of ionizing radiation on living systems are studied at the 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 is collaborating in developing corresponding research proposals to the National Cancer Institute. NSRL is uniquely positioned to study the effects of exposure of materials and electronic components used in satellites and instrument to cosmic rays. BNL Management is in discussions with NASA about the modality of a user program at the NSRL, which will allow users supported by other funding sources equitable access to the facilities.

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 supports RAP's planned deployments to secure national sporting, political, and cultural events and unplanned deployments to provide radiological support to local, regional, and tribal governments and private industry.

BNL has extensive expertise in nuclear nonproliferation and international nuclear safeguards that includes nearly forty years of program management for the International Safeguards Project Office (ISPO) for 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 through the USSP to the IAEA's Department of Safeguards. BNL 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. Applying its expertise with detector materials, BNL is working with FLIR Radiation Inc. to improve the detection capabilities of the NanoRaider handheld radiation detectors.

BNL's development of cadmium zinc telluride (CZT) prototype radiation detectors and imaging arrays for nonproliferation and homeland security applications is also being applied to medical uses for early detection of cancer. This world-class capability includes the conceptualization and design phases for growing, fabricating and characterizing semiconductor crystals and/or scintillators, designing the ASICs, and assembling and testing the radiation detector prototypes for incorporation into instruments. BNL synthesizes, purifies, and grows CZT and other detector crystals in-house, and serves as an R&D hub for analysis of materials and detectors provided by other institutions. The program has used the synthesis and characterization capabilities at NSLS and CFN and has benefitted from the *Condensed Matter Physics and Materials Science* core capability (CC 8). Going forward, BNL will utilize NSLS-II, CFN, NSRL and other DOE synchrotron sources to advance this effort.

Using position-sensitive ^{3}He pixelated detectors fabricated by its Instrumentation Division, BNL has developed unique coded-aperture thermal-neutron imaging systems for arms control treaty verification and counterterrorism applications. One such system was used in the Warhead Measurement Campaign to acquire radiation signatures from stockpiled nuclear weapons. BNL participated in long-range stand-off neutron imaging exercises, collaborating with ANL and the Remote Sensing Laboratory. BNL also developed a high-bandwidth system for data acquisition from correlated gamma and neutron events that are indicative of fission chains, and demonstrated expertise in modeling of radiation transport and simulating the response of these measurement systems.

BNL staff members have twenty years of experience in nuclear security analysis and technology through the NNSA Materials Protection Control and Accounting program (MPC&A). This capability is now in demand by other countries, where there are similar nuclear material security concerns. BNL is using the experience amassed through MPC&A and ISPO to assist IAEA member states in understanding and meeting their commitments under the Nuclear Nonproliferation Treaty, especially in the Middle East, North Africa, and Southeast Asia. The Department of State's (DOS) Chemical Security Program is employing BNL for similar skills aimed at the chemical industries in these regions. BNL is also assisting with the construction of a nuclear security training center in Kazakhstan.

Funding in this area comes from several sources, including NP [mission area SC 31], DOS, NASA, NNSA [mission area NS 1, 2], DHS [mission area HS 2, 6], and a CRADA.

Nuclear Physics

Summary: BNL conducts pioneering explorations of the most fundamental aspects of matter governed by Quantum Chromodynamics (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 the infant universe was filled with a previously unknown type of liquid matter, the quark-gluon plasma (QGP). The QGP produced in RHIC collisions has a lower viscosity, relative to its density, than any other material known and has been called the "perfect fluid." The RHIC results have led to profound intellectual connections with other physics frontiers, including string theory, the origin of the universe's matter-antimatter asymmetry, strongly correlated condensed matter systems, fermion gases trapped at nano-Kelvin temperatures, and density fluctuations in the early universe reflected in cosmic microwave background maps. Important upgrades to the RHIC accelerator and detector complex (3-dimensional stochastic cooling, the Electron Beam Ion Source, collision region compressing cavities, electron lenses; DAQ upgrade and Heavy Flavor Tracker in STAR, central and forward Si vertex detectors in PHENIX) are now in place and have allowed RHIC to run at more than 20 times design luminosity for the first time in FY 2014. The vertex detector upgrades enable a robust program of heavy quark measurements from FY 2014 to FY 2016, which will be followed by a focused campaign in FY 2017-18 on the dynamics of spin in the proton and chiral effects in the QGP. A future low-energy electron beam cooling upgrade, which will allow for precision mapping of the QCD phase diagram, is in preparation for a physics program in FY 2019-2020. A major upgrade to the PHENIX experiment to allow for an extensive array of measurements using jets to precisely probe the transport properties of the QGP is in the proposal stage, in preparation for a multi-year experimental campaign in the first part of the next decade.

Heavy ion collisions, guided by theory, are used: to quantify the transport properties of the QGP and its response to energetic probes, especially jets and heavy quarks; to probe the gluon structure of nuclei at high energy; to study local fluctuations within the QGP corresponding to violations of fundamental symmetries; to search for a predicted critical point in the QCD phase diagram; and to search for fundamental transformations of the QCD vacuum at extreme temperatures. Collisions of polarized protons, both with themselves and, for the first time, on unpolarized heavy ions in FY 2015, uniquely available at RHIC, are used to elucidate the spin structure of the proton and the yet largely unexplored dynamics of spin degrees of freedom in QCD.

The dramatically improved luminosity and the enhanced detector capabilities of RHIC have enabled a series of recent surprising scientific discoveries. These include the discovery that a substantial part of the proton spin is carried by gluons, that quark-gluon plasma droplets as small as a single proton can exhibit the characteristic near-perfect fluidity (the unique ability of RHIC to accelerate and collide protons, deuterons and ^{3}He nuclei with large nuclei, such as Au, were critical in this demonstration), and the first measurement of the force between two antiprotons.

RHIC offers a synergistic environment for collaboration with universities, other National Labs, and industry. 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. They include world-leading programs in high-temperature lattice QCD simulation and the theory of QCD matter at high gluon density.

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 (121 fellows and post docs to date, 90 are associate and assistant professors, of which 60 are tenured).

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 (the Blue Gene/Q QCD with Chiral Quarks [QCDCQ] machines), as well as at leadership class computing facilities to explore theoretically the phase diagram of QCD.

Future addition of an electron accelerator would convert RHIC into an electron-ion collider that would facilitate quantitative study of a regime of saturated gluon densities, present in all ordinary matter and featuring the strongest fields in nature. BNL scientists, in conjunction with Thomas Jefferson National Accelerator Facility (JLab), are leading a national effort to develop the science agenda for a future EIC facility, for which the BNL plan, called eRHIC, is to upgrade the RHIC facility with a high energy electron beam to collide with the existing heavy ion and polarized proton beams. BNL administers a DOE-funded, peer-reviewed R&D program to support universities and Laboratories in the development of advanced instrumentation technologies for an EIC detector.

Development and enhancement of RHIC accelerator facilities benefits from a first-rate program of advanced accelerator R&D (see CC 1), while enhancement of the RHIC detector capabilities benefits from the BNL support of the Instrumentation Division (see CC 9).

BNL operates the National Nuclear Data Center, 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 and reactor design.

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 at high temperature and density. 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" and the "Beam Energy Scan Theory Collaboration," respectively. Recent high profile awards in Nuclear Physics include the American Physical Society Feshbach Prize to L. McLerran in 2015.

Funding is provided by NP [mission areas SC 27, 3, 32] as well as RIKEN and Laboratory Discretionary Funds.

Particle Physics

Summary: BNL provides intellectual and technical leadership in key 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 roles are: host institution for U.S. contributions to particle physics with the ATLAS detector at the LHC; leadership in neutrino oscillation experiments, including co-host Lab for the Daya Bay reactor neutrino experiment and host of the International Project Office for DUNE, with leading roles in the short-baseline experiments at Fermilab (MicroBooNE and the Short Baseline Liquid Argon 1 Near Detector [SBND]), and the long baseline DUNE (Fermilab to the Sanford Underground Research Facility), to complete measurement of the neutrino mixing matrix, including possible CP-violation; and development of a program of observational cosmology (LSST) and precursor efforts, the Dark Energy Survey (DES) and the Baryon Oscillation Spectroscopic Survey [BOSS]).

These roles are enhanced by BNL theory efforts and by BNL's international leadership in critical detector and advanced accelerator research and development (AARD) for next-generation facilities, including a possible energy-frontier proton-proton collider. Detector R&D at BNL is strongly leveraged by Laboratory support for the Instrumentation Division, which has made world-leading contributions to radiation detectors of various types and to low-noise microelectronics and cold electronics (CC 9). BNL has initiated physics motivated detector upgrades to ATLAS for higher luminosity running of the LHC. BNL's expertise in Nuclear Chemistry provides world-leading development of metal-loaded liquid scintillator materials critical to contemporary neutrino experiments. BNL operates a unique national user facility for AARD, the ATF, largely with OHEP funding (see CC 1). The ATF has recently been designated as the first facility to advance the goals of the OHEP in accelerator stewardship and an expansion and upgrade to the facility has been approved and is underway.

BNL develops advanced software and computing facilities for applications in high energy experiments and theory. Key expertise in high throughput computing 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, the Physics Analysis Software group, and US ATLAS Analysis Support Center. Lattice QCD simulations utilize high performance computing facilities that include the augmented Blue Gene/Q (BG/Q) machines. These now include two racks purchased by RIKEN and one purchased by BNL, both in 2012 (QCDCQ), as well as the half rack purchased in 2013 by the U.S. Lattice QCD Collaboration funded by DOE to explore theoretically the properties of elementary particles. Particle physics software and computing development for both experiment and theory benefit very strongly from synergies with RHIC facilities funded by Nuclear Physics and with the RBRC, funded by the Japanese RIKEN Institute. There are ongoing collaborative efforts with BNL's Computational Science Initiative to partially upgrade these computational resources by adding state-of-the-art machines.

The Higgs boson was discovered at the LHC in data taken mainly in 2011-2012 with strong BNL contributions to construction and operation of the detectors, analysis of the data, and computing. This discovery led to the 2013 Nobel Prize being awarded to François Englert and Peter W. Higgs. ATLAS published first results from the 13 TeV Run 2 data in 2016. Following the groundbreaking Daya Bay discovery in 2012 of a non-zero $\sin^2 2\theta_{13}$, which established that the electron neutrino is composed of all three neutrino states, Daya Bay published a precision measurement of the neutrino mixing angle θ_{13}. This measurement establishes that the future DUNE measurements of CP-violation are feasible. In 2013, using a larger data set, Daya Bay performed an analysis based on the energy spectra as well as the relative rates to improve the precision on θ_{13} to better than 10% and to make the first measurement of the atmospheric mass squared splitting in the anti-ν_e disappearance channel. This proved to be fully consistent with the ν_μ channel measured by MINOS and other experiments. More recently, Daya Bay has further improved the precision of these measurements and has published new limits on additional sterile neutrinos predicted in many Beyond the Standard Model theories. In 2015, MicroBooNE started measuring neutrino interactions.

Recent high profile awards in Particle Physics are: W. Marciano was named as a Gutenberg Fellow at the University of Mainz; S. Dawson received a Humboldt Research Award; and the Breakthrough Prize in Fundamental Physics was awarded to the Daya Bay Collaboration along with other neutrino oscillation experiments.

Funding for this work comes from OHEP [mission areas SC 21-26] as well as RIKEN and Laboratory Discretionary Funds.

Systems Engineering and Integration

Summary: BNL solves problems holistically and across multiple disciplines on several levels in order to deliver Large-Scale User Facilities/Advanced Instrumentation. 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.

One example is BNL's development of noble liquid detectors from concept, through demonstration, to implementation in major particle physics at D0 at Fermilab and ATLAS at LHC, and accompanied by continuing R&D to develop the very large liquid argon (LAr) time projection chambers (TPCs) that will serve the MicroBooNE and other short-baseline neutrino experiments at FNAL, and future long baseline neutrino experiments. The cold electronics developed at BNL for LAr TPCs have been utilized in research and development of other TPCs, such as CAPTAIN at Los Alamos National Laboratory, LArIAT at Fermilab, and ARGONTUBE at the University of Bern.

A second example involves application of high-brightness electron beam technology developed at BNL to NSLS-II and the proposed future electron-ion collider (eRHIC). A further example is BNL's integration of leading accelerator, beam delivery, targetry, and radiochemistry expertise at the BLIP Target

Production Lab.

BNL's nuclear energy experts support the 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 also uses state-of-the-art computer tools to analyze nuclear reactor and fuel cycle designs for DOE, the Nuclear Regulatory Commission (NRC), and NIST.

The major sources of funding for this core capability come from BES, HEP, NP, and BER [SC mission areas 10, 11, 21-27, 3-32], NE [NE mission areas 1, 4], National Institute of Standards and Technology (NIST), NRC, and Laboratory Discretionary Funds.

These thirteen 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.
and pre-eminence.

4. Science Strategy for the Future

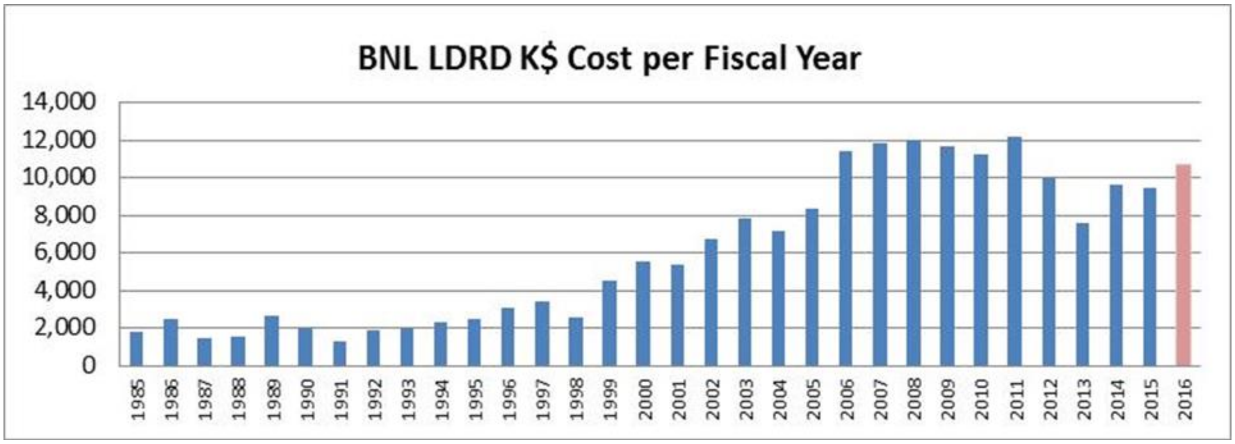
BNL has identified four scientific Critical Outcomes that, when achieved, will help realize the vision for the Lab. These are major initiatives that align with the DOE Strategic Goals in Science, Energy and Nuclear Security and build on core strengths and capabilities of the Laboratory. BNL envisions that it will substantially distinguish itself by delivering transformative science, technology, and engineering in these areas. In order to reap the potentially transformational benefits of these Critical Outcomes, a key element of Brookhaven's strategy is to pursue the evolution of its two largest user facilities – National Synchrotron Light Source II (NSLS-II) and the Relativistic Heavy Ion Collider (RHIC).

Overall LDRD Strategy

To remain at the leading edge of science and technology, BNL continuously fosters exploratory scientific research that aims to renew the Laboratory's research agenda in areas that support BNL's mission, vision, and strategy and areas that fuel Laboratory growth. The Laboratory Directed Research and Development (LDRD) program is vital to this renewal. It seeks to fund the highest quality projects through the use of calls for proposals from all qualified staff and through a highly selective review process based on peer review. The competition for LDRD funds stimulates BNL scientists to think in new and creative ways and to develop cross-disciplinary collaborations. By fostering high-risk, exploratory research, the LDRD program helps BNL to respond to new scientific opportunities related to its core capabilities, four science Critical Outcomes and other research areas where it has leading programs. Additionally, it provides the opportunity to develop new research mission areas in response to DOE and National needs. For the next few years, the emphasis of the LDRD program will be on the Critical Outcomes and Laboratory growth.

As a large portion of LDRD funding supports graduate students, postdoctoral research associates, and young scientists, LDRD provides the basis for continually refreshing the research staff as well as the education and training of the next generation of scientists. The LDRD program is essential to realizing BNL's Critical Outcomes and to the scientific health and vitality of the Laboratory.

LDRD is a key investment tool in ensuring the success of BNL's strategy. The goal is to increase the Lab's LDRD investments through Laboratory growth and cost savings initiatives. Efforts have been made over the last few years to do this but will be accelerated in the future. The history of LDRD costs from FY 1985 through FY 2015 is shown below, together with a projection for FY 2016.



5. Infrastructure

Overview of Site Facilities and Infrastructure

The vision for BNL is structured around the achievement of six Critical Outcomes. The first four are at the heart of BNL's vision for science. BNL's approach to implementing Laboratory operations emphasizes two additional Critical Outcomes. Critical Outcome 5 is a renewal of BNL's campus that will enable BNL's research mission. Critical Outcome 6 is focused on providing safe, efficient operations that ensure delivery of the research mission. The Lab's approach will provide a revitalized physical plant to improve science 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 located 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 both the Townships of Brookhaven and Riverhead. BNL 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 2015, there were 312 buildings totaling 4,839,492 square feet (sf). All buildings are owned by the DOE Office of Science (SC), as the remaining Office of Environmental Management (EM) buildings and trailers were transferred to SC during the second quarter of FY 2014. However, Other Structures and Facilities (OSF) asset ST0704, the High Flux Beam Reactor (HFBR) stack, remains under EM. BNL does not lease any facilities. In FY 2015, three buildings (B130, B810, and B811), totaling 22,642 sf, were demolished. In FY 2016, two buildings B562 and B580, totaling 1,215 sf, were demolished and a portion of B528, comprising 235 sf, is scheduled for demolition.

The average age of all buildings is 43 years. Sixty-five buildings (762,892 sf) date back to World War II (WW-II) and most major permanent science facilities, excluding the Research Support Building, Interdisciplinary Science Building (ISB), National Synchrotron Light Source (NSLS), National Synchrotron Light Source II (NSLS-II), Relativistic Heavy Ion Collider (RHIC) and the Center for Functional Nanomaterials (CFN), were built in the 1950s and 1960s. Excluding the areas covered under the Renovate Science Laboratories (RSL)-I/II Science Laboratories Infrastructure (SLI) projects and minor work done under General Plant Projects (GPP) and laboratory-funded projects, these facilities have not received any major renovation and many building systems are original.

EM has qualified for acceptance several shutdown facilities which are waiting decommissioning and decontamination, subject to available funding. Transfers to DOE-EM from DOE-SC will occur when the projects are funded. Included are the former Brookhaven Medical Research Reactor, Brookhaven Graphite Research Reactor, and HFBR facilities.

There are 11 excess buildings totaling 57,520 sf and 5 modular buildings totaling 15,337 sf connected to non-excess FIMS assets. In addition, there is 322,343 sf of underutilized space in active buildings. Approximately 50% of that is in B725, formerly the NSLS. Most office space will be reused within the next few years and approximately 75% of the former experimental floor will potentially be re-tasked as a data center with funds from the Core Facilities Revitalization (CFR) SLI project. Other major underutilized spaces relate to former HFBR reactor and reactor support space being partially used as the Lab waits for demolition funding.

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. BNL has tailored its ten-year campus strategy to support the programmatic Critical Outcomes thus enabling the Lab's research mission. The resulting strategy consists of four major elements:

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

The BNL Site Master Plan map, shown in (Appendix C), is divided into four zones that functionally guide the development strategy for the site. The Accelerator Zone includes facilities associated with the Collider-Accelerator Complex and RHIC which will be updated to eRHIC, if approved by DOE. The Interdisciplinary Science Zone includes the collaborative science facilities including NSLS-II, CFN, ISB, and the Chemistry, Biology, and the Condensed Matter Physics and Material Sciences buildings. The Lab Support Zone includes maintenance, operations, and housing facilities. The Gateway Zone provides for future development of Discovery Park by repurposing 40-60 acres of the site to provide an entry and office facility, new user housing, and location for future public/private technology transition partnerships.

The location of the key investments of the campus wide strategy is indicated on the site map. The proposed capital funding for these investments is indicated in Enclosure 6. The planned infrastructure investments will promote and support the four scientific Critical Outcomes and the wide range of facilities that enable BNL's thirteen core capabilities. In addition, the Laboratory must provide world-class facilities that will support the recruitment and retention of premier staff.

Since many of BNL's permanent 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 methods. Research labs need to be renewed and modernized 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 issue facing the support divisions 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 office building 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. While BNL's utilities are currently reliable, they are aging and issues impacting reliability and capacity are expected to increase. In FY 2011, BNL completed a 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 and lack of line item funding for utilities. However, progress has been made to increase Central Chilled Water Facility (CCWF) capacity to support growing science process cooling needs with the installation of new electric centrifugal chillers and a project to replace the 25-year-old wood cooling tower at the CCWF. BNL has also started engineering two potable water projects: one to replace the WWII-era 300,000 gallon elevated water storage tank, and one to rebuild low-iron Well No. 12.

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. The Infrastructure Investment Table and Integrated Facilities and Infrastructure (IFI) crosscut reflect both an aggressive program of annual overhead investments to eliminate existing or anticipated future non-contaminated excess facilities as well as funding requests for direct DOE funding for the more costly contaminated facility projects. Over the ten-year span of this plan, it is estimated that over 276,000 sf of primarily WW-II era buildings will be eliminated.

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 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 in Enclosure 6. In addition, there are non-capitalized betterment and alteration projects, not requested as part of Enclosure 6, that round out the Lab's investment strategy.

An alternatives analysis was prepared for the Discovery Park concept and presented to the Office of Science during the third quarter of 2016. This analysis included an approach that proposed all development to be privately financed. A second approach (Alternative 2) proposed a mix of federally funded and privately funded development. A third approach considered the feasibility of achieving Discovery Park's objectives with all private development on private land remote from the BNL site.

The plan for improving asset condition is multipronged and does not solely rely on maintenance investment, which is currently at 1.5% of Replacement Plant Value. Key to BNL's strategy is consolidation out of those assets not worth maintaining, followed by their demolition. This 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, which will enable 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 investment strategy relies on the following indirect and direct sources:

- DOE SLI funds: Will be used to perform major building system revitalization in support of state-of-the-art research facilities that can readily support current and future missions. Over the next ten years, 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. These 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) ($67.1M Preliminary Total Estimated Cost) involves a preferred option that will re-purpose 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 on-going support of the mission need to provide computational and data storage support to both current and planned experiments at both RHIC and the ATLAS detector at CERN. The space will support the planned growth of computing resources for the RHIC ATLAS Computing Facility (RACF) as well as NSLS-II, CFN, and other laboratory users. If located at B725, the office space will be refurbished for scientific staff currently located in poor space, some of which is WW-II era construction. The extensive underutilized high-bay space, supported by the significant power and cooling available, is well suited for conversion to computing use. The scope of the project will potentially include 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 and is proposed to start in FY 2017 with a proposed completion in FY 2020.
    - Science and User Support Center (SUSC) ($75M in FY 2018) will be constructed if Alternative 2 for implementation of the Discovery Park program is pursued. It will include construction of a federally funded 105,000 sf office building at the Discovery Park site to serve as a magnet for further development, enhance user support capability, and address major DOE and BNL infrastructure needs. This building will enhance operational efficiency by consolidating BNL support division staff, currently dispersed in ten WW-II era substandard buildings, into a single modern office building meeting DOE sustainability goals. Full deployment of the Discovery Park vision will also eliminate approximately $34M in deferred maintenance and Environment, Safety and Health (ESH) backlog costs, as resulting vacated buildings are demolished. In addition to the efficiency gain of 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 Procurement and Property Management, the Office of Educational Programs, Technology Commercialization & Partnerships, among others) while maintaining access to support BNL core functions. The construction of this building, coupled with the Discovery Park development, will enable footprint reduction leading to demolition of nearly 300,000 sf of WW-II era substandard and inadequate buildings.
    - B911 Renovation for Accelerator Science & Technology ($40M FY 2021): Building 911 is a 106,000 sf building constructed in 1956 with a major addition in 1964. The facility houses the main operations center and staff for the Collider-Accelerator Complex including RHIC operations. It is expected to be a key facility for eRHIC, once constructed. The revitalization would update most building systems and

    - interior finishes, allowing continued use, with expected completion to support the start of eRHIC operations.

- GPP (DOE SLI) via the Infrastructure Crosscut: In response to the initial call for GPP projects that arose out of the FY 2014 Laboratory Operations Board (LOB) Initiative, prioritized major recapitalization needs to provide upgraded facilities and infrastructure have been identified. These investments cover several investment types identified by the LOB to address the most urgent gaps including:
    - Facility Improvements: B463 Revitalize Biology Labs, Collider-Accelerator Upgrade HVAC Systems, Collider-Accelerator Upgrade Electrical Distribution Systems, B510 North West Wing Rehabilitate Physics Building, Replace Roofs Mission Critical Buildings
    - Mission enabling renovations: B801 Hot Cell & Labs for Ac-225 production
    - Utilities: Site Electrical System Improvements, Site Water System Rehabilitation, Site Steam System Rehabilitation.
- Excess Facilities Disposition (EFD): In concert with the related infrastructure crosscut call for GPP, BNL has proposed several high impact demolition projects proposed for DOE direct funding. A long-range plan for low impact, lower cost demolitions funded from indirect operating funds has been developed and will be prioritized with other indirect-funded infrastructure needs. DOE-EM has committed to incorporating several SC assets into its cleanup program for disposition, but the timeline is uncertain and they may not be accepted by EM until 2030. Included are B491, 650, and 830.
- Indirect Funding: The Laboratory anticipates increasing overall infrastructure spending over the ten-year period. These funds include maintenance, including dedicated DMR projects, IGPP, and Other Infrastructure Projects (OIP). OIP projects are not part of the Investment Table but fund alterations, non-capitalized betterment projects, demolition and infrastructure studies. Collectively, they are 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:
    - 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.
    - Prioritize all proposed investments in infrastructure and ESH 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.
- Non-Federal Funding: 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, and contribute to local and regional economic development. The project would repurpose a currently underutilized tract of DOE property at the BNL entrance through a long-term lease to enable privately funded development. The project would provide attractive modern housing and amenities for the thousands of visiting researchers and users of BNL research facilities that currently rely on substandard WW-II era converted buildings for BNL housing. It would provide a platform for technology partnership space to address mission capability gaps and enable

technology commercialization opportunities with industrial, academic, and other government agency partners that is complementary to local and regional economic development objectives. The proposed privately funded development of housing and technology partnership facilities would also be complementary to the SUSC proposed as an SLI line item project.

In addition, a $12.8M Utilities Energy Savings Contract (UESC) project was completed in May 2015. It included both utilities and building system improvements and a substantial reduction in energy use and Green House Gas emissions. Another opportunity being explored is a possible combined heat and power project that would provide part of the Lab's electricity and most of its steam heating requirements at competitive rates.

Core Capability Infrastructure Gap Analysis

***Accelerator Science & Technology* (CC 1)**: Research &Development (R&D) related to this capability in accelerator design, development and implementation of high brightness guns, stochastic cooling, superconducting RF technology, advanced beam cooling, energy recovery linacs, and fabrication of high Tc magnets occurs in several facilities , such as B510, 902, 911 & 912 and other Collider-Accelerator Department (C-AD) technical support buildings. Other buildings including B703 and 832 support NSLS-II. The Accelerator Test Facility (ATF), currently located in B820, is being relocated to B912. The major gap in this area is that the C-AD technical support facilities used to enable the R&D are spread out over many inadequate and substandard buildings. This will be resolved through the use of indirect funds to renovate and upgrade B912 (complete), B924 (in-progress), and B905 (in planning). The newly renovated facilities will support the needed consolidation and right-sizing of the space to support C-AD technical support groups, improving operational efficiency, throughout eRHIC operations. The continued and planned use of B912 (substandard) for the ATF and other projects will continue to be enabled long-term by select upgrades and maintenance actions. Relocation of the ATF is underway with construction in B912.

***Advanced Computer Science, Visualization & Data* (CC 2)**: Staff associated with the Computational Science Initiative who conduct R&D related to novel computer devices and architectures, as well as their optimization for data intensive computing requirements are spread out in several buildings: B421, 460, 463, 515, 734, and 743 inhibiting collaboration. In addition, much of the staff is in inadequate buildings (B421, 463), and substandard buildings (B515). This gap will be addressed potentially through indirect funding projects to address the sustainment and recapitalization needs of the unutilized B725, whose second floor has significant office space. This consolidation dovetails well with the proposed SLI Line Item CFR project proposed to start in FY 2017. The CFR will create a major new sustainable data center built to meet the needs of high density computing which is currently limited by its current location in B515 where most of the space is 1960s vintage computing space that has major power and cooling deficiencies. The proposed upgrades to B725 will provide a facility with infrastructure capable of fast data storage, fast networking at 100Gb/s, in support of data intensive scientific computing for key RHIC and US ATLAS mission needs and broader scientific computing development.

***Applied Materials Science & Engineering* (CC 3)**: The key buildings for this work are described in *Condensed Matter Physics and Materials Science* (CC 8).

***Biological Systems Science* (CC 4)**: Biology (B463) is the home of the Quantitative Plant Science Initiative and other research in support of the DOE mission with respect to energy and the environment. B463 was constructed over a period of 40 years with the initial phase going back to WW-II. The condition assessment of the laboratories in Phase I and II determined the space was inadequate, with excessive operations and maintenance cost; as such it was deemed unsuitable for major renewal. Research is being consolidated into the newer (mid-1960s) Phase III area. This space can remain effective for an extended period if it is revitalized. Some selective spaces underwent renovation, accommodating recent new hires. Far more work is needed and BNL has proposed a SLI GPP project to address this issue, which will be coupled with sustainment activities to leverage the modernization effort. Continued use of this space will leverage the existing Greenhouse replaced in 2012 and the Growth Chambers. Supporting experimental facilities are NSLS-II and CFN (B735), none of which has major infrastructure gaps impeding the research.

With research associated with the Radiochemistry Scientific Focus Area terminated in FY 2015, a phased decommissioning plan continues that will vacate the Radiochemistry Labs and Cyclotron (B901), Chemistry Labs (B490 and B555), and the Positron Emission Tomography Imaging Facility (B906).

Chemical & Molecular Science **(CC 5)**: Laboratories for fundamental energy-related research, theory, and computation in the chemical and molecular sciences are located in Chemistry (B555). This research is mostly conducted in the approximately 40% portion of the building renovated under the RSL-II project which is now adequate, while the overall building remains substandard awaiting further renovation. Other key enabling facilities are NSLS-II, the CFN, and the facilities associated with the Computational Science Initiative (see CC2).

Chemical Engineering **(CC 6)*:*** The key buildings for this work are described in *Chemical and Molecular Science* (CC 5).

Climate Change Science and Atmospheric Science **(CC 7)**: Key facilities for research in developing process-level insight into the role of aerosols and clouds on Earth's climate and the response of ecosystems to a changing climate and supporting the Accelerated Climate Modeling for Energy project are B490 and B815. Portions of B490, constructed in 1958, have been converted for this use. B490 has major recapitalization needs. Options will be explored in the later part of the ten-year planning period to address these needs as well as to find a way to co-locate the groups now separated in the two buildings. In the interim, the most urgent recapitalization needs, such as HVAC replacement will be accomplished, as needed to sustain facility operations. B815 was constructed in 1961 and expanded in 1995. Major recapitalization in B815 was funded over the years through various DOE and indirect investments and completed by the RSL-I project, making B815 essentially fully capable. Minor sustainment and recapitalization gaps will be addressed with indirect funds.

Condensed Matter Physics & Materials Science **(CC 8)**: The current key facilities for this research that focuses on new and improved materials for renewable energy, energy storage, and energy efficiency are B480 and B734 (ISB) as well as B740 (NSLS-II), B735 (CFN), B515 (Computational Science Initiative), and B912 (ATF-Ultrafast Electron Diffraction Facility). The partial renovation of B480, part of the RSL-I project, has made B480 fully capable. The research, formerly conducted in B510 and B703, is now fully operational in B734 (ISB), which provides the needed high quality/high accuracy space. Long-term computational growth will be addressed by the CFR project. Gaps at B912 are being addressed through select recapitalization projects.

Large-Scale User Facilities/Advanced Instrumentation **(CC 9)**: Facilities for this capability include those for *Systems Engineering and Integration* (CC 13), the user facilities themselves, and those for development of state-of-the art detectors and electronics. They include: B515, 535, 734, 735, 815, 820, 901A, 911, 938, the Alternating Gradient Synchrotron, RHIC, and NSLS-II, all of which are discussed in other sections or have no major gaps current or in the near future. In addition, the Northeast Solar Research Center, consisting of B521 and OSF ST0536, is being expanded, using DOE Sustainability Performance Office and BNL indirect funds. A study of the Collider-Accelerator complex identified a series of projects to be implemented over the next several years that would improve operational efficiency and right-size its space. B911 will require rehabilitation, which is planned under the SLI Line

Item B911 Renovation for Accelerator Science & Technology, proposed for a FY 2021 start. Additional indirect investment to further build out the NSLS-II Laboratory Office Buildings is expected over the planning period.

Nuclear & Radio Chemistry **(CC 10)**: Key buildings are B197 (Nonproliferation and National Security [NN]), 801 (Radioisotope production labs), 931 (Brookhaven Linac Isotope Producer), and 937 (NASA Space Radiation Laboratory). B197, an inadequate WW-II era building needs to be replaced due to deterioration of its structure. Some staff were temporarily relocated to an area in B510 that was partially renovated, although others remain in B197. Projects are underway and additional ones are planned using indirect funds to ultimately consolidate all NN staff into B490 after a major indirect funded renovation is completed. All radioisotope research, processing, and assays are carried out in the 66-year old B801, whose hot cells and labs need modernization to allow the Ac-225 program to advance. An SLI GPP project is proposed for this effort. There are no major gaps in B937, but B931 (substandard) requires some recapitalization actions.

Nuclear Physics **(CC 11)**: B510, B515, and B535 are key facilities for experimental and theoretical nuclear physics research including relativistic heavy ion and polarized proton spin studies, developing the scientific and technical case for eRHIC, and designing and constructing advanced detector instrumentation and electronics. The RIKEN BNL Research Center is located in B510. The gaps and actions are the same as for *Particle Physics* (CC 12). The main experimental facilities are a series of buildings mostly in the buildings 900-1000 series, collectively known as RHIC, housing the accelerator and its support facilities for research dedicated toward RHIC improvements and eRHIC. Facility conditions for the ~100 buildings range from adequate to inadequate. The primary gaps are facility condition and operational efficiencies that have begun to be addressed through consolidation of functions, which in turn, will result in several deteriorated buildings becoming vacant for future demolition. Indirect funds will be used to renovate and upgrade existing facilities, such as B912, which has large high-bay spaces that can accommodate multi-use projects and B924, which will allow the consolidation from B919A, 919B, and 975. B911, the main C-AD office building, needs major modernization and renovation and the SLI Line Item B911 Renovation for Accelerator Science & Technology has been proposed for a FY 2021 start. Some minor issues will be addressed in the interim. The National Nuclear Data Center is located in B817, which is adequate.

Particle Physics **(CC 12)**: The Physics Department (B510) is a key facility for major activities in particle physics at the Large Hadron Collider-ATLAS experiment, studies of neutrino properties, theory, and observational cosmology. The 53 year-old 200,000 sf building, parts of which were recently renovated under the SLI RSL-II project, is comprised mainly of labs, offices, shops, and high-bay assembly space. However, major recapitalization and modernization needs remain in the other portions. For these remaining areas, indirect funds will address needs, as funds become available. B515 houses the RACF and the Computational Science Initiative. A gap for B515 is the continuing need for additional power and cooling, which is inhibited by the small 1960s-era raised floor, which does not provide adequate space for conditioned air. In addition, there are associated electrical infrastructure reliability needs that will need to be addressed. A proposed solution is to relocate most scientific computing to B725, which would be renovated under the SLI CFR project. The remaining area in B515 could then be upgraded to current standards for other computing needs. The Instrumentation Division (B535), which builds detectors for observational cosmology and low-noise electronics and other innovative detectors for applications across the Laboratory, is 50+ years-old and has recapitalization and modernization issues, such as the lack of clean room and other dedicated lab space. These needs will also be addressed with indirect funds as they become available.

Systems Engineering & Integration **(CC 13)**: This area encompasses many buildings that enable BNL to deliver Large-Scale User Facilities and Advanced Instrumentation. All have been mentioned previously. They include: B510, 535, 703, 817, 832, 902, 911, 912 and NSLS-II.

BROOKHAVEN NATIONAL LAB

Objectives:

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

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Footnote	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
																Select from Drop Down Menu		
SLI																		
Core Facility Revitalization	A	**67,072**			1,800	15,200	30,000	20,072								LI	SLI	1,3,5,7,8,9,11,16,20,24,21,22
Science User Support Center	B	**75,000**				8,000	30,000	37,000								LI	SLI	1,3,5,8,11,16,21,22
B/911 Renovation for Accelerator Science & Technology	C	**40,000**							2,000	23,000	15,000					LI	SLI	1,16,20,21,24,22
Total SLI			**0**	**0**	**1,800**	**23,200**	**60,000**	**57,072**	**2,000**	**23,000**	**15,000**	**0**	**0**	**0**	**0**			
PROGRAM LINE ITEMS																		
eRHIC		**995,424**					6,763	11,099	44,762	56,960	82,711	205,894	225,510	232,275	129,450	LI	NP	21
Total Program Line Items			**0**	**0**	**0**	**0**	**6,763**	**11,099**	**44,762**	**56,960**	**82,711**	**205,894**	**225,510**	**232,275**	**129,450**			
IGPP																		
11-005 B/924, Renovate to Increase Operational Efficiency	D	**4,100**		1,265	2,835											IGPP	OH	16,21
12-018 Upgrade B/744 Offices		**3,171**	3,121	50												IGPP	OH	1,3,5,7,8,9,11,16,20,24
12-059 B/600 New Chiller #9		**2,571**	751	1,820												IGPP	OH	None
09-075 Rebuild Wellhouse - Well #12		**865**	35	100	730											IGPP	OH	None
12-016 B/744, 745 Develop New Laboratories		**5,900**		180	1,500	4,220										IGPP	OH	1,3,5,7,8,9,11,16,20,24
12-014 B/480 Upgrade for TEM & Evaporator		**1,118**	93	200	300	525										IGPP	OH	11,3
15-051 B/734 Install HP Liquid He Recovery System		**1,350**		100	400	850										IGPP	OH	11,3
15-014 Discovery Park Infrastructure		**2,735**				2,735										IGPP	OH	
14-021 Stormwater System Upgrades		**726**	56	20		265	385									IGPP	OH	None
09-131 ST0049 Replace 300k Gallon Elevated Water Tank	E	**4,900**		150	629	4,121										IGPP	OH	None
14-036 SFAS Replacement		**2,620**	820	700	700	400										IGPP	OH	None
15-012 B/490 Block 5, Renovate & Alter Space	F	**1,400**		200	1,100	100										IGPP	OH	20
10-001 New Well #4	G	**1,500**					1,500									IGPP	OH	None
12-015 B/742 Construct Offices		**5,600**				100	4,000	1,500								IGPP	OH	1,3,5,7,8,9,11,16,20,24
12-019 B/744/745 Upgrade Labs 1,2,3,4,10		**5,500**						500	5,000							IGPP	OH	1,3,5,7,8,9,11,16,20,24
14-042 B/742 Upgrade Labs		**5,000**								500	4,500					IGPP	OH	1,3,5,7,8,9,11,16,20,24
11-048 B/535 Construct Silicon Processing Clean Room		**2,000**										2,000				IGPP	OH	16,22,21,5,9,24
Various IGPP Projects TBD								3,500	1,000	6,000	2,000	4,500	7,000	7,200	7,400	IGPP	OH	TBD
Total IGPP			**4,876**	**4,785**	**8,194**	**13,316**	**5,885**	**5,500**	**6,000**	**6,500**	**6,500**	**6,500**	**7,000**	**7,200**	**7,400**			
GPP																		
B463 Revitalize Biology Labs*	H	**9,655**				9,655										GPP	SLI	5
B801 Upgrade Hot Cells and Labs for Ac-225*	I	**8,441**					8,441									GPP	SLI	20
Site Electrical System Improvements*	J	**5,756**						5,756								GPP	SLI	16
Collider-Accelerator Upgrade HVAC Systems*	K	**8,680**							8,680							GPP	SLI	21
Collider-Accelerator Upgrade Electrical Distribution Systems*	L	**9,160**								9,160						GPP	SLI	21
B510 North West Wing, Rehabilitate Physics Building*	M	**8,322**									8,322					GPP	SLI	21
Replace Roofs, Mission Critical Buildings*	N	**8,760**										8,760				GPP	SLI	21
Site Water System Rehabilitation*	O	**8,846**											8,846			GPP	SLI	All
Site Steam System Rehabilitation*	P	**9,222**												9,222		GPP	SLI	All
Total GPP			0	0	0	9,655	8,441	5,756	8,680	9,160	8,322	8,760	8,846	9,222	0			
EFD-DF																		
OSF Accelerator-NSLS Demolition	Q	**2,500**				2,500										DF-EFD	SLI	None
Building 650 Demolition	R	**11,500**					5,000	6,500								DF-EFD	SLI	None
Building 491/OSF Reactor-BMRR Demolition	T	**32,500**									2,500	10,000	10,000	10,000		DF-EFD	SLI	None
Total EFD-DF			0	0	0	2,500	5,000	6,500	0	0	2,500	10,000	10,000	10,000	0			
AIP																		
RHIC Accelerator Development Technical Infrastructure Upgrade		**1,500**	1,000	500												AIP	NP	21
Low-Energy RHIC electron Cooling (LEReC)		**8,225**	4,000	2,900	1,325											AIP	NP	21
Linac Vacuum System Upgrade		**3,000**			1,125	1,875										AIP	NP	21
AtR Vacuum Controls Upgrade		**500**				500										AIP	NP	21
BLIP Raster Upgrade		**4,500**	4,318	182												AIP	NP	20
ATF II Stage I upgrade		**4,097**	2,500	100	1,497											AIP	HEP	22
Total AIP		**21,822**	**11,818**	**3,682**	**3,947**	**2,375**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**			
AF																		
																AF	--	
Total AF			**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**			

Fermi National Accelerator Laboratory

1. Mission and Overview

Fermi National Accelerator Laboratory is America's particle physics and accelerator laboratory. Fermilab's 1,800 employees and more than 2,600 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 include 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. The flagship facility comprised of LBNF and DUNE will be the first international mega-science project based at a Department of Energy national laboratory.

Fermilab operates the nation's largest particle accelerator complex, producing the world's most powerful low- and high-energy neutrino beams. It integrates U.S. universities and national laboratories into the global particle physics enterprise through its Large Hadron Collider (LHC) programs, neutrino science and precision science programs, and dark-energy and dark-matter experiments. Large-scale computing facilities drive research in particle physics and other fields of science. The laboratory's R&D infrastructure as well as 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, will leverage this expertise to apply particle physics technologies to problems of national importance in energy and the environment, national security, and industry. Upgrades to laboratory infrastructure and science and technology facilities will meet the needs of the next generation of researchers.

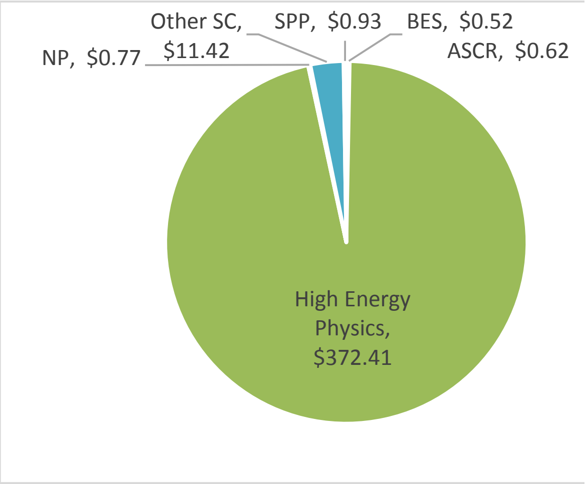
2. Lab-at-a-Glance

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

Physical Assets:
- 6,800 acres and 365 buildings
- 2.4 million GSF in buildings
- Replacement Plant Value: $1,942M
- 10.8k GSF in 4 Excess Facilities
- 19,771 GSF in Leased Facilities

Human Capital:
- 1,801Full Time Equivalent Employees (FTEs)
- 9 Joint Faculty
- 53 Postdoctoral Researchers
- 0 Undergraduate and 0 Graduate Students
- 2,634 Facility Users
- 19 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs (excluding Recovery Act): $386.7M
DOE/NNSA Costs: $385.7M
SPP (Non-DOE/Non-DHS) Costs: $0.93M
SPP as % Total Lab Operating Costs: 0.2%
DHS Costs: $0

Fermi Research Alliance, LLC manages Fermilab for the Department of Energy. FRA is an alliance of the University of Chicago and the Universities Research Association, Inc., a consortium of 89 universities. Fermilab's 6,800-acre site, much of which is open to the public, is located 42 miles west of Chicago in Batavia, Illinois.

3. Core Capabilities

Fermilab has four core capabilities that support the DOE-SC Scientific Discovery and Innovation mission: **Particle Physics; Large-Scale User Facilities/Advanced Instrumentation; Accelerator Science and Technology**; and **Advanced Computer Science, Visualization, and Data**.

As the country's particle physics and accelerator laboratory, Fermilab is the national platform for particle physics and is primarily funded by the DOE Office of High Energy Physics. The laboratory has unique and powerful infrastructure essential to the advancement of discovery in particle physics, including the nation's largest accelerator complex and a suite of particle detectors. Scientific research at Fermilab and around the world is supported by Fermilab's facilities for design, fabrication, assembly, testing, operations, and 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).

The laboratory's four core capabilities are leveraged to deliver on DOE science priorities. High-intensity particle beams are used to answer compelling questions in neutrino science, and reveal new physics phenomena through high-precision tests of the Standard Model of particle physics. High-energy particle beams are used to discover new particles and probe the architecture of the fundamental forces of nature. Underground experiments as well as ground- and space-based telescopes are used to uncover the natures of dark matter and dark energy and probe the cosmic microwave background. The 2014 report of the Particle Physics Project Prioritization Panel (P5) identified the long-term science priorities for the U.S. particle physics community, and the laboratory is executing its strategic plan in alignment and coordination with P5, with DOE, and with the science community.

Particle Physics

Fermilab's Particle Physics core capability is the heart of the laboratory's science mission and is defined by four science themes: neutrino science, Large Hadron Collider science, precision science, and cosmic science. Fermilab's Theory Group and Theoretical Astrophysics Group perform research at the confluence of these four themes. The laboratory's accelerators, particle detectors, and fabrication, assembly, testing, and computing facilities provide unique capabilities within DOE and for particle physics research. For example, Fermilab's test beam facility provides test beams for detector R&D and is in high demand for the development of advanced particle detector technologies. The Education Office and Lederman Science Center support students and faculty in STEM education and support DOE WDTS missions.

Neutrino science: Fermilab is the only laboratory in the world that operates two accelerator-based neutrino beams simultaneously. 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 and MINOS+ experiments operate on the high-energy NuMI beamline, and explore the parameters of the neutrino mixing matrix. This exploration will become comprehensive with the creation of the

Deep Underground Neutrino Experiment (DUNE) in a new beamline created as part of the Long Baseline Neutrino Facility (LBNF). The MicroBooNE experiment on the low-energy Booster Neutrino Beamline searches for sterile neutrinos, and this search will be made comprehensive when MicroBooNE is joined by the SBND and ICARUS detectors in 2018. Experience with these liquid-argon detectors will inform the future flagship international long-baseline neutrino program, consisting of LBNF and DUNE at Fermilab and in South Dakota. This succession of neutrino experiments is prescribed by the P5 report and will be executed by collaborations of scientists enabled by the capabilities that exist at Fermilab.

Large Hadron Collider science: Fermilab serves as the host laboratory for more than 900 U.S. scientists and students working on the Compact Muon Solenoid (CMS) experiment that operates at the Large Hadron Collider (LHC) at CERN, the European center for particle physics. Fermilab is the leading U.S. center for LHC science and second-largest world center after CERN [see 3.2]. In addition, laboratory scientists are engaged in physics analyses of LHC data including studies of the Higgs boson and searches for supersymmetry. The laboratory's globally distributed computational capabilities for the CMS experiment are unparalleled [see 3.4]. Moreover, a skilled and talented workforce of scientists, engineers, and technicians contributes to essential accelerator and detector developments and improvements. By leveraging its accelerator and detector R&D programs the laboratory is positioned to make significant contributions to future planned upgrades of the CMS detector and LHC accelerator.

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 is reconfiguring accelerator components to create high-intensity muon beams, and constructing the Muon g-2 and Mu2e experiments that will use the new beams starting in 2017 and 2019, respectively. The Muon g-2 experiment will precisely measure a property of muons called the anomalous magnetic moment. Muon g-2 will investigate hints from previous experiments that the muon's magnetic moment may be different than that 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 at energies that are 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 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. The Dark Energy Survey, whose camera was built by Fermilab and whose science collaboration is led by a Fermilab researcher, ended its third year of five years of operations in 2016. Fermilab is working with other DOE laboratories to build new large astrophysical surveys. The laboratory is engaged in world-leading searches for particle dark matter by operating several first-generation experiments and taking on major responsibilities for the construction of second-generation experiments. Fermilab is a key partner, together with other laboratories, in a CMB research initiative that promises to produce measurements that establish the world's best limit on the sum of neutrino masses and help explore the phenomenon of cosmic inflation.

Particle Physics is funded primarily by DOE-HEP with additional funding from DOE-BES (and SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission (SC 1, 4, 5, 6, 21, 22, 23, 24, 25, 26, 27, 29, 33, 34, and 35).

Accelerator Science

Fermilab's Accelerator Science and Technology core capability includes five core competencies at the forefront of accelerator R&D: high-intensity particle beams; high-power beam targets; 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 to sustain Fermilab's strategic goal to maintain its world leadership in high-intensity and high-energy accelerator applications. Fermilab has established strategic partnerships in accelerator science and technology with Chicago-area universities that include Northern Illinois University, Illinois Institute of Technology, and the University of Chicago. Fermilab's Illinois Accelerator Research Center 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) 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 2.4 MW. Breakthroughs in accelerator R&D at Fermilab support the flagship neutrino science program and influence how U.S. and international accelerators are designed, constructed, and operated.

High-power beam targets: Beam targets are currently limited to beam powers of 1 MW. Fermilab is developing beam target technologies to address the challenges of design, construction, and operation of multi-MW target facilities. The laboratory is leading the collaborative R&D effort on new radiation- and thermal-shock-compatible materials and technologies.

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 (both in novel magnetic materials and electromechanical magnetic design) 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. In this context, a High Energy LHC (HE-LHC) is being viewed as a very likely future step for the LHC science community demanding further increase of the maximum magnetic field achievable in accelerator-quality magnets. Infrastructure supporting the magnet work includes superconducting strand and cable testing equipment, cable making, coil winding machines, collaring 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 X-ray laser, the highest-priority project in the DOE Office of Science. Fermilab's experienced staff and extensive infrastructure led the way in the design of SRF cryomodules 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 such as PIP-II. This infrastructure and expertise also positions 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.

Beam test facilities: The Fermilab Accelerator Science and Technology (FAST) facility hosts a unique program of advanced accelerator R&D at the Integrable Optics Test Accelerator (IOTA) ring. The research promises to advance accelerator science and enable high-intensity accelerator technologies for multi-megawatt proton beams. An electron injector to the IOTA ring provides an additional platform for accelerator science and technology.

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 4500 students since its inception in 1981. 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 SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission (SC 1, 4, 21, 22, 24, 25, 26, 33, 34, and 35).

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 experiment as a means to increase scientific knowledge through data collection, storage, reconstruction, and analysis, as well as through scientific simulations. Fermilab has a remarkable history of developing, delivering, and deploying computing technologies for the scientific community.

Fermilab scientists and engineers are internationally recognized as experts in high-performance computing algorithms, scientific workflow systems and analysis frameworks, sophisticated scientific simulations, and data analytics toolkits. A prominent and successful example is a community software framework and scientific workflow engine (the "art" framework) that is being adopted by the U.S.-based neutrino and muon experimental communities and by some of the direct-detection dark matter experiments.

Fermilab is recognized for expertise in designing, developing and operating distributed computing infrastructures and facilities, petascale 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 grid computing, which originally evolved to satisfy the rapidly expanding data needs of LHC experiments and is now in use by other areas of science, industry, government, and commerce. Fermilab scientific computing facilities use grid technology to share resources for data processing, storage, and analysis. Fermilab is a leader in providing grid computing resources to scientific organizations outside DOE-HEP through the Open Science Grid, a consortium dedicated to providing secure access to distributed high-throughput computing for scientific research in the U.S.

Due to the collaborative nature of particle physics research, Fermilab does not develop scientific software or computing capabilities in isolation. The laboratory has formed partnerships with all of the DOE Office of Science laboratories as well as international laboratories (such as CERN, DESY, and KISTI) to work on projects that include the open science grid, accelerator modeling, computational cosmology and particle physics simulations.

Fermilab's strategy is to leverage ASCR expertise where appropriate to respond to computational challenges presented by the HEP program through the judicial use of partnership programs such as DOE's Scientific Discovery through Advance Computing (SciDAC) program, as well as regular ASCR data calls.

Fermilab's data center is the single largest U.S. HEP computing center with 80,000 processing cores, 30 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 scientific missions of Fermilab and DOE. 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.

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 builds and operates large computer clusters for such calculations as part of DOE's national Lattice QCD computational infrastructure. Fermilab scientists and engineers also participate in a DOE SciDAC-2 program devoted to the improvement of software for Lattice QCD computing.

FermiGrid: Fermilab is the host laboratory for a large number of 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 SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission (SC 1, 4, 5, 6, 21, 22, 23, 24, 25, 26, 27, 29, 33, 34, and 35).

Large Scale User Facilities/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 2,634 users in FY15. The laboratory has the human capital and infrastructure essential to developing, designing, constructing, and operating these large-scale user facilities.

Fermilab Accelerator Complex: The Fermilab Accelerator Complex is the nation's largest accelerator complex, and the second largest in the world after CERN. Research at this user facility has led to many discoveries over its 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 such as the discovery of new matter-antimatter asymmetries in kaon decays and the world's best determination of the W boson and top quark masses.

The Fermilab Accelerator Complex comprises seven particle accelerators and storage rings with particle-beam capabilities found nowhere else in the world. Fermilab uniquely supplies two very intense neutrino sources (the low-energy Booster neutrino beam and the high-energy NuMI beam) that are enabling the physics programs of the NOvA, MicroBooNE, MINERvA, and MINOS+ experiments. By 2018 the Booster neutrino beam will deliver neutrinos to a new three-detector short-baseline neutrino program. Reconfiguration and upgrades of the accelerator complex will turn Fermilab into the world center for the study of muons by delivering high-intensity muon beams to the Muon g-2 and Mu2e experiments, both currently under construction. Future upgrades of the accelerator complex through the PIP-II project will provide megawatts of beam power to the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE).

CMS Center: For almost two decades Fermilab has served as the host laboratory for the more than 900 scientists and students from U.S. institutions who work on the CMS experiment at the LHC. Researchers using Fermilab CMS facilities played leading roles in the 2012 discovery of the Higgs boson, 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 CMS detector upgrades. The LPC achieves this by lowering the barrier to remote participation and creating a thriving environment for collaboration among participating institutions. The Remote Operations Center enables physicist participation in remote operations and monitoring of the CMS detector, and keeps more than 900 U.S. scientists, students, and technicians connected to operations activities at CERN. The U.S. CMS Computing Facility at Fermilab is the largest and most reliable computing Tier-1 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. Fermilab has proposed to make the CMS Center a national user facility, and this proposal is currently under review.

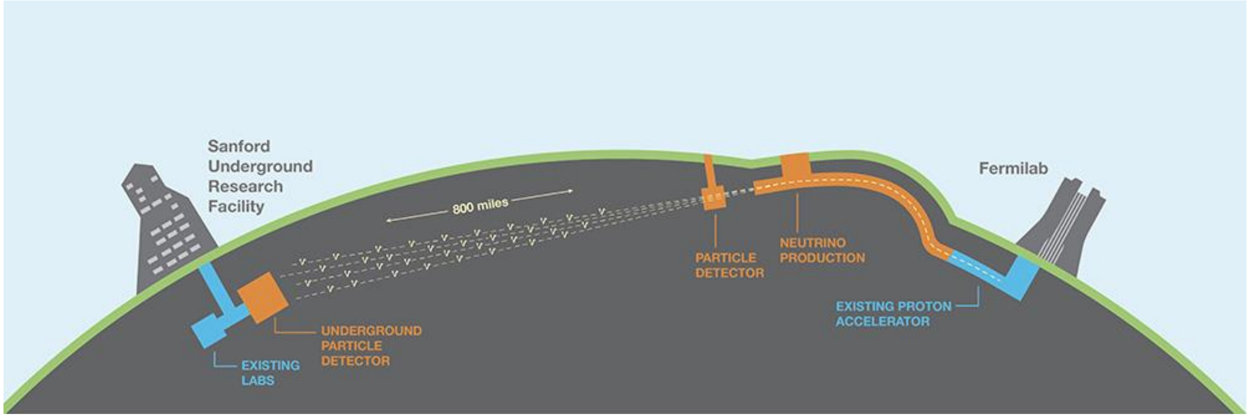
Advanced Instrumentation: An experienced and talented workforce at Fermilab conceives and develops state-of-the-art particle detector technologies and uses them to construct detector systems. Past achievements include the development of very-low-mass silicon detectors for particle physics collider experiments, CCD detectors for the Dark Energy Survey camera, and scintillator detectors that are used for wide variety of particle physics experiments, and Liquid Argon Time Projection Chambers (TPCs) used by current neutrino experiments and the future flagship experiment, DUNE. Current examples of advanced instrumentation at Fermilab include development and construction of a new forward pixel detector and hadron calorimeter upgrade for CMS.

Large-Scale User Facilities/Advanced Instrumentation is funded primarily by DOE-HEP (and SLI for infrastructure), and advances DOE's Scientific Discovery and Innovation mission (SC 1, 4, 5, 6, 21, 22, 23, 24, 25, 26, 27, 29, 33, 34, and 35).

4. Science Strategy for the Future

Fermilab's science strategy for the future has as its primary ten-year goal a world-leading neutrino science program powered by megawatt beams from an upgraded and modernized accelerator complex. This national flagship particle physics initiative comprises the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE). LBNF/DUNE will be the first-ever large-scale international science facility hosted by the United States. Identified by the U.S. particle physics community in its consensus P5 report as the highest-priority domestic construction project in its timeframe, LBNF/DUNE is attracting global partners willing to invest significant financial, technical, and scientific resources. Over the next five years, a program that includes current and near-term neutrino experiments and an R&D platform that serves the wider neutrino physics community will drive the development of capabilities and bring together the international community needed for LBNF/DUNE.

Fermilab’s success in operating the world’s most powerful low- and high-energy neutrino beams, its core scientific and technical capabilities, its project management expertise, and its international reputation as an excellent scientific partner are making it the destination of choice for the world’s neutrino researchers.



Artist's rendering of the Long-Baseline Neutrino Facility (LBNF) that will send a very intense beam of neutrinos 800 miles to a massive liquid-argon detector located deep underground in the Sanford Underground Research Facility in South Dakota.

As the country’s particle physics and accelerator laboratory, Fermilab is moving forward with new experiments, new international and national partnerships, and R&D programs that support all of the science drivers identified in the P5 report. Over the next decade Fermilab will continue to be the leading U.S. center – and the second leading center in the world - for Large Hadron Collider science, enabling leading roles for U.S. scientists in future LHC discoveries and driving key contributions to upgrades of the LHC accelerator and the CMS detector. The start of the Muon g-2 and Mu2e experiments will turn Fermilab into the world center for the study of muons, particles whose properties may open a window onto new physics. Fermilab will support the community-endorsed diversified approach to dark matter detection, including key roles in the Generation 2 dark matter projects. The laboratory’s leading role in the Dark Energy Survey, supporting roles in its successor experiments, and involvement with the South Pole Telescope will ensure continued U.S. leadership in the study of cosmic acceleration. In partnership with academics from nearby universities, Fermilab will support Illinois as a world center for advanced accelerator research with a suite of unique test facilities and R&D programs that will drive major advances in accelerator science and technology.

Fermilab’s core capabilities define the scope of the laboratory’s science and technology strategy. Major initiatives in people, infrastructure and R&D support strategy accomplishment. The laboratory will devote the majority of its time and effort over the next ten years to major initiatives identified for each of the four core capabilities and the supporting “Building for Science” theme.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities & Infrastructure

The Fermilab Campus Master Plan[6] supports the implementation of the recommendations of the P5 report for U.S. particle physics. The master plan is the cornerstone for mission-based facility planning at the laboratory, and it guides the actions of the Campus and Facility Planning Board that ensures coordination, communication, and prioritization for facilities projects. The master plan encompasses three design themes: modernization of facilities;

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

consolidation and centralization of dispersed and inefficient support facilities; and preservation of the laboratory's unique character and identity. Some of the most urgent needs to centralize, consolidate, and modernize scientific, technical, and engineering facilities will be solved by the construction of the SLI-funded Integrated Engineering Research Center (IERC) (described in Section 4.5 as part of the laboratory's science strategy and in Appendix 2). The SLI-funded Utilities Upgrade Project modernizes critical electrical and cooling water core infrastructure, and the SLI-funded Wilson Hall revitalization project will greatly improve efficiencies and density in the laboratory's largest administrative building and enhance circulation of personnel for collaboration within the IERC.

Operating the Fermilab site for science requires the use of buildings, real property trailers, and tunnels as well as hundreds of miles of utility infrastructure including roads, electrical, natural gas, industrial cooling water, potable water, and sanitary systems. The total real property Replacement Plant Value (RPV) is $960M, excluding the laboratory's programmatic accelerator and tunnel assets. Property information associated with all assets is maintained in the DOE's Facilities Information Management System (FIMS) real property database, and is available on site through the Fermilab Infrastructure Database and Geographic Information System. A summary of physical assets is included in Section 2 (Lab-at-a-Glance). All of the laboratory's real property is used and owned by DOE. Property usage is predominately divided among research and development space and administrative areas. Unoccupied land is maintained as restored prairie, tilled agriculture or woodland while being preserved for future science needs.

Executing the master plan will result in a reduction in the number of buildings, trailers, and overall gross square footage. In an ongoing effort to reduce the footprint of physical assets, the demolition of 22 trailers totaling 42,546 gross square feet was completed in FY 2015 using overhead funds. The goal for FY 2016 is to complete the demolition of the master substation control building, one trailer, and two service buildings, totaling 7,202 gross square feet. During FY 2015, Fermilab added eleven buildings to the FIMS inventory, which included six legacy facilities and five new shelters.

Table 4 summarizes the number of facilities and gross square footage for different types of facilities and their conditions.

Table 1. Types and Conditions of Facilities

Types of Facilities	Number of Facilities			Gross Square Footage of Facilities		
	Adequate	Substandard	Inadequate	Adequate	Substandard	Inadequate
Other Structures and Facilities	41	2	0	--	--	--
Mission Unique Facilities	101	0	0	410,367	0	0
Non-mission Unique Facilities	212	35	64	1,795,912	78,754	162,010

Fermilab completed the Laboratory Operations Board (LOB) infrastructure assessment in FY 2014. Electrical substations and the industrial cooling water piping system are the two "Other Structures and Facilities" assets in Table 4 that were rated as substandard during the LOB assessment. Deficiencies in each of these systems are being addressed as part of the SLI-funded Utilities Upgrade Project that is currently under construction. Lab space accounts for 46% of the substandard and inadequate non-mission unique facility square footage, and two thirds of the lab space is in light industrial-frame buildings constructed in the Fermilab Village shortly after the laboratory was founded. The remaining 54% consists of real property trailers or residential houses constructed before the Fermilab land acquisition and is used for office and storage space.

In non-excess facilities with overall utilization less than 75%, there are 338,359 gross square feet that are identified as underutilized in FIMS, based on the space type utilization level. This includes facilities with utilization ranging from 0% to 70%. Most notably, Wilson Hall—the lab's primary administrative building—is estimated to have an overall utilization rate of 70% as determined according to the LOB guidance. The Wilson Hall modernization project, expected to be funded floor by floor, would increase the building density and improve this utilization rate. Wilson Hall's underutilization contributes 126,064 gross square feet to the underutilized square footage, or 36% of the total.

There are four assets currently identified as excess facilities in FIMS, totaling 10,878 gross square feet. FY 2015 carrying costs for these facilities included annual actual maintenance and operating costs totaling $22,460. The four assets include two service buildings, a trailer, and a small office building in the Fermilab Village. A pilot project is underway that will demolish two accelerator service buildings while preserving utilities necessary to serve underground experimental areas. Once the pilot projects are complete, it is expected that an additional 36 accelerator service buildings will be added to the excess facilities list and scheduled for demolition in the future. As part of the April 2015 LOB Excess Facilities Working Group request, Fermilab has identified 46 additional buildings for future excess, including the accelerator service buildings, village lab buildings, and two office trailers. Demolition of the accelerator service buildings is complicated, due to infrastructure requirements of future projects. Demolition estimates will be refined once the pilot project is complete. Excess characterization and priority data for these assets has been populated in FIMS, concurrent with submittal of the Annual Laboratory Plan. Full implementation of the master plan will relocate additional functions and personnel from geographically remote locations to the central and technical campuses, thereby vacating legacy substandard or inadequate facilities that will also be slated for demolition.

Campus Strategy

Fermilab's campus strategy is articulated in the Campus Master Plan, which presents a comprehensive approach to Fermilab's future infrastructure.

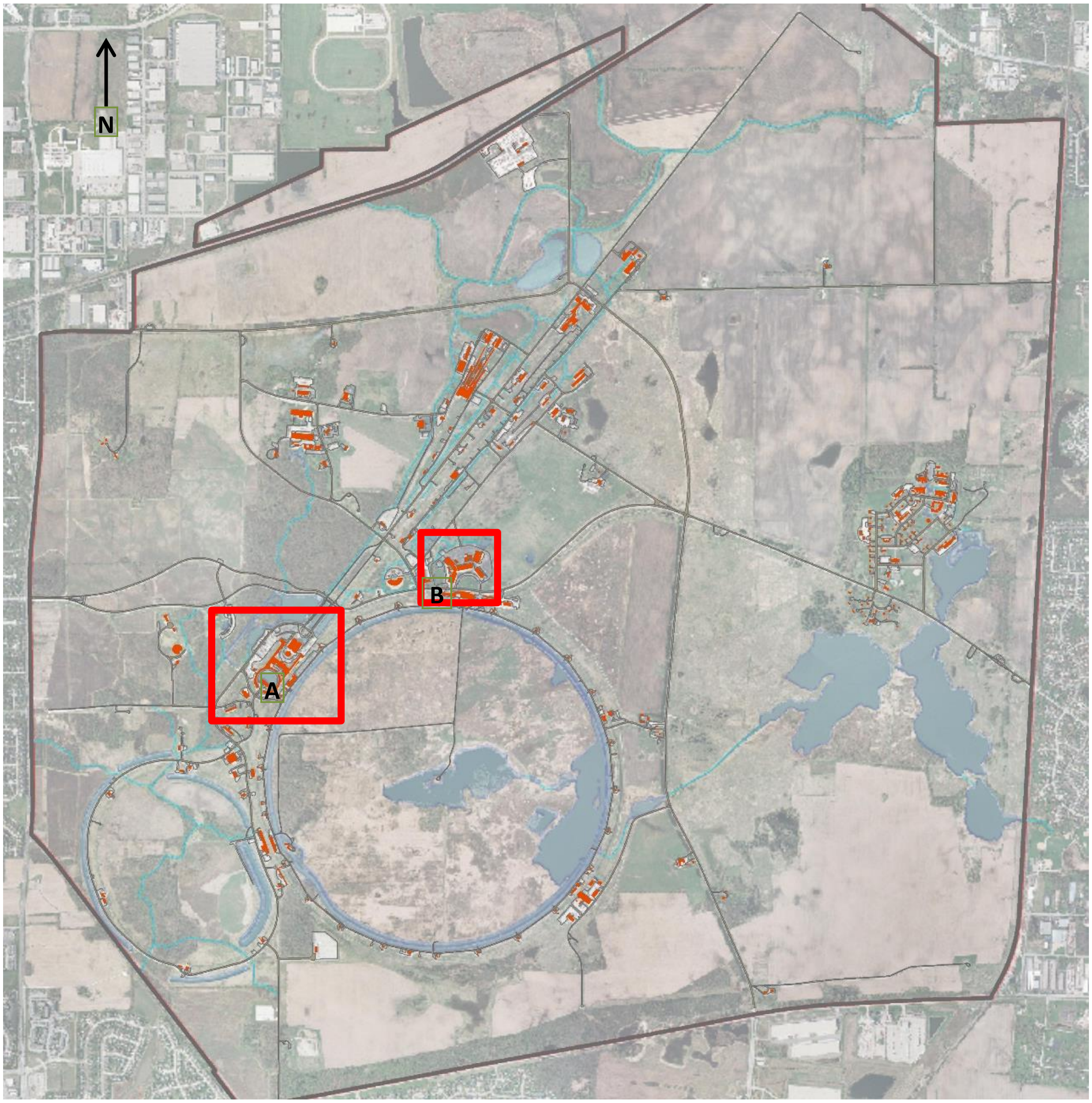
The campus strategy has four primary objectives:

- Construct sustainable infrastructure that will attract international investment and the brightest minds to the world's leading laboratory for accelerator-based neutrino science
- Maximize productivity by establishing an atmosphere of *"eat-sleep-work to drive discovery"* that efficiently meets the needs of the scientific community
- Integrate into one geographic area the entire life cycle of research, engineering, fabrication, and operations expertise for accelerators and detectors
- Consolidate, centralize, and modernize to optimize operational resources, maximize efficiency, enhance communication, and foster succession planning

These objectives address the needs of the laboratory's core capabilities by providing facilities and infrastructure to close identified infrastructure gaps that include:

- Space for project teams and international users associated with the flagship LBNF/DUNE initiative
- New buildings located so as to maximize resource utilization efficiency for projects and operations
- Increased high-bay space for production facilities
- State-of-the-art computing facilities
- Modernized facilities with modular walls and furniture for efficient reconfiguration
- Short-term accommodations for a growing number of users and visiting scientists and engineers

Table 5 provides a roadmap for planned investments in specific projects that are needed to close these gaps. In addition, the laboratory's utility infrastructure will continue to require further investment to accommodate ongoing operations and future mission needs.



Fermilab site map. Buildings are highlighted in orange. The Fermilab Village, which is located on the east side of the site (shown on the right side of the map), includes both residential and technical legacy facilities. The technical facilities will be relocated to the central (A) and technical (B) campus areas.

When siting future projects, Fermilab's Facilities Engineering Services Section works closely with experimental planning groups, project teams, the laboratory's Campus and Facility Planning Board, and the Office of Campus Strategy and Readiness to efficiently use existing facilities or develop plans to expand facilities. Infrastructure gaps are prioritized according to mission need.

The Integrated Engineering Research Center (IERC) is a major initiative in the laboratory's strategic plan and the highest-priority project needed to bring the technical and scientific resources currently scattered across the site into closer proximity, thus fostering a more effective work environment. The IERC is expected to transform

Fermilab's core capability in particle physics by greatly enhancing the laboratory's ability to execute a large portfolio of projects. The IERC will greatly improve the productivity of technical and scientific personnel who will have both project and operational responsibilities by enabling them to perform both functions more effectively and shift more easily between activities. The IERC has obtained CD-0 and is identified in the FY 2017 President's Budget Request for Project Engineering and Design (PED) funding.

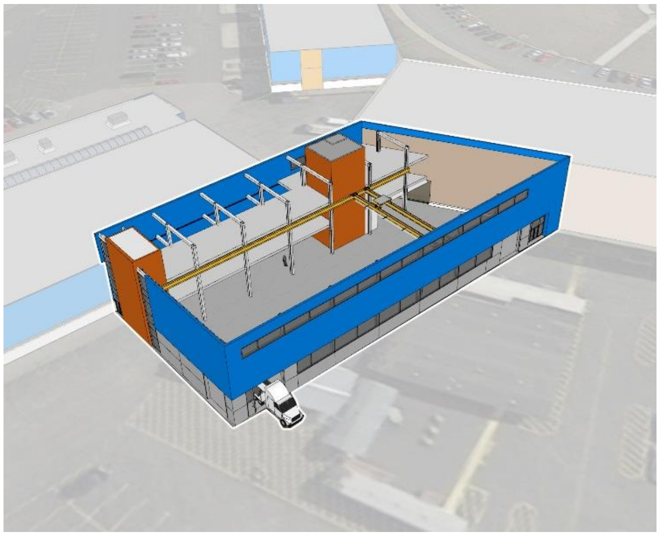
As part of the FY 2015 update to the Fermilab Campus Master Plan, an assessment of future directions for two of the laboratory's other core capabilities was completed. This assessment led to two other major initiatives in the laboratory's strategic plan. Similar to the IERC, the Global Accelerator Center (GAC) and the Next Generation Computing Center (NGCC) are envisioned as mission-driven infrastructure improvements that have the potential to transform the laboratory's core capabilities in accelerator science and technology and advanced computer science, visualization and data, respectively. The three centers would complete the modernization of mission-driven infrastructure needs for laboratory core capabilities identified in the Fermilab Campus Master Plan.


Artist rendering of the scientific hostel located near the existing Lederman Science Center. Wilson Hall is shown in the background.

The campus plan defines a Central Campus that is centered on Wilson Hall and includes a new guesthouse that fulfills the "sleep" portion of the *"eat-sleep-work to drive discovery"* theme. The guesthouse, known as the Scientific Hostel, would serve the needs of short-term visitors and complement the longer-term housing in the Fermilab Village. The Central Campus also includes the future site of the PIP-II accelerator upgrade project, which will provide the beam power that is needed to support the laboratory's future world-leading program in neutrino science.

Wilson Hall itself will see the first step of the WH 2.0 modernization project taken in FY 2016 with funding of $9M from SLI's GPP program. This Wilson Hall modernization project increases density through standardized floor plans, begins to implement a standard for reconfigurable walls and furniture, and will help connectivity with the adjacent IERC. Other GPP crosscut candidates in the Central Campus are the Central Utility Building Improvements and Excess Facilities Removal projects.

South of the Central Campus is the Muon Campus. Fermilab continues with construction of the Muon Campus (using HEP GPP funding) to redevelop and repurpose existing infrastructure in support of the Mu2e and Muon g-2 science projects that are currently under construction. Within a short walking distance from the Central Campus is the Neutrino Campus, which includes the Short-Baseline Neutrino program. The SBN program includes the Liquid Argon Test Facility that houses the MicroBooNE experiment, which began operations in FY 2015, and includes construction of two new general-purpose detector hall buildings for SBN that began construction in FY 2015.



Rendering of the Industrial Center High Bay Addition.

East of the Central Campus, the Technical Campus houses fabrication, production, and testing facilities for LCLS-II and PIP-II cryomodules, high-field magnets for CERN's LHC accelerator, and solenoids for Mu2e. The challenge for the Technical Campus is to provide the needed production capacity for the laboratory's large project portfolio. The first step towards satisfying this infrastructure gap is to construct the Industrial Center High Bay Addition. Initially proposed as an SLI project, further definition of the requirements and a more urgent timeframe have resulted in a change in strategy. The addition will now be constructed in FY 2017 and FY 2018 using HEP GPP funding. The Industrial Center Building Gateway and Central Fabrication Facility projects, proposed in FY 2015 as SLI candidates, will also be considered under HEP GPP and are included in the industrial revitalization program.

Deferred maintenance requirements of the laboratory's utility infrastructure, shown as "Other Structures and Facilities" (OSF) in Table 4, currently comprise 87% of the site's total FY 2015 deferred maintenance backlog, or $39M of a total $45M. Most notably, electrical systems and industrial cooling water underground piping are in need of significant investment, accounting for 65% of the FY 2015 OSF deferred maintenance. The SLI Utility Upgrade Project currently underway will reduce deferred maintenance projected at the end of FY 2016 by as much as $10M under guidance by the OIC working group for deferred maintenance. The integrated facilities and infrastructure cross-cut budget profile through FY 2020 includes investments in domestic water and industrial cooling piping systems, the Central Utility Building and computing upgrades, in addition to support for the SBN program. While additional utility GPP projects are identified in the laboratory's five-year infrastructure budget plan, the investment via the Office of Science's SLI Modernization Initiative provided critical investment for improved utility reliability for existing and future science needs. The combination of ongoing maintenance at 2% of Fermilab's conventional replacement plant value, laboratory and Office of Science GPP projects, SLI investment, and substantial demolition of facilities is expected to control the deferred maintenance backlog to an acceptable level as represented in Table 5.

Fermilab's core capabilities are subject to the same risks described above from deferred maintenance and infrastructure gaps. The potential failure of Fermilab's Master Substation (MSS) is the highest-rank risk, but is being mitigated by the SLI UUP project. The second-highest-rank risk is continued inefficiency in operations, particularly due to functionally obsolete buildings, geographically dispersed locations, utility failures due to aging systems, isolated downtimes due to localized failures, and resources consumed by excess facilities. Several legacy buildings from the original site development in the Fermilab Village are still used for lab space and manufacturing facilities despite being classified as inadequate or substandard under the LOB assessment.

A candidate for an FY 2018 GPP crosscut is funding for excess facilities removal of these and other buildings as elements of the Campus Master Plan are implemented and functions are relocated to modern facilities in the Central Campus.

Table 2. Infrastructure Investment Table

Objectives:

Construct sustainable infrastructure to attract international investment
Maximixe productivity by establishing an atmosphere of "eat-sleep-work to drive discovery"
Integrate in one geographic area the life cycle of research, engineering, fabrication, and operations expertise
Consolidate, centralize, and modernize to optimize operational resources and maximize efficiency

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
															Select from Drop Down Menu		
Integrated Engineering Research Center	**86,000**	500	500	2,500	16,500	33,000	33,000								LI	SLI	Particle Physics
Global Accelerator Center	**90,000**					500	500	6,000	20,000	35,000	28,000				LI	SLI	Accelerator Science and Tech.
Wilson Hall Modernization	**9,000**		9,000												GPP	SLI	Large Scale User Facilities
Excess Facilities Removal *	**3,000**				3,000										GPP	SLI	Large Scale User Facilities
Central Utility Plant Expansion *	**9,500**					4,500	5,000								GPP	SLI	Large Scale User Facilities
Scientific Hostel (Guest House)	**20,000**			20,000											AF		Large Scale User Facilities
Next Generation Computing Center	**40,000**				40,000										AF		Advanced Computer Science
Muon Campus Beam Transport	**4,300**	3,700	600												AIP	HEP	Large Scale User Facilities
Muon Campus Cryogenic System	**3,400**	1,300	700	1,400											AIP	HEP	Large Scale User Facilities
Muon Campus Delivery Ring	**7,200**	3,300	3,900												AIP	HEP	Large Scale User Facilities
Muon Campus Recycler RF	**7,300**	3,800	3,500												AIP	HEP	Large Scale User Facilities
BNB Horn Power Supply Upgrade	**1,500**			500	500	500									AIP	HEP	Large Scale User Facilities
BNB Horn Upgrade	**5,000**			500	3,000	1,500									AIP	HEP	Large Scale User Facilities
CDF Refurbishment	**2,560**		2,560												GPP	HEP	Particle Physics
C0 Radiation Storage Improvements	**3,613**	1,513	390	900	810										GPP	HEP	Large Scale User Facilities
OTE Outfitting	**1,550**	650	900												GPP	HEP	Accelerator Science and Tech.
Muon Campus Beamline	**3,500**	3,500													GPP	HEP	Large Scale User Facilities
Muon Campus Infrastructure	**500**	500													GPP	HEP	Large Scale User Facilities
Short Baseline Neutrino Near Detector Hall	**5,350**	2,050	3,300												GPP	HEP	Particle Physics
Short Baseline Neutrino Far Detector Hall	**8,800**	5,298	3,502												GPP	HEP	Particle Physics
Short Baseline Neutrino Site Development	**2,200**	1,500	700												GPP	HEP	Particle Physics
Domestic Water Improvements	**708**		708												GPP	HEP	Large Scale User Facilities
Industrial Center Building Addition	**8,000**			6,500	1,500										GPP	HEP	Accelerator Science and Tech.
Central Utility Building Improvements	**8,839**				4,090	4,749									GPP	HEP	Large Scale User Facilities
Computing Facility Improvements	**3,700**				1,500	2,200									GPP	HEP	Advanced Computer Science
Misc GPP	**100,851**					6,051	11,300	14,000	15,500	14,000	10,000	10,000	10,000	10,000	GPP	HEP	Large Scale User Facilities

Lawrence Berkeley National Laboratory

1. 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. From discovery science to mission-driven basic research, Berkeley Lab develops **open** science and technology solutions for the benefit of the nation.

Berkeley Lab specializes in **integrative** science and technology, leveraging our core strengths in materials and chemistry, physics, biology and environmental science, and in mathematics and computing to conduct cross-cutting forefront research. With our expertise in multi-disciplinary team science, we create and operate advanced S&T tools that are closely linked to our research programs and are widely used by the broad national research community. Berkeley Lab delivers high-impact contributions for DOE science, sustainable energy technology and policy.

The sense of public spirit and **sharing** runs deep within the organization to extend and integrate science that fulfills DOE's missions and benefits the world. Berkeley Lab collaborates with national labs and other institutions through partnerships, user facilities and data networks. Each year, Berkeley Lab's five national user facilities serve 10,000 researchers, one third of all national lab users. Finally, the Lab's Energy Sciences network (ESnet) provides powerful data connectivity for the entire DOE system.

Berkeley Lab's close relationship with the University of California brings the intellectual capital of the university's faculty, postdocs and students to bear on the pursuit of DOE's missions. The Lab's scientific strength is enhanced by its open programs and culture, its integrative science and technology, and its emphasis on collaboration with the national and global scientific community – sharing our world class user facilities, research and expertise to solve the challenges that define our time.

2. Lab-at-a-Glance

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

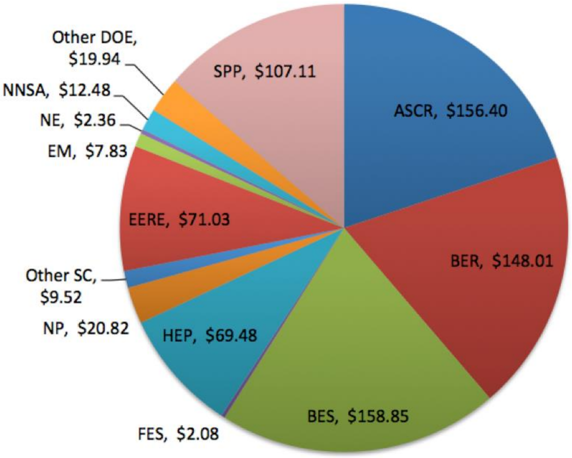
Physical Assets:

- 202 acres and 97 buildings and 27 trailers
- 1.98M gsf in buildings
- Replacement plant value: $1.348B
- 55,756 gsf in 6 excess bldgs, 1 excess trailer
- 399,258 gsf in leased facilities

Human Capital:

- 3,304 Full Time Equivalent Employees (FTEs)
- 1,549 Scientist and Engineers
- 245 Joint Faculty
- 476 Postdoctoral researchers
- 330 Graduate students
- 149 Undergraduates
- 10,798 Facility users
- 2,170 Visiting scientists and engineers

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs
(excluding Recovery Act): $786M
DOE/NNSA Costs: $790.1M
SPP (Non-DOE/Non-DHS) Costs: $103.5M
SPP as % Total Lab Operating Costs: 13.6%
DHS Costs: $3.6M
ARRA Costed from DOE Sources in FY 2015: $4.8M

3. 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. The descriptions below summarize the Lab's Core Capabilities, their targeted missions and their funding sources.

Mutually supportive, the Core Capabilities lend an exceptional depth to Berkeley Lab's research portfolio while maintaining an integration of efforts to better support DOE targeted outcomes. Consistent with our scientific themes, the Lab has grouped these Core Capabilities into 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.

User Facilities and Accelerator Science

Since its inception, Berkeley Lab has had a 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, who 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 sections 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 a world-leading facility for high-brightness soft X-ray science, with additional excellent performance in the hard X-ray and infrared spectral regions. ALS researchers use the data they collect to understand, predict and ultimately control matter and energy at the electronic, atomic and molecular levels. This research underpins many of DOE's Core Capability areas, including those involving chemical, material and biological systems. Each year, this facility supports the research of about 2,500 scientist-users, whose ALS based results appear in more than 900 refereed publications. Funded primarily by BES, it has an annual budget of ~$60 million.

The Molecular Foundry provides users with expert staff and leading edge instrumentation for multi-disciplinary, collaborative nanoscale research. Users come from academic, industrial and national laboratories, both domestic and international. For FY15, research at the Foundry resulted in 325 publications. The Molecular Foundry encompasses facilities specializing in characterization, made up of the National Center for Electron Microscopy along with 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 Foundry's FY15 BES budget was $26.4 million, with 677 onsite and remote users.

Berkeley Lab's ***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 more than 1,200 users per year; its FY15 budget of approximately $69 million is funded primarily by BER.

The National Energy Research Scientific Computing Center (NERSC) is the high-end scientific computing facility available to researchers across DOE's Office of Science. With nearly 6,000 users from universities, national laboratories and industry, it supports the largest and most diverse research community of any DOE computing facility. NERSC provides large-scale, state-of-the-art computing for DOE's unclassified research programs. The scientific impact of NERSC is enormous; more than 1,900 scientific publications cite NERSC each year. Its current systems, NERSC-6 (aka Hopper, and retired at the end of 2015), NERSC-7 (aka Edison) and NERSC-8 (aka Cori), provide over 3 billion computational hours annually. The NERSC Division also manages the data-analysis systems for the JGI, the Large Hadron Collider (LHC), Daya Bay and other high-energy and nuclear physics experiments. NERSC's FY15 funding was $76 million, all provided by ASCR.

The Energy Sciences Network (ESnet) is a high-speed network infrastructure optimized for very large scientific data flows, dedicated to the mission of accelerating DOE science. ESnet provides connectivity for all major DOE sites and facilities, and joins them to more than 140 research and commercial networks around the world. During FY15, ESnet completed a transatlantic extension project to support DOE science collaborations in Europe, including the newlyupgraded experiments at CERN's LHC. Every day, tens of thousands of DOE-funded researchers at national laboratories and in universities depend on ESnet's services, and the network transports roughly 30-40 petabytes of traffic each month. FY15 funding for ESnet is approximately $38 million (DOE/ASCR).

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. FLEXLAB's FY15 budget is $1.06M. Our major sponsors are DOE (BTO, OE), GSA, SCE, PG&E and CEC.

Basic Energy Science Research

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 Xray sources; photon and electron spectrometers; spectromicroscopy; *in situ*, *operando* and other capabilities advance the understanding of key chemical reactions and reactive intermediates that govern chemistry in realistic environments. The Lab is a world leader in momentum imaging instrumentation, reaction microscopy and theoretical methods that probe how photons and electrons transfer energy to molecular frameworks and provide critical knowledge in atomic, molecular and optical sciences needed to understand and ultimately control energy flow. Ultrafast attosecond and femtosecond probes enable studies of electron motion that may lead to reaction engineering 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 that 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 Elements 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 photosynthesis 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).

Berkeley Lab leads the scientific community in the control and manipulation of the interaction of living and nonliving molecular systems by addressing the communication between live cells and organic/inorganic surfaces at the molecular level. The Chemical Dynamics and Molecular Environmental Science Beamlines at the ALS provide the pioneering 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.

Berkeley Lab also has preeminent capabilities in molecular and isotopic geochemistry, focusing on liquid-solid and liquid-liquid interactions, synchrotron X-ray and mass spectrometric analysis, including molecular dynamics and *ab initio* computational analysis. Molecular-scale studies complement experimental and modeling studies of larger-scale systems, and include the physics and chemistry of Earth materials. The Center for Nanoscale Control on Geologic CO2 (NCGC) is directed at the molecular, nanoscale and pore scales to reveal properties and processes that affect the transport of supercritical CO2 in subsurface environments.

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 Process Demonstration 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 industrially-relevant proteins. 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.

This Core Capability is supported by BES, ASCR, BER, EERE and SPP, including the National Institutes of Health, 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 and theoretical techniques to discover, design and understand new materials and phenomena across multiple time, length and energy scales. These materials can have a direct and significant impact on solutions to global challenges in energy efficiency, solar power conversion devices, energy storage systems, and carbon capture and sequestration.

In recent years, novel materials of interest at the Lab have included quantum materials, where quantum mechanics play a role in determining the nature of ordered phases and the transitions that take place between them. This includes transition metal oxide superconductors, materials that exhibit novel forms of magnetic and geometric/spatial order, and specifically 2D materials, such as graphene or van der Waals heterostructures. Additionally, Berkeley Lab is interested in artificially engineered "metamaterials" that can be tailored in shape and size to be tuned at a sub-wavelength scale and have potential to bring solutions to real-time imaging that is limited by diffraction effects. Another interesting category of materials are bio-inspired hybrid structural materials whose unique properties derive from hierarchical architectures controlled over length-scales from nano– to macro dimensions.

Theory and computational simulations are critical to the development of new materials. Berkeley Lab researchers develop models for understanding, predicting and controlling complex materials with targeted properties. Open access to analysis tools and computed information on known and predicted materials provided by the Materials Project helps the Lab to conduct theoretical work in high-throughput scenarios.

The characterization of properties including structure, diffusion, reactions, catalysis, friction and wear enable Berkeley Lab researchers to understand how new materials may perform. Efforts rely on time-domain approaches in ultrafast spectroscopy, diffraction and quantitative microscopy. Advancing electron beam and scanning probe techniques is a key focus, and new characterization tools include custom scanning probe tips for near-field sub-wavelength imaging of heterogeneous materials at unprecedented length scales.

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. The ability to understand materials and chemical processes at a fundamental level should enable technologies beyond traditional lithium-ion batteries and store at least five times more energy than today's batteries at one-fifth the cost. Berkeley Lab is a key partner of this hub, which is led by Argonne National Laboratory.

This Core Capability is primarily supported by BES, with important contributions by ASCR, EERE, and DoD, as well as other SPP sponsors. 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 and Engineering. Berkeley Lab's Geosciences group, the largest team of its kind in the DOE complex, develops knowledge and capabilities that enable judicious use of the Earth's energy resources. The deep subsurface supplies more than 80% of the nation's primary energy, including from fossil fuels and geothermal systems. It also provides a vast resource for disposal of energy waste products (e.g., CO2, nuclear waste, produced water).

Understanding how fundamental processes influence reservoir-scale processes – and how to manipulate them for beneficial utilization while minimizing environmental risks – is a significant challenge, given the complexity, remoteness, and elevated temperature/pressure of subsurface reservoirs.

This research is developing and integrating cutting-edge analytical, characterization and simulation capabilities to improve understanding of subsurface system behavior – from molecular through reservoir scales. Berkeley Lab's preeminent capabilities in molecular and isotopic geochemistry query fundamental aspects of mineral-fluid and fluid-fluid interactions, employing synchrotron X-ray and mass spectrometric analysis and molecular dynamics and *ab initio* computational approaches. The NCGC team develops predictive understanding of nanoto-pore scale processes and features that control trapping of CO2 in the subsurface. The Lab creates world-unique experimental platforms to measure seismic signatures under stress, with the first models to jointly simulate stress, strain, flow and geophysical responses to subsurface fluid injection. The unique facilities include the Center for Isotope Geochemistry, the Geosciences Measurement Facility, the Center for Computational Geophysics, and the Environmental Applied Geophysics Laboratory.

Complementing the fundamental research support from BES-geosciences, Berkeley Lab has a significant portfolio supported by EERE-Geothermal, FE Clean Coal, NE Used Fuel Disposition, and by several significant SPPs. Specific objectives of Berkeley Lab's subsurface energy research program include the control of subsurface fluid flow and reactions, the characterization and control subsurface stress and induced seismicity, and the development of risk assessment frameworks. This subsurface program is well aligned with the DOE Subsurface Crosscut Initiative (SubTER), which Berkeley Lab co-leads for the nation. The Lab is also active in subsurface energy field observatories, such as the Frontier Observatory for Research in Geothermal Energy (FORGE) (see Section 4.6).

In 2015, Berkeley Lab's geoscientists helped to solve several relevant challenges to subsurface energy utilization. For example, Berkeley Lab led a major study to assess the energy, environmental and health impacts of hydraulic fracturing in California. Berkeley Lab scientists provided significant scientific and technical support to the State of California to resolve the gas well blowout disaster at Aliso Canyon. Berkeley Lab has also started a major study looking into the seismic risk of nuclear power plants, a project that involves development of new transformational modeling tools for earthquake rupture simulation and impacts on buildings.

This core capability is sponsored by BES, FE, EERE, NE, EPA, CA State Agencies, ARPA-E, Energy Bioscience Institute, and DOD. Berkeley Lab has BES-geoscience programs in geophysics, geochemistry and isotope geochemistry, leads the Energy Frontier Research Center on nanoscale control of carbon sequestration, and co-leads Subsurface Crosscut (SubTER) and CERC-WET. Berkeley Lab also has a significant DOE applied energy portfolio, including FE, geothermal and NE.

Biological and Environmental Sciences

Many of the most pressing 21st Century energy and environmental challenges require an ability to understand, predict, and in some cases manipulate increasingly complex natural systems. Berkeley Lab is transforming our ability to discover and harness interactions within and between cells, biological systems, and host environments. This enables predicting how environmental changes impact biological systems; harnessing biology for sustainable energy and other valuable products; predicting how terrestrial systems feedback to climate; and improving climate predictions for a greater understanding of global change for DOE energy and environment missions.

Biological and Bioprocess Engineering. Berkeley Lab's strengths in biological systems science are complemented by 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 Joint BioEnergy Institute (JBEI), DOE Systems Biology Knowledgebase (Kbase), ENIGMA, the ALS, the Molecular Foundry and NERSC, Berkeley Lab is able to develop the new technologies and processes needed to create renewable fuels and chemicals, remove environmental contaminants and support biosequestration of carbon.

The 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. Recently, the ABPDU has applied for a patent on a new reactor vessel and executed partner projects with over fifteen companies and five research organizations.

JBEI's biofuels successes have given rise to a nascent BioFoundry at Berkeley Lab, with the potential to transform manufacturing practices through advanced bioconversion technologies in support of a bio-based economy. Funded initially with LDRD, the BioFoundry is supported by EERE in FY16 to demonstrate rapid improvement over the state of the art for production of adipic acid. This effort is a collaboration with NREL, PNNL and Sandia. The Biofoundry integrates computer-assisted biological design, advanced metabolomics and proteomics techniques, and machine learning to optimize biological process design and develop methods for predictable scaling. A fully funded effort would expand the synergistic capabilities of ten national labs for a multi-functional BioFoundry for academia, national labs and companies.

EERE is the primary supporter of this Core Capability, building upon capabilities and programs established with BER funding. Other key sponsors include industry and other SPP sponsors. Anticipated sponsors include USDA, DoD, and the NIH. This Core Capability supports DOE's objectives to increase commercial impact through: (1) the transition of national laboratory developed technologies to the private sector; (2) utilization of national laboratory facilities and expertise; and (3) demonstration and deployment for the economic, energy, and national security of the nation.

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 and computational biology. The capability is further enhanced by instrumentation at the ALS, DOE JGI, the Molecular Foundry, NERSC and JBEI. Berkeley 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.

Kbase (kbase.us) provides the computational capabilities to address the grand challenge of systems biology: to predict and ultimately design biological function. KBase enables users to collaboratively integrate the array of heterogeneous data sets, analysis tools, and workflows needed for a predictive understanding of biological systems. It incorporates functional genomic and metagenomic data for thousands of organisms, and diverse tools including (meta) genomic assembly, annotation, network inference and modeling, allowing researchers to combine varied lines of evidence to create increasingly accurate models of the physiology and community dynamics of microbes and plants. The KBase collaboration (LBNL, ANL, ORNL, BNL and seven universities) is a developing community resource. The project is committed to supporting the optimal use and dissemination of data and algorithms generated by DOE programs, specifically by the main Science Focus Areas (SFAs), Bioenergy Research Centers (BRCs), and at user facilities. KBase enables transparency and reproducibility in the multidisciplinary and iterative, workflows necessary for addressing complex biological problems in energy and the environment. KBase works closely with JGI to ensure that its data are available to its users.

JBEI is one of the three DOE BRCs whose mission is to advance science, engineering and technology to support conversion of lignocellulosic biomass to liquid transportation fuels. 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 conversation to sugars needed to produce energy-rich fuels. The production of commodity chemicals from biomass rather than petroleum heralds 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. The licensed technologies from JBEI's activities have resulted from a strong industrial affiliate program.

The multi-institutional Berkeley Lab-led BER-funded SFA called ENIGMA (Ecosystems and Networks Integrated with Genes and Molecular Assemblies) advances an 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.

BER is the primary sponsor; others include NIH, DoD, industry, and other SPP sponsors. This Core Capability supports DOE's mission to: (1) obtain new molecular-level insight for cost effective biofuels; (2) make discoveries for DOE's needs in climate, bioenergy, and subsurface science; (3) understand mechanistic interactions of low doses of ionizing radiation with biological systems for future radiation-protection standards; and (4) coordinate bioenergy, climate and environmental research across DOE's applied technology offices.

Environmental Subsurface Science. Physical, chemical, biological and atmospheric interactions regulate the geochemical flux of life-critical elements, influence contamination migration, control the production of food and biofuel, and purify water. These interactions also influence the greenhouse gas feedbacks to climate systems, including carbon and methane. With support from BER, Berkeley Lab has been advancing and connecting research ongoing in biosciences, terrestrial ecosystems studies and climate modeling (described above), to advance the understanding of environmental subsurface biogeochemistry.

Berkeley Lab's Genome-to-Watershed SFA focuses on quantifying and predicting the dynamics of mountainous watershed hydrologic and biogeochemical cycles to determine how water, carbon, nutrients and metals are retained or released. In particular, this SFA is addressing how droughts, early snowmelt, and other perturbations that are expected to increase will influence these watershed dynamics and impact downstream water availability and biogeochemical cycling at seasonal to decadal timescales. The Subsurface Biogeochemistry SFA has transitioned this year to a mountainous headwaters catchment in the Upper Colorado River Basin, which is expected to lead to a cascade of effects on downgradient water availability, nutrient loading, carbon cycling and water quality. This SFA's strategies include the development of adaptive approaches to predict terrestrial environment behavior from genome to watershed scale, and advancing new sensing platforms that synchronously and autonomously monitor above and below ground processes in terrestrial environments. Berkeley Lab is collectively advancing predictive understanding of bedrock-to-canopy-to-atmosphere processes using model-inspired experimental design (MODEX) and approaches to manage widely heterogeneous environmental datasets. BER offers primary support for this core competency.

Within the national lab network, Berkeley Lab leads the largest BER Subsurface Biogeochemistry SFA, is a key partner in multi-institutional IDEAS project as well as the multi-institutional ASCEM project, and participates in the JAEA collaboration: Fukushima Environmental Program. This capability is sponsored by BER, EM, LM, DoD/DHS/ EPA, CAState Agencies, UC, SBIR and ARPA-E; it contributes to DOE's linked energy and environmental security mission.

Climate Change Science and Atmospheric Science. Berkeley Lab conducts internationally recognized research on advancing the understanding and prediction of ecosystem responses and feedbacks to climate. The Lab leads the Next Generation Ecosystem Experiment in the Tropics (NGEE-Tropics), focused on a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers. NGEETropics held workshops this year (hydrology, forest mortality, plant trait-based modeling), is taking advantage of the El Niño-Southern Oscillation to measure and model drought impacts on tropical forests, and established Pan-Tropical sites and partnerships. Paired with NGEETropics research, the Lab is advancing new dynamic vegetation modeling approaches.

Berkeley Lab is a key partner in the NGEE-Arctic project, contributing its expertise in environmental geophysics, soil biogeochemistry and microbial ecology, and mechanistic modeling of ecosystem-climate feedbacks. In 2015, the monitoring approaches enabled observations of Arctic dynamics in near real-time, documenting a significant pulse of methane and carbon dioxide associated with early thaw. Also developed was an approach to quantify functional zones in the Arctic landscape for a tractable vehicle for scaling.

To explore how soils will respond to warming *in situ*, Berkeley Lab is conducting two controlled manipulation experiments in the field: one in Barrow as part of the NGEE-Arctic project and one in California as part of the TES SFA. These warming experiments are closely coupled to modeling activities, which will result in more robust understanding and tools for prediction.

Berkeley Lab also leads the AmeriFlux program, a network of over 120 sites in North and South America that measure ecosystem atmosphere fluxes of carbon, water and energy. During the past year, the Berkeley Lab AmeriFlux site data were downloaded by thousands of scientists from around the world. Key strategic thrusts associated with the terrestrial ecosystem science include dynamic vegetation observation and modeling, and together with subsurface science, developing terrestrial community observatories that enable scientific and modeling advances.

To understand the forcing, response and feedbacks of the Earth's climate system, Berkeley Lab has developed a highly integrated climate program. Scientists collect comprehensive measurements of CO2 and CH4, and employ these field data together with detailed observations of the surrounding ecosystems to accelerate the development of DOE's new Accelerated Climate Model for Energy (ACME). Further, in pursuit of more reliable climate projections, Berkeley Lab leads several multi-lab projects to advance DOE's modeling of the mechanisms and impacts of climate change.

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. The Lab developed and operates the carbon measurement capabilities for ARM. With PNNL and LLNL, Berkeley Lab co-leads development of the emerging land-atmosphere-cloud interactions theme, which couples land surface and atmospheric dynamics to address cloud and precipitation biases in DOE climate models.

Berkeley Lab co-leads DOE's flagship ACME project, with its integrated assessment models to create a fully coupled Earth system model that can project the future interactions among energy, food, water resources and climate using state-of-the-science treatments of physical, chemical and biogeochemical processes. Lab researchers are members of the ACME council, land model group co-lead, and leads and task leads for NERSC exascale applications. The Lab launched the Calibrated and Systematic Characterization, Attribution and Detection of Extremes (CASCADE) project to detect and attribute the influence of anthropogenic climate change on past, current and future climate trends through the application of DOE's uncertainty quantification capabilities integrated with new highly parallel computational "pipelines." The Lab also leads a DOE SciDAC project constructing models telescoped through advanced numerical techniques to simulate climate phenomena with high resolution and physical fidelity.

Primary support for this Core Capability comes from BER and ASCR. Additional research in Earth observations from space is obtained through the NASA, and the state of California.

Computing and Mathematics

Advanced Computer Science, Visualization and Data. Berkeley Lab is a leader in computer architecture research, with expertise in low-power parallel processor design, optical interconnects and memory systems unique within DOE. Hardware emulation capabilities enable leadership and participation in multiple co-design centers. The partnership with Sandia in deploying DOE's Computer Architecture Lab (CAL) enables Berkeley Lab to play a critical role in an exascale program. Recent work from CAL includes the specification of an Abstract Machine Model, which defines and summarizes the likely space of possible exascale architectures. While ASCR's main focus – and ours – is on exascale technology, we have also begun to explore quantum information, neuromorphic computing and alternative devices to address the anticipated end of transistor density scaling.

Berkeley Lab is also a leader in performance analysis and algorithms research, with multiple award-winning papers on application performance analysis and the use of emerging computer architectures for scientific applications. The Lab and UC Berkeley established and continue to lead the field of automatic performance tuning research, with recent work on tensor contraction kernels used in computational chemistry resulting in a speedup of between 10-15X on a single node of the NERSC Edison system and scalability to thousands of processors. Recent progress in designing parallel graph-based algorithms for genome assembly has resulted in orders of magnitude speedup, as well as the ability to utilize the largest supercomputers.

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 global leader in programming languages and compilers for parallel machines, and takes a leadership role in programming models for exascale systems. Both the Lab's Unified Parallel C compiler and its Global-Address Space Networking (GASNet) runtime system are broadly deployed by computing-system vendors, government agencies and academic institutions. This programming model is especially powerful for problems that require random access to large data sets, and offers new application opportunities for future exascale systems.

Berkeley Lab is also a leader in the development of new capabilities in high performance and data-intensive visualization and analysis. Key new developments include: *in-situ* visualization and analysis, where the visualization algorithms run concurrently with simulations; more scalable algorithms to deal with increasingly larger datasets; finding solutions to the widening gap between computer performance and I/O rates; and improved feature detection algorithms.

Berkeley Lab is a pioneer in scalable solutions for scientific data, including management, curation, quality-assurance, distribution and analysis. Area highlights include: Based on the Lab's FastBit technology, the Scientific Data Service brings database functionality and efficient parallel query algorithms directly to scientific data files. This has been applied to gene context analysis in the IMG project, as well as to astronomical image retrieval, realizing speedups of almost two orders of magnitude. SPOTsuite, which has enabled ALS beamline scientists to seamlessly integrate experimental data from the ALS and simulations performed at NERSC, utilizes data management and workflow integration techniques. For the Ameriflux program, where ecosystem-level field sites acquire continuous measurements from a large number of sensors at high temporal resolution, the Lab heads up the data assimilation, curation and distribution services. Data collected at individual sites is sent to an archive, where processing creates high quality, standardized datasets to be distributed to a variety of data users.

Berkeley Lab is a leader in troubleshooting and performance-analysis tools for complex, distributed applications, such as the PERFormance Service Oriented Network monitoring ARchitecture (perfSONAR) application, which recently reached the milestone of 1,400 worldwide deployments in national laboratories, commercial and research networks, universities and corporations. ESnet and Berkeley Lab computer scientists work with researchers around the globe to meet the distributed computing and networking needs of the next generation of DOE science experiments. ESnet's On-Demand Secure Circuits and Advance Reservation System (OSCARS) technology, deployed in almost 50 networks worldwide, operates like a dynamic expressway, creating uncongested paths between endpoints.

ASCR is the primary support for this Core Capability, 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 worldwide 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 pool of highly recognized experts in applied mathematics, many of whom are members of NAS, NAE and SIAM Fellows.

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 nuclear flames in supernovae. Adaptive mesh refinement (AMR) is globally recognized as a key enabling technology. Coupled with AMR algorithms, the Lab's hierarchical structured-grid finite difference capabilities can solve turbulent flow problems 10,000 times faster than previous techniques. Researchers have recently applied low-Mach-number techniques to models of cloud formation that are required for the next generation climate models, resulting in dramatically increased computational efficiency.

Berkeley Lab and UC Berkeley have developed fast-marching and level-set methods, numerical techniques that can follow the evolution of multiple moving interfaces and boundaries for problems in fluid mechanics, combustion, computer-chip manufacturing, robotics, biomedical and seismic image processing, and tumor modeling. To this end, we recently established the Center for Applied Mathematics for Energy Research Applications (CAMERA), an integrated, cross-disciplinary center aimed at developing and delivering the fundamental new mathematics now required to support DOE user facilities. The development of new computational methods, utilizing techniques from graph theory, computational harmonic analysis and maximum likelihood estimation has significantly enhanced the fidelity of crystallographic reconstruction.

In numerical linear algebra, Berkeley Lab is the only SC lab with researchers who have expertise in large-scale eigenvalue calculations and direct solutions in sparse matrix computation. The recently released STRUMPACK library – designed for efficient computations with sparse and dense structured matrices – shows improvements of over 5x when compared with currently available libraries.

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. These capabilities also support the development of mathematical descriptions, models and algorithms to understand the behavior of climate, living cells and complex systems related to the 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 using these research areas in conjunction with high-performance computing resources to obtain significant results in many areas of science and engineering.

Key collaborations connected with DOE's Energy Frontier Research Centers (EFRC) and Hubs continue, targeting gas separation and storage, carbon capture and sequestration, solar energy 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. Indeed, DOE's JCESR leverages the computational resources, tools and expertise at NERSC to predict the properties of electrolytes (liquid solutions that conduct ions between battery plates and aid in energy storage). JCESR continues to work with DOE's Materials Project to get a complete scope of battery components for a predictive approach to battery design. The effort is coordinated with DOE's Center for Functional Electronic Material Design (CFEMD) at Berkeley Lab, which conducts large-scale data generation, data mining and benchmarking for new materials.

As mentioned in the Climate Change Science core capability, an extensive collaboration with domain scientists, applied mathematicians and computer scientists is now focused on largescale climate science efforts. The relationship includes interactions with SciDAC institutes SUPER, FastMATH and SDAV to ensure applications are scalable and achieve high performance on next generation computing platforms, which will enable novel climate science research at unprecedented scales and fidelity.

To increase the speed and reduce the errors in identifying astronomical objects as part of the Dark Energy Survey, computational scientists at Berkeley Lab have used Random Forest, a machine learning technique, to vet detections of supernova candidates automatically and in real time. Random Forest employs an ensemble of decision trees to automatically ask the types of questions that astronomers would typically consider when classifying supernova candidates. At the end of the process, each candidate detected is given a score based on the fraction of decision trees that considered it to have the characteristics of a detection of a supernova.

The Integrated Microbial Genomes (IMG) system contributes improving the overall quality of microbial genome and metagenome data. It integrates genomes from all three domains of life, as well as plasmids, viruses and genome fragments, and provides tools for analyzing and reviewing the structural and functional annotations of genomes in a comparative context. With about 50,000 datasets, IMG is one of the largest publicly available data management and analysis systems for microbial genome and metagenome datasets. The system also has more than 13,500 registered users from 93 countries across 6 continents, has contributed to thousands of published papers and served as a tool for teaching genome and metagenome comparative analysis at numerous universities and colleges around the globe.

In terms of presenting computational science tools to new audiences, Berkeley Lab supports the Carbon Capture Simulation Initiative (CCSI), which is deploying state-of-the-art computational modeling and simulation tools to accelerate the commercialization of carbon-capture technologies from discovery to development, demonstration and ultimately the widespread deployment to hundreds of power plants. By developing the interface and workflow tools of this comprehensive, integrated suite of validated science-based computational models, this effort will provide increased confidence in designs, reducing the risk associated with incorporating multiple innovative technologies into new carbon-capture solutions.

With regard to this core capability within the national lab network, Berkeley Lab's key collaborations connect with DOE's EFRCs and Hubs, targeting gas separation and storage, carbon capture and sequestration, solar energy and batteries. In addition, the Lab leads or participates in numerous SciDAC projects connects computer science and applied math work across the network.

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 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: host and network intrusion detection, computer forensics, Byzantine fault tolerance, insider threat modeling, smart grid/industrial control system security, data provenance, HPC program fingerprinting, data sanitization and privacy, network evolution modeling, and host and network resilience.

In addition, 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 network testbed provides an international research platform for cybersecurity research at all network layers. The Lab leads the world in developing technologies to enable the optimal connection of local and wide-area networks, the "Science DMZ," and has championed this concept across the national and international research and education community. The Lab also conducts fundamental research in software-defined networking and network function virtualization forensics tools.

The "Bro" network security software, started at Berkeley Lab in mid-1990s to monitor network traffic in open scientific environments, is now deployed in National Labs, major universities, supercomputer centers and Fortune 100 companies. Bro has recently been adapted for 100 Gbs speeds to enable scaling for the next generation of networks.

ASCR is the primary support for this Core Capability, with additional support from EDER. 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 with disciplines, technologies and practices designed to protect, analyze and disseminate information from electronic sources, including computer systems, computer networks and sensor networks.

High Energy and Nuclear Physics

Particle Physics. Berkeley Lab has a long record of leadership and innovation in particle physics and cosmology. Berkeley Lab has two premier programs in HEP: in the Energy Frontier on the ATLAS experiment, with many hardware and software contributions and leadership roles; and in the Cosmic Frontier, where the Lab is leading next-generation projects in both dark energy and dark matter, and plans to play a lead role in the upcoming CMB-S4 experiment. For the Intensity Frontier, the Lab is a leader in the Daya Bay experiment, is growing new efforts on DUNE, and is a key contributor in reconstruction and simulation software and detector prototyping for the Mu2E experiment. The program is fully aligned with the P5 roadmap, and is enabled and enhanced by strengths in instrumentation and detector R&D, computation and theory.

On the Energy Frontier, Berkeley Lab has played leading roles in the ATLAS pixel and silicon strip tracking detectors, computing and software systems, and physics analysis. The Lab pioneered the pixel development and led the international ATLAS pixel project. Physicists and computational scientists led the development of the ATLAS software framework. Lab scientists have lead roles in all aspects of ATLAS, including Physics Coordinator

(Einsweiler, 2012-13), Deputy Spokesperson (Heinemann, 2013-17), Upgrade Coordinator (Einsweiler, 2015-17) and Simulation Convenor (Marshall, 2014-16). Lab scientists will have lead roles in both the pixel and strip inner tracking detectors for the HL-LHC ATLAS upgrades, with Lab staff serving in management positions in US-ATLAS and the international ATLAS upgrade teams.

In 2011, Saul Perlmutter shared the Nobel Prize in physics “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.” Berkeley Lab has also become a leader in a second technique for dark energy, the measurement of baryon acoustic oscillations (BAOs) in the distribution of galaxies. The Lab led the Baryon Oscillation Spectroscopic Survey (BOSS) project, which successfully completed its five-year survey in 2014, obtaining more than 1.5 million spectra of galaxies and quasars and publishing the most precise cosmological distance measurements to date. For his scientific leadership, David Schlegel was awarded the 2015 DOE E.O. Lawrence Award “for exceptional leadership and innovation to transform cosmology into a precision science.” The Lab now leads 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 20 million galaxies, successfully passing CD1 and CD2, and with CD3 review in Spring 2016.

A critical element of Berkeley Lab’s leadership has been the development of advanced detectors. Red-sensitive charge-coupled devices were invented in our 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. The Lab also developed detectors and a multiplexed readout for cosmic microwave background (CMB) measurements, including the South Pole Telescope and POLARBEAR. The POLARBEAR project, led by Berkeley Lab Faculty Scientist and PI Adrian Lee, was commissioned in Spring 2010 and produced the first direct detection of CMB polarization in late 2013. POLARBEAR will expand into the Simons Array, with three identical telescopes with advanced multichroic polarization detectors, also invented at Berkeley Lab.

Berkeley Lab is also the lead for the Large Underground Xenon (LUX) experiment, and manages the science operations at the Sanford Underground Research Facility in South Dakota where LUX is located almost one mile underground. Updated results from LUX provide the most sensitive limits in the search for dark matter to date and rule out earlier hints of low-mass dark matter. The next-generation successor to LUX, called LZ, has been selected for the Generation 2 Dark Matter initiative at DOE HEP, with Berkeley Lab as the lead. LZ passed CD1/3a with CD2/3b in Spring 2016.

In the Intensity Frontier program, Berkeley Lab provides scientific and computing leadership, as well as project management, for the Daya Bay reactor-based neutrino oscillation experiment. Both the Daya Bay U.S. spokesperson and U.S. operations manager are from Berkeley Lab. The Daya Bay project received a DOE award for excellence in project management in 2013; the cospokespeople, Kam-Biu Luk and Yifang Wang, have been awarded the 2014 APS W.K.H. Panofsky Prize and the 2015 Breakthrough Prize in Fundamental Physics. Berkeley Lab has a small but strategically important effort on DUNE, and makes key contributions to the Mu2e experiment, both led by Fermilab.

The Berkeley Lab Theoretical Physics Group (closely integrated with the UC Berkeley Center for Theoretical Physics) 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 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, nuclear structure, nuclear chemistry and nuclear instrumentation.

In the study of neutrinos, Berkeley Lab's critical role in the discovery of neutrino oscillations at the Sudbury Neutrino Laboratory has been widely recognized. KamLAND and IceCube resulted in the first observations of geoneutrinos 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, 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) and the Cryogenic Underground Observatory for Rare Events (CUORE), the latter having recently set the lowest sensitivity limit for observation of the process.

Accomplishments in quark-gluon plasma physics include the discovery of near-perfect liquid behavior and co-discovery of jet quenching in collisions of gold ions at Brookhaven's Relativistic Heavy Ion Collider (RHIC) by the STAR detector. Most recently, the Heavy Flavor Tracker (HFT) constructed at Berkeley has quantified that the heavy quarks lose a large amount of their energy in the plasma as the jets do. Other notable achievements include producing new forms of antimatter at RHIC (the anti-alpha particle and the anti-hypertriton), possible evidence of the phase transition to quark gluon plasma in lower energy collisions at RHIC, and measurements of higher temperature plasma properties with heavy-ion collisions in the ALICE (A Large Ion Collider Experiment) detector at the LHC. The study of heavy quarks will continue using the Inner Tracker Upgrade for ALICE, which is currently under construction with Berkeley playing a lead role. Recently, NSD initiated a role in defining physics goals and detector components for the future electron-ion collider.

Berkeley Lab has a vibrant program studying nuclear structure, with a focus on the structure of exotic nuclei, especially those with the largest neutron excess or the heaviest masses. For gamma-ray spectroscopy, the Lab conceived and built state-of-the-art detector arrays including Gammasphere, currently deployed at ANL, and GRETINA, which recently completed highly successful campaigns involving beams of rare isotopes at NSCL at Michigan State and ANL's CARIBU facility. This tradition continues with CD-0 for the next-generation gamma-ray tracking array (GRETA), with anticipated DOE funding. Another future example for a strong science case being developed by Berkeley Lab theorists is the next generation Electron-Ion Collider, which will help elucidate the nature of gluonic matter and the structure of the nucleon. There is a growing competency for high-performance computing to study nuclear physics, especially in subfields of quantum chromodynamics on the lattice (lQCD) and supernovae. The Lab's Applied Nuclear Physics program is growing, with applications ranging from nuclear safeguards, radiological monitoring, biomedical applications and detectors for astrophysics. These capitalize on the Lab's capabilities in innovative instrumentation. The U.S. Nuclear Data Program contributes to the Applied Physics capabilities through evaluation and organization of nuclear data for national interests, and relies upon future targeted measurements at the 88-Inch Cyclotron at Berkeley Lab to address gaps in existing data. The 88-Inch Cyclotron supports a local research effort (especially focused on super-heavy nuclei and nuclear data) and outside users interested in testing electronics and materials for radiation hardness.

The Nuclear Physics Core Capability includes innovative equipment and instrumentation, and large-scale data handling designed for experiments that produce multiple petabytes of data per year. Berkeley Lab is leading the development of next generation Electron Cyclotron Resonance (ECR) ion sources essential for next generation accelerator facilities including FRIB at MSU and the future Electron Ion Collider. At the Sanford Lab in South Dakota, the Majorana Demonstrator for neutrinoless double-beta decay is taking first production data, utilizing multiple components produced by Berkeley Lab. The Cryogenic Underground Observatory for Rare Events is also taking production data at Gran Sasso in Europe, and the Lab has a strong lead role. GRETINA is producing data, and GRETA is also advancing. In heavy ion collisions, the Electromagnetic Calorimeter (EMCal) and Di-jet

Calorimeter (DCAL) for ALICE and the high precision, silicon-based STAR HFT were recently completed, building up the very successful construction of the heart of STAR, the time projection chamber. Construction is currently underway of the Monolithic Active Pixel Sensor layers for the ALICE inner tracker upgrade. The Semiconductor Detector Lab provides world-class instrumentation for development of advanced germanium and CdZeTe detectors.

Support for the Nuclear Physics 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 that reveal the characteristics of nuclear matter.

Accelerator Science and Technology

Accelerator Science and Technology. Founded as the first accelerator laboratory, Berkeley Lab has maintained leading capabilities in accelerator development for more than seven decades. The Lab presently has core expertise in the areas of electron and ion sources, magnetic technologies including superconducting magnets, permanent magnets and insertion devices, linear accelerators, synchrotron radiation sources and laser-plasma acceleration. Through novel upgrades and developments (e.g., superbends, top-off, brightness upgrade), the ALS continues to expand its capabilities and is currently the world's brightest source of soft X-rays. Investigations are underway for a future facility upgrade that would increase the brightness by up to 3X to produce fully transverse coherent soft-X-ray beams. This would be a cost-effective upgrade, leveraging the investment and existing infrastructure, and will position the ALS as the premier soft-x ray source for decades to come.

Berkeley Lab programs for the development of high-repetition-rate electron sources, advanced FEL design, superconducting undulators, high-brightness electron beam control and manipulations, and laser systems for accelerator applications are coordinated with several other national labs. The Lab leads the world in the developing simulation tools and techniques that model conventional and advanced accelerators, and the physics of high-intensity laser-matter interaction. This advanced computation is further described in the Computational Science Core Capability.

The Accelerator Science programs greatly enable photon-production systems into the femtosecond and attosecond regime. They are being applied to SLAC's Linac Coherent Light Source (LCLS) and its successor, LCLS-II. Berkeley Lab is contributing significantly to the new LCLS-II undulators, with expertise derived from our undulator R&D and ALS construction. The Lab is also responsible for principal subsystems of the LCLS-II injector, leveraging expertise gained from the APEX gun, which has recently achieved slice emittance results that are very close to meeting LCLS-II requirements. Further, the Lab has contributed to LCLS-II's design in the areas of linac systems and accelerator physics.

The ALS remains at the forefront of the technology used for synchrotron light sources, including high-repetition-rate photoinjectors and novel storage-ring designs. The undulator design capabilities, particularly superconducting devices, have the potential to greatly extend the performance of existing synchrotrons, enabling a new suite of fourth-generation facilities that will provide brighter sources at reduced capital and operating costs. This new endeavor benefits from the development of the ultra-high repetition rate electron gun.

Berkeley Lab is the world leader in ultrahigh-gradient laser-driven plasma acceleration technology, producing high-quality GeV electron beams with compact accelerators, a fundamentally new approach for high-energy particle acceleration. The Berkeley Lab Laser Accelerator (BELLA) project, completed in 2012, is enabling laser-plasma acceleration technology in discrete 10 GeV modules using a meter-scale plasma.

The Lab's Fusion Science and Ion Beam Technology (FS-IBT) Program has significant expertise in developing both ion sources and low-energy beam transport systems. The group has plans to deliver front-end systems for MSU's Facility for Rare Isotope Beams (FRIB) and neutrino projects at FermiLab. The IBT Group has developed novel, high-yield neutron generators recognized by R&D 100 Awards; it has recently extended its research to include gamma- generating devices for national security applications. The group is using the intense, short-ion- beam pulses from the recently completed Neutralized Drift Compression Experiment-II (NDCX-II) to study defect dynamics in solids.

Berkeley Lab has formed a new cross-divisional Berkeley Center for Magnet Technology (BCMT) that covers all areas of magnetic technology: superconducting, permanent, electromagnetic, pulsed and specialty. The primary areas include the superconducting magnet program development of high-field magnets employed in accelerator applications, undulators for light sources and FELs, and specialty magnets for science and applications, as well as fully integrated capabilities from design to manufacturing to testing. Berkeley Lab is the lead lab for R&D on high field magnets. The Lab has been involved in the recent successful application that led to the first isolation of a significant mass of antimatter. Future applications will include neutrino science and potentially the development of the next proton or muon collider.

The Lab's state-of-the-art superconducting magnet development integrates novel conductors, fabrication and testing. This expertise is being applied across SC programs. A notable example is the design and fabrication of a superconducting electron-cyclotron resonance source for FRIB. On the international front, Berkeley Lab is a key member of the LHC Accelerator Research Program (LARP) with a significant role in the LHC upgrade for the new interaction-region focusing magnets. This includes responsibilities for the production of the niobium-tin superconducting cable, mechanical structure and final assembly of the high-field quadrupoles. The alignment of the BCMT with SC priorities is also exemplified in the recent HEP Accelerator Stewardship Program award for developing lighter weight superconducting magnets in gantries to improve patient access to proton or carbon medical therapy.

Supported by HEP and BES, with further sponsorship from ASCR, NE, NNSA, DHS, DoD and other federal agencies, 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.

Applied Science and Energy Technology

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

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 described in section 4.1. The related field of fuel-cell research enables the commercialization of polymer- electrolyte and solid-oxide fuel cells for similar applications. This research involves advanced materials and nanotechnology for clean energy, including hydrogen storage and nanostructured organic 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 also leads 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, which was recently recognized with an R&D 100 Award. 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.

This Core Capability is sponsored by 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 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, Berkeley 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. Berkeley Lab's work for DOE NE through the Used Fuel Disposition Campaign (UFDC) 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; reactor safety modeling is conducted for NRC.

Berkeley Lab is a world leader for developing instrumentation that detects and measures ionizing radiation. Radiation-detection materials, 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 purposes 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 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.

The Air Force and the National Reconnaissance Office support the testing of critical space-based electronic components by the National Security Space Community (NSSC), using heavy-ion beams at the Lab's 88-Inch Cyclotron. "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 Laboratory.

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. Berkeley Lab is also obtaining and evaluating 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, analysis and dissemination of gamma-ray background data, including detailed annotation. Standardization and analysis frameworks developed at the Laboratory 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 engineer, construct and integrate complex systems underpin many of the core capabilities described in this section, and those of major user facilities described above. Within DOE's SC, Berkeley 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.

Berkeley Lab's 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 are responsible for the injector, undulator and low level RF systems. The Lab also responsible leads the US-CUORE, LUX, DESI and LZ collaborative projects. This approach also underpins the pre-conceptual development of the ALS's diffraction limited upgrade. Other successfully integrated systems and project management include: the ATLAS inner detector, 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 was subsequently 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. The Lab develops and transfers new energy- efficient building and industrial technologies from the laboratory to the industrial and commercial world and stimulates the use of high-performance technologies through innovative deployment programs. Berkeley 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 lab network, Berkeley Lab leads management of transmission reliability programs (CERTS); collaborates with DOE, independent power authorities and states (DRRC); and collaborates with other 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 California and other states, and other federal and SPP sponsors, including the Federal Energy Regulatory Commission and the California Energy Commission (CEC). 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. The Lab provides 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.

Berkeley Lab's role within the 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 in developing 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 California Public Utilities Commission (CPUC).

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, Berkeley Lab is a lead partner in the JCESR Hub collaboration. Battery systems research encompasses the development of new materials, theoretical modeling and systems engineering; the Lab also applies its extensive experience in subsurface science to underground compressed-air energy storage. The research in large-subsurface energy storage encompasses numerical simulation 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 system and refrigeration, as well as analysis and development of control systems, fault diagnostics, measurement and verification, agent based IT, energy information and management systems. Berkeley Lab is also a leader in the research of indoor environmental quality, lighting quality, ventilation and health. 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.

Power Systems and Electrical Engineering. The Lab leads the world in advanced sensing modeling and short-term control in the distribution grid and microgrids. The Lab developed key analytics around grid measurement and Distributed Energy Resources Customer Adoption Model (DER-CAM) for dispatch and the control of microgrids. Berkeley Lab develops 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. The 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 core capability is supported by EERE-OE, ARPA-E, DoD's DARPA and ESTCP, and the CEC.

4. Science Strategy for the Future

Berkeley Lab's science strategy extends and integrates spatial and temporal scales to solve the most pressing and profound scientific challenges facing humankind, including advancing the basic science foundation for energy research, providing sustainable long-term energy supplies, protecting the environment, and understanding the most abundant but largely unknown constituents of the universe. Particular areas of emphasis are: Advanced energy science for understanding and predicting the behavior of physical, chemical and biological systems; understanding biological and integrated environmental systems to improve sustainable energy supplies and protect the environment; extending computational and mathematical capabilities; and advancing high-energy and nuclear physics, all of which will assure U.S. leadership in science. Conducting energy technology research and understanding complex subsurface systems can enhance energy supplies, sequester carbon and provide for sustainable energy and environmental benefits for a secure future.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

Overview of Site, Facilities and Infrastructure. The Mission Readiness Facilities and Infrastructure Strategy supports Berkeley Lab's Core Capabilities and meet the Campus Strategy objectives (below) effectively, safely and efficiently. The strategy addresses construction, protection of assets through 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, UC and Berkeley Lab to comprise our 10-year infrastructure strategy.

The main Berkeley Lab campus is located adjacent to UC Berkeley, on 202 acres of (UC) land, of which 85.3 acres are leased to DOE. The site is located within the boundaries of Berkeley and Oakland, California, though 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 at http://www.lbl.gov/community/planning/ldrp/.

The main campus structures consist of 1.714 million gross square feet (gsf) of DOE-owned and operated buildings and trailers, 65% of which are 40-80 years old. In addition to the 1.714M gsf, there are 55,756 gsf of excess structures slated for demolition by the EM Old Town Project over the next several years. Based on updates to the 2015 Laboratory Operations Board (LOB) infrastructure condition assessment, less than 36% of all building assets were ranked as adequate; their average age is 36 years.

There are also 269,185 gsf of UC facilities at the main site, including the domed portion of the ALS, the UC Guest House, Chu Hall (formerly named the Solar Energy Research Center), and Shyh Wang Hall (formerly named the Computational Research and Theory Facility) that were financed by UC, the State of California, and philanthropic donations.

The utilities infrastructure includes domestic water, low conductivity water, sanitary sewer, storm drain, natural gas, compressed air, electrical, life safety and technology systems. These systems and their respective components vary greatly in age and condition, reflecting generations of alterations and betterments over Berkeley Lab's long history. Updates to the 2015 LOB assessment identify only 38% of utilities and site systems as adequate. Significant and ongoing investments in utility systems will be necessary to adequately serve the future needs of science and support operations. To the extent possible, a phased replacement strategy that is coordinated with new development activities is one way to cost effectively execute large component and branch replacements. The Lab will use these opportunities to transition towards the use of common utility corridors and modular utility plants (MUPs). Common utility corridors 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 economical means to meet the chilling and heating loads of building clusters, rather than each building functioning as self-supporting. The generational renewal Berkeley Lab will be experiencing over the next decade provides a unique opportunity for this transition. Taken together, common utility corridors and MUPs will transform the Lab's utility infrastructure into a modern, sustainable and cost effective configuration that has become standard among physical plants throughout the world.

Berkeley Lab leases 11 off-site facilities totaling 339,258 sf for biosciences research (JBEI, ABPDU, KBase, JGI and the Life Sciences Division), NERSC and the Office of the Chief Financial Officer. Off-site NERSC computing operations will continue its consolidation during FY16 in Shyh Wang Hall. This consolidation will allow for termination of 15,135 sf of leased space during FY16. Pursuant to the UC-DOE Prime Contract, Berkeley Lab also has no-fee use of 50,576 gsf of UC space on the UC Berkeley campus.

Space Utilization Summary for Non-Excess Facilities. In 2009, Berkeley Lab implemented a utilization assessment program of laboratory, high bay, storage, shops, and support space; in 2013 it added offices to the program. The program's primary drivers are to identify areas for new or expanding research opportunities and create a lab-wide and transparent data set. Of the ~0.8M gsf assessed as shown in the table below, ~84% was ranked as fully- or over-utilized; ~16% was ranked as less than fully utilized.

Non-Excess Facilities with Underutilized or Excess Space (GSF)

Room Category	Repurpose/Reuse	Not Utilized	Under Utilitzed	Fully Utilized	Over Utilized	Total
HBAY	**0**	**0**	**4,102**	**46,666**	**0**	**50,768**
LAB	**10,216**	**17,403**	**14,660**	**254,853**	**0**	**297,132**
OFFICE	**14,099**	**18,182**	**35,541**	**256,078**	**249**	**324,149**
SUPPORT	**0**	**781**	**3,517**	**612**	**0**	**4910**
STORAGE	**25**	**359**	**185**	**84,984**	**0**	**85,553**
TOTAL	**24,340**	**36,724**	**58,006**	**643,193**	**249**	**794,801**

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, existing facilities modernization, utility infrastructure transformation, and the preparation of sites for future development. 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.

Objective 1: Construct new facilities to advance research collaborations: This includes the partially funded Integrative Genomics Building (IGB), the proposed Biological and Environmental Program Integration Center (BioEPIC) Building, the proposed State of California and philanthropically funded the Bioenergy and Bioproducts

Research Center (BBRC), and other facilities for Biosciences integration, as well as additional Energy Sciences buildings, such as a chemical sciences building and a material sciences laboratory building. These facilities will integrate research programs from geographically dispersed locations onto the former Bevatron and Old Town sites, advance interdisciplinary sciences, further increase the scientific integration and impacts of the ALS, and vacate leased and seismically deficient buildings.

Objective 2: Modernize existing facilities for evolving scientific needs: Upgrades at the ALS (B6) and its support buildings (B37 and B80) are required to meet new performance standards for air and water-cooling systems for the unique, breakthrough research conducted there. Replacement and upgrades of the controls and HVAC systems are required at the Advanced Materials Lab (B2), Materials Sciences Lab (B62), Materials Sciences and Energy Technologies Shared Lab (B66), Chemical Sciences Lab (B70A), and the Laser Accelerator facility (B71) to meet demanding mission-performance requirements for ongoing research that requires equipment sensitive to minor temperature changes and air currents. Power and HVAC upgrades, as well as installation of LCW service, at the Engineering Division complex (B77A) are required to improve production capabilities in support of several Berkeley Lab programs and other DOE complex projects. Centralized air compressors in the Site Compressor Building (B43) that are beyond their useful life require replacement to meet research support reliability requirements, additional capacity for new buildings service, and backup units for continuous service availability. Centralized IT Systems (B50B) requires a utility and fire suppression system upgrade to meet growing institutional needs. Consolidation and modernization of Earth and Environmental Sciences Lab (B84) and improvements needed to create space for the Center for Isotope Geochemistry (B83) to support the integration and growth of earth and environmental sciences programs is planned. Finally, improvements to the building that will become the Safety Training Facility (B75), and relocation of the radiation storage facility currently housed in B70, are captured as items to be considered.

While the majority of these projects will avoid growth of Berkeley Lab's deferred maintenance (DM), the highest priority and mission-critical site-wide DM proposed items in the Infrastructure Investments table are targeted to significantly reduce DM. These proposed projects would rehabilitate HVAC systems, controls, electrical, and other elements within numerous buildings across the site.

Objective 3: Transform utility infrastructure for expansion and reliability: To support new facilities and resolve existing utilities' deficiencies and relocation requirements, the first phases of a site-wide utility corridor are being developed at the Bayview (former Bevatron) and Old Town areas respectively. This includes proposing site-wide water supply, storm-drain, effluent and hillside stabilization systems replacements and repairs to increase service reliability, minimize environmental risk and increase hillside stability. Critical life safety systems, such as standby power generators and electrical distribution equipment, are proposed for upgrade and replacement to serve load increases, promote reliable emergency service and improve electrical worker safety. The majority of these will avoid an increase to Berkeley Lab's DM.

Objective 4: Prepare sites for future development: UC and the Laboratory decided 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 Old Town Demolition Project and Bayview site preparation activities. Currently underway, this razing of an aging cluster of research buildings will demolish excess facilities and remove some legacy contamination.

A campus map (see next page) provides a summary-level overview of the needed infrastructure investments and highlights of our multiyear strategy. This is followed by a discussion of the current and 10-year infrastructure investment gaps of infrastructure support of the laboratory's core capabilities. This is followed by details of Berkeley Lab's 10-year facilities and infrastructure strategy, as well as funding required to achieve the objectives outlined above.

Current Infrastructure Gaps

Contamination & Photon Beam Tunnel Demolition at the Bayview (former Bevatron) site: The Laboratory has been funded to construct and operate the IGB to co-locate the DOE JGI and KBase research programs (currently in leased off-site facilities). The IGB project gained CD-2 approval in March 2016; CD-3 approval is anticipated in August. Berkeley Lab's multiyear strategy includes proposing to construct facilities to support full integration of the biosciences programs adjacent to the IGB. These activities are currently dispersed across four off-site locations within a 25-mile radius of the main site. Program integration would enhance biosciences' synergy, productivity and innovation, and create operational efficiencies over time.

Several areas of VOC-contaminated soil, soil vapor, and groundwater pose a risk to the redevelopment potential of the site, two of which are located just outside the IGB footprint. The contamination from these two areas does not pose a risk to the IGB construction schedule as long as utilities that service the building are not routed through areas of contamination or, if so, are properly designed. VOC-contamination in areas north of the IGB site is unknown and poses a risk to future development activities, such as BioEPIC and BBRC. Berkeley Lab is in the early planning stages of an environmental investigation of the Bayview site.

In addition to the previously discussed challenges, demolition of the underground Photon Beam Tunnel (PBT) and any required environmental remediation will need to be addressed prior to development. The PBT is a remnant of the former Bevatron Facility; its removal was outside the scope of the Bevatron Demolition Project. Due to its use as a beamline, the shielding, as well as the concrete walls, floor and roof of the tunnel must be treated as radioactively contaminated material. Lack of funds to demolish the PBT could delay full integration of the biosciences programs, and result in increased costs for leased space. Therefore it is a priority for the Laboratory to identify the funds needed to complete demolition of the Tunnel as early as possible. Initial planning indicates that tunnel demolition and remediation activities, as well as VOC clean-up activities, could feasibly occur during IGB construction. Berkeley Lab is currently researching funding options for addressing these legacy constraints so that it can make use of its largest and most promising development zone.

Berkeley Center for Magnet Technology (BCMT). A Helium liquefier is needed because many science programs involve experiments and facilities operating at cryogenic temperatures. For example, the HEP-funded Superconducting Magnet Program (SMP) within the BCMT, requires a Helium liquefier. 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 has developed a plan for a cryoplant upgrade that can leverage the prior He storage investments while satisfying broader LHe needs. The plan's 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 (Buildings 6 and 2). The Engineering Division would run the cryoplant facility and support science programs within ATAP, ALS, MSD and others.

Building 71 Mechanical System Upgrades. B71 Mechanical System Upgrades would provide the utility infrastructure necessary for the operation of a proposed new beamline with multiprogram benefits. The utility infrastructure would upgrade the existing mechanical system capabilities to support the planned use of a short focal length beamline as an extension of the existing BELLA petawatt laser. Sources of funding are being investigated.

Building 71 Experimental Cave Infrastructure. The B71 Experimental Cave Infrastructure would provide utility infrastructure to support the installation of a high average power laser system to enable high repetition rate applications of laser plasma accelerators. This infrastructure is needed in the 2018 to 2019 timeframe.

High Risk Compliance Items: There are remaining seismic deficiencies that require improvements to core support facilities: Health Services (B26), Food Services (B54) and the Emergency Operations Center (B48). Additionally, several seismically deficient facilities are planned for demolition, including B50C, B56, B58A, B64, B70, B73, and B73A.

The Fire and Safety Alarm Future Enhancements (Fire SAFE) Project is a plan to replace and upgrade the existing fire and safety alarm systems. The plan is sequenced over a funding dependent, multi-year period based upon building risks, operational priorities and the condition of the existing systems. Objectives include: replacement of fire alarm control panels and connected devices, the majority of which are controlled by panels that will reach end-of life in 2017; identify and connect existing and new safety detection and alarm devices (e.g., toxic gas, oxygen depletion, etc.) to a life safety system; and upgrade existing buildings to current life safety standards including mass notification system, horn/strobe lights for the hearing impaired, exterior building strobes and moving message signs, and placement of manual pull stations to meet Americans with Disabilities Act requirements. FireSAFE ensures continued compliance with applicable building codes, fire codes and DOE Orders; it increases the protection to personnel and assets through early detection and notification of fire and life/safety events.

The Building Perimeter Protection project will improve personnel and property protection in Lab buildings to ensure compliance with the 2016 Site Security Plan and emerging DOE requirements. The national increase in workplace violence has focused DOE attention on the need to protect persons as well as assets. At present, the Lab lacks the ability to remotely lock all exterior doors in the event of an active shooter or other significant security event that requires excluding a threat from buildings. Many key buildings must be manually locked and unlocked each business day by a security patrol officer, and cannot be quickly secured in emergencies.
This multi-year effort will extend the access control system's reach by installing access control equipment on exterior building doors and adding intrusion detection devices in areas housing high risk operations or equipment. Improvements will be completed on a building-by-building schedule based on each building's risk level, addressing the riskiest buildings first. Project timeline is dependent upon funding availability, operational priorities and the complexity of retrofitting buildings constructed in many different ways. The Building Perimeter Project will improve personal safety for Lab workers, visitors and security patrol officers, exclude external threats from building entry remotely and ensure compliance with anticipated DOE and contract requirements. This effort builds an industry standard set of building perimeter access control and detection capabilities that strengthen the Lab's ability to protect its employees as well as DOE property.

The Video Surveillance Replacement Project provides foundational industry-standard video capabilities essential to controlling the increases in security personnel costs and providing affordable protection of Lab personnel and DOE assets. This effort will meet the Lab's need for improved situational awareness and remote visibility of high-value/high-consequence locations, and provide high quality detection of potential security threats without costly human surveillance. The Lab's small current video installation is past the end of its useful life, lacks video analytics capability and is not integrated with alarm monitoring. Field security officers must go to the location of alarms and complaints to assess the severity and source of threats, exposing them to potential harm from active shooters or toxic substance releases. This multiyear project builds an integrated, industry-standard video system consisting of cameras, network video recorders, central video management system, alarm monitoring integrations and video analytics. Cameras will monitor the exterior entries of Lab buildings, and incorporate video analytics capabilities that identify potential threats and alert security operations analysts. Video analytics technology detects threats by constantly analyzing a camera's view for suspicious conditions, e.g., movement and person shapes in a location that should be empty, car stopped in a location where stopping is prohibited; major predator animal shapes present. When a potential threat is detected, the video analytics capability transmits an alarm to the security monitoring system for attention. The network video recorders and central video management system pair video with intrusion detection and access alarms to show the alarm location at the time of the alarm as well as it currently appears. This project will build a stable and expandable framework that complements and integrates with other security operations improvements to manage the Lab's potential threats at an affordable cost.

Future (10 years) Infrastructure Gaps

Replace the ALS Support Building: The ALS is a global center for soft X-ray science and innovation for DOE. As such, ALS's facilities should provide researchers with unique opportunities to interact on the theoretical and experimental facets of photon science. However, the Old Town area, which is functionally obsolete and well beyond its useful lifespan, borders the ALS to the east. The Old Town Demolition Project currently underway will raze the aging cluster of research buildings, creating opportunities to build state-of-the-art research facilities. Currently, $53M has been appropriated for the Old Town Demolition Project (about $5M of which was spent prior to 2015). The project's objective includes the removal of seven seismically deficient Word War II-era buildings and 11 building slabs. It will remove legacy contamination and prepare a two-acre site for productive reuse. With this development opportunity, Berkeley Lab is planning to consolidate centers for the Materials and Chemical Sciences Divisions, and also to extend beamlines from the ALS into the Chemical Sciences Building through the area where B7 (ALS Support Bldg.) is located. A current Investment Gap identified in the Infrastructure Investments table on page 62 is the replacement of B7 in an alternate location strategically placed and custom configured to improve support functions. This is a Lab priority to improve and expand this critical support function.

Additional Grizzly Substation Transformer Bank: The main Grizzly Peak Substation is currently configured with two 41MW transformer banks, either of which can provide Berkeley Lab's full electrical power demand. This configuration provides the ability to perform routine and unplanned maintenance on one transformer bank while the Laboratory remains fully operational on the other.

Shyh Wang Hall will provide the NERSC HPC program with electrical energy at ~60% the cost of their former location in Oakland. The program is expecting new generations of NERSC high Berkeley performance computers to come on-line in 2016, 2020 and 2024. The current power load increase projection for 2020, inclusive of sitewide incremental power increases, may exceed the 41MW capacity of each existing transformer bank. If these projections are realized, an additional transformer bank will be required at the Grizzly Peak Substation to maintain the existing maintenance capabilities. Without the additional transformer bank, the Lab could experience research program load curtailments for each routine and unplanned maintenance event.

Demolition of Seismically-Deficient Buildings: Berkeley Lab's facility and infrastructure Objective 1 includes facilities for biosciences integration, as well as joint physical, energy science and technology collaborations. These facilities will integrate research programs from geographically dispersed locations onto the Bayview and Old Town sites, advance interdisciplinary sciences, further increase the scientific integration and impacts of the ALS, and vacate leased and seismically deficient buildings. To achieve this objective, several seismically deficient lab and research office buildings (55, 56, 60, and 63) must be vacated and demolished. B70 must also be vacated and demolished due to its inadequate condition assessment and poor seismic ratings. Its occupants would need to be dispersed across the site, including the facilities proposed for the Old Town Site. Buildings 73 and 73A are unusable due to severe seismic deficiencies. Trailers 13B, 31A, and 75E are significantly beyond their useful lives and their sites could be used much more effectively.

These research spaces were constructed under the codes of the 1940's–70's; it would not be cost effective to retrofit them. Safe and mission-capable research space is fundamental to DOE's challenging scientific mission objectives. Recent engineering evaluations have identified both significant and extensive seismic safety hazards in these buildings that will fail during the predicted magnitude-7.0+ earthquake on the nearby Hayward Fault or a magnitude-8.3+ earthquake on the San Andreas Fault. Berkeley Lab proposes to vacate and demolish these buildings to eliminate seismic risks, and prepare the sites for productive re-use.

Bldg. 46 Landslide Stabilization: Berkeley Lab's facility & infrastructure Objective 1 includes facilities for biosciences integration. The IGB's Conceptual Design Report locates the building on the Bayview Site, where there is a risk of a potential landslide. Known as "the Bldg. 46 Landslide," this risk was last addressed in 1973. The results of more recent seismic events have significantly improved landslide modeling, and these new models indicate that the existing stabilization system is under-designed relative to current standards.

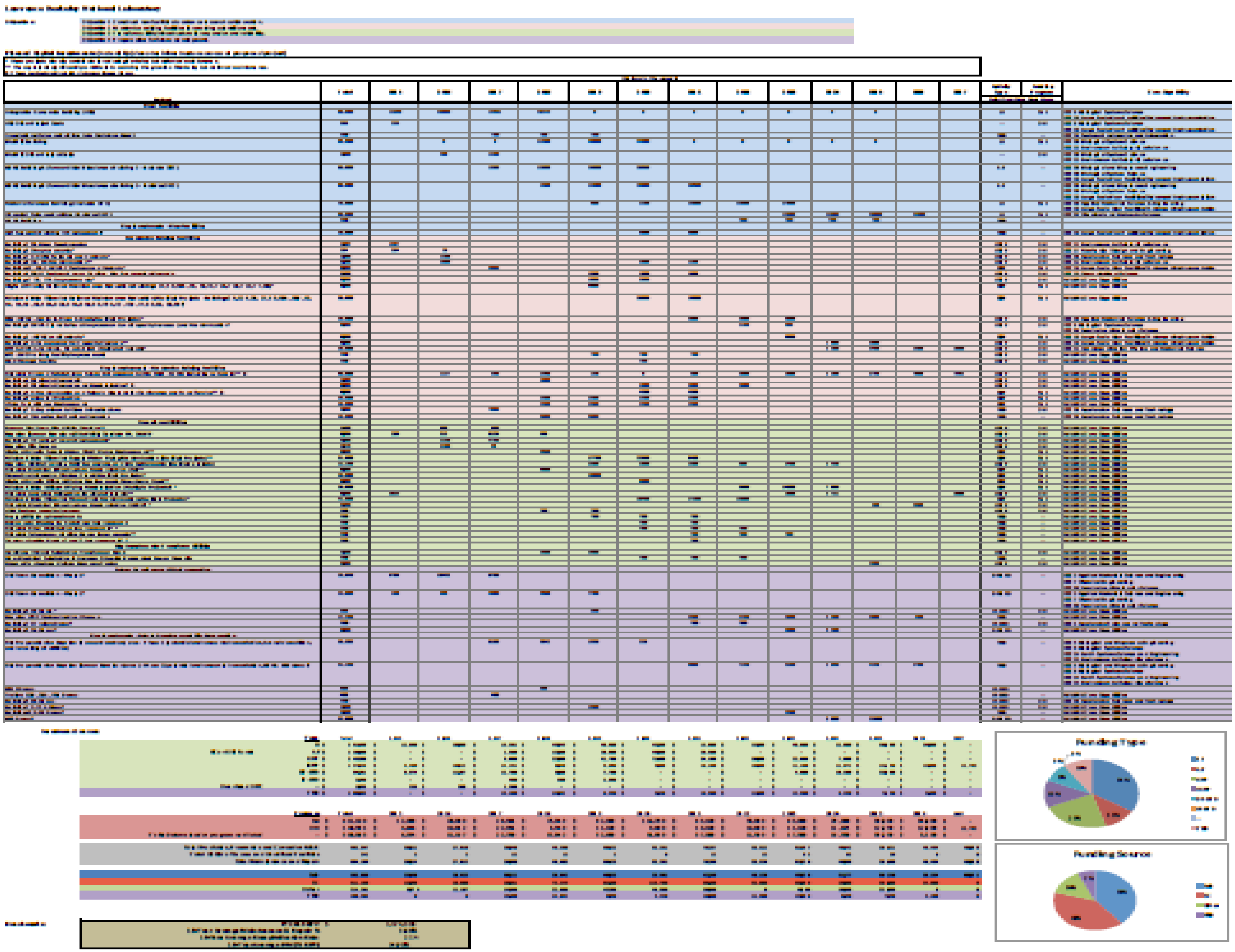
The analyses predict seismic displacements on the order of six feet, even after accounting for the resisting force provided by the existing caissons and tiebacks. From these results it appears that a design-level earthquake ground shaking could produce downslope landslide-related movements that would: 1) cause existing stabilization caissons and/or tiebacks to fail; and 2) result in significant damage in areas upslope. Benefits of a future stabilization project addressing the Bldg. 46 Landslide include: 1) reducing earthquake-induced landslide hazards to McMillan Road, Building 46, subsurface utilities and other existing features that overlie or are intersected by the 1973 landslide deposit; and 2) increased flexibility in siting future buildings on the Bayview flat.

Maintenance and Repair as a % of Replacement Plant Value

The FY16 projected Maintenance Investment Index (MII) at Berkeley Lab is 2.04%, which is a clear increase from the 1.77% in FY15. Current forecasts show MII at 2% each year through FY27. Looking at the period as a whole, the average MII rate from FY16-FY22 is 2.19%, excluding any potential directly funded maintenance related investments. Through a comprehensive maintenance assessment in FY15, increased planning activities in FY16, and continual condition assessment updates, Berkeley Lab has made significant progress towards determining appropriate funding levels for maintenance activities. These activities have also helped target maintenance investments to maximize mission-readiness. The Lab will continue to build upon these recent improvements with the goal of meeting or exceeding the 2% target each year.

Deferred Maintenance

In FY15 Annual Lab Plan LBNL discussed the modified deferred maintenance projection that resulted from the Laboratory Operations Board (LOB) driven assessment. A more comprehensive review, including the re-evaluation of failure consequence to the scientific mission, re-characterization of equipment condition rating, inclusion of greater numbers of assets, reduction of asset maintenance intervals, and inclusion of cost escalation, has continued following last year's submission. This now updated review has resulted in an increase in LBNL's deferred projection of $88.0M stated in the FY15 Annual Lab Plan to the $255.4M stated herein. The deferred maintenance trend forecast for 2016 will remain relatively flat with a slight increase, but will trend down starting in 2017 and continuing through 2025, as shown in the IFC Crosscut. Increased investment in DM reduction by LBNL will provide the means for a decreasing DM trend during this period. If the plan described in these pages is implemented as proposed, the projected year 2027 deferred maintenance value would be reduced to the $116.9M stated herein.



Oak Ridge National Laboratory

1. Mission and Overview

The mission of Oak Ridge National Laboratory (ORNL), the largest multi-program science and energy laboratory of the US Department of Energy (DOE), is to deliver scientific discoveries and technical breakthroughs that will accelerate the development and deployment of solutions in clean energy and global security, thus creating economic opportunity for the nation.

Located near Oak Ridge, Tennessee, ORNL was established in 1943 as part of the Manhattan Project. After pioneering plutonium production and separation, the Laboratory focused on nuclear energy, later expanding to address other energy sources and their impacts. Today, signature strengths in materials, neutron science, nuclear science and engineering, and high-performance computing (HPC) underpin a broad set of core capabilities focused on DOE mission needs.

ORNL manages one of the nation’s most comprehensive materials programs, integrating basic and applied research and development (R&D) to deliver advanced materials for energy applications. Two of the world’s most powerful neutron science facilities—the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor (HFIR)—offer unmatched capabilities for understanding materials structure and dynamics, biological systems, and fundamental neutron physics. Unique resources for nuclear science and technology (S&T) are exploited to expand nuclear power, enhance national security, and produce isotopes. Leadership-class computers—including the 27 peta¬flops (PF) Titan, flagship system of the Oak Ridge Leadership Computing Facility (OLCF)—accelerate scientific discovery and innovation across ORNL’s R&D portfolio, which comprises a diverse set of programs linked by an urgent focus on clean energy and global security challenges.

Partnerships leverage other major investments in research infrastructure [e.g., the Center for Nanophase Materials Sciences (CNMS), the Manufacturing Demonstration Facility (MDF), the Carbon Fiber Technology Facility (CFTF), and nuclear and radiological facilities]. ORNL leads several S&T collaborations for DOE, including two Energy Frontier Research Centers (EFRCs), the BioEnergy Science

2. Lab-at-a-Glance

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

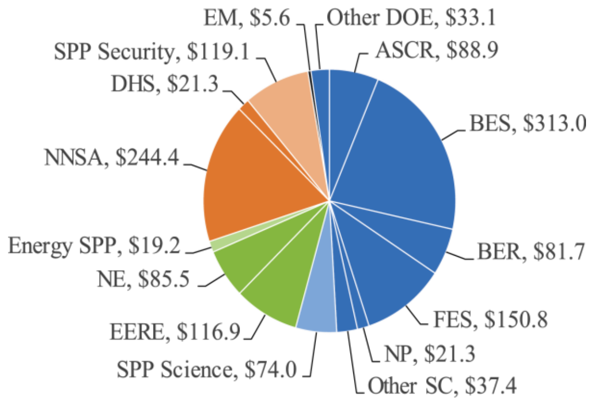
Physical Assets:

- 4,421 acres and 308 buildings
- 4.4M GSF in active operational buildings
- Replacement Plant Value: $6.4B
- 0.207k GSF in 26 Excess Facilities
- 1M GSF in Leased Facilities

Human Capital:

- 4,628 full-time equivalent (FTE) employees
- 155 joint faculty
- 328 postdoctoral researchers
- 252 undergraduate students
- 283 graduate students
- 2,899 facility users
- 1,728 visiting scientists

FY 2015 Funding by Source (Costs in $M):



FY 2015 Lab Operating Costs (excluding Recovery Act): $1,412.1M

FY 2015 DOE/NNSA Costs: $1,145.5M

FY 2015 SPP (Non-DOE/DHS) Costs: $212.2M

FY 2015 SPP as % Total Lab Operating Costs: 15.0%

FY 2015 Total DHS Costs: $21.3M

Center (BESC), the Next-Generation Ecosystem Experiments–Arctic (NGEE-Arctic), and the Consortium for Advanced Simulation of Light Water Reactors (CASL), and it is a founding partner of the Institute for Advanced Composites Manufacturing Innovation (IACMI). ORNL also manages the US contributions to the ITER Project and the Exascale Computing Project (ECP) for DOE's Office of Sciences (SC).

3. Current Laboratory Core Capabilities

Of the 24 core capabilities distributed across DOE's national laboratories, ORNL possesses 23, indicating the exceptional breadth of its scientific and technological foundation. Each comprises a substantial combination of people, equipment, and facilities having unique or world-leading components and is employed in mission delivery for DOE, the National Nuclear Security Administration (NNSA), the US Department of Homeland Security (DHS), and other sponsors. Synergies among these core capabilities enable ORNL to tackle the fundamental science challenges posed by DOE's missions and to carry out the translational research required to accelerate the delivery of solutions to the marketplace, with an emphasis on development, demonstration, and deployment.

As discussed in greater detail in Sect. 5 and Appendix A, the application of ORNL's core capabilities to the needs of non-DOE sponsors through Strategic Partnership Projects (SPPs) and other mechanisms ensures the fullest use of the results of DOE's investment in R&D. At the same time, non-DOE sponsored research strengthens ORNL's core capabilities and sustains the Laboratory's ability to deliver on DOE's missions.

To sustain and extend our core capabilities, we have launched a Laboratory-level effort to strengthen ORNL's science and innovation culture, with an emphasis on investing in our staff, supporting them in building productive careers in R&D, and challenging ourselves to be the best science and energy laboratory in the world.

ORNL core capabilities

- Large-Scale User Facilities/Advanced Instrumentation
- Accelerator Science and Technology
- Condensed Matter Physics and Materials Science
- Applied Materials Science and Engineering
- Chemical and Molecular Science
- Advanced Computer Science, Visualization, and Data
- Computational Science
- Biological Systems Science
- Climate Change Science
- Environmental Subsurface Science
- Plasma and Fusion Energy Sciences
- Nuclear Physics
- Applied Nuclear Science and Technology
- Chemical Engineering
- Systems Engineering and Integration

Accelerator Science and Technology

ORNL has world-leading expertise in the basic physics of high-intensity beams and the technology to support production, acceleration, accumulation, and utilization of high-intensity, high-power beams. The SNS accelerator complex, operating at ≥1MW beam power on target, is the world's most powerful pulsed proton accelerator and the world's sole superconducting linear accelerator for hadrons. Through SNS, ORNL leads the investigation of the dynamics of high-intensity hadron beams and the development of high-power proton targets.

Other ORNL leadership areas include expertise in ion sources and low-energy beam chopping and manipulation; superconducting radio-frequency (RF) 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 exploited to develop beam dynamics modeling and data management tools to design next-generation spallation neutron sources, high-intensity linear accelerators (linacs), and storage rings. 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 have allowed SNS to operate for sustained periods at ~1.3 MW.

The comprehensive Cryogenic Test Facility supports a robust research program that has led to the development and successful deployment of a novel in situ plasma-cleaning technology that can increase the peak gradients of superconducting high-beta accelerator cavities by up to 25%. The sponsor of this program has asked ORNL to contribute this technology to other important accelerator projects in its portfolio. ORNL 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 advanced beam instrumentation systems. Recent advances in high-level real-time applications, in combination with improvements in warm accelerator structure vacuum systems, have led to significant gains in efficiency for facility turn-on.

ORNL has constructed a low-energy Beam Test Facility (BTF) to commission a spare RF quadrupole (RFQ) structure. After this device is installed in the production facility, the original RFQ structure will be installed in the BTF to support a robust program of scientific study aimed at understanding the formation of beam halo in high-intensity hadron accelerators as well as developing novel neutron moderator technologies.

The impact of ORNL's research in high-intensity beam dynamics and technology spans all fields of science enabled by high-power hadron accelerators. ORNL staff members are strongly engaged with similar international accelerator facilities as reviewers and advisors. SC is the primary source of funding [mission areas SC-10, 30] with additional support provided through partnerships with the University of Tennessee (UT) funded by SC's High Energy Physics program and the National Science Foundation (NSF).

Approximately 221 full-time equivalent (FTE) staff, including 3 postdoctoral researchers support accelerator S&T. SCs Basic Energy Science (BES) program [mission area SC-10] and SCs Nuclear Physics (NP) program [mission areas SC-25, 30] are the primary sources of funding for the ongoing accelerator S&T activities.

Advanced Computer Science, Visualization, and Data

ORNL's scientists develop tools and system software for leadership-class computers and applications (e.g., ADIOS, Aspen, Oxbow, Hercules, OpenARC) that are used to address problems of national importance. In addition, ORNL develops visual analytics tools to support scientific visualization of data and information (e.g., EVAL, Eden, Origami) for use with the Exploratory Visualization Environment for Research in Science and Technology (EVEREST), the Compute and Data Environment for Science (CADES), and OLCF. ORNL enables translation from R&D to deployment through colocated, integrated expertise in scalable system software, component technologies, architecture-aware algorithms, virtualization, and real-time large-scale data analytics for exascale and advanced computing.

ORNL also enables scientific discovery and accelerates deployment of advanced technologies in energy and national security by developing, managing, and exploiting scientific data repositories [e.g., the Atmospheric Radiation Measurement (ARM) Data Archive, Carbon Dioxide Information Analysis Center (CDIAC), Distributed Active Archive Center (DAAC), Earth System Grid Federation, National Extreme Events Data and Research Center, 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. These R&D activities will deliver exascale-capable systems that will contribute to solving critical national challenges in science, energy assurance, national security, advanced manufacturing, and health care.

ORNL is a leader in predictive performance and future-generation high-end computing architectures. Researchers have significant expertise in system software, component technologies, run time optimization, architecture-aware algorithms, resilient computations, and networking. This expertise is applied to improve the performance, efficiency, reliability, and usability of extreme-scale architectures and to execute large-scale HPC science and engineering applications. Researchers in computer science and mathematics focus on computational code performance improvement (e.g., testing and developing tools, libraries, languages).

The HPC resources of OLCF, including the Cray XK7 Titan, 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. In addition, the Cray XT6-HE Gaea system is operated for the National Climate-Computing Research Center of the National Oceanic and Atmospheric Administration (NOAA), facilitating multi agency cooperation and R&D partnerships across the climate research community. CADES, launched internally to provide a fully integrated infrastructure offering compute and data services for researchers, is now being applied to the needs of external users, including the National Library of Medicine. With this platform, researchers can process, manage, and analyze large amounts of data using scalable storage, data analysis, and visualization tools. ORNL is home to a national center of excellence in HPC architecture, software, and data analytics, the Extreme-Scale Systems Center, funded by the US Department of Defense (DoD), and maintains the nation's chemical security database and vulnerability modeling capability, funded by DHS. The availability of forefront HPC resources on the ORNL campus also supports the Urban Dynamics Institute (UDI), the Institute for Functional Imaging of Materials (IFIM), and CASL.

At least 236 FTE staff, including 21 postdoctoral researchers, support this core capability. ORNL is committed to growing the nation's expertise in data analytics and visualization through a joint Data Science and Engineering Ph.D. program with UT within the Bredesen Center for Interdisciplinary Research and Graduate Education. This capability is supported by SC [mission areas SC-1–8, 12, 13, 16], DOE's Office of Electricity Delivery and Energy Reliability (OE) [mission area ES-10], and SPP customers including DHS, US Intelligence Community (IC), DoD, and US Department of Health and Human Services (DHHS).

Applied Materials Science and Engineering

ORNL possesses world-leading expertise in experimental, theoretical, and computational materials research. ORNL exploits this capability for a wide variety of materials for energy and national security applications and focuses on developing new materials for optimized performance, especially in extreme environments. For example, a new class of alloys has been demonstrated for application in accident-tolerant fuel cladding [B. A. Pint et al., *J Nucl Mater* **440**, 420 (2013)]. 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, environmental acceptability, 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 fission and fusion energy, transportation, high-efficiency steam generation, and advanced power cycles utilizing supercritical CO_2 among other applications. Researchers work very closely with industry, and results are a source for the majority of ORNL's patents. Novel processing techniques for manufacturing include additive manufacturing of metals, alloys, and polymer composites. For example, recent work demonstrated, for the first time, site-specific texture control during e-beam powder-bed deposition of a Ti alloy [R. R. Dehoff et al., *Mater Sci Technol* **31**, 931 (2015)]. Specialized capabilities in this area include materials joining, surface engineering, corrosion studies under harsh but well-controlled conditions, mechanical testing in a variety of environments, and physical property determination. Specific materials expertise exists in advanced alloys, ceramics, nanomaterials, carbon fiber and composites, nanostructured carbons, polymers, and energy materials, including batteries and capacitors, photovoltaics, and thermoelectrics, among others. Outstanding examples of alloy development/qualification are the clad and insulation materials used in radioisotopic thermoelectric generators that power the National Aeronautics and Space Administration's (NASA) deep space probes, including New Horizons, and the recent discovery of a new family of cast Al alloys with higher temperature strength than those currently used (US patent applied for).

ORNL's materials science resources include a range of state-of-the-art capabilities for materials development and testing: DOE user facilities, such as CNMS, SNS, HFIR, and OLCF; major research facilities CFTF and MDF; and other facilities such as the Low Activation Materials Design and Analysis (LAMDA) laboratories and Irradiated Materials Examination and Testing hot cell facility. Examining materials behavior at extremes, which is essential for alloy development and processing, is enabled by ORNL facilities offering access to high temperatures, high pressures, neutron irradiation, and intense magnetic fields, coupled with testing capabilities that range from basic fracture mechanics to a modern creep testing facility to friction and wear.

Strong industrial interactions and technology transfer result in substantial impacts on materials production and utilization, with benefits for efficient and environmentally acceptable power production and transmission, sustainable transportation, and spacecraft power systems.

ORNL's applied materials science and engineering core capability comprises 365 FTE staff, including 86 postdoctoral researchers. Funding comes from SC [mission areas SC-11, 18], DOE Office of Energy Efficiency and Renewable Energy (EERE) [mission areas ES-2, 4, 5, 8, 10, 13, 14, 15], DOE Office of Fossil Energy (FE) [mission areas FE-3, 4], DOE Office of Nuclear Energy (NE) [mission areas NE-1–3], NNSA [mission areas NNSA-1–3], DHS [mission area HS-9], DOE Advanced Research Projects Agency-Energy (ARPA-E), DoD, and other SPP customers.

Applied Mathematics

ORNL has extensive expertise in the development of theoretical and numerical solutions of complex deterministic and stochastic physical processes and engineered systems (e.g., ACUMEN, TASMANIAN) needed to deliver next-generation science at large-scale computational and experimental facilities. ORNL's capabilities in the construction, approximation, and analysis of novel, massively scalable and resilient mathematical and computational methods are applied to deliver at scale applications for scientific discovery and decision science. ORNL expertise in innovative numerical and functional analysis, approximation theory, statistics, and optimization is applied to interdisciplinary research, such as network problems, signal processing, and image reconstruction.

ORNL's applied mathematicians are developing the fundamental mathematics needed to enable next-generation simulation capabilities for large-scale applications of national and global interest. Examples of applications include smart grids, renewable energy technologies, vulnerability analysis of water and power supplies, biological networks, climate change estimation, and design and discovery of new materials. ORNL researchers are developing extreme-scale, architecture-aware, and resilient mathematical and computational approaches for exploiting and realizing the potential of exascale and future computing platforms.

ORNL provides leadership in the areas of uncertainty quantification and optimization for high-dimensional stochastic physical and engineering systems; research into massively scalable and resilient programming models; extreme-scale linear and nonlinear solvers; high-quality mathematical software, and open source numerical libraries (e.g., TASMANIAN and EISPACK); optimal reconstruction from both sparse and extensive noisy data (e.g., neutron, tomographic, and magnetic resonance); and advanced methods for multiphysics/multiscale and network problems (e.g., model reduction and hybrid methods and atomistic-to-continuum coupling). ORNL's body of work comprises completely new approaches and enhancements to existing methods, which have led to the creation of state-of-the-art algorithms, mathematics, and computational science, but have also had a strong impact on several important applications in energy, materials science, and national security.

The applied mathematics core capability is supported by staff affiliated with OLCF, CNMS, and SNS; CASL; ORNL's IFIM, Climate Change Science Institute (CCSI), the UT-ORNL Joint Institute for Computational Sciences (JICS); and the UT Knoxville Department of Mathematics. A total of 52 FTE staff, including 6 postdoctoral researchers, support this core capability. Additionally, ORNL's Householder Fellowship supports this core capability. Funding comes primarily from SC [mission areas SC-1, 2, 8, 13], DoD, NSF, DHHS, and other SPP sponsors.

Biological and Bioprocess Engineering

ORNL brings substantial strength in the scientific and technical foundations for applying fundamental biological understanding to bioprocessing and bioengineering in addressing DOE missions in bioenergy production, carbon biosequestration, and environmental contaminants processing. ORNL is (1) leading BESC, a nexus for research on biomass utilization for advanced biofuels and products (e.g., higher alcohols, esters, and lignin coproducts); (2) characterizing the largest population of *Populus* genotypes for biomass deconstruction gene discovery; (3) developing new microbial platforms for the control of biomass deconstruction and global carbon cycles; (4) coupling fundamental and applied research in biomass production and conversion for applications in materials and advanced combustion; and (5) making sustained contributions to bioenergy feedstock resource assessment and supply projections (e.g., the “Billion-Ton” studies[7]).

ORNL leverages its broad capabilities in chemical engineering, materials science, and systems engineering to accelerate research outcomes into demonstrable improvements in biofuels, bioproducts, and bioremediation moving from the lab to the field or pilot level. Integrated teams at ORNL bridge science to applications. For example, ORNL recently licensed technology to reduce lignin content and recalcitrance in biofuels crops (licensed to Greenwood Resources). ORNL utilizes expertise in plant sciences, microbiology, molecular biology, and bioinformatics, in combination with facilities such as our common gardens and the ORNL computing resources (CADES, OLCF) to address biofuels production and carbon sequestration. ORNL applies materials and chemical sciences capabilities to develop corrosion-resistant materials for use in bioprocessing systems, and to improve microbial fuel cells, improve carbon fiber production at CFTF, and produce bionanomaterials such as nanomaterials for use in light-emitting diodes (LEDs) and radar-reflecting coatings.

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 in the development of the “Billion Ton” studies and of sustainability metrics and analysis, including those for water impacts. ORNL also leads in the exploitation of a suite of biomass conversion processes: novel microbes and applied systems biology, pyrolysis modeling, and biofuels and bioproduct upgrading to advance bioenergy production. Building on identification of key genes that can be manipulated to improve bioprocessing for fuel and co-product production, ORNL has developed innovations resulting in both patents and licenses (e.g., C5 FUEL™).

ORNL has 111 FTE staff supporting this core capability. ORNL user facilities SNS, HFIR, OLCF, and the National Transportation Research Center (NTRC), along with the UT-ORNL Joint Institute for Biological Sciences (JIBS), greenhouse facilities and CADES provide the needed infrastructure to accelerate discovery and technology development.

SC [SC-12, 15], and EERE [ES-8] 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), US Department of Agriculture (USDA), 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, synthetic biology, ecology, computational biology, imaging, and microbiology; (2) gene discovery; (3) foundational research in plant science that enables development of plant feedstocks for bioenergy and materials; (4) modeling of molecular dynamics of proteins; and (5) development of adaptive imaging at multiple spatial and temporal scales. The fundamental understanding delivered through application of this core capability is essential to the solution of challenging societal problems in bioenergy, climate change, carbon management, and environmental remediation. For example, ORNL is the

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[7] U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p.

host institution for BESC, which has a strong record of research that is leading to demonstrable improvements in the economics and sustainable production of biomass and its conversion to advanced biofuels and other products, including carbon fiber. Fundamental research performed by BESC is rapidly advancing the understanding of cell wall structure and plant feedstock systems. The BESC partnership accelerates the translation of fundamental science outcomes into demonstrable improvements in sustainable biofuel and bioproduct production at field or pilot-level scales.

BESC and other ORNL Science Focus Areas (SFAs) are 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 their physical and chemical environment. Research on plant-microbe interfaces at ORNL characterizes the soil and plant microbiome but also examines fundamental aspects of plant-microbe signaling and beneficial associations to predict carbon sequestration in the terrestrial biosphere and ecosystem response to climate change, and to increase sustainability. These data-rich experimental efforts interface with bio-informatics expertise in microbial annotation and in construction and interpretation of complex systems biology data.

ORNL has strategic strengths in plant biology that have largely focused on *Populus*, in part through a series of highly successful genome-wide association studies focusing on our unique genetic resource of more than 1000 genome-sequenced *Populus* lines in common gardens. ORNL researchers were the first to discover genes enabling colonization of plants by microbes, potentially enabling technologies for nutrient uptake (J. L. Labbé et al., A *Populus* lectin receptor-like kinase mediates non-host interaction between *Laccaria bicolor* and *Arabidopsis*, *Science*, submitted). This discovery positions ORNL to address additional species of interest for bioproducts (e.g., *Agave*, and *Eucalyptus*) and food crops.

Biological systems science at ORNL also focuses on the biological transformations of critical DOE-relevant pollutants such as mercury, nutrients, and carbon. Capabilities in biomass, neutrons and computing are combined in the Biofuels SFA. ORNL is advancing adaptive biosystems imaging by combining nanoscale, multimodal spectroscopic, and neutron imaging with a strong computational simulation component. Additionally, ORNL partners with other national laboratories on SC Biological and Environmental Research Program (BER) projects such as the Ecosystems and Networks Integrated with Genes and Molecular Assemblies (ENIGMA) consortium and the Systems Biology Knowledgebase (KBase).

ORNL's unique resources include the Center for Structural Molecular Biology (CSMB), the Biological Small-Angle Neutron Scattering (Bio-SANS) instrument at HFIR, and specialized mass spectrometry instruments and expertise. CSMB takes advantage of specialized facilities for sample deuteration, neutron scattering, and HPC. The 80 research staff supporting this capability rely on ORNL's impressive research infrastructure including SNS; OLCF; CADES; JIBS; and state-of-the-art greenhouses, environmental chambers, and characterization laboratories.

SC [mission areas SC-4, 12–16] and EERE [ES-2, 8, 13] are the primary sponsors of the work within this capability. Additional work is sponsored by DHS [HS-3], NIH, ARPA-E, DoD, and EPA.

Chemical Engineering

ORNL's capabilities in chemical engineering span discovery and applied research. These capabilities 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, high-efficiency clean combustion, and biofuel production enables ORNL to develop new chemical processes and separations technologies that improve efficiency, economy, environmental acceptability, and safety in energy generation, conversion, and utilization. Research in isotope production and separation, in environmental remediation, and in actinide separations, is also underpinned by this capability.

Technology development through chemical engineering often builds directly on (1) SC Basic Energy Sciences Program (BES)-sponsored fundamental research in materials design, synthesis, and characterization; (2) BES-sponsored research in chemical separations and catalysis; (3) BER-sponsored research in bio-based fuels and chemical production; and (4) SC Nuclear Physics Program (NP)-sponsored research in isotope production. Example results include new polymeric materials to extract uranium from seawater and novel materials to separate and capture CO_2. This capability also enables ORNL to develop environmentally friendly methods for lithium isotope separation, flowsheets for the recovery and purification of ^{238}Pu to fuel the nation's space exploration missions and of ^{63}Ni to enable sensitive explosives detection, and separations methods for extracting rare earths for the Critical Materials Institute (CMI). ORNL's expertise was used to develop the Next-Generation Caustic Side Solvent Extraction (NG-CSSX) process for the extraction of cesium from alkaline waste that is 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 exploits this core capability to develop chemical separations techniques and measurements that support the validation of modeling and simulation (M&S) tools and enable advances in stable isotope enrichment, used nuclear fuel (UNF) reprocessing, waste treatment technology, production of important radioisotopes (including ^{252}Cf, ^{238}Pu, and ^{63}Ni), and development of isotope applications for NP and other customers. Innovative chemical processes being developed for recovery and recycle of non-nuclear materials from UNF assemblies have great potential for simplifying secure UNF disposition pathways and reducing the mass and volume of the waste stream. 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 (GHG) emissions, are being examined using novel adsorbents, including nanostructured materials and ionic liquids.

Chemical engineering research at ORNL engages more than 100 FTE staff and makes use of unique resources that span radiological laboratories and nuclear facilities, including the Radiochemical Engineering Development Center (REDC); biochemical laboratories for investigating environmental and biofuels technologies; and chemical and materials laboratories for synthesis and characterization resources. These resources include SNS, HFIR, CNMS, OLCF, and NTRC.
Funding for chemical engineering originates from several sources, including SC [mission areas SC-11, 14, 31], EERE [mission areas ES-1, 3, 5, 8, 11, 15], NE [mission area NE-3], DOE's Office of Environmental Management (EM) [mission area EM-3], DHS [HS-3], NNSA [mission area NNSA-2], and SPP programs.

Chemical and Molecular Science

ORNL's core capability in chemical and molecular science is focused on understanding, predicting, and controlling physical processes and chemical transformations at interfaces over a broad range of length and time scales, relevant to DOE's science, energy, national security, and environmental missions. For example, the Fluid Interface Reactions, Structures and Transport (FIRST) EFRC takes advantage of neutron scattering, spectroscopy, and other characterization tools, coupled with precise synthesis and computation to develop a fundamental understanding and validated predictive models of the unique nanoscale environment at the fluid–solid interface that will enable transformational advances in electrochemical energy storage and electrocatalysis. As part of our spectroscopy activities, novel chemical imaging techniques, utilizing combinations of mass spectrometry, optical spectroscopy, and scanning probes, have been developed to characterize interfaces and interfacial processes; many of these advances have been licensed to industry. These tools have been used to gain a fundamental understanding of the structure-function relationship in catalysts, providing new insights into the design of catalysts with superior selectivity and activity, and to detect drugs in brain tissue [V. Kertesz, *Anal Bioanal Chem* **407**, 5989 (2015)].

ORNL is applying this core capability to create new materials for separations, including molecular recognition agents with higher selectivity and control in ion separations. This expertise has been used, for example, in the development of self-assembled capsules that selectively encapsulate sulfate [R. Custelcean et al., *Angew Chem*

Int Ed **54,** 10525 (2015)]. This approach could be used to remove sulfate from Hanford tank waste [R. Custelcean et al., *Cryst Growth Des* **15**, 517 (2015)], potentially saving billions of dollars in preparing materials for vitrification. ORNL's strengths in separations, as well as geoscience, interfacial chemistry, and synthesis science, are being applied to address key challenges for CMI including development of more efficient strategies for improving critical materials extraction and recycling and resource recovery.

A core strength of the chemical and molecular sciences portfolio at ORNL is in understanding and controlling transport and reactions at interfaces, which is relevant to DOE-sponsored research in catalysis, geosciences, chemical separation, actinide chemistry, and electrical energy storage. For example, this strength is used to uncover the relationship between molecular-scale and pore-scale geochemical processes and connect it with the larger goal of making more reliable predictions of resource and waste migration in subsurface environments. These strengths also support our activities in catalysis and chemical transformations, where efforts are focused on understanding and controlling reaction selectivity through tuning cooperativity in multi-functional catalysts. These studies have developed a noble-metal-free mesoporous heterogeneous catalyst that is superior to the state-of-the art commercial catalyst for the selective aerobic oxidation of C–H bonds at low temperature (100–120 °C) [P. Zhang et al., *Nature Commun* **6**, 8446 (2015), DOI: 10.1038/ncomms9446].

ORNL is a leader in the use of neutron scattering methods at SNS and HFIR to address fundamental problems in chemical and molecular sciences, such as the structure and dynamics of fluids, solids, and interfaces. For example, a BES catalysis program PI, funded by LDRD, is building a sample environment for in situ vibrational spectroscopic studies of catalytic processes using VISION at SNS. Researchers also make extensive use of CNMS for specialized synthesis and characterization tools, especially world-class electron and scanning probe microscopies, and OLCF for computational resources. The chemical and molecular science core capability also comprises novel characterization tools including solution and solid-state nuclear magnetic resonance, surface sampling mass spectrometry, and femtosecond laser spectroscopy.

Approximately 177 FTE staff, including 49 postdoctoral researchers, support this core capability. Funding comes primarily from SC [mission areas SC-7–9, 11, 14]. Applied programs sponsored by EM [EM-2, 3], NE, EERE [ES-] and BER [SC-14] closely couple to the Chemical and Molecular Science core capability.

Climate Change Science and Atmospheric Science

ORNL's core capability in climate change and atmospheric sciences is focused on improving the understanding of 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) performance workflow and terrestrial model development (e.g., Accelerated Climate Model for Energy); (3) integrating multidisciplinary research connecting data, terrestrial, and atmospheric science and large-scale computing; (4) developing novel software to improve credibility and scalability of next-generation climate models in preparation for exascale computing [e.g., International Land Model Benchmarking project, Land-Ice Verification and Validation Toolkit (LIVV)]; and (5) utilizing computing expertise and HPC data/infrastructure to exploit and improve climate modeling tools.

ORNL advances next-generation integrated models of the human-earth system by improving the characterization of ecosystem processes and land-atmosphere exchange of carbon and energy. The Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) experiment and NGEE–Arctic are large-scale experiments conducted in a variety of climate-sensitive ecosystems. ORNL leads in the use of data from these long-term experiments to improve the representation of key carbon and other biogeochemical cycles in climate models. ORNL is the premier source for reliable global and national time series of the major anthropogenic sources of CO_2 emissions from fossil fuel use (approximately 15,000 data downloads annually). By evaluating the risk of climate change and associated extreme events on energy production and use, and 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.

Unique ORNL infrastructure supporting climate change science and atmospheric science activities includes petascale computing (OLCF), which supports M&S and big data applications, and neutron sources (SNS, HFIR), which enable characterization of soil organic matter and imaging of whole plant/soil systems and plant/water interactions. CADES provides domain scientists with easy access to powerful computing, storage, advanced algorithms, and computational tools.

ORNL has approximately 85 multidisciplinary FTE staff dedicated to research within this capability. Many of these researchers are affiliated with Climate Change Science Institute (CCSI) and work in partnership with other national laboratories and institutions to build broad understanding of global and regional climate.

SC [mission areas SC-3, 13, 16] is the primary sponsor for these efforts; NNSA, NASA, DoD, DHS, the US Geological Survey (USGS), NOAA, and the US Forest Service also sponsor or collaborate on activities that leverage DOE investments in climate change and atmospheric science to generate solutions for the nation.

Computational Science

Computational science at ORNL is focused on the development and delivery of scalable computational applications and data analytics [e.g., CASL Virtual Environment for Reactor Applications (VERA), DCA++, QMCPAC, Bellerophon Environment for Analysis of Materials (BEAM)] for current and future leadership computing platforms. These resources enable integrated, scalable solutions of complex problems of interest to DOE and other sponsors, including materials by design, nuclear reactor efficiencies and lifetimes, fusion plasma containment, climate change science, and scalable analytics to address complex problems associated with the food/energy/water nexus.

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. ORNL’s expertise in this area is composed of integrated teams of domain scientists, computational scientists, computer scientists, and mathematicians who provide scalable computational and analytical solutions delivered through integration of algorithms, M&S software technologies, computer and information sciences, and HPC infrastructure to enable transformative science applications that span computational design of innovative nanomaterials; predictive understanding of microbial, molecular, and cellular systems; reliable predictions of climate change at the regional scale, including biogeochemical feedbacks; simulation of nuclear fission and fusion systems; and supernovae simulation.

The capability also supports a strong industrial partnerships program that solves urgent problems for companies of all sizes, including SmartTruck Systems, Ramgen Power Systems, Ford, and Boeing.

A distinctive feature of this core capability is the ability to build multidisciplinary teams to tackle science and engineering problems of national interest through the development and application of scalable algorithms requiring tightly coupled workflows requiring experimental data, data analytics, and M&S.

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 has responded to this situation by creating CADES, thus establishing an integrated compute infrastructure for delivering data science solutions and workflows that will be sustainable over the long term. CADES is effectively creating a new environment for scientific discovery with its diverse computing and data ecosystem, enabling scientists to free themselves from trying to manage, manipulate, and process large data sets.

This core capability is supported by at least 298 FTE staff, including 65 postdoctoral associates, who are affiliated with OLCF, the NOAA system, and CADES; JICS; UDI, IFIM, CCSI, the Health Data Science Institute (HDSI); and CASL.

Funding for this work comes from SC [mission areas SC-1–6, 7–9, 12, 13, 16, 18], NE [mission areas NE-1, 2] and EERE [mission areas ES-15]; OE, DoD, IC, DHHS, 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, observing, 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. For example, the Energy Deposition Defect Evolution (EDDE) EFRC focuses on elucidating the origin of radiation damage using a unique set of high-entropy alloys combined with atomic-level characterization and computational approaches [Y. Zhang et al., *Nature Commun* **6**, 8736 (2015)]. The information obtained will be invaluable for designing the next generation of radiation-resistant alloys for nuclear and other applications.

Precise synthesis of materials enables the studies of fundamental properties that ultimately lead to the control of material properties, such as layered oxides producing quantum switches for oxide electronics [W. S. Choi et al., *Nature Commun* **6**, 7424 (2015)]. ORNL has specialized expertise in synthesis of single crystals, atomically layered oxides, alloys, nanophase materials, polymers, and polymer composites. In addition, ORNL develops unique approaches for characterizing the structure and behavior of materials, making extensive use of key DOE user facilities at ORNL. Neutron scattering at SNS and HFIR provides, for example, direct measurements of magnetic structure, lattice dynamics, and in situ probes of material response such as deformation behavior or material changes during operation [J. D. Budai et al., *Nature* **515**, 513 (2014)] and provides unique insight into the structure and dynamics of polymers and composites [S. Cheng et al., *Phys Rev Lett* **116**, 038302 (2016)]. For example, small-angle neutron scattering contributed to the development of a "greener" way to assemble materials for solar applications using surfactants [J. Zhu et al., *Nanoscale* **7**, 15134 (2015)].

Leadership capabilities in materials imaging, including novel in situ electron microscopy, scanning probe microscopy modalities, atom probe tomography and chemical imaging (such as imaging mass spectrometry and optical imaging), are made available through the user program at CNMS. These imaging capabilities are combined with exceptional resources for theory, simulation, and data analysis to enhance both data interpretation and the depth of information that can be obtained from these analytical tools [R. K. Vasudevan et al., *Adv Funct Mater* **26**, 478 (2016)]. ORNL's experimental condensed matter and materials science efforts are deeply integrated with theory, modeling, and simulation. ORNL has particular strengths in the development and application of scalable computational approaches and codes [e.g., quantum Monte Carlo (QMC), Locally Self-consistent Multiple Scattering] that take advantage of leadership-class computational facilities, including OLCF, and is developing approaches to apply these codes to next-generation exascale computation [K. Feyevtsova et al., *Phys Rev X* **4**, 031003 (2014)].

ORNL's condensed matter physics and materials science core capability involves 298 FTE staff, including 76 postdoctoral researchers. Activities within this core capability contribute to advances in several DOE energy and national security mission areas and also enhance US competitiveness, as illustrated by many licenses to industry, including the Rolling-Assisted Biaxially Textured Substrate (RaBiTs$^{\text{TM}}$) process for producing superconducting cables, thin-film batteries, and alumina-forming austenitic steels. In addition, resources developed in this core capability underpin the technologies being developed by CMI.

This work is primarily supported by SC [mission areas SC-7–11]; however, there is extensive support through other programs, including SC Fusion Energy Sciences Program (FES), EERE, NE, ARPA-E, DoD, US Nuclear Regulatory Commission (NRC), NASA, and other SPP programs.

Cyber and Information Sciences

ORNL conducts cutting-edge R&D in visual analytics, big data analytics, machine and deep learning, knowledge discovery, and information security in order to (1) collect, share, analyze, and classify data; (2) create knowledge from disparate and heterogeneous data sources; and (3) understand, secure and defend against, and defeat known or unknown adversaries to protect the nation's energy, economic, and security infrastructures. Outcomes from this core capability are translated from R&D to deployment through a partnership with operational cyber infrastructure and colocated expertise in predictive analytics (e.g., social, geographic, visual, graph). ORNL is successfully transferring technologies based on mathematical rigor to address cyber and information security challenges, with Hyperion and other tools licensed to multiple parties.

Leveraging our talented scientific staff and unique resources such as OLCF and CADES, ORNL has emerged as a leader in machine learning, information visualization, and heterogeneous data analytics (e.g., graph analytics) at large scale to enable scientific discovery and support the applied programs within DOE and national security agencies. Critical to producing solutions to cyberspace challenges is the ability to acquire, process, and transform massive amounts of data into usable information. ORNL data scientists have a proven track record in developing solutions for customers with diverse data requirements.

ORNL cyber and information security researchers apply strong mathematical rigor and computationally intensive methods, leveraging and exploiting HPC, to solve cyber security challenges at scale and/or in near real-time. Core to our unique capabilities in this space are statistics, repeatability and reproducibility, observation of trends, and integration of social and behavioral factors, geographic data, and cyber data to yield insights at all levels. ORNL's unique resources allow for deep learning on HPC systems which provides unparalleled insights into the behavior of malicious and nefarious cyberspace actors. Quantum information science R&D is providing game-changing capabilities for how cybersecurity is being conducted on cyber-physical infrastructure systems such as the electric grid. The unique combination of these capabilities span offensive and defensive aspects of cyber operations involving areas such as Industrial Control System/Supervisory Control And Data Acquisition (ICS/SCADA) system protection, advanced persistent threat detection and mitigation in networks, and detection and understanding of malicious code in software and hardware. Furthermore, ORNL develops mathematical methods for identifying the impacts of complex attacks on cyber infrastructures, including software-defined networks, and also develops game-theoretic strategies for ensuring infrastructure resilience in presence of intentional and incidental disruptions.

Unique ORNL infrastructure supporting this capability includes staff affiliated with the Cyber Network Test Lab, Distributed Energy Communications and Control Laboratory (DECC), classified HPC systems, Center for Trustworthy Embedded Systems, and Vehicle Security Center. ORNL has 109 FTE staff in cyber and information sciences, including 4 postdoctoral researchers.

Funding for this work comes from SC Advanced Scientific Computing Research Program (ASCR) [mission areas SC-1, 3, 5, 6], OE [mission area ES-10], EERE [mission area ES-16], NNSA, IC, US Department of Transportation (DOT), DHS [mission area HS-4], and DoD.

Decision Science and Analysis

ORNL has demonstrated expertise in the development and application of data-driven methods, models, analyses, and tools for creating knowledge and insights useful in anticipating, planning for, managing, and understanding responses to a wide variety of events and technologies. ORNL's capabilities comprise a diversity of tools, methods, and topical expertise, which is brought to bear on compelling local, regional, national, and international problems, including disaster recovery (e.g., southeast Asia tsunamis; Hurricane Katrina, Tropical Storm Sandy; Deepwater Horizon oil spill); geographic data analytics and spatial demography for health, urban, and energy planning; siting analysis for power expansion and expedited license review for commercial nuclear power plants; complex environmental and technological assessments; and critical information repositories for a variety of S&T applications.

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 uncertainty quantification necessary to address impacts of technologies on environmental systems, market dynamics, regulation, and other social factors. These impact assessments are often complex, cross-disciplinary, data driven, and computationally demanding. Through the application of these capabilities and expertise, scientists are able to observe, model, analyze, and simulate physical, social, economic, and governance dynamics with unprecedented spatial and temporal resolution, providing an unparalleled opportunity for scenario-driven analysis and evaluation of the consequences of current and future technologies and policies. ORNL uses geographic information science for decision/risk analysis of critical infrastructure expansion (e.g., solar panel adoption). Topical experts integrate patterns and trends in high-dimensional data with physical and human factors, including economics, health, education, and political stability, to glean trends and responses to technological and policy changes on a global scale. ORNL supports DOE and other agencies in strategic planning and program direction, policy formulation, and implementation and is a leader in performing risk analysis of extreme events for siting critical infrastructure.

ORNL is a demonstrated leader in a number of areas within this capability, including (1) spatial demography, geographic data analytics, and techno-social analytics; (2) data-driven decision science, risk analysis, uncertainty quantification, 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 advanced fuel cycle performance; (5) climate change impacts, adaptation, and vulnerability modeling and assessment; (6) energy economics; and (7) development of decision support tools.

This capability is supported by staff from OLCF, CADES, DECC, the NTRC Center for Transportation Analysis, Center for Radiation Protection Knowledge, Aquatic Ecology Laboratory, Center for Bioenergy Sustainability; and CCSI, HDSI, and UDI. ORNL has at least 170 FTE staff, including 18 postdoctoral researchers, supporting this core capability.

Funding for this work comes from SC [mission areas SC-1, 3, 13], NE [mission area NE-1], EERE [mission area ES-8, 3], DHS [mission area DH-7], FEMA, NRC, CDC, FDA, and CMS.

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 changing climate conditions on spatial patterns and processes on the Earth's surface. Activities enabled by this core capability include (1) linking a fundamental understanding of mercury biogeochemistry to engineering applications to advance the development of transformational solutions for legacy mercury contamination at Oak Ridge; (2) applying highly sensitive tracers in CO_2 capture and storage to validate the integrity of CO_2 geosequestration; (3) assessing the potential for adding power production capacity to hydropower dams, including assessment of impacts on coastal and marine environments (e.g., integrating diverse technical expertise with unique resources at ORNL's aquatic research facility); and (4) developing and assessing sustainability indicators for bioenergy feedstock production.

This capability supports DOE's energy and environmental missions and provides the technical basis for policy decisions. ORNL takes advantage of laboratory- tofield-scale resources and expertise in geochemistry, hydrology, microbial ecology and genetics, aquatic ecology, civil and environmental engineering, and chemical engineering 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.

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) under- standing 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 distribution systems on aquatic ecosystem integrity through sensor systems, geospatial tools, and modeling to identify thresholds and promote adaptability in energy production; (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 energy production and water use.

Approximately 74 FTE staff conduct R&D related to this core capability. 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., Titan), state-of-the-art greenhouses, field and laboratory facilities (including the Environmental Science Laboratory, Aquatic Ecology Laboratory, Mercury SFA Field Site, Integrated Field Research Challenge Site, and Advanced Microscopy Laboratory), JIBS, the Center for Bioenergy Sustainability, and CNMS. Funding comes from SC [mission areas SC-13, 14, 15], EM [mission areas EM-1–3], EERE [mission areas ES-3, 8, 9, 10], FE [mission area FE-1], NNSA [mission area NNSA-1], DoD, NE, and NRC.

Environmental Subsurface Science

ORNL's core capability in environmental subsurface science is exploited to advance 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 enable discovery of the genes responsible for mercury methylation and their organismal and environmental distribution (explaining the concentration of methyl mercury in rice and highlighting the potential for massive mercury methylation in the Arctic); (3) state-of-the-art subsurface hydrology and reactive transport model development; and (4) integration of neutron scattering and HPC to understand enzymatic mechanisms for metal transformation in subsurface systems.

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 energy, disposal of nuclear waste, and cleanup of legacy contamination. ORNL leads one of the world's largest ongoing efforts in mercury research. The ORNL-led 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 advance a predictive understanding of exchange and feedback processes in low-order streams. 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 Mercury SFA Field Site, the Integrated Field Research Challenge Site, SNS, HFIR, OLCF, CADES, and CNMS. Other DOE user facilities at other national laboratories (e.g., Stanford Linear Accelerator Center, Advanced Photon Source, Environmental Molecular Sciences Laboratory) are also utilized.

ORNL has approximately 42 multidisciplinary FTE staff dedicated to research within this capability.

Funding comes from SC [mission areas SC-14, 15], EM [mission areas EM-1–3], FE [mission area FE-5], NNSA [mission area NNSA-1], 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 advanced instrumentation. ORNL is notable not only for the breadth of the facilities and instrumentation that it develops and deploys for SC and other sponsors, but also for its integration of these assets to deliver mission outcomes. The national user facilities at ORNL attract thousands of researchers and support the development of the next generation of scientists in exploring science and developing technologies that are important to humanity.

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 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. In addition, HFIR's capabilities for isotope production, materials irradiation, neutron activation analysis, and neutrino research make it a unique asset for radioisotope, materials and fuels irradiation, and nuclear security sciences. ORNL has begun conceptual design and preparation of CD-1 for a high-brightness short-pulse STS at SNS.

The HPC resources of OLCF, including the Cray XK7 Titan, are available to users to solve computationally intensive scientific problems and accelerate innovation for industry partners. ORNL's HPC resources include the Gaea system, operated for NOAA to facilitate multi-agency cooperation and R&D partnerships across the climate research community.

CNMS comprises forefront instrumentation and expertise in nanofabrication, synthesis and characterization of inorganic nanomaterials and organic polymers, enhancing the understanding of structure, dynamics, and functionality of nanostructured materials. Studies of nanoscale structure in soft matter rely on site-specific deuteration capabilities, which enable unique neutron experiments. Development of new instrumentation and methods emphasizes new imaging capabilities, with a focus on quantitative measurements of functional properties, state-of-the-art scanning transmission electron microscopy, scanning probe microscopies, atom probe tomography, and helium ion microscopy. New approaches for direct-write nanofabrication, using electron or ion beams, are being advanced, as are multimodal approaches for chemical imaging. Theoretical, computational, and data analytics approaches underpin the research activities across all areas of work at CNMS.

ORNL is home to four major research facilities sponsored by DOE's Office of Energy Efficiency and Renewable Energy (EERE): MDF, which includes the pilot-scale CFTF; the Buildings Technology Research and Integration Center (BTRIC), reinvigorated with the addition of 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. For example, NTRC researchers have collaborated with industry to exploit HFIR's neutron imaging capability for capturing dynamic images of fuel injectors, and OLCF's computational resources are being used to provide a better understanding of the materials properties obtained under varying additive manufacturing conditions and parameters.

Large-scale user facilities and advanced instrumentation are fundamental to ORNL's ability to deliver on its mission for DOE, DHS, and other customers. Work in this area is supported primarily by SC [mission areas SC-5, 10, 12, 13, 14, 16, 17, 18, 30, 34, 35] and EERE [mission areas ES-5–7], with contributions from NE [mission area NE-1], NNSA [mission area NNSA-1–3], and DoD.

Mechanical Design and Engineering

ORNL has extensive experience in the design of remote systems and equipment for nuclear applications (e.g., reactors, accelerators, fusion experimental devices, spallation sources, and instruments). This experience includes the seminal development and continued advancement of enrichment technologies manifested today in the development of new stable isotope enrichment systems. Expertise in the analysis of stress, strain, and thermal effects in composite materials and the dynamic analysis of rapidly rotating devices has been developed in support of these efforts. ORNL has leveraged its access to basic science and scientific tools to innovate solutions for practical mechanical applications. For example, HFIR's neutron scattering capabilities have been applied to map residual stress in manufactured components to help improve material reliability and reduce mass in agricultural vehicles, transportation vehicles, and the space shuttle. This capability also has been exploited for the improvement of additively manufactured components, optimizing heat exchangers and fuel injectors. Further, ORNL's science resources have been exploited to translate research into mechanical design and engineering practice for improvement in energy-efficient manufacturing; in the energy efficiency and durability of building envelopes, equipment, and appliances; and in transportation (multi-cylinder combustion R&D, exhaust aftertreatment development).

ORNL has developed remote systems for SNS, REDC, and, most recently, FRIB. Also, ORNL combines its expertise in mechanical design and engineering with other disciplines to support the Laboratory's nuclear facilities. This capability is applied to a wide range of challenging problems 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 (W7-X) superconducting stellarator. ORNL also utilizes OLCF and other computing resources to develop advanced thermal/hydraulic M&S tools in support of CASL's modeling of light water reactors.

ORNL's interdisciplinary teams of engineers and scientists perform R&D to address the needs of industry, helping to reduce risk and accelerate commercialization of energy-efficient technologies on industry's timescale. Leveraging ORNL's leadership in manufacturing innovation into energy-efficient transportation, homes, and buildings enables the achievement of EERE's Clean Energy Manufacturing Initiative, which aims to increase US competitiveness in the production of clean energy products and to increase US manufacturing competitiveness across the board by increasing energy productivity; it also supports the President's Advanced Manufacturing Partnership, which focuses on enabling US innovation in critical emerging manufacturing technologies and securing the talent pipeline.

ORNL scientists and engineers are providing the fundamental science for this next-generation manufacturing technology that is affecting multiple industry sectors. They are providing the knowledge that is accelerating the deployment of new vehicles and efficient transportation systems powered by domestic, renewable, and clean energy. Also, through use of extensive experimental facilities and advanced hardware-based design models, and incorporation of emerging materials, ORNL's expertise in buildings technologies has helped industry launch some of the most energy-efficient building equipment technologies on the market today.

ORNL's applied research facilities (MDF, CFTF, BTRIC, NTRC, and the remote systems development high-bay facility) are leveraged by over 160 FTE staff in the areas of robotics and remote systems design, thermal/hydraulics, energy-efficient manufacturing, transportation, homes and buildings. Funding in this area originates from several sources, including the SC [mission areas SC-10, 17, 19, 30], NE [mission area NE-1], EERE [mission areas ES-13–15], NNSA, and SPP programs.

Nuclear Engineering

ORNL expertise in handling and processing unirradiated and irradiated nuclear materials, developing and operating nuclear reactors, and radiation detection, predates the formal discipline of nuclear engineering. In fact, the Oak Ridge School of Reactor Technology, founded at ORNL in 1950, provided the only comprehensive postgraduate nuclear engineering education until the 1960s. This legacy continues as ORNL leads nuclear fuel and irradiated materials S&T, M&S for reactor physics and radiation transport, reactor systems and safety, radiation detection and imaging, and radioisotope production. ORNL operates world-class nuclear research facilities and leads the US ITER Project Office (USIPO), playing a central role in the nuclear engineering design of the world's largest fusion experiment.

ORNL's nuclear engineering expertise is critical to the continued viability of the nuclear power industry, including life extension of the existing fleet and improved operations. ORNL's expertise in the design and postirradiation examination of HFIR irradiation capsules is exploited 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 advanced next-generation reactor technology through the development and testing of new fuels and materials, improved instrumentation and controls, regulatory research, thermal-hydraulic experiments, and innovative system concepts. ORNL is the world leader in molten salt reactor technology, collaborating internationally to advance the concept's maturity. ORNL is commissioning a liquid salt test loop to support a Cooperative R&D Agreement (CRADA) with the Shanghai Institute of Applied Physics that is focused on development of a thorium molten salt reactor.

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 is applied world-wide 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 provide a high-fidelity virtual reactor capability that has been validated using operating cycles of Tennessee Valley Authority's Watts Bar pressurized water reactor (PWR). Through 2019, CASL will continue to provide scientific understanding to improve the operation of PWRs, boiling water reactors, and small modular reactors. 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.

ORNL's expertise in uranium enrichment, nuclear fuel cycle, radiation detection and imaging, and nuclear systems M&S enables nonproliferation and safeguards research that has been vital in supporting negotiations of global nonproliferation agreements. The Nuclear Materials Identification System (NMIS) and the On-line Enrichment Monitor (OLEM) are two examples of ORNL imaging and detection technologies currently having worldwide impact. ORNL nuclear forensics research employs the HFIR neutron activation analysis laboratory, modeling of postdetonation physics, and inverse modeling of reactor depletion and radiation transport. Government agencies depend on ORNL experience in nuclear material processing, handling, and transportation security. For example, ORNL's Mobile Uranium Facility is positioned to be deployed worldwide to support emergent security missions.

ORNL nuclear engineering involves more than 300 FTE staff and employs HFIR; the hot cells of the Irradiated Fuels Examination Laboratory, the Irradiated Materials Examination and Testing Laboratory in Building 3025E, and REDC; and other radiological facilities. Funding in this area comes from several sources, including NE [mission areas NE-1–5], SC [mission areas SC-3, 31, 32], NNSA [mission areas NNSA-1–3], DHS [HS-1], the Defense Threat Reduction Agency (DTRA), NASA, NRC, and other government agencies.

Nuclear Physics

ORNL's core capability in nuclear physics spans theoretical and experimental research that is relevant to DOE's mission of developing an understanding of nuclear matter 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 very neutron-rich nuclei through beta-decay spectroscopy, low-energy nuclear reactions relevant to astrophysics, and gamma-ray spectroscopy. ORNL leads aspects of the Separator for Capture Reactions (SECAR) astrophysics detector development and gas jet target development for secondary beams at the Facility for Rare Isotope Beams (FRIB). In addition, ORNL's OLCF is used to investigate the structure and reactions of neutron-rich rare isotopes and nuclear astrophysical processes. For example, calculation of the weak charge radius, derived from the neutron distribution of neutron-rich nuclei, has been compared to experimental data taken at Thomas Jefferson National Accelerator Facility [G. Hagen et al., *Nature Phys* **12**, 186 (2016)]. These calculations also provide constraints on the size of neutron stars.

ORNL has special expertise in neutron physics, including the development and operation of the Fundamental Neutron Physics Beamline (FnPB) at SNS. For example, the FnPB supports an ORNL-led search for the neutron electric dipole moment (nEDM), which will improve the sensitivity by a factor of 50 to 100 over previous experiments and make precision tests of symmetry principles underlying the Standard Model of particle physics. ORNL leads the development of light-collection devices and low-temperature, high-electric-field electrodes for the experiment utilizing the Laboratory's core capability in materials science to develop the appropriate materials.

The nuclear physics core capability also sustains activities associated with the proposed ton-scale ^{76}Ge Majorana experiment, which will search for the hypothesized (and very rare) neutrinoless double-beta decay mode of nuclei. The Majorana Demonstrator (MJD) project, a feasibility demonstration for the Majorana experiment, has produced more than 30 kg of high-purity ^{76}Ge detectors for the project. MJD is taking data on the first cryomodule and is currently commissioning the second cryomodule. ORNL expertise in the development of specialized electronics and detectors is also relevant to research at Brookhaven National Laboratory and at the Large Hadron Collider (LHC) at CERN, where ORNL researchers also conduct relativistic heavy ion collision experiments to investigate the physical properties of the quark-gluon plasma. ORNL is the lead laboratory for upgrades of LHC's ALICE heavy-ion detector.

Actinide targets and sources are generated, drawing on unique capabilities at HFIR and REDC, to expand international collaborations in superheavy element research. Preliminary research indicates success in improving the release of fission fragments from high-capacity ^{252}Cf ion sources. The next ion source for the Californium Rare Isotope Breeder Upgrade (CARIBU) project at Argonne National Laboratory will be manufactured later in FY 2016. ORNL has also supported efforts to discover element 119 and new isotopes of element 117 and their decay products. Observations of element 117 have been confirmed at GSI Darmstadt (Germany) using ^{249}Bk produced at ORNL. The discoveries of elements with atomic numbers $Z = 113$, 115, and 117 have been confirmed by the International Union of Pure and Applied Chemistry [P. J. Karol et al., *Pure Appl Chem* **88**, 139 (2016), doi:10.1515/pac-2015-0502], and element 117 has been provisionally named tennessine in recognition of the contributions of ORNL, Vanderbilt University, and UT to superheavy element research. ORNL's nuclear data program, recognized for its international leadership, includes differential cross-section measurements, evaluation and data analysis methods development, and data processing. These activities provide nuclear data libraries for radiation transport analysis. Further, ORNL leads the ENDF/B Formats Committee that standardizes all nuclear data formatting. The nuclear physics core capability includes 58 FTE staff, including 10 postdoctoral researchers. SC funds work in this area [mission areas SC-22, 23, 28–32] and supports ORNL work on isotope production and applications. ORNL's record of excellence in cross-section physics continues to support new measurements and improved evaluations that are important for defense programs [mission area NNSA-1 and Appendix A)], nuclear energy, and nuclear safeguards and nonproliferation.

Nuclear and Radio Chemistry

ORNL's radiochemistry and radiochemical engineering expertise, combined with its unique nuclear infrastructure, enables production, processing, purification, and handling of a wide range of isotopes. Stable and radioisotopes are produced and provided to the scientific community for use in a variety of important applications, ranging from scientific and medical research to commercial uses.

For scientific applications, research includes super-heavy element discovery, development of specialized sources, isotope dilution mass spectrometry, radioisotope power source development, and cross-section measurements. Radioisotope applications span a broad range, including cancer treatment and commercial uses. ORNL's nuclear chemistry and enrichment expertise is applied to maintaining and improving our nation's uranium enrichment capabilities. The Isotope Business Office at ORNL (part of NP's National Isotope Development Center) maintains and distributes the US inventory of enriched stable and radioisotopes.

HFIR, which provides the world's highest neutron flux, is exploited to irraidate target materials for production of various radioisotopes through the NP Isotope Program. The nuclear hazard category 2 hot cells and laboratories at REDC enable the remote production and post-irradiation processing of heavy actinide targets. The HFIR/REDC complex 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 other important radioisotopes such as ^{75}Se, used in radiography, and medical isotopes ^{188}W, ^{227}Ac, and ^{212}Pb. HFIR and REDC are also being used to produce ^{238}Pu in support of NASA's planetary science mission.

With support from NP, ORNL is establishing new capabilities for producing research quantities of enriched stable isotopes at the Enriched Stable Isotope Pilot Plant (ESIPP) using both electromagnetic and centrifuge technologies. The electromagnetic separation techniques build on expertise in mass spectrometry at ORNL. This capability will ensure a future supply of critical stable isotopes for research and industry. ORNL is also considering the long-term needs for expanded radiochemistry hot cells to support radiopharmaceutical development. As part of the DOE Isotope Program, ORNL maintains inorganic chemistry and materials laboratories to convert the purified isotopes from their stable storage form to user-specified custom forms. These forms frequently are in the shapes of foils, thin films and coatings, plates, and wires.

ORNL's nuclear and radiochemistry expertise, extensive radioanalytical capabilities (especially advanced mass spectrometry), and neutron activation analysis capability at HFIR, provide world-leading resources for ultra-trace analysis with applications ranging from environmental analysis to forensics. Expertise in radiochemical separations, analyses, and nuclear material examinations are being applied to the management of nuclear material such as UNF; the detection of important to nuclear fuel cycle management and security; the development of safer, more efficient nuclear fuels; and for improvements in nuclear waste treatment. As an example, ORNL recently developed an alternate dissolution/extractions concept for tritium pretreatment (nonaqueous) that can potentially eliminate the high-acid raffinate waste stream.

Nuclear and radiochemistry research at ORNL involves more than 165 FTEs and makes use of a number of unique facilities, including HFIR, REDC, hot cells in Building 3025E, laboratories and hot cells in Buildings 4501 and 3047, and other radiological laboratories. Funding in this area comes from several sources, including SC [mission areas SC-8, 11, 31, 32], NE [mission area NE-3], NNSA [mission areas NNSA-1–3], DHS, DoD, NASA, NRC, and other government agencies.

Plasma and Fusion Energy Sciences

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 researchers have decades of experience in collaborating nationally [General Atomics DIII-D, Princeton Plasma Physics Laboratory (PPPL), etc.] and internationally (Joint European Torus, Experimental Advanced Superconducting Tokamak, Korea Superconducting Tokamak Advanced Research, W7-X, etc.) to solve critical experimental and theoretical problems on the road to fusion energy. Using HFIR and ORNL's nuclear R&D infrastructure, researchers study the effects of neutron irradiation with plasma-facing and structural materials, including tungsten, copper, and their composites. ORNL leads R&D in plasma theory and applies HPC resources to fusion challenges (e.g., the Plasma Surface Interactions project and the Advanced Tokamak Modeling project supported by SC's Scientific Discovery through Advanced Computing program).

ORNL has distinguished expertise in atomic and plasma boundary physics, plasma heating and fueling systems, and fusion materials science. ORNL utilizes its broad experimental and theoretical expertise in high-temperature plasma science and 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 facilities to meet their performance objectives. ORNL is DOE's lead laboratory for pellet fueling systems and is responsible for providing key enabling technologies and components for ITER. Materials scientists at ORNL conduct fundamental experiments to support development of advanced alloys and silicon carbide composites, the results of 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.

The USIPO, hosted by ORNL, manages the US contributions to ITER. As delegated by DOE, ORNL executes US ITER project activities with its partners, PPPL and Savannah River National Laboratory. US ITER fabrication activities and US participation in the overall project will lead to the capability for creating, sustaining, and studying burning plasmas, the next major step toward fusion energy. As the pace of ITER construction has increased, the USIPO has placed substantial procurement contracts with suppliers for component fabrication. US hardware contributions include the central solenoid (the world's highest-stored-energy pulsed superconducting magnet); a 1 GW cooling water system; high-power, long-pulse plasma heating systems; electrical power components; parts of the tritium exhaust system; plasma instrumentation; plasma disruption mitigation systems; and plasma fueling systems. The USIPO also works with the ITER Organization and other domestic agencies to achieve the required integration of management, design, and procurement activities. The United States was the first to deliver any ITER Plant components and the first to deliver an "exceptional heavy load." Components delivered include a set of five nuclear-qualified drain tanks for containing radioactive water from the vacuum vessel and blankets/divertor.

Facilities supporting this core capability include HFIR for materials irradiation; hot cells for material handling and testing; the Irradiated Materials Examination and Testing Laboratory and the LAMDA laboratory for materials characterization; the Fusion Pellet Laboratory for building, testing, and commissioning systems for use on fusion experiments around the world; and the Prototype Materials Plasma Exposure Experiment (Proto-MPEX) for testing the source concept for MPEX, which will provide a world-leading capability for plasma–materials interface studies when completed. Approximately 90 FTE staff carry out this mission, including 6 postdoctoral fellows and 2 winners of DOE Early Career Research Program awards.

SC funds work in this area [mission areas SC-17–20] including the US ITER project. Additional funding is received via SPP sponsors.

Power Systems and Electrical Engineering

ORNL's core capability in power systems and electrical engineering builds on a long history of expertise and creativity in the design and development of electronics, sensors, and controls for extreme environments. This core capability is applied to deliver innovations in power flow, electric grid modernization, energy-efficient buildings and transportation, and smart manufacturing. For example, ORNL advances in high-performance inverters and converters for electric vehicles are now deployed in Chevy Volt systems. More recently, ORNL demonstrated the first wireless bidirectional charging and energy management system for building and vehicle operating as an integrated energy system.

This core capability comprises substantial expertise in (1) delivering advances in high-temperature, high-power-density applications for energy, transportation, and defense, (2) enabling high-efficiency transportation and electrification systems to reduce US reliance on foreign oil, (3) developing 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) creating advanced building sensors, communications, and controls for power management systems to maximize energy efficiency.

The addition of renewable energy sources to the nation's electricity mix is creating the need for new tools and technologies to manage instabilities that can lead to outages and reduced reliability. ORNL is a recognized leader in the creation of alternating current power flow control systems for grid control and increased resiliency. An advanced grid requires new materials for power electronics and energy storage devices. ORNL is a leader in power electronics R&D (Vehicle Technologies Office lead laboratory for power electronics) and is exploiting resources at NTRC to develop high-power devicesthat will improve reliability and reduce costs. ORNL's core capabilities in materials are leveraged for designing, developing, and testing new materials capable of supporting cost-effective and higher performing, electricity control devices and systems. ORNL is participating (as lead or a key partner) in collaborations to develop power electronics from concept to prototype and to apply expertise in advanced materials to develop innovative electronics and sensors (e.g., 3D manufacturing of power electronics, motors, and functional materials for integrated sensing in structure materials).

Because an advanced grid will be heavily dependent on information and communication technologies, enhanced cyber security 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 ability for users to approach, understand, and implement guidance 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 the LHC and FRIB. Current activities exploit broad expertise in electronics for extreme environments, compact high-voltage power supplies, pulsed power conversion, Internet-of-Things (connected sensor and Internet framework), RF, and communications capabilities for intelligent systems support.

ORNL’s core capability in power systems and electrical engineering 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 supported by 73 FTE staff (including 9 postdoctoral researchers). Infrastructure that supports this capability includes 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); tools for characterization of materials, devices, and communications; and DOE’s Office of Energy Policy and Systems Analysis (EPSA). EERE [mission areas ES-10, 13, 14, 15], OE, and the Electric Power Supply Association are the primary sponsors for research within this capability. SC also benefits from ORNL expertise in this area [mission area SC-30].

Systems Engineering and Integration

ORNL’s core capability in systems engineering and integration takes advantage of the Laboratory’s breadth of capabilities. Optimal solutions to pressing energy challenges are developed by (1) utilizing expertise in integrating fundamental science, technology, systems engineering, and project management in multidisciplinary and multi-institutional teams; (2) leveraging large-scale basic and applied science facilities (SNS, HFIR, HPC, OLCF infrastructure, MDF, NTRC, BTRIC, CFTF) to provide foundational science for technology advances (e.g., modeling of combustion processes with industry, understanding materials properties for additive manufacturing, modeling the energy use of buildings at the community scale); and (3) accelerating research innovation in buildings, manufacturing, and transportation through partnerships, such as the Additive Manufacturing–Integrated Energy (AMIE) demonstration project and the manufacturing of a Shelby Cobra replica. ORNL exploits the synergistic potential of collaborations internally across disciplines and externally through multi-institutional collaborations. ORNL has a successful track record of delivering innovative tools and technologies as a lead and partner on hubs (CASL, CMI), IACMI, and other multi-institutional collaborations (Fuels/Engine Optima, Grid Modernization Laboratory Consortium, Lightweight Innovations For Tomorrow).

Our strength in pursuing solutions from concept to implementation and in spanning fundamental to applied research ensures the success of national and international science and energy projects such as SNS, Proto-MPEX, the Enriched Stable Isotope Pilot Plant (ESIPP), FRIB, ITER, and next-generation fusion experiments (e.g., W7-X). ORNL delivers 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. This core capability also leverages the development and deployment of large-scale science tools such as SNS and HFIR, REDC and other facilities for examination of irradiated materials and components, and the HPC systems and infrastructure of OLCF.

ORNL is a recognized leader in development of novel research platforms and experimental systems. Recent achievements include

- combining advanced materials and additive manufacturing to advance vehicle technology as demonstrated in the design and manufacturing of a Shelby Cobra replica and a Willys Jeep replica using 3D printing;
- connecting a 3D-printed building and a 3D-printed vehicle with advanced technologies to explore new approaches to energy generation, storage, and use in AMIE; and
- designing, constructing and operating complex experimental systems, including the Mobile Uranium Facility, CFTF, the Ultra-trace Forensic Science Center, and the HFIR cold neutron source, and DECC.

Additionally, ORNL's EERE research facilities (NTRC; BTRIC including MAXLAB and DECC; and MDF, including 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.

ORNL has more than 234 multidisciplinary technical FTE staff dedicated to research within this capability. These researchers utilize the EERE research facilities as well as SNS, HFIR, HPC, Vehicle Systems Integration Laboratory, microgrid, Ultra-trace Forensic Science Center, high-bay facility for large-scale components, and remote systems testing. The primary sponsors for these efforts include SC [mission areas SC-10, 17–20, 30–32], EERE [mission areas ES-13–15], OE, NE [mission area NE-3], and NNSA [NNSA-2]. Some support is also provided by DHS, NRC, DoD, and other SPP sponsors.

4. Mission Readiness/Facilities and Infrastructure

ORNL has established seven major science and technology (S&T) initiatives, listed in Table 4.1, that are strategically aligned with the international Mission Innovation initiative, the Quadrennial Technology Review, and DOE's mission of ensuring America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative S&T solutions. These initiatives are designed to sustain, extend, and exploit the Laboratory's core capabilities; to provide the scientific and technological focus required to deliver breakthrough solutions in critical national mission areas; and to facilitate the application of these solutions to real-world problems.

In developing these solutions, ORNL will continue to field the interdisciplinary teams that are a hallmark of the Laboratory, partnering with other laboratories, universities, and industry to deliver on its mission objectives; to strengthen our science and innovation culture; and to accelerate the deployment of technology advances. As part of this strategy, ORNL has formed four institutes specifically designed to catalyze multidisciplinary R&D: the Climate Change Science Institute (CCSI), the Health Data Sciences Institute (HSDI), the Institute for Functional Imaging of Materials (IFIM), and the Urban Dynamics Institute (UDI), building on successful models such as CASL and BESC. Our science strategy is refined in consultation with the advisory committees established to assess our S&T directorates and the ORNL Science Advisory Board, which reports to the Laboratory Director.

In making Laboratory Directed Research and Development (LDRD) investments, ORNL gives priority to projects that address a set of focus areas that are closely aligned with its major S&T initiatives. In FY 2017, this set of focus areas spans next-generation data, modeling, and simulation for neutron science; computer science and mathematics for exascale computing; materials innovation: from atoms to function; nuclear S&T; integrated studies of complex biological and environmental systems; and transformational energy S&T. It also includes cross-cutting initiatives in quantum computing, with an emphasis on quantum materials and interfaces, and in cyber security and resilience. Influencing all of these focus areas is a set of nine topics that are being addressed through an exercise launched in FY 2016 to identify the "Big Science Questions" (BSQs) that will inspire ORNL's staff over the next decade. A diverse group of ORNL R&D staff, including senior, mid-career, and early-career staff, are evaluating these topics as part of an ongoing conversation about the Laboratory's mission, capabilities, and goals.

As part of an ongoing effort to sustain and expand its core capabilities, ORNL has increased its LDRD investment by $2M/year for the past 3 years; in FY 2016, the LDRD budget is $46M. As discussed in Sect. 8.3, ORNL will continue this trend in FY 2017, with a proposed budget of $48M (4.1% of the Laboratory's operating budget).

5. Mission Readiness/Facilities and Infrastructure

Future Infrastructure Gaps within a 10 year Window

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) with three primary campuses. On a daily basis, ORNL hosts ~6,500 people comprising UT-Battelle's 4,600 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, unique fabrication and assembly services, a guest house, and other support functions. Work is performed in 203 operational SC buildings (4.6M GSF) and 48 operational EM buildings (0.3M GSF). Buildings in shutdown status, owned by SC, EM, and NE, represent 19% (1.5M GSF) of ORNL's building inventory.

All SC mission unique facilities (1.2M GSF) have an adequate condition rating; 90% of SC's non-mission-unique facilities are rated adequate, with the balance rated substandard. Substandard buildings (typically more than 50 years old and underutilized) will be repurposed or excessed. The condition rating for 88% of SC's operating Other Structures and Facilities (OSFs) is adequate with the balance (12%) rated substandard. Aged utility systems (i.e. substandard OSFs) are a key focus of modernization.

Research is also conducted in off-site leased facilities (16 facilities totaling 0.23M GSF). ORNL's Hardin Valley campus, about seven miles from the main campus, hosts MDF and the NTRC. The CFTF is located in Oak Ridge, 5 miles from the main campus. Both provide ready access for industrial partners. ORNL's leased space portfolio is evaluated frequently for consolidation and/or reduction opportunities.

ORNL's Site 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, TN).

Campus Strategy

ORNL's campus strategy has four main objectives:

1. Advance science and energy leadership
2. Establish a modern, adaptable infrastructure to support research
3. Return the ORNL central campus to productive science missions
4. Reduce excess facility liabilities

These objectives are accomplished through addition of capacity as needed to support research, sustainment and recapitalization of key assets, and footprint consolidation with deactivation and demolition of excess assets. The most important needs for each objective are identified and addressed through ORNL's annual Mission Readiness process. Figure 6.1 depicts planned facilities and infrastructure investments linked to these objectives.

Infrastructure Investment Summary

Non-mission-unique facility investments are summarized in Appendix D. Institutional capital and expense investments are the predominant funding sources for continued site modernization. Funding priorities for disposing of excess facilities are identified in Sect. 6.2 and in Appendix D. Maintenance and repair investment is between 2% and 4% of the replacement plant value. More than 45% of ORNL's non-mission-unique facilities are more than 50 years old and carry 90% of the DM. As shown in Appendix D, DM will fluctuate over the next decade at around 2.5%. This fluctuation reflects ORNL's plans to reduce DM by deactivating and excessing aging facilities, leading to footprint reduction, and by repurposing older facilities to support current and future mission needs.

D.1 Infrastructure Investment Tables (for non-mission unique facilities)

Objectives:

Objective 1	Advance Science and Energy Leadership
Objective 2	Establish a Modern Adaptable Infrastructure to Support Research
Objective 3	Return the ORNL Central Campus to productive Science Missions
Objective 4	Reduce Excess Facility Liabilities

Planned Capital Investments, 2015–2027 (There are no planned capital investments in NE Facilities at ORNL & Y-12.)

(Dollars in Millions)

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
Construct a Greenhouse with Head house and Storage	3.0		0.2		2.8										IGPP	OH	**SC 06:** Biological Systems Science **SC 09:** Climate Change Science & Atmospheric Science **SC 15:** Environmental Subsurface Science **SC 24:** System Engineering & Integration **SC 13:** Decision Science & Analysis
Construct a Low Vibration/EMF facility for Sensitive Equipment	9.6		0.3	0.2	5.0	4.1									IGPP	OH	**SC 08:** Chemical & Molecular Science **SC 11:** Condensed Matter Physics and Material Science

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
Renovate Bldg. 6010	9.6	0.5	4.5	4.6											IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 18:** Nuclear Engineering **SC 19:** Nuclear Physics **SC 24:** System Engineering & Integration
Replace Bldg. 6025	9.6		1.0	2.0	6.0	0.6									IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 18:** Nuclear Engineering **SC 19:** Nuclear Physics **SC 24:** System Engineering & Integration
Renovate Labs and Offices in Building 4500N Wing 1	9.6		0.3	0.2	5.0	4.1									IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 08:** Chemical & Molecular Science **SC 18:** Nuclear Engineering
Construct water tank at Chestnut Ridge	9.6					4.0	5.6								GPP	SLI	**SC 01:** Accelerator Science & Technology **SC 02:** Advanced Computer Science, Visualization, and Data

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
																	SC 03: Applied Materials Science and Engineering **SC 06:** Biological Systems Science **SC 07:** Chemical Engineering **SC 08:** Chemical and Molecular Science **SC 10:** Computational Science **SC 11:** Condensed Matter Physics and Material Science **SC 15:** Environmental Subsurface Science **SC 16:** Large Scale User Facilities Advanced Instrumentation **SC 19:** Nuclear Physics **SC 22:** Plasma and Fusion Energy Science
Modernize Lab and Office Spaces (Aggregate of	165.0					5.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 08:** Chemical & Molecular Science **SC 09:** Climate

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
several individual projects)																	Change Science & Atmospheric Science **SC 11:** Condensed Matter Physics & Materials Science **SC 18:** Nuclear Engineering
EMC Capital Lease for Network Storage	3.1	0.7													IGPP	OH	All ORNL Core Capabilities
Replace Bldg. 7920 Cave B cell liner	2.0	0.5	1.0	0.5											IGPP	OH	**SC 07:** Chemical Engineering **SC 03:** Applied Material Science and Engineering **SC 20:** Nuclear and Radio Chemistry **SC 18:** Nuclear Engineering
Upgrade RH-TRU Waste Loading Station	7.6	1.3	1.1	4.9	0.3										IGPP	OH	**SC 07:** Chemical Engineering **SC 08:** Chemical and Molecular Science **SC 03:** Applied Materials Science & Engineering **SC 20:** Nuclear and Radio Chemistry **SC 18:** Nuclear Engineering **SC 17:** Mechanical Design and Engineering

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
																	SC 24: Systems Engineering and Integration
Restore Bldg. 7603 Bridge Crane	3.2		1.0		2.2										IGPP	OH	**SC 18:** Nuclear Engineering **SC 17:** Mechanical Design and Engineering **SC 24:** Systems Engineering and Integration
Renovate and Expand Bldg. 7018	9.6	6.9													IGPP	OH	All Core Capabilities
Replace Fiber Optic Network	9.6		2.5	7.1											IGPP	OH	All Core Capabilities
Construct Bldg. 4508 Once-through Cooling Water Elimination	3.0		1.5	1.5											IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 08:** Chemical & Molecular Science **SC 11:** Condensed Matter Physics & Materials Science **SC 18:** Nuclear Engineering
Construct new facility to replace 7002 garage	5.0			5.0											IGPP	OH	All ORNL Core Capabilities

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
Renovate 7012 Material Fabrication Facility	9.0				4.0	5.0									GPP	SLI	All ORNL Core Capabilities
Upgrade Electrical System in 4500 Area (2.4 to 13.8kV)	1.5				1.5										IGPP	OH	All Core Capabilities
Provide Chilled Water to meet Volume and Redundancy	5.8				1.7	4.1									IGPP	OH	All Core Capabilities
Replace Bldg. 7040 (Gas Bottle Facility)	0.9			0.9											IGPP	OH	All Core Capabilities
Replace/Sustain Aging Infrastructure (aggregate of several individual projects)	45.0					5.0	7.0	8.0	7.0	5.0	5.0	4.0	2.0	2.0	IGPP	OH	All Core Capabilities
Sustain Bldg. 3025 E by replacing hot cell windows, refurbishing charging area, and new LVS	7.2				2.0	5.2									IGPP	OH	**SC 03:** Applied Material Science and Engineering **SC 18:** Nuclear Engineering **SC 19:** Nuclear Physics **SC 22:** Plasma &

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
																	Fusion Energy Science
Replace Boiler in Bldg. 2719	6.6	5.3													IGPP	OH	All Core Capabilities
Renovate Third Floor of Bldg. 2519	3.1	2.3													IGPP	OH	All Core Capabilities
Replace Primary Treatment Pump Station	9.6	0.5	3.6	5.5											IGPP	OH	All Core Capabilities
Replace/Sustain Aging Infrastructure (aggregate of several individual projects)	30.0					3.0	3.0	5.0	6.0	5.0	2.0	2.0	2.0	2.0	IGPP	OH	All Core Capabilities
Construct a Translational Research Building	145.0								30.0	45.0	50.0	17.0	3.0		LI	SLI	**SC 03:** Applied Material Science and Engineering **SC 08:** Chemical & Molecular Science **SC 11:** Condensed Matter Physics & Materials Science **SC 18:** Nuclear Engineering **SC 24:** System Engineering & Integration
Construct Research	25.0					5.0	15.0	5.0							LI	SLI	All Core Capabilities

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
Operations Support Center																	
HRIBF Decommission	32.8	5.0	4.9	4.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	--	NP	**SC 01:** Accelerator Science & Technology **SC 19:** Nuclear Physics
Demolish buildings 7001 & 7002 (7000 Area Modernization)	8.0				4.0	4.0									DF-EFD	SLI	All ORNL Core Capabilities
Demolition of Priority 1 Facilities - Biology Complex Y-12	76.40		5.0												--	EM	--
Demolition of Priority 3 Facilities - High-risk Central Campus - 3026C & 3026D	15.41														IF-EFD	EM	--
Demolition of Priority 3 Facilities - High-risk Central Campus - 3038	11.57														IF-EFD	EM	--

Project Title	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Fund Prg.	Core Capability
Demolition of Priority 3 Facilities - High-risk Central Campus-balance	853.4														IF-EFD	EM	--

Objective 4 Notes:

- Excess Contaminated Facilities Working Group (ECFWG) risk ranking prioritized demolition
- EM is the funding program for demolition of priority 1 and 3 facilities (outlined above)
- ORNL Central Campus includes 79 facilities (SC, EM, NE) in the 1000-4500 area
- Majority of estimated Central Campus D&D costs are attributed to four facilities (2026=$94M, 3042-Reactor only=$34M, 3517=$74M, and 3019A=$351M)
- Bldg. 3026C is no longer in the ECFWG database and is not included in the "total" column

Pacific Northwest National Laboratory

1. Mission and Overview

Pacific Northwest National Laboratory (PNNL) is a multidisciplinary national laboratory advancing the frontiers of science and technology (S&T) in areas that inspire and enable the world to live prosperously, safely, and securely. Located in Richland, Washington, PNNL is one of 10 United States (U.S.) Department of Energy (DOE), Office of Science (SC) national laboratories. Operated by Battelle Memorial Institute, PNNL had 4,377 staff members and total costs of $875M during fiscal year (FY) 2015.

Since 1965, PNNL has made significant S&T discoveries that have benefitted the nation. These include major advances in our scientific understanding of changes in frequency and intensity of climate events, which help us prepare for droughts, floods, and other extreme conditions. In the area of energy, PNNL has developed advanced computing tools that analyze grid congestion faster and more accurately, saving utilities millions of dollars. The Laboratory has also developed a new organic aqueous flow battery that uses water-based liquid electrolytes and is 60 percent less expensive than current flow batteries. Research in national security has resulted in the development of low-cost attachments to a mobile platform, enabling detection of infectious pathogens in the field.

Several major research and development (R&D) facilities enable mission accomplishment. On behalf of DOE-SC's Office of Biological and Environmental Research (BER), PNNL operates the Environmental Molecular Sciences Laboratory (EMSL) and provides technical and operational leadership to the Atmospheric Radiation Measurement (ARM) Climate Research Facility. The Radiochemical Processing Laboratory (RPL) is a Hazard Category II non-reactor nuclear facility that provides PNNL with a core capability in Applied Nuclear Science and Technology, furthering innovative radiological material processes and solutions for the environmental, nuclear energy, and national security research. PNNL operates DOE's only facility for marine sciences in Sequim, Washington, building upon a rich history of research related to marine and coastal resources, environmental chemistry, water resources modeling, ecotoxicology, biotechnology, and national security.

PNNL also has satellite offices in Seattle, Washington; Portland, Oregon; and College Park, Maryland.

2. Lab-at-a-Glance

Location: Richland, Washington
Type: Multi-program Laboratory
Contractor: Battelle Memorial Institute
Responsible Site Office: PNNL
Website: www.pnnl.gov

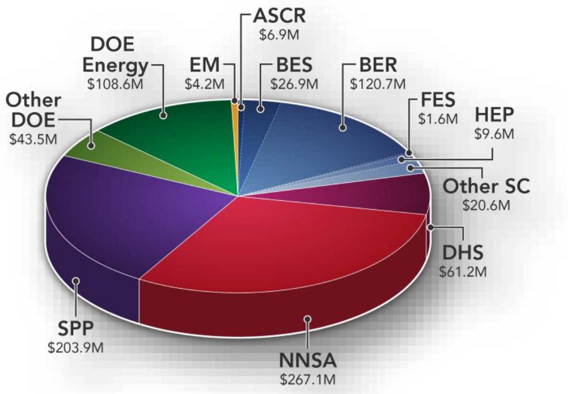
Physical Assets:

- 379 acres DOE, 203acres Battelle (including 39 in Sequim, WA), *(DOE acres include 31 acres in the Hanford 300 Area)*
- 861,547 gross square feet (GSF) of DOE-owned, active operating buildings (21) and 18 other structures and facilities (OSFs)
- Replacement Plant Value: $459,790,018
- 956,713 GSF in 26 leased facilities
- 486,260 GSF in 31 Battelle facilities
- 2,304,520 GSF total buildings and trailers

Human Capital:

- 4,061 Full Time Equivalent Employees (FTEs)
- 12 Joint faculty
- 244 Postdoctoral researchers
- 218 Graduate and 207 Undergraduates
- 1,915 Facility users(715 EMSL; 1,200 ARM Climate Research Facility
- 104 Visiting scientists and engineers

FY 2015 Funding by Source (Costs in $M):



FY15 Total Lab Operating Costs (excluding Recovery Act):	$874,967
FY15 Total DOE/NNSA Costs:	$609,805
FY15 SPP (Non-DOE/Non-DHS) Costs:	$203,944
FY15 SPP % of Total Laboratory Operating Costs:	23.3%
FY15 Total DHS Costs:	$61,218
Recovery Act Costed from DOE Sources in FY15:	$2,262

3. Core Capabilities

PNNL has 19 core capabilities; each a powerful combination of people, equipment, and facilities. These capabilities represent a collective set of skills and a body of world-leading scientific and engineering work that provides exceptional value and mission delivery to DOE, the National Nuclear Security Administration (NNSA), and the U.S. Department of Homeland Security (DHS). Our core capabilities also enable the Laboratory to support the missions of other federal agencies and industry through our strategic partnership projects (SPPs).

One of PNNL's strengths is the ability to bring multiple capabilities to bear on complex S&T challenges. Synergies among these core capabilities enable PNNL to tackle the fundamental science challenges posed by DOE's missions and to deliver transformational research required to accelerate the delivery of solutions to the marketplace. This approach is evident in the core capability descriptions that follow. See Appendix 3 for the alignment of PNNL's core capabilities with the DOE key mission areas they support.

Large-Scale User Facilities/Advanced Instrumentation

EMSL is a DOE-SC, BER scientific user facility that is pioneering molecular-level discoveries to enable the predictive understanding that will provide the foundation for critical biological, environmental, and energy challenges. EMSL accomplishes its mission through four transformational science themes: atmospheric aerosol systems, biosystem dynamics and design, terrestrial and subsurface ecosystems, and the new molecular transformations, which replaces energy materials and processes. Multidisciplinary teams of users working on these themes collaborate with the expert staff and use instrumentation and computation within EMSL to solve complex scientific problems. EMSL provides scientific leadership and access to instrumentation in high-performance mass spectrometry (MS), high-resolution microscopy, high-field magnetic resonance spectroscopy and imaging, surface and interface spectroscopies, sophisticated biological characterization techniques, and high-performance molecular science computing, all unmatched in sensitivity and resolution, sample throughput, and variety of *in situ* sample environments.

PNNL is recognized nationally 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 recently demonstrated this ability with the development, design, construction, and operation of the 21-Tesla Fourier-Transform Ion Cyclotron Resonance (FTICR) mass spectrometer.

This capability also enables PNNL's contribution to the design and operation of the ARM Climate Research Facility. ARM is the world's premier ground-based observational facility for advancing climate change research, used by scientists worldwide to improve the understanding and representation of clouds, aerosols, and other key processes in climate and earth system models. Providing 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 observation sites are in climate-critical regions like the eastern North Atlantic, Antarctica, and the north slope of Alaska. To support model development and associated atmospheric-process studies, ARM is developing two supersites in the continental United States and the north slope of Alaska that will provide three-dimensional constraints to high-resolution model simulations at these locales. PNNL is responsible for the overall technical direction of ARM's scientific infrastructure through continual collaboration among nine DOE laboratories.

This capability is funded by DOE-SC (BER, Advanced Scientific Computing Research [ASCR], Basic Energy Sciences [BES], and the Office of High Energy Physics [HEP]), the Office of Energy Efficiency and Renewable Energy (EERE), DHS, and the National Institutes of Health (NIH; National Institute for General Medical Sciences).

Advanced Computer Science, Visualization, and Data

PNNL is a national leader in energy-efficient computing; performance, power, and reliability modeling; the exploration and design of novel computing architectures; and data-driven discovery at extreme scales. PNNL has domain experts in programming models, resiliency, fault tolerance, information visualization, data analytics, and data management. Among the staff are world leaders in performance, power and reliability modeling for co-design of systems and applications, design space exploration and optimization, and visual analytics.

Expertise in programming models for extreme-scale computing is demonstrated through toolkits such as Global Arrays, which powers NWChem and other important scientific applications. 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). As a recognized leader in the field of visual analytics and exploratory data analysis, PNNL advances the state of the art in visual metaphors for complex, high-volume data and signature discovery algorithms that apply advanced statistics and machine learning to derive novel indicators for complex phenomena. 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 Performance and Architecture Laboratory, a state-of-the-art lab for measuring performance, power, and thermal effects for advanced technologies to predict their overall potential and guide their designs; computing resources, such as the 3.4 petaflop Cascade supercomputer, PNNL Institutional Computing (PIC) mid-range cluster, and research cloud; advanced testbeds for computing technologies, from embedded to extreme; 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 DOE-SC's ASCR, BES, BER, HEP, EERE, Office of Fossil Energy (FE), NNSA, DHS, and other SPP sponsors, including U.S. Department of Health and Human Services (DHHS) and the Department of Defense (DoD).

Applied Materials Science and Engineering

PNNL is recognized internationally for its capability in Applied Materials Science and Engineering, with a strong emphasis on materials synthesis, manufacturing, and device fabrication and testing that can be scaled up and transferred to industry. PNNL has made significant contributions to commercialization of automobile catalysis, organic lead-emitting devices, biofuels, redox flow batteries, and many other clean-energy technologies. PNNL has domain expertise in materials characterization; materials theory, simulation, design, nucleation, and synthesis; materials structural and chemical modification; the role of defects in controlling material properties; and materials performance in hostile environments, including the effects of radiation and corrosion. PNNL's strength in this capability is supported by the Laboratory's core capabilities in chemical, molecular, biological, nuclear, and subsurface science, as well as the ability to engineer enabling nano-structured and self-assembled materials, tailored thin films, ceramics, glasses, alloys, composites, and biomolecular materials. PNNL is developing advanced glass formulations, key process control models, and tactical processing strategies to ensure safe and successful operations for the high-level waste and low-level waste vitrification facilities.

Staff members have expertise in energy storage materials, solid oxide fuel cells, solid-state lighting, absorption cooling, lightweight alloys, magnetic materials, organic electronic materials, and radiation effects on materials, as well as proficiency in synthesizing and processing of bulk nano-structured materials, high-surface-area materials, catalysts, and nanoporous materials for energy applications. PNNL's technical staff members contribute to the development and use of state-of-the-art *in situ* characterization and imaging instrumentation at EMSL; high- and low-dose radiological facilities, including RPL, Physical Sciences Laboratory (PSL), and the Materials Science and Technology Building (3410); laboratories for thin-film material synthesis and deposition; and the Solid State Lighting Test and Analysis Facility. PNNL works closely with other national laboratories and industrial partners and plays a critical role in high-impact national programs such as the Joint Center for Energy Storage Research (JCESR).

The Applied Materials Science and Engineering capability forms the basis of PNNL's programs in materials synthesis; radiation effects in materials; multi-scale 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 is funded through programs in DOE-SC's BES, Fusion Energy Sciences (FES), the DOE Office of Nuclear Energy (NE), EERE (vehicle technologies, hydrogen storage, building technologies, and fuel cell technology), DOE's Advanced Research Projects Agency-Energy (ARPA-E), the DOE Office of Environmental Management (EM; waste processing), DoD (materials for storage devices), NNSA, and the U.S. Nuclear Regulatory Commission (NRC).

Applied Mathematics

PNNL is a leader in Applied Mathematics, leveraging mathematical models to predict behavior of complex multi-scale systems and quantify associated uncertainty to further scientific discovery. As a leader in applied mathematics research, we have a core team of researchers located in the Information Sciences Building 1 (ISB1), ISB2, the Biological Sciences Facility (BSF), and CSF, who develop novel multi-scale methods for uncertainty quantifications and data analysis.

PNNL has broad expertise in multi-scale mathematics, including dimension reduction, mesoscale Lagrangian particle methods, and hybrid methods for coupling multi-physics models operating at different scales. Building on its strength in multi-scale modeling, PNNL is developing capabilities in multi-fidelity 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 highly nonlinear and high-dimensional systems and include surrogate and multi-fidelity modeling for both forward prediction and inverse models.

PNNL is a leader in designing extreme-scale machine learning and data mining algorithms with the Machine Learning Toolkit for Extreme Scale, which includes several supervised learning algorithms (*e.g.*, deep learning, support vector machine) and unsupervised learning algorithms (*e.g.*, auto-encoders, spectral clustering). 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 leverages these capabilities to solve cross-cutting 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.

Biological and Bioprocess Engineering

PNNL is a recognized leader in Biological and Bioprocess Engineering, developing technologies and processes to convert biomass and waste materials into fuels and chemicals that will reduce our dependence on petroleum. Biomass sources include lignocellulosic materials (*e.g.*, corn stover, wood wastes) and other waste materials (*e.g.*, waste water treatment plant wastes), as well as algae. Decades of research and national contributions have established Biological and Bioprocess Engineering as a PNNL core capability. This core capability leverages expertise in catalysis and reaction engineering, separations, process engineering and flowsheet development, materials science, and techno-economic modeling. The Biological and Bioprocess Engineering research spans from fundamental science to understandingmolecular interactions and surface science involved in the conversion processes to pilot-scale operations to demonstrate technologies, allowing them to be transferred to industry for commercial application.

PNNL's biologists, chemists, and chemical engineers specialize in fermentation, algae growth and processing, catalysis and reaction engineering, separations, process engineering, techno-economic and lifecycle analyses, and resource assessments. Staff members are housed in our Bioproducts, Sciences, and Engineering Laboratory and Marine Sciences Laboratory (MSL) to solve the most challenging bioprocessing issues. PNNL technical leadership areas 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 (validated by both the Air Force and industry), 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. We also utilize a unique Biomass Assessment Tool used by the government and industry to quantify potential fuel production from microalgae and waste feedstocks.

The PNNL Biological and Bioprocess Engineering portfolio is protected with significant intellectual property that enables commercialization of DOE and other investments. The PNNL team has 7 distinguished inventors, each with 14 or more awarded U.S. patents, for a total of 65 bio-based U.S. patents since the year 2000. This core capability supports other PNNL core capabilities, including Biological Systems Science, Chemical Engineering, Applied Materials Science and Engineering, Chemical and Molecular Sciences, and Earth Systems Science and Engineering. PNNL provides leadership in Biological and Bioprocess Engineering to the EERE Bioenergy Technologies Office, DOE-EM, academia, and industry. Industrial partners include companies such as Archer Daniels Midland, Genifuel, and LanzaTech.

Biological Systems Science

PNNL is a recognized leader in Biological Systems Science, developing a mechanistic understanding of complex multicellular systems and their response to perturbation, to enable prediction of impacts of climate, energy production, and emerging technologies on environmental sustainability and human health. PNNL has made significant contributions in deciphering mechanisms of microbial community metabolic interactions and dynamics, understanding multi-scale 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 missions of bioenergy, carbon cycling, and climate change. PNNL's fundamental science program leverages this core capability to study how microbial metabolic and spatial interactions impact carbon, nitrogen, and energy dynamics and give rise to functional stability. 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 provides insight into the development of medical countermeasures, early diagnostics, biodetection, and bioforensics to improve health and biosecurity.

PNNL is recognized for leadership on panels such as those at the White House and the National Academy of Sciences. For example, Dr. Janet Jansson, an internationally known microbial ecologist, was selected as a participant in the White House Microbiome Roundtable, and Dr. Katrina Waters was invited to serve on the National Research Council committee for predictive toxicology approaches to military assessments of acute exposures. PNNL has nationally recognized staff members in microbial ecology, microbiome science, fungal biology and biotechnology, pathogen biology and biological threat analytics, 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 mechanisms of metabolic exchange among members of microbialcommunities), leverage this broad suite of expertise to provide unprecedented molecular- to meso-scale resolution of the structure and activity of biological systems.

Key facilities supporting this capability include BSF; CSF; the Bioproducts, Sciences, and Engineering Laboratory; MSL; the Aquatic Research Laboratory; Life Sciences Laboratory (LSL) I; Microbial Cell Dynamics Laboratory; and EMSL. PNNL partners with the Joint Genome Institute (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.

This capability is funded through programs in BER, ASCR, BES, EERE, EM, DHS's Science and Technology, DoD, NIH, National Aeronautics and Space Administration (NASA), and the U.S. Environmental Protection Agency (EPA). Our core capability in Biological Systems Science supports and is supported by other PNNL core capabilities, including Biological and Bioprocess Engineering; Chemical and Molecular Sciences; Earth Systems Science and Engineering; Environmental Subsurface Science; Advanced Computer Science, Visualization, and Data; Applied Mathematics; and Large-Scale User Facilities/Advanced Instrumentation.

Chemical and Molecular Sciences

PNNL is an international leader in Chemical and Molecular Sciences, a core capability that advances the understanding, prediction, and control of chemical and physical processes in complex, multi-phase environments. The Laboratory has domain expertise in chemical physics, catalysis science, chemical analysis, geochemistry, computational chemistry, and actinide science. This core capability has strong ties to the Condensed Matter Physics and Materials Science, Computational Science, and the Applied Mathematics core capabilities, combining with expertise in those areas to advance our understanding of complex phenomena at interfaces of molecular liquids and solids and developing computational tools that retain fidelity to essential molecular processes controlling macroscopic phenomena.

PNNL has made significant contributions in condensed phase and interfacial molecular science, catalysis science, geochemistry, and chemical analysis. 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 also were essential for the award and renewal of an Energy Frontier Research Center in Molecular Electrocatalysis from DOE's BES program and an award from DOE's Office of Science 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 application (NWChem), which is used worldwide to efficiently solve large molecular science problems on computing resources ranging from high-performance parallel supercomputers to workstation clusters. Capability stewardship efforts, such as those proposed in the Energy Sciences Capability (ESC) initiative, will accelerate scientific discovery in chemical transformations by enabling close integration of synthesis with dynamic characterization capabilities and real-time computation capabilities.

The Chemical and Molecular Sciences capability forms the basis for PNNL's fundamental science programs in catalysis science, condensed phase and interfacial molecular science, computational and theoretical chemistry, geosciences, and separations and analysis. Applied programs include improved energy technologies, catalysis and reaction engineering, hydrogen storage, biomass conversions, environmental remediation, and carbon capture/sequestration. Staff members are housed primarily in PSL, EMSL, and the Mathematics Building. This capability receives support from programs in BES, BER, DHS, EERE (geothermal, biomass, and hydrogen; fuel cells; and infrastructure technology), FE (carbon- and co-sequestration), EM (environmental remediation), NNSA (nonproliferation), DHHS, and DoD. BER's support of EMSL capabilities greatly enhances this core capability PNNL is recognized internationally for Chemical Engineering capabilities that translate scientific discovery into innovative, first-of-a-kind processes to solve our toughest energy and environmental challenges. 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 sponsoring client 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 multi-phase systems.

PNNL applies Chemical Engineering capabilities to a broad array of challenges and successes. Successes include development and commercialization of NOx reduction units for automobile emissions control, leading the development and application of software to predict the thermal and structural performance of spent nuclear fuel storage and transportation systems, development of novel heat pumps and building systems to increase our energy efficiency, and invention and development of micro-technology-based reactors and separations systems for applications such as fuel cells and solar natural gas reforming. Challenges include biomass and fossil fuel conversion to fuels and chemicals, as well as subsequent fuel upgrading; nuclear waste processing and immobilization research to solve the nation's legacy nuclear waste challenges; and cost-effective startup and operation of the Hanford Waste Treatment Plant.

Our core capabilities in Chemical Engineering support (and are supported by) PNNL core capabilities in Applied Materials Science and Engineering, Biological and Bioprocess Engineering, Chemical and Molecular Sciences, Nuclear Engineering, and Systems Engineering and Integration. PNNL provides leadership in Chemical Engineering to DOE-SC, BES, EM, EERE (Vehicle Technologies Office, Bioenergy Technologies Office, Geothermal Technologies Office, Solar Energy Technologies Office, and Fuel Cell Technologies Office), FE, NE, NNSA, ARPA-E, and DoD.

Climate Change Science and Atmospheric Science

PNNL is an international leader 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 Earth's climate system. This capability includes activities ranging from laboratory and field measurements to multi-scale numerical simulations to integrated analyses of climate impacts and response options. PNNL has domain expertise in atmospheric measurement systems, atmospheric aerosol chemistry, cloud physics and cloud-aerosol-precipitation interactions, boundary layer meteorology, land-atmosphere interactions, biogeochemistry, hydrology, ecosystem science, integrated assessment, and multi-scale atmospheric and earth system modeling. 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, and Advanced Computer Science, Visualization, and Data.

PNNL's climate change and atmospheric systems research focuses on improving our basic understanding of the causes and consequences of climate change and on developing the data-driven regional and global modeling frameworks needed to predict changes in climate, as well as in related human and environmental systems. Key facilities include the Atmospheric Measurements Laboratory (AML), ARM Climate 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

G-10F[8] research aircraft, a flow-through environmental chamber, and wind energy lidar buoys. PNNL is also a leading developer of atmospheric, climate, and earth system models, such as the Global Change Assessment Model, the Weather Research and Forecasting model, DUSTRAN, and the Accelerated Climate Model for Energy (ACME), 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 assessment, and atmospheric wind energy research. Increasingly, these research activities are being integrated and connected with other research areas and programs; for example, through integrated multi-scale, multi-sector modeling that brings together models of climate, hydrology, land surface dynamics, energy systems, and socioeconomics in order to develop more robust understanding of how extreme events and long-term stresses are influencing the energy-water nexus and national security. This core capability is funded by programs in BER, ASCR, EERE (wind and water power technologies), FE (carbon dioxide storage), NASA, EPA, and the National Oceanic and Atmospheric Administration (NOAA).

Computational Science

As a national leader in Computational Science, PNNL actively employs high-performance computing (HPC) to solve compelling, extreme-scale scientific problems. PNNL has a long history of developing computational tools and application codes built in collaboration by multidisciplinary teams composed of domain scientists, computer science experts, and applied mathematicians. PNNL maintains a leadership position in many computational science domains, including computational chemistry, computational materials science, high-energy physics, computational engineering, and subsurface science, as well as climate, including participation in developing community climate codes and management of the ARM Climate Research Facility.

PNNL's vibrant HPC research is directly driven by applications, systems, and technologies of interest to DOE. In the HPC field, PNNL is a recognized leader in performance and power analysis, modeling and simulation, and integration of measurements with modeling and simulation of performance, power, and reliability; programming models; and computer system architectures.

At PNNL, applied mathematicians develop algorithms that are scalable, resource-efficient, and load-balanced, with particular focus on mathematical methods and algorithms for mesoscale science, uncertainty quantification, and creating numerical libraries that support specific scientific applications.

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[8] The current U.S. Army Air Forces aircraft, a Gulfstream G-1, has been well-suited to ARM field campaigns over the past 6 years and would be appropriate to address many of the new scientific challenges documented in recent ARM and Atmospheric System Research workshops. Key characteristics of the G-1 for research flights are a payload capacity of 4,200 lbs., a service ceiling of 25,000 ft., and an endurance with full payload of approximately 4 hours. A replacement for the G-1, which is expected to reach the end of its service life around 2020, should meet or exceed these specifications.

Data science at PNNL is represented in a variety of research, development, and support areas that impact computational science. Working closely with domain science researchers from computational, experimental, and observational fields, PNNL's data science teams emphasize architecting integrated solutions, from data capture to knowledge generation, that are closely embedded into the scientific research processes.

Computing at scale is enabled at PNNL through leading-edge computational resources provided by DOE's BER. Computational science also is fostered by Laboratory investments in the PIC capability. Independently, many PNNL scientists have received Innovative and Novel Computational Impact onTheory and Experiment program allocations that span varied computational science domains. PNNL-developed codes, such as NWChem, also are heavily used on DOE's Leadership Computing Facility systems and at the National Energy Research Scientific Computing Center.

Notably, multidisciplinary teams of domain and computer scientists and applied mathematicians have long been an elemental part of the research process at PNNL. For example, as part of developing NWChem, PNNL pioneered engaging teams of computational scientists to create a molecular modeling capability that dramatically advanced the state of the art. This same integrative, co-design-based approach now is being employed to develop advanced computational models 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 projects.

Staff members are housed primarily in CSF, ISB1, ISB2, and the Environmental Technology Building. 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.

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 the generation, storage, and use of energy and for mitigation of the environmental impacts of energy use.

The Laboratory has domain expertise in synthesis of nano-structured and biomolecular materials, *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 and combines with expertise in those areas to advance our ability to understand and manipulate complex phenomena at solution-solid and solid-solid interfaces, design and synthesize 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 initiative will strengthen the strategic link with our world-class efforts in the predictive design and understanding of chemical transformation processes. The ESC initiative will provide close integration with the Chemical and Molecular Sciences capabilities to enable rapid advancement of our catalysis science agenda, including the development of novel approaches to synthesize three-dimensional multifunctional catalysts and exascale computational tools that will transform our ability to predict and design catalytic processes.

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 computations. PNNL's capability is particularly strong in the area of complexity at interfaces, both through their role in synthesis itself and through the creation of interfaces that control the transport of matter and energy. These strengths have advanced PNNL's research at JCESR, an Energy Innovation Hub led by Argonne National Laboratory (ANL).

The Condensed Matter Physics and Materials Science capability forms the basis for PNNL's 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; multi-scale 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. Staff members are housed primarily in PSL, EMSL, and LSL-II. This capability receives support from programs in BES, BER, and DOE's Offices of Electricity Delivery and Energy Reliability (OE), NE, EERE, and NIH. BER's support of EMSL capabilities (*i.e.*, expertise, instrumentation, and facilities) greatly enhances this core capability.

Cyber and Information Sciences

PNNL is a recognized national leader in Cyber and Information Sciences. The Laboratory improves the security and reliability of critical networks and infrastructures through advanced sensing, analysis, defense, and response. This includes novel information sharing methods and the development and implementation of analytic methods to extract value from data. The research staff includes internationally recognized leaders in cyber resiliency theory, cyber analytics, graph theory, semantic computing and knowledge representation, machine learning, text and multimedia analytics, statistics, and human-computer interaction.

PNNL's cyber security portfolio is based on 3 decades of expertise in developing and deploying novel cyber security sensors for wide-scale enterprise network monitoring and situational awareness, including operation of the Cooperative Protection Program for DOE-complex cyber defense and the Cybersecurity Risk Information Sharing Program, a voluntary information sharing and threat intelligence program for critical infrastructures. PNNL has developed unique expertise in the scientific foundations of cyber security, including leadership in biologically inspired cyber security, multi-scale graph methods for active cyber defense, secure Supervisory Control and Data Acquisition architectures and communications, critical infrastructure resiliency analysis and modeling, and holistic cyber-physical security.

PNNL's information science expertise includes recognized leadership in data acquisition, management, and storage systems (*e.g.*, data workflow, provenance, and quality assurance); analytics and algorithms (*e.g.*, streaming and graph analytics, 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 heterogeneous sources, including emerging techniques for recommender systems that power new human-machine analytic collaboration.

Major computing resources that support this capability include PIC resources, including the Constance cluster, real-time operating system and scalability testbeds, and the CyberNET virtual enterprise testbed to simulate real-world cyber activity and understand blended cyber-physical attacks. In addition, facilities such as the Cyber Innovation and Operations Center, the Electricity Infrastructure Operations Center (EIOC), the cyber-physical powerNET testbed, and the Electricity Infrastructure Cybersecurity Resilience Center support this capability. PNNL's cyber security research staff works closely with the Laboratory's internal cyber security operations groups, evaluating and deploying analytic and security solutions. External collaborations include industry, academic, and governmental partners from across the nation and around the world. We are united in our pursuit of analyzing, protecting, and ensuring the operations of the nation's critical cyber infrastructure. Primary sponsors for PNNL's cyber and information sciences research include ASCR, OE, DoD, and DHS.

Decision Science and Analysis

PNNL is recognized internationally for its strong capabilities in modeling, analyzing, communicating, and mitigating cross-cutting impacts at the interface between science, technology, and society. Working collaboratively with scientists and engineers across the Laboratory and with external partner organizations, our experts continue to develop and implement innovative, end-to-end solutions to complex decision problems on the front lines of the nation's energy and national security challenges. PNNL's staff expertise is focused in the areas of decision science, risk analysis, economics, systems engineering, computer science, policy analysis, social and behavioral science, statistics, and safety analysis. PNNL's Decision Science and Analysis capability enables the development and application ofcutting-edge decision and risk analysis, safety and risk assessment, 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.

Decision Science and Analysis expertise at PNNL is housed in the Sigma 2 building, Mathematics Building, Battelle Portland Office, ISB2, and the National Security Building and is recognized in the areas of nuclear and alternative energy operational safety review and risk assessment; technology field testing and evaluation and performance assessment; dynamic, programmatic risk assessment; geo-spatial decision analytics and visualization; nuclear proliferation risk modeling; multi-organizational collaboration decision support; distributed decision-making for power grid reliability; energy policy and regulatory development and deployment; appliance and commercial equipment 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, and other sustainable energy technologies, such as hydrogen-powered vehicles, is a specific strength. Current stakeholders that primarily utilize our capabilities include EERE, OE, EM, DHS, NRC, EPA, and several offices within the DoD.

Earth Systems Science and Engineering

PNNL is providing world-leading capabilities to solve the nation's most pressing environmental challenges. PNNL's Earth Systems Science and Engineering capability researches the impacts of energy systems and operations on valued environmental resources and functions; addresses regional climate impacts to watersheds, soils, water supplies and builds infrastructure; and develops and deploys technologies to mitigate impacts of past, current, and future energy production systems. This capability spans terrestrial, aquatic, and coastal ocean systems, including invertebrates, fish, birds, marine mammals, and bats. Applications of our expertise include energy systems (*i.e.*, hydropower, wind power, marine and hydrokinetic generation, and nuclear), Arctic and deep-ocean oil and gas, and legacy waste.

PNNL has scientists and engineers in fields ranging from aquatic and terrestrial ecosystems science, oceanography, biogeochemistry, hydrology, environmental engineering, and microbiology. PNNL has domain expertise in molecular-to-field-scale biogeochemistry and transport modeling; laboratory-to-field-scale geohydrology, surface-water hydrology, and multi-phase flow modeling; integrated (*e.g.*, biogeochemical, physical, ecological) aquatic modeling, ecosystem-level adaptive management, ecological modeling, monitoring, 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 ecosystems; 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 sensors. 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. The advanced experimental and instrument capabilities of EMSL are also used to advance research in this area.

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 regulatory protocolsthat are protective of human health and the environment. The Earth Systems

Science and Engineering capability is funded through programs in BER, BES, EM, EERE (wind and water power), NRC, EPA, DHS, Department of the Interior, NOAA, and the U.S. Army Corps of Engineers.

Environmental Subsurface Science

PNNL is an international leader in Environmental Subsurface Science. This capability focuses on developing and applying knowledge of fundamental biogeochemical reactions, energy, and mass transfer processes to the prediction and assessment of natural processes, including the natural attenuation of contaminant plumes and engineered systems, such as the design and operation of carbon sequestration reservoirs. PNNL provides DOE with domain expertise in molecular-through-field-scale biogeochemistry and reactive transport modeling, lab-to-field scale geohydrology and multi-phase flow modeling, computational geochemistry, subsurface technology development and deployment, advanced geophysical monitoring and isotopic analytical capabilities, high-temperature and pressure geochemistry for geologic carbon storage and geothermal energy development, and technology development for deep borehole nuclear waste repositories.

For DOE-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 resulting in PNNL emerging as a national leader in mitigating greenhouse gas (GHG) emissions through geologic sequestration science. Through the Big Sky Carbon Sequestration Partnership, PNNL led one of the world’s first carbon storage projects into basalt formations, completing a 1,000-ton injection into the Grande Rhonde basalt formation. On the FutureGen 2.0 project, PNNL is the only national laboratory to lead the siting, characterization, design, and permitting of a commercial-scale carbon dioxide sequestration reservoir, including securing the world’s first Class VI Underground Injection Control permits. PNNL has key roles in DOE-FE’s National Risk Assessment Partnership, leading the Groundwater Protection Focus Area, and is also leading one of the candidate sites for DOE-EERE’s Frontier Observatory for Research in Geothermal Energy. Through its BER-funded Science Focus Area, 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, DOE-EM, DOE-FE, DOE-EERE (Geothermal Technologies Office), NRC, NNSA, DHS, EPA, NASA, and DoD, as well as DOE’s emerging integrated program in Subsurface Technology and Engineering Research, Development, and Demonstration Crosscut.

Nuclear and Radio Chemistry

PNNL is an international leader in Nuclear and Radio Chemistry, demonstrating the ability to integrate nuclear material assay capability across research and operations to enable proliferation detection, waste disposal, and isotope production. PNNL's strength is supported by Hazard Category II and III nuclear facilities able to support missions ranging from fundamental science to pilot-scale operations in a fast and flexible fashion and able to work from micrograms to kilograms of fissionable materials and megacurie activities of other radionuclides. The Laboratory also has the only user facility(the EMSL Radiochemical Annex [RadEMSL]) for radio chemistry in the nation (and one of few such facilities in the world), with spectroscopic and imaging instruments ideally designed for the study of contaminated environmental materials and examination of radionuclides and chemical signatures. Mission-ready instrumentation, including suites of microscopy, mass spectrometric detection, magnetic resonance, and specialized ultra-low-background radiation detectors; numerous specialized wet chemistry laboratories; and ultra-trace radioanalytical and radiometric facilities, including a shallow underground lab, provide one of the largest collections of instrumentation and expertise at any single institution in the world.

PNNL is specifically known for staff expertise and hands-on experience in production environments, including Hanford, medical isotopes, post-irradiation examination of materials, nuclear process science, and tritium target fabrication. PNNL is recognized for the ability to engage in both research and operational programs, with a track record of maturing scientific breakthroughs into operationally approved methods and for the ability to make some of the most sensitive measurements of radioactive material in the world (*e.g.*, the development and deployment of the world's most sensitive fieldable radionuclide detection system). This expertise is delivered by specialized technical staff members at PNNL with experience in spectroscopy, microscopy, radio chemistry, separations, irradiated materials characterization, and nuclear process and actinide science.

The Nuclear and Radio Chemistry capability forms the basis of PNNL's programs addressing high-priority needs in new and improved nuclear systems (DOE-NE), elementary particles (HEP), radioisotope production and advanced instrumentation for nuclear medicine (DOE-SC's Nuclear Physics), development of methods and systems to assure nonproliferation (NNSA) and combat terrorism (DHS, DoD), and environmental studies, monitoring, and remediation (DOE-EM).

Nuclear Engineering

PNNL is internationally recognized for our Nuclear Engineering capability, with 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 and criticality safety, non-destructive evaluation, and robotics, as well as materials science and microscopy. A strong knowledge base and expertise in commercial nuclear industry enables 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 is specifically recognized for the development of the Graphite 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 to plutonium metal. PNNL is the design authority for tritium production targets used in a commercial reactor and is noted for expertise in remote sensor design to enable reactor life-extensions. The combination of thermal, nuclear, and structural skills is also used to evaluate spent nuclear fuel storage and transportation options. PNNL staff members have a unique understanding of international nuclear capabilities and, thus, the ability to assess all source information.

PNNL is able to apply these skills in both high- and low-dose facilities (*e.g.*, RPL and RadEMSL) to characterize and understand irradiation effects on materials through post-irradiation examination and make precise measurements and analysis that enable nuclear archeological assessments. In addition, PNNL has experimental testing capabilities that enable design, development, and fabrication of advanced, accident-tolerant fuel for commercial reactors and low-enrichment fuel for research reactors, as well as design, modeling, fabrication, and deployment of complex irradiation tests to evaluate nuclear materials. The Nuclear Engineering capability is funded through programs in the BES, HEP, Nuclear Physics (NP), EERE, EM, DOE NNSA Defense Programs, DOE-NE, DoD, DHS, EPA, and NRC.

Power Systems and Electrical Engineering

PNNL is recognized internationally for its capability in Power Systems and Electrical Engineering, with domain expertise in the power grid's generation, market systems, transmission, distribution/smart grid, and demand response/end use/loads areas. PNNL experts apply 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 systems and grid interface of variable generation. Primary supporting disciplines include electrical engineering, power systems engineering, computational science, and materials synthesis, characterization, and processing. With a focus on system-level issues, PNNL is the national leader in defining the inherently resilient grid of the 21st century, delivering new tools to enable unparalleled grid performance (reliability, security, efficiency, and sustainability) and new control and architecture paradigms spanning future demand and supply for unprecedented consumer engagement.

PNNL is specifically known for its expertise in power grid research, with power systems and electrical engineering researchers, computing, and data experts. The research includes transmission and distribution system analysis, advanced grid data and computing analytics, and grid cyber security. This world-class expertise in grid simulation and analytics enables high-performance grid monitoring and control at unprecedented speed, from minutes to subseconds. PNNL's unique expertise in advanced control theory, application, and testbeds supports advances in the control of complex systems. PNNL's leadership in phasor measurement technologies supports broader national deployment, enabling unprecedented grid visibility. 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 to inform research. This research is made possible with the use of the EIOC, Interoperability Laboratory, and the Power Electronics Laboratory in the Systems Engineering Building (SEB) and the Electricity Infrastructure

Cybersecurity/Resilience Center in the Systems Engineering Facility. These laboratories and facilities support world-class commercial tools, as well as the GridLAB-D™ simulation and analysis tool for designing and operating power distribution systems and the VOLTTRON™ software platform enabling smart appliances, electric vehicle charging, and distributed renewable generation. These capabilities are funded through programs in OE, EERE (transportation technologies, hydrogen storage, building technologies, and fuel cell technology), ARPA-E, DHS, and the DoD.

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 material 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 lifecycle, 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 field-deploying international nuclear materials safeguards, security, and complex radiation detection systems. PNNL also leads in developing integrated building energy technologies, 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, Applied Processes and Engineering Laboratory, Radiation Detection Laboratory, and the Large Detector Test Facilities.

The Systems Engineering and Integration capability is funded through programs in DOE-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 the DoD.

4. Science Strategy for the Future

PNNL's scientific vision is to understand, predict, and control the behavior of complex adaptive systems. We are expanding our leadership in climate and environmental sciences into leadership in integrated earth-energy systems science, with a particular emphasis on understanding clouds and aerosols, the water and carbon cycles, and the emergent behavior of microbial communities. Our leadership in molecular sciences will grow into scientific leadership in the mesoscale sciences, with a particular emphasis on the principles of scalable synthesis for energy storage and conversion, new control theories for complex adaptive systems, and the construction of integrated, predictive earth-energy system models. Lastly, we are applying our strengths in measurement sciences and analytics toward ultra-trace detection, the development of complex signatures, and real-time, data-driven discovery.

We will focus these fundamental scientific advances on the following specific earth, energy, and security systems central to DOE's strategic objectives:

Earth System. Understand the critical natural and human processes that govern the evolution of specific earth systems and build robust predictive models that enable sound technical and societal decision-making to enhance resilience against external perturbations.

Energy System. Advance the science to achieve sustainable distributed energy production, conversion, storage, and use; develop transformational grid control systems and tools that enable an efficient, reliable, resilient, and secure energy infrastructure.

Security System. Develop and deploy new measurement and analytic systems to transform our nuclear and cyber security infrastructure, increase our situational awareness, and reduce the threat from weapons of mass effect.

Interactions in complex adaptive systems give rise to behaviors at larger scales that cannot be predicted from an understanding of the properties at smaller scales alone. Because of this, we must

- close the fundamental knowledge gaps within biological, climate, chemical, and materials sciences to understand processes at individual scales (from atomic to global)
- develop new frameworks for coupling adaptive models across multiple processes and scales to identify the design principles that govern overall system behavior
- advance the science of computing to develop the systems and algorithms to analyze large volumes of heterogeneous data needed to validate models and realize the potential of data-driven discovery.

Our seven major initiatives are designed to meet these challenges. All of them have a significant focus on the fundamental scientific questions critical to understanding complex adaptive systems, with an additional focus on those aspects important to DOE's strategic objectives in the earth, energy, and security systems, as described above.

Major initiatives are funded primarily through sponsor-funded research. The Laboratory also uses Laboratory Directed Research and Development (LDRD) funding to develop and evolve our core capabilities that support our major initiatives. Each of our major initiatives has identified where we use LDRD to accelerate the rate of innovation, leading to significant scientific advancements, technological breakthroughs, and new strategic partnerships with other research organizations.

1.145. Mission Readiness/Facilities and Infrastructure

Site Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

PNNL is located primarily in southeastern Washington State, mostly in the city of Richland, and includes buildings on DOE's PNNL and Hanford Sites. PNNL also conducts operations at MSL in Sequim, Washington. PNNL consists of 78 buildings1F[9] and 41 OSFs, which reside on approximately 379 DOE acres and other public and private land (see Figure 1).

- 21 DOE-owned buildings—10 owned by DOE-EM and 11 owned by DOE-SC (861,547 gsf; average age 27 years)—and 18 OSFs
- 31 Battelle-owned buildings (486,260 gsf; average age 44 years) and 23 OSFs on 203 acres, including 39 acres in Sequim
- 26 buildings from third-party leases and agreements (956,713 gsf; average age 23 years)

As part of the PNNL contract, Battelle has provided DOE with exclusive use of the Battelle-owned facilities for PNNL purposes. Battelle facilities comprise 23 percent of the PNNL laboratory space and are provided to the government at cost.

PNNL's non-federal-owned space portfolio is evaluated frequently for operational efficiency, consolidation, and/or reduction opportunities. In 2015, PNNL extended five, terminated three, added one, and changed square footage on five leased buildings. An expiration schedule for PNNL's lease portfolio can be found at http://www.pnnl.gov/campusplan/lab_plan_real_estate_actions_schedule.pdf.

Electrical utility infrastructure in the Hanford 300 Area is owned, operated, and maintained by the City of Richland. Over the last few years, PNNL has coordinated the commercialization of other Hanford Site services. The combined site services and utility infrastructure transfers will continue to deliver $4.5M annual savings and benefit from improved operational efficiency. DOE owns, operates, and maintains the water and sewer utility infrastructure in the 300 Area. The City of Richland owns, operates, and maintains the power, water, and sewer infrastructure for the balance of the PNNL campus in Richland.

The FY 2015 condition and utilization assessment designated a majority of federally owned buildings and trailers as adequate relative to mission (20 of 21) and fully utilized (19 of 21). None of the assets were designated inadequate relative to mission or not utilized. Actions to resolve the substandard assets relative to mission and/or underutilized buildings or trailers are described in section 6.2, Campus Strategy.

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[9] The site land use is described in PNNL's Campus Master Plan and can be found at http://www.pnnl.gov/campusplan/campus_master_plan.pdf.

A majority of non-federal-owned buildings and trailers were designated as adequate relative to mission (53 of 57) and fully utilized (44 of 57) in the FY 2015 condition and utilization assessment. None of the assets were designated inadequate relative to mission or not utilized. Actions to resolve the substandard assets relative to mission and/or underutilized buildings or trailers are described in section 6.2, Campus Strategy.

Campus Strategy

PNNL is implementing a rolling 10-year campus strategy (initiated in FY 2013) designed to increase federal control of assets, optimize facility operating costs through effective and efficient operations, and improve facility functionality and utilization to enable the science strategy discussed in sections 3 and 4. The 10-year strategy results in a mission-ready campus that optimizes utilization of new DOE assets and existing DOE, Battelle, and leased facilities in the PNNL core campus, the 300 Area, and Sequim.

Successful execution of the campus strategy has resulted in the following accomplishments to date:

- Exited 13 buildings (6 Battelle2F[10] and 7 leased3F[11]), reducing our facility footprint by more than 150,000 gsf and operational costs by more than $3M annually.

Started operations of SEB, a new federal facility completed in FY 2015. The building provides space for developing fundamental knowledge, technology, and tools to transform the U.S. electric infrastructure, allowing future grid operators to detect, predict, and respond to threats. The facility houses PNNL's Buildings Operations Control Center, enabling collaboration between Facilities and Operations and R&D experts, as well as other national laboratories with the goal of discovering and applying the latest building controls technology. This holistic approach creates an intelligent, operational campus and applies a "Living Laboratory" approach to our facilities and research.

- Constructed a new, federally owned, general purpose chemistry building, started in FY 2015 and completed with operations initiated in FY 2016. The building provides wet, ventilation-intensive laboratory space used to advance chemistry, materials science, and electronics capabilities dedicated to the development of radiation detector materials and systems, the synthesis and characterization of novel two-dimensional materials, and development of concepts for their applications to security-systems-related objectives.
- Relocated radiological work from the Research Technology Laboratory (RTL) 520 to reduce DOE risk from radiological operations adjacent to residential development.

Figure 1 shows PNNL's campus strategy site map, with ownership, new construction, and exits of non-DOE buildings. In FY 2016 and over the next 10 years, we plan to invest $270M to build 8 new federal buildings and a modular radiological laboratory at MSL totaling 189,000 gsf, exit 20 buildings

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[10] Plant Growth Facility 1, 2, 3, 4, and 5 and Battelle Inhalation Toxicology Laboratory.

[11] Sigma 3, 4, and 5; Consolidated Information Center; Lexington; Microproducts Breakthrough Institute 11; and Port of Skamania.

totaling 230,000 gsf, and modernize and sustain existing, retained buildings and infrastructure while achieving the strategy objectives stated below. Additionally, we are developing the mission needs to support $70.5M in direct funding for 3 new federal buildings totaling 87,000 gsf. Replacement of the exited space will be a combination of consolidation into existing space and creation of the new federal buildings. Battelle and DOE continue to work together closely to reach the necessary agreement on the funding of final disposition and remaining depreciation cost for exited Battelle facilities.

We updated our 10-year rolling campus strategy based on our annual evaluation of current space utilization and mission projections. The update incorporates identified infrastructure gaps, associated risks, and the investment plans and actions necessary to resolve the gaps. The investment plans and actions are summarized below by campus strategy objective and core capability (see Table 5). If the gaps are not addressed, we believe the identified risks would be realized within the planning horizon.
Mission Alignment. General Plan Project investments in EMSL (a mission-unique facility) are needed to increase the cooling capacity to support the predictive understanding of molecular-to-mesoscale processes in climate, biological, environmental, and energy systems.

Three new, direct-funded, federally owned buildings are proposed to enhance understanding and concepts for application in earth- and energy-system-related objectives. The first building in the ESC initiative could be funded by Science Laboratories Infrastructure to fill the gaps identified in section 4.2.4 and deliver the desired end-state with the required integration and collaboration, which will provide:

- Accelerated scientific discovery by close integration of unique, dynamic characterization capabilities with synthesis and computation capabilities
- Ability to transfer samples *in situ*, which our current capabilities do not allow, ensuring sample integrity moving from one station to the next
- Increased utilization of EMSL capabilities and impact of EMSL science on BER programs by creating space in EMSL through the departure of capabilities with small impact on the EMSL User Program to accommodate new capabilities or those currently housed outside of the facility
- Laboratory space and capabilities focused on aerosol life cycle, soil science, hydro-biogeochemical cycling, and plant science, as well as enhancing the availability of these capabilities to EMSL's users
- Rapid advances of computational architectures and software through co-design by synergistic mapping of domain science, algorithms, tools, and computer science
- Development of exascale computational tools that will transform our ability to predict and design catalytic processes.

The second and third buildings will be funded by EERE. One of the buildings will provide high-bay research and engineering space to improve the biological performance (*e.g.*, fish passage) of hydropower turbines, hydrokinetic devices, and related structures, and will test and validate those water power technologies at several readiness levels. The other DOE-EERE building will provide high-bay space in an area designated for higher risk work, to house experimental test stands and capabilities for bioenergy technologies research in higher hazard processes.

Campus Continuity. We are focused on improving campus continuity, with an emphasis on increasing federal control and continuity of facility assets. This concept is particularly important because of the mix of federal, Battelle-owned, and third-party leased facilities at PNNL. Proposed new, federally owned buildings will advance campus continuity by replacing and/or consolidating non-federal office, high-bay, warehouse/storage, and laboratory space. PNNL plans to exit 17 non-federal facilities on a schedule corresponding with federally owned acquisitions through FY 2027. PNSO and Battelle Memorial Institute are currently in negotiations, the result of which may change this information. The new federally owned buildings include a currently underway office building (FY 2017, 26,000 gsf), a high bay (FY 2021, 20,000 gsf), a warehouse (FY 2021, 45,000 gsf), a general purpose instrument building (FY 2025, 16,000 gsf), an office building (FY 2026, 26,000 gsf), and a general purpose physics building (FY 2027, 16,000 gsf).

We have undertaken a facilities restoration program to retire DOE-SC's current liability associated with the historical use of radiological and other materials in Battelle-owned buildings. The program will characterize and remediate the buildings as required to achieve unrestricted release. One specific building, RTL 520, has known contamination (*e.g.*, beryllium, radiological, and other) and has residential development within 440 feet. The strategy includes PNNL internal investments to deactivate, decommission, decontaminate, and demolish RTL 520 and the RTL outbuildings.

Reasonable and Achievable. We strive to balance the achievement of the campus continuity and mission alignment objectives, while optimizing operating costs and delivering effective stewardship of the PNNL campus facilities and infrastructure. Enhancement activities include replacing acid-degraded hoods and end-of-life utilities and building systems, as well as improving capabilities for handling radiological materials in support of the Nuclear and Radio Chemistry, Environmental Subsurface Sciences, and Systems Engineering and Integration core capabilities.

We will continue to invest internally in relocations and consolidations to optimize utilization for existing DOE, Battelle, and leased assets in the PNNL core campus, the 300 Area, and Sequim that are planned for retention through the planning horizon. We will continue to maintain the existing assets planned for retention in adequate condition through internal investments commensurate with PNNL's replacement plant value. Planned investment examples include:

- Exit three (64,192 gsf) substandard, underutilized buildings, relocating the capabilities to existing buildings planned for retention.
- Deliver the approved project to address a portion of the underutilized and substandard basement in a 102,107 gsf building. The project will level sloped, trenched floors in 14 labs; renovate 7 vivarium laboratory spaces into functional, general purpose, wet laboratories; and relocate hydrocarbon processing capabilities from leased space to the renovated laboratories.
- Continue actions to drive better utilization of our mission-unique, Hazard Category II nuclear facility through investments in staff and equipment to enhance the overall facility capabilities. Examples include providing quiet space capabilities, replacing an end-of-life process chiller, and replacing acid-degraded fume hoods to avoid potential failures in the ventilation system.

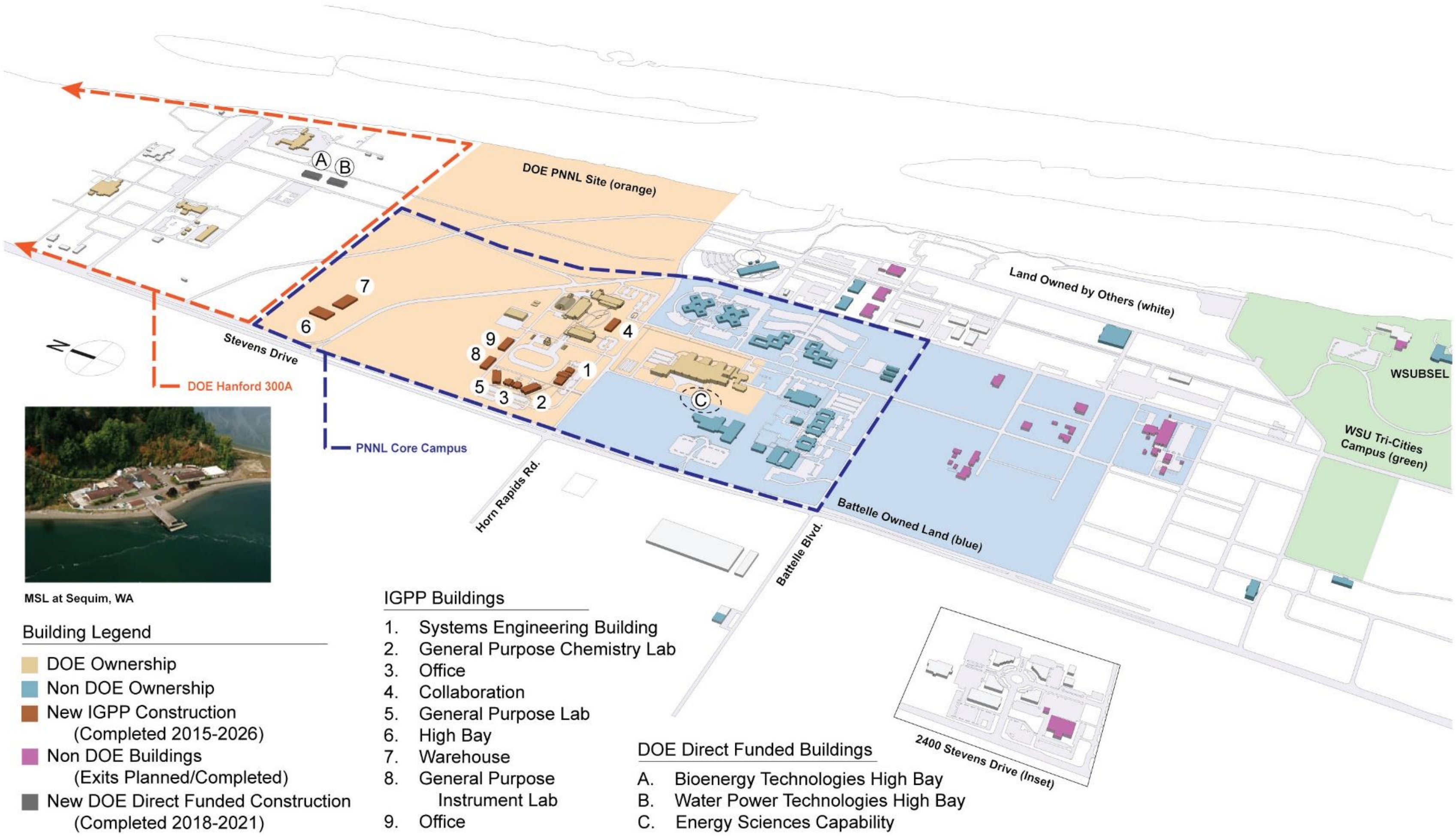
Continue to implement and/or complete actions in the following underutilized, non-federal buildings: complete operational readiness activities in a high-bay building, complete planned building exits, continue to implement the strategy for improved utilization of Sequim buildings, and investigate additional consolidation of leased facility space.

Modern, Collaborative, Flexible, and Sustainable. PNNL is delivering a modern campus that enhances collaboration, is flexible enough to easily accommodate the frequently changing research portfolio, and is sustainable. We will

- Enable research operations and collaboration as a way to increase researcher effectiveness and scientific innovation. PNNL plans include an internal investment in new, flexible S&T collaboration; food services; and meeting spaces. Improve arrival at PNNL by consolidating point-of-entry activities and decreasing onboarding time for visitors, interns, and new hires, making it a positive experience that quickly transitions personnel to the purpose of their arrival.
- Proactively provide the modern facilities and infrastructure required to achieve science missions and emerging research needs.
- Deliver flexibility in design and space use (allocation) to respond rapidly to changing research needs.

PNNL 10-year Campus Strategy Site Map

Figure 1. PNNL 10-year Campus Strategy Site Map Showing Land Ownership, Core Campus Area, New Construction, and Non-DOE Building Exits Planned/Completed (new construction building locations are notional)



Building Legend

- 🟨 DOE Ownership
- 🟦 Non DOE Ownership
- 🟫 New IGPP Construction (Completed 2015-2026)
- 🟪 Non DOE Buildings (Exits Planned/Completed)
- ⬛ New DOE Direct Funded Construction (Completed 2018-2021)

IGPP Buildings

1. Systems Engineering Building
2. General Purpose Chemistry Lab
3. Office
4. Collaboration
5. General Purpose Lab
6. High Bay
7. Warehouse
8. General Purpose Instrument Lab
9. Office

DOE Direct Funded Buildings

A. Bioenergy Technologies High Bay
B. Water Power Technologies High Bay
C. Energy Sciences Capability

- Be environmentally and operationally sustainable.

PNNL's has undertaken a facilities restoration program to retire DOE-SC's current liability associated with the historical use of radiological and other materials in Battelle-owned buildings. The program will characterize and remediate the buildings as required to achieve unrestricted release. One specific building, RTL 520, has known contamination (beryllium, radiological, and other) and has residential development within 440 feet. PNNL submitted a $9.5M request to accelerate an activity to deactivate, decommission, decontaminate, and demolish RTL 520 through the Laboratory Operations Board infrastructure crosscut proposal request for FY 2016. The request was well-received but not funded. The strategy has been updated to include PNNL internal investments to deactivate, decommission, decontaminate, and demolish RTL 520 while continuing to pursue acceleration through DOE funding. As such, RTL 520 was also submitted in the DOE Excess Facility data call.

Reasonable and Achievable. PNNL strives to balance the achievement of the campus continuity and mission alignment objectives, while reducing the operating costs and delivering effective stewardship of the PNNL campus facilities and infrastructure. Enhancement activities include replacing acid-degraded hoods and end-of-life utilities and building systems, as well as improving capabilities for handling radiological materials in support of the Applied Nuclear Science and Technology, Environmental Subsurface Sciences, and Systems Engineering and Integration core capabilities.

Optimization of the campus will continue through internal investments to address substandard buildings. Each year, the campus strategy is jointly reviewed and validated or revised based on current mission projections and business case analyses. PNNL's asset condition assessments are summarized in Table 2. Most of the assets are in adequate condition, with eight assets (two OSFs and six buildings) currently assessed as substandard and none assessed as inadequate. Striving to align with the strategic objectives of campus continuity and being reasonable and achievable, PNNL will

- address the conditions underlying the two substandard OSFs.
- exit three (64,192 gsf) substandard buildings.
- develop a plan and take the necessary action to address LSL-II, a 102,107 gsf substandard and under-utilized building; internal investments in FY 2015 addressed the substandard LSL-IIA building and it is now rated adequate. The remaining substandard building is a leased airplane hangar with no planned investment actions. Operational controls for the airplane hangar are in place to minimize the risk of damage because the cost to resolve is high.
- maintain the remaining assets in an adequate condition through continued internal investments in maintenance and repairs at a level commensurate with PNNL's replacement plant value.

Modern, Collaborative, Flexible, and Sustainable. PNNL is delivering a modern campus that enhances collaboration, is flexible enough to change easily with the business environment, and is sustainable. PNNL will

- enable research operations and collaboration as a way to increase researcher effectiveness and scientific innovation. PNNL plans to accelerate an internal investment in new, flexible S&T collaboration; food services; and meeting spaces.
- improve arrival at PNNL by internally investing in a building that consolidates point-of-entry activities and decreases onboarding time for visitors, interns, and new hires, making it a positive experience that quickly transitions personnel to the purpose of their arrival.
- proactively provide the modern facilities and infrastructure required to achieve science missions and emerging research needs.
- deliver flexibility in design and space use (allocation) to respond rapidly to changing research needs.
- be environmentally and operationally sustainable.

Figure 3 shows PNNL's campus strategy site map with ownership, new construction, and exits of non-DOE buildings over the 10-year planning horizon (FY 2015 to FY 2025). Since initiating the 2013 campus strategy, PNNL has exited 130,000 gsf in 11 buildings. In the next 10 years, PNNL plans to invest $240M to build 10 buildings totaling 218,000 gsf and exit 21 buildings totaling 155,000 gsf, while achieving the strategy objectives stated above. Replacement of the exited space will be a combination of consolidation into existing space and creation of the eight new federal buildings. Battelle and DOE continue to work together closely to reach the necessary agreement on the funding of final disposition and remaining depreciation cost for exited Battelle facilities.

PNNL's infrastructure gaps are summarized by core capability in Table 3. PNNL is addressing space utilization gaps through consolidations, additions, and exits consistent with the campus strategy objectives. If gaps are not addressed, it is assumed the risks will be realized within the planning horizon.

Investments in the mission-unique RPL 325 building include replacing acid-degraded fume hoods to avoid potential failures in the ventilation system resulting in the spread of contamination, which requires expensive mitigation, challenges to worker safety and health, and impacts to analytical capability for the Applied Materials Science and Engineering and Applied Nuclear Science and Technology core capabilities.

GPP investments in EMSL are needed to increase the cooling capacity to support the predictive understanding of molecular-to-mesoscale processes in climate, biological, environmental, and energy systems.

Table 3. Current and Future Infrastructure Gaps by Core Capability

Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
Environmental Subsurface Science	Current	RTL 520 is an underutilized, substandard, non-federal, non-core-campus building. RTL 510 is a non-federal, non-core building.	Continued use of underutilized, substandard excess space increases operational costs.	Invest internally to modernize existing buildings (331, 318, LSL-II, and Applied Process Engineering Laboratory); relocate capabilities from RTL 510 and RTL 520; scheduled completion in FY 2017. Prepare exited buildings for demolition; scheduled completion in FY 2020.
		Insufficient general wet/dry space for geo-mechanics research.	General wet/dry lab space at capacity.	Invest internally to relocate unaligned capabilities from 331 and modernize existing 331 lab space for additional capacity to meet need.
Earth Systems Science and Engineering	Current	Research Support Warehouse (RSW) is a non-federal, non-core-campus building and available footprint is inadequate to meet need.	Continued use of an asset located off the core campus; not aligned with the campus continuity objective.	Invest internally to build new federal, core-campus warehouse space. Scheduled for completion in FY 2021; relocate infrastructure items in leased storage space (RSW); vacate current boat storage and relocate boats to RSW.
		Insufficient high-bay space to test and validate readiness levels for water power technologies.	Use of existing high-bay space would create operational and research inefficiencies, increasing mission and operating cost.	DOE-EERE investment in high-bay building to test and validate readiness levels for water power technologies.
		LSL-II is an underutilized, substandard building on the core campus.	Continued use of underutilized, substandard building increases operational costs.	Invest internally to modernize LSL-II and relocate hydrocarbon processing capabilities.
Chemical and Molecular Sciences **(and)** **Chemical Engineering**	Current	Insufficient ventilation-intensive and characterization tools space to enable the transformation of catalysis science and how catalysts are designed, synthesized, and engineered.	Limits ability to understand, predict, and control behavior of complex adaptive systems specific to energy, earth, and security systems central to DOE's strategic objectives.	ESC investment in wet, ventilation-intensive labs and characterization tool labs to advance understanding and control of catalytic processes. Scheduled for completion in FY 2021. Invest internally to relocate capabilities to the new ESC building; modernize and backfill the exited spaces to increase adjacency and collaboration across the campus.
		Insufficient space for non-radiological, wet chemistry research and technology development.	Limits ability to conduct research efficiently and attract and retain top researchers.	Invest internally to build a federally owned, general purpose laboratory for non-radiological chemistry research and technology development on the core campus; scheduled for completion in FY 2020.
		Insufficient high-bay space for experimental test stands and capabilities for bioenergy	Current higher hazard, bioenergy processes located in high-bay space adjacent to residential and related	DOE-EERE investment in high-bay space, located in areas designated for higher risk work, to house experimental test stands

Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
		technologies research in higher hazard processes.	commercial building developments.	and capabilities for bioenergy technologies research.
	Future	Process Development Laboratory East and West, and Chemical Engineering Laboratory are non-federal, non-core-campus facilities.	Continued use of an asset located off core campus; not aligned with campus continuity objective.	Invest internally to build a new, federally owned high-bay space on the core campus; scheduled for completion in FY 2021.
Large-Scale User Facilities/ Advanced Instrumentation	Current	Insufficient space in EMSL to accommodate new capabilities or those currently housed outside of the facility to maximize impact of EMSL User Program.	EMSL User Program sub-optimized due to limited access to capabilities focused on aerosol life cycle, soil science, hydro-biogeochemical cycling, and plant science housed outside of EMSL.	Invest internally to modernize LSL-II and relocate unaligned capabilities in EMSL, making room for new capabilities and relocating capabilities focused on aerosol life cycle, soil science, hydro-biogeochemical cycling, and plant science housed outside of EMSL.
Nuclear Engineering	Current	Acid condensation in 3410, 3420, and 3430 Buildings.	Potential cross-contamination failures for time-sensitive samples, impacts to long-term clients and safety, and health risks to employees.	Invest internally in 3410, 3420, and 3430 to resolve acid condensation impacts; scheduled to complete in FY 2017.
		RTL 520 is an underutilized, substandard, non-federal, non-core-campus building.	Continued use of underutilized, substandard, excess space increases operational costs; liability of radiological asset in close proximity to the public.	Invest internally to modernize an existing building (318), relocate capabilities, and prepare exited building for characterization and demolition (RTL 520); scheduled for completion in FY 2020.
Nuclear and Radio Chemistry	Current	Insufficient space for low-background radiological work at MSL for ultra-trace measurements and performance testing.	Non-federal-owned space will be characterized and restored by FY 2017. No further rad work in this low-background environment can be conducted.	Invest internally in a Modular Rad Lab to establish federally owned space for radiological work in this low-background environment at MSL. Scheduled for completion in FY 2017.
		Insufficient ventilation-intensive wet space, specifically radio chemistry labs.	Limits ability to simultaneously achieve DOE's Security Systems mission while conducting research efficiently and attracting and retaining top researchers.	Invest internally to relocate non-radio-chemistry work from 3420 and 331 and modify 3420 space for additional radio chemistry labs.
Applied Materials Science and Engineering	Current	RTL 520 is an underutilized, substandard, non-federal, non-core-campus facility with a surplus of ventilation-intensive and general purpose space.	Continued use of underutilized, substandard, excess space increases operational costs; liability of radiological asset in close proximity to the public.	Invest internally to modify existing buildings (318 and LSL-II) and relocate capabilities from RTL 520; scheduled for completion in FY 2016. Prepare for demolition scheduled for completion in FY 2020.
Systems Engineering and Integration	Current	Inadequate prepared, outdoor testbed space for conducting larger-scale experiments.	Limits ability to meet full-breadth of PNNL's scientific vision in earth, energy, and security systems central to DOE's strategic objectives.	Invest internally to develop a testbed/site for conducting larger-scale experiments (Modernization).

Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
	Future	Insufficient federally owned instrument lab space to optimize campus continuity.	Limits ability to improve campus continuity; increased life cycle operating costs through continued reliance on non-federal-owned buildings.	Invest internally to build a federally owned building for instrument labs on the core campus, relocating staff from non-core-campus building(s); scheduled completion in FY 2026.
		Insufficient federally owned physics lab space to optimize campus continuity.	Limits ability to improve campus continuity; increased life cycle operating costs through continued reliance on non-federal-owned buildings.	Invest internally to build a federally owned building for physics labs on the core campus, relocating staff from non-core-campus building(s); scheduled completion in FY 2027.
All	Current	Insufficient federally owned office space to optimize campus continuity.	Limits ability to improve campus continuity; reduced operational efficiency due to distances between labs and offices; increased life cycle operating costs from continued reliance on non-federal-owned buildings.	Invest internally to build a federally owned office building on the core campus; scheduled completion in FY 2017.
		Insufficient space to enable research operations and collaboration as a way to increase researcher effectiveness and scientific innovation.	Future gains in researcher effectiveness and pace of scientific innovation are constrained by limited collaboration opportunities.	Invest internally to build a federally owned collaboration building on the core campus; scheduled completion in FY 2017.
	Future	Insufficient federally owned office space to optimize campus continuity.	Limits ability to improve campus continuity; reduced operational efficiency due to distances between labs and offices; increased life cycle operating costs through continued reliance on non-federal-owned buildings.	Invest internally to build a federally owned office building on the core campus, relocating staff from non-core-campus building(s); scheduled completion in FY 2026.
Enabling Infrastructure	Current	Fire and sanitary water lines installed in 1959 to service 325 RPL need to be replaced/repaired due to failing system, beyond its useful life.	Single point failure (sanitary water line) that possibly shuts down 325 RPL operations, causing lengthy interruptions to energy, national security, and science R&D programs.	Invest internally to repair existing infrastructure servicing 325 RPL (Sustainment Betterments).
		The remaining RTL complex facilities are non-federal, non-core-campus facilities.	Continued use of an asset located off core campus; not aligned with campus continuity objective.	Consolidate into existing space through internal investments (Modernization).
		Insufficient cooling capacity in power-intensive space and in a 300 Area building during summer months.	Limits the ability to maintain continuity or research in the affected spaces and/or affected buildings during summer months.	Invest internally to determine options for delivering cooling capacity and implement best option. In the interim, provide standby capacity (Sustainment Betterments).
	Future	Need for additional infrastructure and utilities to support federal building development.	New facilities may be delayed or may be sited in undesired locations due to lack of necessary service utilities.	Invest internally in campus utility expansion to establish infrastructure capabilities to support future development on the PNNL Site.

Core Capability	Time Frame	Infrastructure Gap	Risk	Investment Strategy
		Battelle Receiving and Shipping Warehouse, Technical Support Warehouse, and Grounds Equipment Storage buildings are non-federal, non-core-campus assets.	Continued use of assets located off core campus; not aligned with campus continuity objective.	Invest internally to build a new, federally owned warehouse/shop building on the core campus; scheduled for completion in FY 2021.

[1] This table does not include mission-unique facilities, per guidance. See section 6.2 for mission-unique facility investments.

Infrastructure Investment Summary

Funding for the campus strategy is primarily leveraged through significant internal infrastructure investment. The investments in the strategy, including type and timing of funding, are summarized in Table 5, PNNL Investments. The items listed in colored bars align with our campus strategy objectives.

Table 4. PNNL Investments

Laboratory Name Pacific Northwest National Laboratory

Objectives:

Mission Alignment
Campus Continuity
Reasonable and Achievable
Modern, Collaborative, Flexible & Sustainable

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
															Select from Drop Down Menu		
Systems Engineering	**6,964**	6,964	0	0	0	0	0	0	0	0	0	0	0	0	IGPP	OH	PS&EE, SE&I
GPCL	**8,825**	4,651	4,174	0	0	0	0	0	0	0	0	0	0	0	IGPP	OH	N & RC
General Purpose Office	**8,343**	361	5,400	2,581	0	0	0	0	0	0	0	0	0	0	IGPP	OH	All
Collaboration	**9,500**	0	1,500	8,000	0	0	0	0	0	0	0	0	0	0	IGPP	OH	All
High Bay - EERE bioenergy	**6,000**	0	0	0	6,000	0	0	0	0	0	0	0	0	0	GPP	--	Chemical Engineering
High Bay - EERE WPT	**6,000**	0	0	0	6,000	0	0	0	0	0	0	0	0	0	GPP	--	Earth Systems
Campus Utility Expansion	**9,150**	0	0	2,000	2,500	0	0	0	0	2,565	2,085	0	0	0	IGPP	OH	Enabling Infrastructure
General Purpose Lab	**9,500**	0	0	0	3,131	5,390	979	0	0	0	0	0	0	0	IGPP	OH	C&MS, Chemical Engineering
Energy Sciences Capability	**58,500**	0	0	0	2,500	30,000	20,000	6,000	0	0	0	0	0	0	LI	SLI	C&MS
High Bay/Instrument	**9,500**	0	0	0	0	2,808	5,445	1,247	0	0	0	0	0	0	IGPP	OH	C&MS, Chemical Engineering
Warehouse/Shop	**5,250**	0	0	0	0	0	2,565	2,685	0	0	0	0	0	0	IGPP	OH	Enabling Infrastructure
General Purpose Instrument	**9,500**	0	0	0	0	0	0	0	0	2,808	5,445	1,247	0	0	IGPP	OH	SE & AM
General Purpose Office	**9,500**	0	0	0	0	0	0	0	0	0	2,208	5,445	1,847	0	IGPP	OH	All
General Purpose Physics	**9,500**	0	0	0	0	0	0	0	0	0	0	2,108	5,445	1,947	IGPP	OH	SE & AM
RTL Exit 318 Remodel	**2,242**	1,337	905	0	0	0	0	0	0	0	0	0	0	0	IGPP	OH	AMS & E
LSL2 Lab Space Utilization	**1,439**	0	1,439	0	0	0	0	0	0	0	0	0	0	0	IGPP	OH	AMS & E
Modular Rad Lab	**1,500**	0	0	1,500	0	0	0	0	0	0	0	0	0	0	IGPP	OH	N & RC
3420 Rad Chem	**1,500**	0	0	1,500	0	0	0	0	0	0	0	0	0	0	IGPP	OH	N & RC
331 Rad Chem	**500**	0	0	500	0	0	0	0	0	0	0	0	0	0	IGPP	OH	Environmental Subsurface
LSL2 Lab Upgrades	**2,000**	0	0	2,000	0	0	0	0	0	0	0	0	0	0	IGPP	OH	A & MS, EnvSsub, ES, AMS
Modernization	**62,175**	0	0	5,800	5,800	2,550	5,450	6,225	6,150	6,000	6,050	6,050	6,050	6,050	IGPP	OH	All
Sustainment Betterments	**29,788**	0	0	1,600	2,900	1,275	2,725	3,113	3,075	3,000	3,025	3,025	3,025	3,025	IGPP	OH	All

Princeton Plasma Physics Laboratory

1. Mission and Overview

The Princeton Plasma Physics Laboratory is a collaborative national center for plasma and fusion energy sciences. It is the only Department of Energy (DOE) Laboratory devoted to these areas, and it is the lead U.S. institution investigating the science of magnetic fusion energy.

The Princeton Plasma Physics Laboratory (PPPL) has two coupled missions. First, PPPL develops the scientific knowledge to realize fusion energy as a clean, safe, and abundant energy source for all nations. Plasma is a hot, ionized gas that under appropriate conditions of temperature, density, and confinement produces fusion energy. PPPL has been a leader in developing the physics of high temperature plasmas needed for fusion. PPPL will continue to solve plasma physics problems crucial to fusion energy, as well as contribute to solutions of key engineering science challenges associated with the material structure that surrounds the hot plasma. The second mission is to develop plasma science over its broad range of physics challenges and applications. Modern plasma physics began with the advent of the world fusion program, and continues to lead to new discoveries in the nonlinear dynamics of this complex state of matter. The vast applications range from scientific (e.g., plasmas in the cosmos) to technological (e.g., plasma-aided manufacturing).

For over six decades PPPL has been a leader in magnetic confinement experiments and theory. PPPL is a partner in the U.S. Contributions to the ITER Project and leads multi-institutional collaborative work on the National Spherical Torus Experiment - Upgrade. The Laboratory hosts smaller experimental facilities used by multi-institutional research teams and collaborates strongly by sending scientists, engineers and specialized equipment to other fusion research facilities in the U.S. and abroad. To support these activities, the Laboratory maintains nationally leading programs in plasma theory and computation, plasma science and technology, and graduate education.

2. Lab-at-a-Glance

Location: Princeton, New Jersey
Type: Single-program Laboratory
Contractor: Princeton University
Responsible Site Office: Princeton Site Office
Website: www.pppl.gov

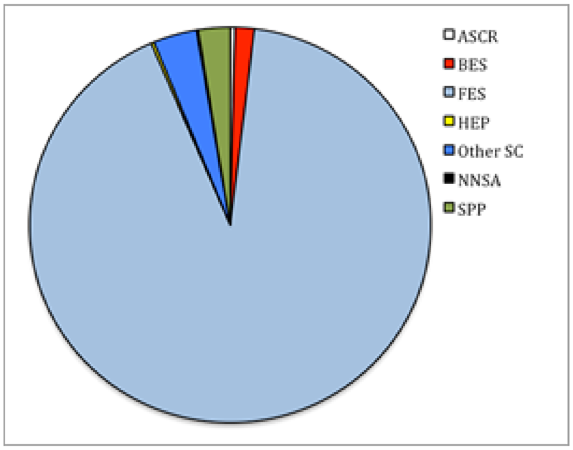
Physical Assets:

- 90.7 acres; 30 buildings
- 765K GSF in Active Operational Buildings
- Replacement Plant Value: $660M (total)
- Deferred Maintenance: $108M
- Asset Condition Index: 0.84
- Asset Utilization Index: >95%

Human Capital:

- 462 Full Time Equivalent Employees (FTEs)
- 5 Joint Faculty
- 12 Postdoctoral Researchers
- 40 Graduate students
- ~350 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs
(excluding Recovery Act): $90.0M
DOE/NNSA Costs: $87.7M
SPP (Non-DOE/Non-DHS) Costs: $2.3M
SPP as % Total Lab Operating Costs: 2.6%
DHS Costs: $0M

3. Core Capabilities

PPPL has significant scientific and engineering capabilities to support the DOE Office of Science's mission to develop the knowledge base for fusion energy and high temperature plasmas. These capabilities are vital for the Princeton University's Graduate Program in Plasma Physics, ranked one of the highest in the nation.

Plasma and Fusion Energy Sciences

PPPL has unique experimental and theoretical capabilities and facilities 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 (LTX); high-resolution techniques to measure plasma properties and processes at a wide range of space and time scales; extremely 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; world-leading basic plasma experimental facilities such as the Magnetic Reconnection Experiment (MRX); 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.

PPPL also has unique computational capabilities to accelerate progress in understanding the physics of high temperature and burning plasmas (e.g., ITER). 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. PPPL leads in advanced algorithmic development to enable efficient utilization of DOE-SC's leadership-class computing facilities for fusion research. This allows us to validate physics-based predictive models against existing experiments, to investigate innovations to successfully development fusion energy, and use the integrated models to guide ITER operations in the future.

Substantial expertise exists in the interaction of plasmas with materials. PPPL with Princeton University's Engineering Department has established two surface analysis laboratories to study fusion-relevant material issues. In addition PPPL has established a nano-laboratory to study the development of plasma produced carbon nanotubes. PPPL has theoretical and laboratory capabilities with regard to topics in plasma astrophysics.

Large Scale User Facilities/Advanced Instrumentation

PPPL has unique engineering 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 site for fusion research (shielded test cells, high-current power supplies, extensive cryogenic facilities, and high-speed broad-band network) support the operation of NSTXU, aid 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 U.S. ITER Program, and specifically manages the U.S. role in ITER diagnostics and the ITER steady state electric network. These capabilities provide a flexible, capable location for possible 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. PPPL'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 providing diagnostics to fusion programs around the world (JET, JT-60U, LHD, W7X, C-Mod, DIII-D, EAST, and KSTAR).

Mechanical Design and Engineering

The primary activity of PPPL is the development of fusion power based on magnetic confinement and high power heating of thermonuclear plasmas. The corresponding range of mechanical engineering technologies is multidisciplinary and overlaps plasma physics and electrical engineering activities at the Lab. PPPL's design engineers employ the latest in computer aided design tools. Design engineers benefit from the challenges of designing and fabricating state of the art components for experiments under construction such as ITER; and from experience maintaining large operating fusion experiments, historically TFTR and now, NSTX Upgrade. Collaborations within the U.S. augment the exposure of PPPL engineers to a wide range of technological advancements. Collaborations with laboratories and projects outside the U.S. expose PPPL engineers to the requirements of next generation nuclear experiments and power reactors.

PPPL's engineering analysis staff is expanding their simulation capabilities to include coupled multiphysics analysis of nuclear shielding, breeding, and activation; heat transfer; fluid dynamics of flow in magnetic fields and with free surface effects; transient non-linear magnetics; and structural mechanics including advanced materials models. Fully coupled simulations based on detailed CAD models are extremely demanding of computer resources. PPPL is exploring both fully consistent models and models dedicated to the physics being simulated with data mapping between models. At this time, PPPL engineering staff is making limited use of the advanced computing capabilities at PPPL. Currently nuclear and some electromagnetic simulations are run on the LINUX cluster, but this will change as more sophisticated coupled models are developed. Allied with the capabilities to perform materials tests and gain insight from performance of materials in NSTX-U, engineering mechanics and material science activities at PPPL will grow.

Power Systems and Electrical Engineering

The primary activity of PPPL is the development of fusion power based on magnetic confinement and high power heating of thermonuclear plasmas. The corresponding range of electrical engineering technologies is extraordinary and overlaps those needed to address issues of transmission grid efficiency, reliability, and integration of variable generation. The utility-scale power systems at PPPL 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. Peak power level is ~ 1000 MW with voltages up to 120kV and currents up to 150kA. 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 operating above 1kHz on signals derived from advanced plasma diagnostic sensors as well as power system voltages and currents. PPPL's engineering staff has deep experience in the design, fabrication, and operation of the diagnostic, control, protection, electromagnetic, and power systems as cited above, including proficiency in related design and simulation tools. These core competencies 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, etc. The PPPL competency and infrastructure as cited above exceed those at any other DOE laboratory and most if not all international laboratories. Moreover, PPPL electrical engineering has played a key role in the design of the ITER power systems which, when implemented, will be world-leading.

Systems Engineering and Integration

PPPL has the capability to produce whole-system design, fabrication and operation of fusion, plasma and large electro magnetic systems. Systems Engineering and Design Control and Integration is applied at three levels of fusion research. First, systems studies are applied at the reactor studies/concept stage. Second, systems studies are used to prepare for and conduct major construction projects. Third, systems simulations are used to control and protect large experiments during operation. PPPL personnel have the experience to provide the numerical modeling and optimization of systems with simultaneous physics and engineering simulations. On the physics side, PPPL has participated in the whole tokamak simulation project, which integrates many physics simulations and interfaces with the plasma facing components. Completing the reactor modeling, PPPL has provided the integrated engineering and physics system design studies of future U.S. & International facilities and programs including, the ARIES studies, the current Fusion Nuclear Science Facility (FNSF) Study, KDEMO (S. Korea), CFETR (China) and other Future U.S. tokamak and stellerator facilities.

During execution of major projects, systems studies are used to initially size and cost the project. The most recent example of this is the initial design study for NSTX-U. As the project progresses, PPPL employs a full complement of integrated CAD modeling as a part of design integration and configuration management. In parallel, engineering models are analyzed, and updated with the current configurations. This has included global models of the core and ancillary systems. The larger simulations provide design parameters and boundary conditions for sub models and subsystem models. These support component qualification, work progressing and value added reporting. The engineering department maintains a complete set of guidelines and procedures under the office of project management to provide guidance on project management, work planning, design verification, reporting, and ensures consistent technical excellence of the design and engineering process. Design verification includes multiple levels of peer reviews, often with outside participants, and requirements for preparation checking, and filing calculations.

The lab has provided management of and participation in multi-lab integrated design teams. PPPL maintains ongoing collaborations with other national labs to foster an understanding of operations at other collaborators institutions. PPPL has provided the systems engineering manager for the U.S.-ITER program, the ITER System design for auxiliary power systems, and the ITER system design for the diagnostic interface system including first-wall and shielding structures. PPPL has led the design of some of the ITER Internal Systems using integrated design capabilities. The ITER system designs included the equatorial and upper diagnostic port plugs and the internal magnetic coils.

The PPPL engineering staff has developed many parameter, multi-physics advanced real-time control systems, to optimize system performance while maintaining protection to the equipment. The newest of these systems is the NSTX-U Digital Coil Protection System (DCPS) which combines the electrical and power systems controls of NSTX-U with mechanical performance models to provide combined electro-mechanical protection. This system is proving itself a reliable and valuable operational constraint during initial operations of NSTX-U. Structural instrumentation is beginning to support benchmarking of the mechanical modeling. Such a system has been suggested to ITER and is of increasing necessity for the higher value, higher consequence protection of next generation reactors.

4. Science Strategy for the Future

PPPL has a dual mission to develop the scientific knowledge base needed for fusion energy for the world and to lead discoveries across the broad frontier of plasma science and technology. As evidenced by surging research in fusion abroad, there is a rapidly increasing imperative to develop clean, plentiful, and safe fusion energy. PPPL plans to provide solutions to the key physics and engineering challenges of fusion, seeking nothing less than development of a new energy source that will transform the way the world produces energy. The understanding of plasma has huge consequences to neighboring sciences (such as the visible cosmos, mostly composed of plasma) and to technological applications (from plasma-based nanotechnology to plasma centrifuges).

PPPL focuses on the approach fusion energy in which the hot fusion plasma is confined magnetically. PPPL is developing the compact, high pressure (relative to magnetic pressure) approach known as the spherical tokamak (ST), through its major collaborative user facility, the National Spherical Torus Experiment – Upgrade (NSTX-U). The ST provides unique physics information important for the international experiment ITER and fusion in general, develops novel solutions to the challenge of the plasma-material interface, and is a prime candidate for major next step facilities in fusion research. PPPL collaborates with conventional tokamak facilities in the U.S. and abroad, pursuing improved understanding of plasma confinement and enhanced performance scenarios in preparation for ITER. ITER is an international fusion experiment, based on the standard tokamak design, that will demonstrate net fusion power generation (of 500 MW) for the first time. ITER-focused research and development is spread throughout PPPL – including NSTX-U, collaboration on tokamaks in the U.S. and abroad, theory and simulation, and design/construction activities. A lab-wide program is exploring the use of a liquid wall as the material that faces a fusion plasma – a potential breakthrough solution if it is proven to be scientifically feasible. PPPL aims to enter the new era of integrated modeling using the most advanced computers to understand the full fusion plasma system. New 3D designs for fusion systems are under study – computational physicists can devise new, remarkable configurations that confine hot plasmas in steady state with reliability. Beyond fusion, PPPL performs research to understand how plasma processes determine the behavior of major astronomical objects. PPPL will enhance its contributions to plasma science and applications generally, in areas such as plasma-based mass filters for nuclear waste remediation, plasma-based nanotechnology for improved production of nanomaterials, plasma-based metamaterials and more. In addition to a broad program of national and international collaboration, new activities are being initiated between PPPL and other units of Princeton University, particularly with material scientists and astrophysicists. PPPL conducts an expansive education and outreach program, including operation of the Princeton University graduate program in plasma physics, research activeties for undergraduates, and science outreach activities for the general public.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

Overview of Site Facilities and Infrastructure
The Laboratory is located on 90.7 acres within the Princeton University Forrestal Campus. The 1,750-acre Forrestal Campus is punctuated by dense woods, brooks and nearby streams; almost 500 acres remain in their natural state in order to protect and enhance the character of the campus. The PPPL Environmental Management System (ISO 14001 certified) provides a comprehensive approach for controlling PPPL activities to minimize negative impacts to the environment.

The Laboratory uses 766,181gross square feet (GSF) of space in 30 Government-owned buildings and 2 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 FY15 and none are currently planned. For the IOI Project, PPPL will rent temporary office trailers to house the staff displaced by the project.

As listed in the FIMS FY15 report, the total Replacement Value (RPV) of all PPPL facilities and infrastructure was ~$660M; Previously the Non-Programmatic RPV ~$478M was used for calculating indices. Recent Operational Improvement Committee guidance indicates that the total RPV ($660M) should be used for consistency. Every PPPL building asset utilization rating is greater than 95%, which is "Over Utilized" by the Laboratory Operations Board (LOB) criteria. The Laboratory has very little margin for growth. The Laboratory Operations Board directed condition assessments in FY14 that identified ~$81.6M of deferred maintenance. In 2015 PPPL learned that several laboratories use VFA Inc. to perform their condition assessments. In the interest of uniformity, PPPL also hired VFA Inc. to perform condition assessments of all C-Site buildings and D-Site mechanical equipment rooms. They did not assess OSFs or the D-Site buildings. By incorporating their data, our updated deferred maintenance is $108M with an overall ACI of .84. Most of the real property building assets have exceeded their expected life by more than ten years and therefore, have been placed on the deferred maintenance list. Much of the maintenance budget is spent keeping this aged equipment functional. Operation Improvement Committee working groups were recently formed to obtain uniform agreement amongst all laboratories for deferred maintenance, replacement plant value, and condition assessment calculations. PPPL will reassess assets based on this new guidance once received. The PPPL maintenance and repair budget for FY16 is approximately $7M.

SC Infrastructure Data Summary

Total Building Assets	30
Total Building Assets Assessed	30
Total Area Assessed*	764,837GSF
Total OSF	26
Total OSF Assessed*	24
Total Deferred Maintenance ($)	$108,157,324

* NSTX and TFTR experimental OSF assets and two trailers are not summarized as part of the infrastructure

Core Capabilities: Plasma/Fusion and User Facilities/Advanced Instrumentation				
Condition		Adequate	Substandard	Inadequate
	Buildings	3	5	22
Utilization	Under Utilized (GSF)	Not Utilized (GSF)	Excess (GSF)	Repurpose / Reuse (GSF)
	10,828	0	0	122,642
Other Structures (OSFs)				
Condition		Adequate	Substandard	Inadequate
	OSFs	23	2	1

Campus Plan

The Laboratory has a 10-year Campus Plan to cost-effectively improve the capacity, maintenance, and operations of the Laboratory in order to provide facilities that enable world-leading science and support the priorities discussed in the Science Strategy section above. Specifically, the objectives are to fully support the NSTX-U operations, to enable more international collaborations, to modernize the research and development space, and to update the office and collaborative spaces. The Plan addresses how real property assets will be used to support the objectives of the DOE Strategic Plan and guidance provided by the Office of Fusion Energy Science. Planning is developed in accordance with the Real Property Asset Management Order, DOE 0430.1B and the DOE-SC objective of integrating land use, facilities and infrastructure acquisition, maintenance, recapitalization, safety and security, and disposition plans into a comprehensive site-wide management plan. PPPL plans on updating the campus plan to determine if a more aggressive approach can be deployed to address the deferred maintenance issue. In addition, the plan will address a facility that will address the National Fire Protection Association Code for use of lithium research.

While the size of the PPPL site is adequate for current and anticipated future needs, the Condition Assessment identified many substandard and inadequate facilities and utility systems (as summarized in the previous table and shown in the figure below). The number of PPPL employees and activity mix is expected to remain unchanged in the near-term, while the number of onsite collaborators is expected to grow modestly with funding for the new initiatives and ITER work.

Items submitted for funding in previous SC Infrastructure Cross-cut Data Requests were not approved, but the need for investment still exists. Improving crosscut items would provide robustness to key site utilities that are required for NSTX-U operations and other facilities at PPPL. As a result, a request was made to increase GPP funds to support the utility improvements. This was favorably received and increases in GPP funding have been made. Nevertheless, deferred maintenance projections indicate a very slow reduction. The Laboratory must often use GPP funding to cover site-wide improvements and upkeep routinely required (e.g., road paving or roof replacement). The Laboratory's 2016 maintenance budget is $7M; ~1% of the overall RPV. Recent guidance indicates that laboratories with less than adequate overall ACI should receive 1-2% above the recommended 2-4% for future years to bring the Laboratory to a fully "adequate" condition. Also, recent guidance from SC is to use an escalation rate of 3% for the deferred maintenance. The RPV also rose 3%. Applying the 1% maintenance budget to routine maintenance and repair items while adding 1-2% of the total RPV direct funded investments through GPP and SLI funding streams for Deferred Maintenance would realize a significant reduction in deferred maintenance and achieve an ACI greater than .95, fully "adequate" condition, by the year 2027. It is also vital that the maintenance budget keep up with continual total property RPV escalation rate increases (difficult to do with pressure on indirect funding and other significant items that need to be replaced – e.g. new business system). SLI funded Infrastructure Operations Improvement project began in FY15 and provides a large initial investment toward implementing the Campus Plan. This investment will address $6.3M of deferred maintenance through the demolition of Mod VI ($899K), Renovation of the LSB Annex ($553K), and the repurposing of the CMG into a centrally located machine shop ($4,850K).

To prioritize the allocation of limited infrastructure funding, PPPL uses the Mission Readiness Process. In the Planned Investments table, the infrastructure funding is shown as individual items. The Laboratory uses the Capitol Asset Management Process (CAMP) to rank both capital and operationally funded improvements based on their risk and the benefit they provide to the Laboratory Mission. The Laboratory is considering newer, less subjective tools available such as VFA. Facilites, which is based on Pairwise comparison.

Condition Assessment (as of May 31, 2016)

Infrastructure Funding Needs

The Laboratory Cross-cut proposal for 2016 includes the following key areas: The 138kV yard main duct bank has exceeded its expected life and could threaten laboratory wide power including experimental operations; a number of HVAC units that have greatly exceeded their useful life and pose serious risk and direct impact to operational systems; renovation of the RF and COB building to accommodate small and medium size experiments in accordance with the campus plan. As part of that the laboratory is looking at other buildings or new construction to accommodate the liquid metals program described in section 4.0 of this document. Lithium in quantity requires specific controls to comply with the NFPA code and this will be an activity developed and deployed in FY17. The CMG and RF buildings have transite external walls that have an insulation value of R1.5, allowing significant energy waste. The neighboring CS building was previously covered with insulation panels that will extend the life of the transite walls indefinitely, while providing an additional benefit of raising the insulation rating of R19. The insulation of the CMG wall will be addressed in the SLI project; the remaining RF building wall will need to be covered with GPP funding.

Infrastructure Funding Needs

Objectives	Fully Support NSTX-U Operations
	Enable Improved International Cooperation
	Modernized, Flexible, Safe Laboratory Space for Small and Medium Experiment
	"People Space" that Facilitates the Exchange of Ideas
	General Purpose Infrastructure that is updated to support R&D efforts

Planned Capital Investments (Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program
Install 2400SF, Plasma Based Nano Lab in 1st floor at RF BLDG C40	**1,770**	700	1,070												GPP	FES
Install 2700SF, FLARE Experiment in 1st floor at CS BLDG C41	**1,700**	949	751												GPP	FES
Years 2019-2027	**0**														GPP	FES
Improve 3 floors, 7500SF of LSB Annex at BLDG C01[1]	**3,460**			3,460											LI	SLI
Demolish 8216SF, Module 6 in C-Site at BLDG C55[2]	**231**				231										LI	SLI
Consolidate 4600SF, HAZMAT C93 into 6360SF RAD WASTE BLDG D45[3]	**444**			444											GPP	FES
Improve 12000SF, 1st floor in C-Site at BLDG ENG Wing C20	**1,541**		1,541												GPP	FES
Improve 2622SF second Floor in C-Site at BLDG Facilities C61	**174**				174										GPP	FES
Years 2019-2027 (SLI Funding)	**50,000**							25,000	25,000						LI	SLI
Improve 32400SF, in C-Site at CMG C51[4]	**8,269**				8,269										LI	SLI
Improve 20000SF, in C-Site at RESA C90	**2,120**				2,120										LI	SLI
Replace S2A1 to S2 Cables	**1,022**		200	822											GPP	FES
Improve DI Water and Electrical Service in C-Site at BLDG CS C41	**905**			905											GPP	FES
Replace RF Chilled Water Header	**119**			119											GPP	FES
Replace 1500FT, Chilled water transite pipe	**2,142**	2,142													GPP	FES
Replace 4824SF, Roof D-Site LEC Tank D34	**94**	94													GPP	FES
Replace 4750SF, Roof in D-Site at Pump House D70	**94**	94													GPP	FES
Replace 8 HVAC Control systems in D-Site at BLDG D42*[5]	**624**				624										GPP	FES
Replace 1 138kV Underground duct bank in C-Site at power yard*[6]	**1,284**			1,284											GPP	FES
Replace 1 Heat Pump in C-Site at Material Services C64*[7]	**117**			117											GPP	FES
Replace 1 UPS Emergency Lighting system in C-Site at BLDG LSB C01[8]	**578**			578											GPP	FES
Replace 1 fire alarm Panel in C-Site at BLDG ESAT C50[9]	**75**			75											GPP	FES
Replace 1 fire alarm Panel in C-Site at BLDG PLT Power C52[10]	**75**			75											GPP	FES
Replace 1 fire alarm Panel in C-Site at BLDG CMG C51[11]	**75**			75											GPP	FES
Improve 19600SF exterior transite wall in C-Site at RF BLDG C40*	**1,848**				1,848										GPP	FES
Replace 2 HVAC Units in C-Site at BLDG COB C42*[12]	**768**				768										GPP	FES
Replace 2 HVAC Units in C-Site at BLDG Shop C32*[13]	**768**				768										GPP	FES
Replace 1 HVAC Unit inD-Site at BLDG DMG D72*[14]	**138**				138										GPP	FES
Repair 60000SF roadway[15]	**308**				308										GPP	FES
Improve cell phone communications	**115**				115										GPP	FES
Years 2019-2027 (GPP Funding)	**92,858**	3,979	3,562	7,954	15,363	10,000	10,000	10,000	9,000	7,000	4,000	4,000	4,000	4,000	GPP	FES

Overall funding needs for infrastructure during the next ten years is shown below.

Investment Summary ($M)

(Dollars in Thousands)

FES Funding Investments	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
Direct Funded (GPP)	2,500	5,000	4,321	5,000	10,000	10,000	10,000	9,000	7,000	4,000	4,000	4,000	4,000
Direct Funded (SLI)	25,000						25,000	25,000					
Maintenance and Repair (For Federally Owned Facilities)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
Predictive, Preventive and Corrective M&R (incl. DM Reduction)													
Direct Funded	0	0	0	0	0	0	0	0	0	0	0	0	0
Indirect Funded	6,800	7,000	8,000	8,200	8,500	8,700	9,000	9,200	7,200	7,400	7,700	7,900	8,100
Total Predictive, Preventive and Corrective	**6,800**	**7,000**	**8,000**	**8,200**	**8,500**	**8,700**	**9,000**	**9,200**	**7,200**	**7,400**	**7,700**	**7,900**	**8,100**
Operation, Surveillance & Maintenance (OS&M) of Excess and Unutilized Facilities													
Direct Funded													
Indirect Funded													
Total OS&M of Excess and Unutilized Facilities	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Maintenance and Repair	**6,800**	**7,000**	**8,000**	**8,200**	**8,500**	**8,700**	**9,000**	**9,200**	**7,200**	**7,400**	**7,700**	**7,900**	**8,100**
Deferred Maintenance Projection*	140,515	108,157	107,081	105,293	98,452	91,405	70,698	50,039	44,540	41,876	39,132	36,306	33,395

Other	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
Replacement Plant Value Projection ($000)	654,099	659,582	679,369	699,751	720,743	742,365	764,636	787,575	811,203	835,539	860,605	886,423	913,016
Building Area (Thousands GSF)	766	766	766	758	758	758	758	758	758	758	758	758	758
Excess and Unutilized Facilities (Thousands GSF)	0	0	0	0	0	0	0	0	0	0	0	0	0

*DM adjusted based on OIC DM working group guidance (3% 2016 and continuing 3% thereafter) reduced primarily through GPP and SLI investments

Excess Facilities

PPPL does not have any excess facilities at this time. When the Infrastructure Operations Improvement Project is implemented, the Mod VI facility will be vacated and removed as part of that project. In accordance with the latest FIMs guidance, PPPL will record excess facilities when identified into the system.

PPPL Computing Decision Making Process

At PPPL computing is organized under the Chief Information Officer and Head of Information Technology Department. The department is currently comprised of five divisions: cyber security, systems and networking, business computing, operations and user support, and controls and data acquisitions. The systems and networking division is responsible for scientific computing (R&D computing) along with networking and telecommunications (commodity IT). Cyber security and controls and data acquisition divisions are direct funded, while systems and networking, business computing, and operations and user support are indirect funded.

Our computing decision making process is based around a series of councils and committees that provide recommendations to the Laboratory leadership regarding proposed priorities and suggested strategic investments. These groups include: the Laboratory Council (comprised of senior leadership of the lab and set general direction), the Business and Human Resources Committee (comprised of senior leadership and evaluate both staffing and resources), and the Scientific Computing Resources Committee (comprised of the users of our high performance computing clusters).

Every year the Scientific Computing Resources Committee meets to review the status of the high performance computing clusters through a presentation delivered by the head of systems and networking. The committee then discusses the millions of simulations needed, the event size, the anticipated data rates and storage, etc. From those discussions, a universal view of the evolving demands on scientific computing is developed. Based on this input the ITD management team then sets priorities and provides multiple suggestions on how to upgrade and/or expand hardware infrastructure, partition hits M&S resources into disk, tape, and CPU to best meet the changing demands over the next fiscal year. The yearly allocation of hardware purchased is via General Purpose Equipment (GPE) direct fund that is approved by the Director's Office.

Enclosure 6: PPPL Investments

Objectives:
- Fully Support NSTX-U Operations
- Modernized, Flexible, Safe Laboratory Space for Small and Medium Experiment
- "People Space" that Facilitates the Exchange of Ideas
- General Purpose Infrastructure that is updated to support R&D efforts

Planned Capital Investments

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
															Select from Drop Down Menu		
Install 2400SF, Plasma Based Nano Lab in 1st floor at RF BLDG C40	**1,770**	700	1,070												GPP	FES	Plasma and Fusion Energy Sciences
Install 2700SF, FLARE Experiment in 1st floor at CS BLDG C41	**1,700**	949	751												GPP	FES	Plasma and Fusion Energy Sciences
Years 2019-2027	**0**														GPP	FES	Plasma and Fusion Energy Sciences
Improve 3 floors, 7500SF of LSB Annex at BLDG C01 [1]	**3,460**			3,460											LI	SLI	Plasma and Fusion Energy Sciences
Demolish 8216SF, Module 6 in C-Site at BLDG C55 [2]	**231**				231										LI	SLI	Plasma and Fusion Energy Sciences
Consolidate 4600SF, HAZMAT C93 into 6360SF RAD WASTE BLDG D45 [3]	**444**			444											GPP	FES	Plasma and Fusion Energy Sciences
Improve 12000SF, 1st floor in C-Site at BLDG ENG Wing C20	**1,541**		1,541												GPP	FES	Plasma and Fusion Energy Sciences
Improve 2622SF second Floor in C-Site at BLDG Facilities C61	**174**				174										GPP	FES	Plasma and Fusion Energy Sciences
Years 2019-2027 (SLI Funding)	**50,000**							25,000	25,000						LI	SLI	Plasma and Fusion Energy Sciences
Improve 32400SF, in C-Site at CMG C51 [4]	**8,269**				8,269										LI	SLI	Plasma and Fusion Energy Sciences
Improve 20000SF, in C-Site at RESA C90	**2,120**				2,120										LI	SLI	Plasma and Fusion Energy Sciences
Replace S2A1 to S2 Cables	**1,022**		200	822											GPP	FES	Plasma and Fusion Energy Sciences
Improve DI Water and Electrical Service in C-Site at BLDG CS C41	**905**			905											GPP	FES	Plasma and Fusion Energy Sciences
Replace RF Chilled Water Header	**119**			119											GPP	FES	Plasma and Fusion Energy Sciences
Replace 1500FT, Chilled water transite pipe	**2,142**	2,142													GPP	FES	Plasma and Fusion Energy Sciences
Replace 4824SF, Roof D-Site LEC Tank D34	**94**	94													GPP	FES	Plasma and Fusion Energy Sciences
Replace 4750SF, Roof in D-Site at Pump House D70	**94**	94													GPP	FES	Plasma and Fusion Energy Sciences
Replace 8 HVAC Control systems in D-Site at BLDG D42* [5]	**624**				624										GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 138kV Underground duct bank in C-Site at power yard* [6]	**1,284**			1,284											GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 Heat Pump in C-Site at Material Services C64* [7]	**117**			117											GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 UPS Emergency Lighting system in C-Site at BLDG LSB C01 [8]	**578**			578											GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 fire alarm Panel in C-Site at BLDG ESAT C50 [9]	**75**			75											GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 fire alarm Panel in C-Site at BLDG PLT Power C52 [10]	**75**			75											GPP	FES	Plasma and Fusion Energy Sciences

Replace 1 fire alarm Panel in C-Site at BLDG CMG C51 [11]	**75**			75											GPP	FES	Plasma and Fusion Energy Sciences
Improve 19600SF exterior transite wall in C-Site at RF BLDG C40*	**1,848**				1,848										GPP	FES	Plasma and Fusion Energy Sciences
Replace 2 HVAC Units in C-Site at BLDG COB C42* [12]	**768**				768										GPP	FES	Plasma and Fusion Energy Sciences
Replace 2 HVAC Units in C-Site at BLDG Shop C32* [13]	**768**				768										GPP	FES	Plasma and Fusion Energy Sciences
Replace 1 HVAC Unit in D-Site at BLDG DMG D72* [14]	**138**				138										GPP	FES	Plasma and Fusion Energy Sciences
Repair 60000SF roadway [15]	**308**				308										GPP	FES	Plasma and Fusion Energy Sciences
Improve cell phone communications	**115**				115										GPP	FES	Plasma and Fusion Energy Sciences
Years 2019-2027 (GPP Funding)	**92,858**	3,979	3,562	7,954	15,363	10,000	10,000	10,000	9,000	7,000	4,000	4,000	4,000	4,000	GPP	FES	Plasma and Fusion Energy Sciences

SLAC National Accelerator Laboratory

1. Mission and Overview

SLAC National Accelerator Laboratory (SLAC) pursues transformative research on some of the most important scientific questions and technology challenges within the mission of the Department of Energy (DOE) using unique cutting-edge accelerator facilities and world-leading light sources. Founded in 1962 with a 2-mile-long linear accelerator used for revolutionary high energy physics experiments, SLAC has evolved into a multi-program laboratory whose mission leverages our intellectual capital, unique relationship with Stanford University (Stanford) and location within Silicon Valley to:

- Innovate, develop and operate world-leading accelerators, light sources and scientific tools;
- Deliver transformative chemical, materials, biological and fusion energy science enabled by our unique facilities and define their direction;
- Perform use-inspired and translational research in energy; and
- Define and pursue a frontier program in particle physics and cosmology.

SLAC draws more than 4,000 researchers from around the world to use our facilities and participate in laboratory-hosted science programs each year. We operate two leading X-ray scientific user facilities – the Linac Coherent Light Source (LCLS) and the Stanford Synchrotron Radiation Lightsource (SSRL) – as well as the Facility for Advanced Accelerator Experimental Tests (FACET), a unique research and development (R&D) facility opened in 2012 for research on next-generation accelerator concepts. We also run the Instrument Science and Operations Center for the Fermi Gamma-ray Space Telescope (FGST), a joint DOE-National Aeronautics and Space Administration (NASA) mission that launched in 2008, and are leading the DOE contributions to the construction and operation of the Large Synoptic Survey Telescope (LSST).

2. Lab-at-a-Glance

Location: Menlo Park, California
Type: Multi-program Laboratory
Contractor: Stanford University
Responsible Site Office: SLAC Site Office
Website: www.slac.stanford.edu

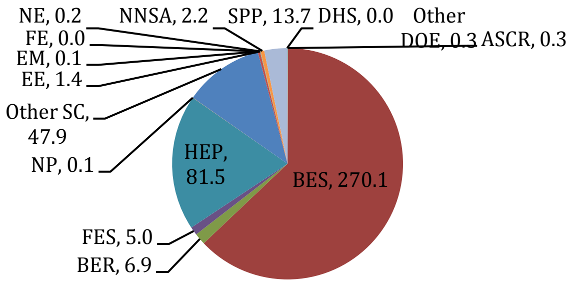
Physical Assets:

- 426 acres, 140 buildings and 35 trailers
- 1.559M GSF in buildings
- Replacement Plant Value: $1.459B
- 2,662 GSF in 2 Excess Facilities
- 654 GSF in Leased Facilities 1 Leased Trailer

Human Capital:

- 1,452 Full Time Equivalent Employees (FTEs)
- 55 Joint faculty
- 119 Postdoctoral Researchers
- 0 Undergraduate Students
- 167 Graduate Students
- 2,737 Facility Users
- 47 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



FY 2015 Lab Operating Costs (excluding Recovery Act): $429.6
FY 2015 DOE Costs: $430.2
FY 2015 SPP (Non-DOE/Non-DHS) Costs: $13.7
FY 2015 SPP as % Total Lab Operating Costs: 3.2%
FY 2015 DHS Costs: N/A

[#] GSF and building count relates only to DOE-owned active, operational buildings per FIMS.
* Facility Users as reported to DOE from the user facilities LCLS, SSRL, FACET and test facilities ASTA, ESTB, NLCTA. Excludes SLAC employees.

Since LCLS began operations in 2009, it has redefined the frontiers of X-ray science as an unprecedented source of ultrashort, ultrabright pulses of coherent X-rays. The recent demonstration of hard and soft X-ray self-seeding and other advanced techniques has further enhanced the unique capabilities of this facility. Breakthrough scientific results achieved at LCLS have garnered worldwide attention and prompted construction of similar facilities around the world. Work is well underway on an upgrade, LCLS-II, which will provide a much higher repetition rate, increasing the number of experiments run each year, and an expanded range of X-ray wavelengths, adding important new capabilities to keep the U.S. in an internationally leading position.

SLAC is operated by Stanford for DOE's Office of Science (DOE-SC). Four Nobel Prizes have been awarded for research done at SLAC.

3. Core Capabilities

The DOE Office of Science has identified six core capabilities at SLAC, which reflect the Laboratory's scientific and technical excellence: large-scale user facilities/advanced instrumentation; condensed matter physics and materials science; chemical and molecular science; accelerator science and technology; particle physics; and, a new addition this year, plasma and fusion energy science.

Large-Scale User Facilities/Advanced Instrumentation

At SLAC, we have the intellectual capital, infrastructure and experience to innovate, develop, design, construct, maintain and effectively operate large-scale scientific user facilities, delivering breakthrough discoveries that are in support of the DOE-SC mission, as well as other relevant DOE missions. We currently operate three DOE-SC user facilities – LCLS, SSRL and FACET – and run the joint DOE/NASA FGST mission.

Linac Coherent Light Source: SLAC's LCLS is the world's first and most powerful X-ray free-electron laser (FEL) operating in the hard X-ray spectral range. LCLS provides extremely high brightness beams to its user community (with 837 unique users, and over 2,000 user visits in FY 2015), enabling frontier science into the fundamental processes of chemistry, materials, energy and life sciences and technology. The impact of the X-ray FEL on our nation was recognized in 2015 when President Barack Obama presented the Fermi Award to Professor Claudio Pellegrini, a visiting scientist and consulting professor at SLAC, for research that aided in the development of X-ray FELs. In the past 12 months, scientists have used LCLS's six instruments to make many important advances in crystallography, ultrafast chemical dynamics, catalysis, neurotransmitter signal generation and more. These include:

- Long-sought information on the structure of superconducting materials, making use of intense magnetic fields;
- The achievement of a new mode of X-ray crystallography that is likely to lead to much higher resolution images of important biomolecules for clean energy and medical applications;
- Generation of "molecular movies," revealing the ultrafast dynamics of a gas molecule when a chemical bond is broken;
- Use of advanced spectroscopy to study how chemical catalysts could be optimized to produce hydrogen fuel from sunlight;
- Observations of how synapses in the brain generate neurotransmitter signals, and separate studies of cell signaling pathways that could have tremendous therapeutic implications for a range of common diseases;
- Investigations into the interaction between light and matter at the very highest intensities led to unexpected results that challenge our understanding of this fundamental process; and
- Studies into materials science included ultrafast observations of how matter behaves under conditions that simulate a meteorite impact, improving our ability to simulate such extreme events.

These experiments use the facility's groundbreaking X-ray beam, which offers a photon energy range from 270 electronvolts (eV) to 12.8 kiloelectronvolts (keV), recently extended from 11.2 keV. The pulse energy is typically 1 to 4 millijoules (mJ) and up to 6 mJ, with recent research raising the average energy by approximately 30 percent. The pulse length is typically 50 femtoseconds (fs) and can be varied from about 5 to more than 300 fs, while the maximum repetition rate of LCLS is 120 Hertz (Hz). Self-seeding modes are now available in both soft X-ray and hard X-ray spectral regimes (0.5-1.0 and 4.5-9.5 keV), benefitting experiments that require narrow bandwidth. The peak power achieved using seeding is over an order of magnitude higher than standard (SASE) operation. We introduced a new mode of operation in 2015, using a "delta undulator" to provide circularly polarized X-ray light, opening up a range of new experimental techniques. A major advance has been in the development of multiple pathways for the generation of double X-ray pulses, with the ability to vary their temporal separation (from femtoseconds to nanoseconds), spectral separation and seeding. This opens up a wide range of new pump/probe experiments across all elements of the LCLS program.

LCLS has been extremely reliable, providing more than 4,500 hours of user operation in FY 2015 with 94 percent uptime, resulting in 5,400 beam time hours for users, including multiplexing.

Stanford Synchrotron Radiation Lightsource: Building on many of the same core competencies that support LCLS, SSRL provides synchrotron X-rays from its third-generation storage ring (SPEAR3) and associated beamlines and instrumentation, serving the research needs of more than 1,600 unique users annually across many areas of science, engineering and technology. SPEAR3 performance continues to be excellent, providing high uptime at high-current [500 milliamperes (mA)] operation, with top-off injections every five minutes as the standard operating mode, along with the ability to run in the low-α mode, allowing for picosecond (ps) time-resolved experiments.

Research at SSRL supports the DOE's SC and energy missions, including condensed matter physics, energy-related materials research, catalysis, sustainable energy, environmental science, life sciences and biopharma drug-discovery programs. SSRL is also involved in larger DOE and other initiatives, including the Joint Center for Artificial Photosynthesis (JCAP), the Joint Center for Energy Storage (JCESR) and Energy Frontier Research Centers (EFRCs). SSRL is developing new programs in support of DOE Energy Efficiency and Renewable Energy (EERE) applied energy mission focused on *in situ* characterization of materials fabrication and growth. To improve its support of these programs, ongoing R&D is aimed at further reducing the SPEAR3 emittance to 6 nanometer-radians and improving time-resolved capabilities to keep SPEAR3 competitive with other third-generation sources. Ongoing beamline construction projects include advanced spectroscopy capabilities for energy-related materials and catalysis with a focus on time-resolved science, a calibration beamline to support DOE National Nuclear Security Administration (NNSA) mission needs and a micro-beam facility for macromolecular crystallography, which is also coupled to the structural biology R&D and user program at LCLS. Future beamlines include an X-ray scattering beamline for energy sciences with a focus on interfaces and time-resolved science. These beamline developments align with and benefit from the scientific and technical opportunities being pursued at the Photon Science Laboratory Building (PSLB).

The different properties of X-ray beams at LCLS and SSRL allow the design of complementary types of experiments in time-regimes from femtoseconds to minutes. In addition, to maximize the impact of the light sources on innovation and scientific discovery, LCLS and SSRL coordinate R&D programs focused on new methodologies and instrumentation. SSRL offers an R&D test bed for new instrumentation and techniques prior to deployment on LCLS, allowing more optimal use of limited LCLS beam time.

Facility for Advanced Accelerator Experimental Tests: With the aid of powerful electron and positron beams from the first two kilometers of SLAC's 2-mile-long linear accelerator, FACET, which opened to scientists in 2012, is exploring how to harness plasmas and specialized materials to boost particles quickly to multi-gigaelectronvolt (GeV) energies over an approximately 1-meter distance. The goal is to shrink the size of particle accelerators for use in HEP research as well as for other applications across DOE-SC, in medicine and in industry. Results demonstrating multi-GeV, high-efficiency acceleration of electron and positron beams were published in FY 2015. Scientists are also using FACET to study magnetic properties in materials, with applications in data storage; high-energy sources of terahertz (THz) radiation, with applications in materials science and chemical imaging; and diagnostics for future accelerators. In FY 2016, FACET, combined with the Laboratory's other test facilities – the Next Linear Collider Test Accelerator (NLCTA), the Accelerator Structure Test Area (ASTA) and the End Station Test Beam (ESTB) – expects to support 33 experiments for 274 users from SLAC, Stanford and other institutions. In FY 2016, FACET alone supported 13 experiments with a total of 120 users.

Particle Physics and Astrophysics Facilities and Instruments: SLAC plays an important role in major particle physics and astrophysics (PPA) projects. We led the design, development, construction and operation of the state-of-the-art Fermi Large Area Telescope (LAT), which launched in June 2008 on the FGST, a major space observatory that is revolutionizing the understanding of high-energy processes in the universe. We are applying the experience gained from this program to future facilities that will be located off-site: the wide-field LSST in northern Chile; upgrades to the A Toroidal LHC Apparatus (ATLAS) detector at the Large Hadron Collider (LHC); two next-generation experiments for direct detection of relic dark matter – Super Cryogenic Dark Matter Search (SuperCDMS) and LUX-ZEPELIN (LZ); development of next-generation experiments for precision cosmology with Cosmic Microwave Background (CMB) studies; and development of the future national neutrino program with the Deep Underground Neutrino Experiment (DUNE) at Fermi National Accelerator Laboratory. We are playing a lead role in designing and developing important elements of each of these large international projects.

In support of our large-scale facilities and science programs, we have developed and continue to maintain multiple advanced instrumentation and computational tools driven by the needs of existing and future experiments. The tools' capabilities include system design for high-bandwidth data acquisition (DAQ) systems, extending all the way from custom sensors and application-specific integrated circuits for detectors, to storage and distributed access for 100-petabyte-class data sets; advanced instrumentation and diagnostics for characterization and control of micron-scale photon beams; and highly automated, robotic-enabled, computer-based instrument control and remote access. Applications include highly integrated X-ray beamlines and instrumentation for photon science experiments; ultralow background experiments for direct dark matter detection; and space-qualified electronic systems, as well as computational resources for automated and optimized DAQ strategies, data collection and data analysis. We have significant expertise and capability in managing very large sets of experimental data, and are actively developing strategies for DAQ and management for LCLS and for future opportunities with LSST and ATLAS.

Funding for this core capability primarily comes from Basic Energy Sciences (DOE-BES) and High Energy Physics (DOE-HEP). Other sources include Biological and Environmental Research (DOE-BER), Fusion Energy Sciences (DOE-FES), internal Laboratory Directed Research and Development (LDRD) investments and Strategic Partnership Projects (SPP) from the National Institutes of Health (NIH). SLAC's efforts support the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23, 24, 25, 26).

Condensed Matter Physics and Materials Science

Materials, chemistry and energy sciences are central to many of today's most critical technical challenges. Condensed matter physics and materials science research at SLAC addresses DOE-BES mission needs and science questions from the 2008 DOE-BES Grand Challenges report and the 2015 BES Transformational Opportunities report. We focus on selected areas of materials science, including quantum materials, topological insulators, atomically engineered heterostructures, chalcogenides and nano-diamondoid materials. We also apply this research toward the development of future energy technologies, including methods for storing energy, more efficient energy conversion and carbon-free energy production.

SLAC uses and helps drive the development of forefront materials science techniques and methodologies at LCLS and SSRL. Recent work has demonstrated the ability of spectroscopy to illuminate fundamental electron, spin, orbital and lattice dynamics on natural time and length scales. For example, unique laser-based capabilities allow ultrafast photoemission studies to investigate single particle dynamics, resolved according to the electron's energy, momentum and spin in the time domain, where processes such as ultrafast charge and spin dynamics become accessible for direct observation. Coupling these efforts with *in situ* materials synthesis and characterization at SSRL, and with advanced theoretical simulation, provides synergistic advancement on all fronts. Adding to the capacity already in place at LCLS's soft X-ray end station has enabled pump-probe resonant inelastic soft X-ray scattering to study the time evolution of coupled order parameters. Our efforts are helping to set the science agenda for materials spectroscopy at LCLS-II. Other recent efforts in ultrafast materials science enable studies of the physics of coupled orders in nickelates, cuprates, manganites and other correlated materials, charge density wave collective modes, and magnetization dynamics in magnetic films and interfaces, important for next-generation electronic devices.

SLAC's materials science research is coordinated under a joint institute between SLAC and Stanford called the Stanford Institute for Materials and Energy Sciences (SIMES). Through SIMES, SLAC provides a strong coupling to energy technology and policy initiatives at Stanford, such as the Global Climate and Energy Project (GCEP) and the Precourt Institute for Energy (PIE). SIMES is also involved in larger DOE initiatives including JCESR, the Bay Area Photovoltaic Consortium (BAPVC) and EFRCs. In addition, SIMES is dedicated to outreach activities for energy science education and training, helping to develop the next generation of talent.

Funding for this core capability comes from DOE-BES, with support from other DOE offices such as EERE and LDRD investments, and serves the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23).

Chemical and Molecular Science

Our efforts in chemical and molecular science explore selected areas at the interface between ultrafast physics, chemistry, materials, X-ray science, and theory and simulation. Ultrafast science has synergies across SLAC and enables technology for many different areas of the Laboratory.

Research programs in ultrafast chemical science focus on areas that lie at the scientific frontier and are also of particular relevance to our mission. Experiments permit access to dynamics occurring down to femto- and even attosecond time scales using Laboratory sources and capabilities, including high harmonics, time-resolved electron scattering and time-resolved ultraviolet and soft X-ray spectroscopy, as well as ultrafast X-ray measurements using the unique capabilities of LCLS. These methods are currently being applied to study non-Born-Oppenheimer dynamics, strong-field laser-molecule interactions, solution phase dynamics, non-periodic X-ray imaging, nonlinear X-ray optics, and, most recently, time-resolved studies of reduced dimensional systems. The experimental efforts are coupled to a strong theory program supported by advanced computational capabilities.

Another major research area addresses the fundamental challenges associated with the atomic-scale design of catalysts. The overall aim of the SLAC catalysis program is to develop understanding of surface phenomena and catalysis to the point where science-based design strategies for new catalysts can be developed. Major challenges where new catalysts are essential include artificial photosynthesis, chemical fuels, energy storage and sustainable chemical processes. Over the last five years, SLAC and Stanford have jointly developed a theoretical description of surface reactivity and heterogeneous catalysis, electrocatalysis and photocatalysis.

By combining theoretical research with complementary experimental activity in catalyst synthesis, characterization and testing, we can make great headway toward realizing the full potential of the catalysis initiative. Experimental activity has now been established, and the plan is to expand it significantly, while exploiting the unique possibilities provided by SSRL and LCLS. The theoretical activities have also paved the way for new “materials genome” approaches to catalyst discovery that call for new infrastructure in terms of computing strategies and the development of databases.

Our research efforts in chemical science are closely coupled to aligned departments and institutes at Stanford, specifically through the Stanford Photon Ultrafast Laser Science and Engineering (PULSE) Institute and the SUNCAT Center for Interface Science and Catalysis, providing a broad foundation for the research and an essential educational role, in addition to supporting DOE-BES mission objectives.

Funding for this core capability comes from DOE-BES with support from LDRD investments, and serves the DOE-SC mission in scientific discovery and innovation (SC 2, 21, 22, 23).

Plasma and Fusion Energy Science

The SLAC program in plasma and fusion energy sciences explores the research enabled by the unique combination of high-power lasers with the properties of the LCLS X-ray laser beam. This novel capability marks the beginning of a new era of precision in high energy density science by probing the ultrafast transformation and evolution of matter in extreme conditions. Fusion science research drives new technology developments in high-repetition rate (approximately 100 Hz) 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. We apply precision X-ray Thomson scattering, Bragg scattering, phase contrast imaging and near forward scattering techniques to investigate plasmons, phase transitions to new materials, relativistic laser-matter interactions and high strain-rate material responses. These studies provide critical experimental tests of our physics models for matter in extreme conditions 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 the Laboratory.

Another major research area is the development of particle acceleration in plasmas with high-power short-pulse lasers, work that is done in collaboration with researchers at FACET that are exploring similar acceleration with electron-beam driven plasmas. Our experiments and 3-D particle-in-cell modeling of high energy density plasmas can resolve the femtosecond time scales and sub-micrometer spatial scales for exploration of advanced physics regimes for ion acceleration such as enhanced target normal-field acceleration or radiation pressure. In addition, we are exploring laser wakefield acceleration to produce GeV electron beams and associated betatron X-rays for ultrafast pump-probe studies. The direct interaction of high-power short-pulse lasers is especially important for understanding of 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.

These ultrafast pump-probe experiments are enabled by investments in a technology program such as the development of cryogenic targets for high-repetition rate studies of liquid hydrogen, deuterium and other important materials for fusion research. In addition, the program develops probe techniques unique to ultrafast studies with X-ray lasers or Ultrafast Electron Diffraction (UED).

Our experimental efforts are coupled to a new theory program that uses advanced computational capabilities. State-of-the-art 3-D particle-in-cell models and density functional theory provide experimental designs, specific predictions for dominating physics processes, and allow the development of reduced models for implementation in large-scale calculations for fusion experiments.

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).

Accelerator Science and Technology

The future development of light sources, UED/Ultrafast Electron Microscopy (UEM) and particle physics facilities serving the research missions of DOE-SC and SLAC relies on continuing advancement of accelerator science and associated technology. We have a strong core competency in accelerator physics and technology, and major thrusts in accelerator R&D include the development of forefront light sources, UED/UEM, novel compact and ultra-high gradient acceleration schemes, and high brightness beams. We also play a significant role in the design of future colliders, both linear and circular. These endeavors support our strategic goal of maintaining world leadership in accelerator design for X-ray FELs, storage ring light sources, high energy physics applications and various industrial, medical and security-related applications. At the same time, we maintain a renowned accelerator education program in conjunction with Stanford, training future leaders in the field.

FEL R&D: We have the most advanced operational hard X-ray FEL in the world today, LCLS, and the associated R&D guides the designs of new international projects. However, the X-ray FEL is at an early stage of development and an FEL R&D program begun a few years ago aims to bring a new capability to the X-FEL users approximately every six months. This highly successful program, which has demonstrated both hard and soft X-ray self-seeding, two-color FEL beams, a wakefield de-chirper, ultrafast diagnostics technology, advanced undulator technology and more will continue in order to further realize the discovery potential of LCLS and LCLS-II.

The LCLS-II upgrade project uses high-repetition-rate superconducting accelerator technology, leveraging core capabilities of other U.S. laboratories through a large-scale collaboration. In contrast to the pulsed superconducting European XFEL, LCLS-II will operate in a highly stable 1-megahertz (MHz), continuous-wave (CW) mode. Full exploitation of the new science possibilities afforded by LCLS-II will require developments in accelerator physics simulation tools, beam instrumentation and accelerator control technology. Future advanced FEL techniques being developed include: precision synchronization among X-ray, laser and radio frequency (RF) systems; circularly polarized undulators; and manipulation of bandwidth and duration of pulses to enable new capabilities in spectroscopy and dynamics.

Working together with the X-ray scientists and users for LCLS and LCLS-II, the FEL R&D group has laid out a roadmap to enhance the capabilities of both facilities. The R&D is divided into five major thrusts: X-ray seeding and brightness; electron beam brightness and manipulation; ultrafast techniques; diagnostics and optics; and technology development. Within each of these thrust areas, the program includes both near- and long-term R&D.

Advanced RF Accelerator Technology R&D: SLAC has a long history of developing and delivering new technologies for compact high-gradient accelerators. Over the last decade, we have systematically investigated the limits on RF breakdown phenomena in high-vacuum metallic accelerating structures, achieving gradients in the range of 175-300 MV/m at X-band, depending on materials, geometry and temperature. Novel accelerator structure topologies have demonstrated high shunt impedance, nearly twice conventional structures, enabling very high RF-to-beam efficiency.

We have embarked on a new program that uses RF structures in a novel way, extending beyond the traditional 11.4-gigahertz (GHz) X-band regime to THz frequencies. This is accompanied by a development effort for next-generation, compact and highly efficient RF-to-THz power sources. These programs are relevant for our ongoing research program, including SPP activities. SLAC stewards a world-wide unique integrated capability in RF power source and accelerator technology tapped by federal agencies, industry and labs around the globe and maintains the only remaining integrated concept-design-prototype-construct capability within DOE-SC.

Advanced Acceleration R&D: We play an internationally unique role in developing novel accelerating methods, including beam-driven plasma wakefield acceleration (PWFA), laser-driven PWFA, dielectric wakefield acceleration, and laser-driven dielectric acceleration (DLA). These technologies hold the promise of reaching accelerating gradients of GeV per meter (in the case of DLA and beam-driven dielectric acceleration) to tens of GeV per meter (in the case of beam-driven PWFA), which would revolutionize the world of compact accelerators used for medicine, industry, light sources and teraelectronvolt (TeV)-scale linear colliders. FACET, a user facility operated by DOE-HEP, is the centerpiece of this program. Key recent breakthroughs include finding a new regime to accelerate positrons in plasmas efficiently, demonstrating high efficiency acceleration of electrons (up to 50 percent) with small energy spread and validating the viability of the PWFA technology for future accelerators. FACET-II, the proposed follow-on facility, will expand the wide range of high-energy electron and positron beam experiments that are unique at SLAC and support a variety of accelerator science needs over the next five to 10 years. In parallel, concepts for a PWFA-based application are under development. This application would be an intermediate step towards a multi-TeV e^+e^- collider, and would provide essential validation of the PWFA technology through integration of the various accelerator systems. Both the FACET-II facility and the intermediate application are necessary in order to sustain this promising line of research after the closure of FACET in April 2016.

Particle acceleration using DLA is a new advanced acceleration approach with a wide range of potential applications, including compact low-cost accelerators and X-ray devices for security scanning, medicine, biology and materials science. In the last three years, SLAC and Stanford have collaborated to achieve tremendous progress in this developing field. Initial results include the first demonstrations of on-chip acceleration at both relativistic and sub-relativistic particle energies, and measured accelerating gradients in excess of 300 MV/m. Encouraged by these initial successes, in 2016, the Gordon and Betty Moore Foundation awarded $13.5 million to an international collaboration led by Stanford, to develop a working prototype tabletop accelerator based on this approach over the next five years. The SLAC program provides key in-kind contributions in support of this expanded university effort. A major goal of the Moore Foundation program is to demonstrate scalability to particle energies of interest for real-world applications, making it a viable technology for further development under the support of the traditional funding agencies.

Accelerator Test Facilities: The SLAC accelerator test facilities, including the low-energy ASTA facility, the medium-energy NLCTA, and the higher-energy ESTB, support next-generation acceleration development, as well as a wide range of experiments in materials science, THz generation, Compton-scattered photon sources, photocathode R&D, FEL seeding, high energy physics accelerator component and detector development, and general accelerator R&D.

The UED/UEM facility is presently housed in ASTA, and leverages SLAC's accelerator core competencies to provide the most advanced nano-UED facility in the world, complementary to the X-ray FELs. As with the novel RF technology program, these programs are relevant for both SLAC's increasing SPP activities and the DOE-HEP Accelerator Stewardship program.

Funding for this core capability comes from DOE-BES, DOE-HEP, SPP customers and LDRD investments. The core capability supports the DOE-SC mission in scientific discovery and innovation (SC 2, 22, 23, 24, 25, 26).

Particle Physics

SLAC's science and technical workforce provides leading contributions to a comprehensive combination of underground-, surface- and space-based experiments to explore the frontiers of particle physics and cosmology. This program spans the five primary science drivers identified by the Particle Physics Project Planning Panel (P5) report for DOE-HEP as the compelling lines of inquiry showing great promise for discovery over the next decade.

At the energy frontier, the ATLAS experiment at the LHC is exploring TeV mass scales and beyond with prospects for elucidating the properties of the Higgs boson and discovering new particles and interactions. SLAC plays a significant role in ATLAS in the pixel tracking system, DAQ and trigger systems, jet physics simulations, and operations of the detector, as well as in R&D leading to construction projects for the high-luminosity detector upgrade.

The neutrino program at the intensity frontier in DOE-HEP and in the fundamental symmetries program of DOE Nuclear Physics (NP) studies fundamental properties of the neutrino. SLAC has stewardship of the Enriched Xenon Observatory (EXO) for neutrinoless double-beta decay, which will determine if the neutrino is its own anti-particle. SLAC leads the 200 kg EXO demonstrator, which has obtained the most sensitive constraint on this process to-date and has significant roles in the R&D of the high-voltage system, electronics, purity and Time Projection Chamber (TPC) for the next generation ton-scale experiment. SLAC supports research in the accelerator-based short- and long-baseline neutrino programs, designed to search for sterile neutrinos, CP-violation and supernova neutrinos. SLAC takes the lead in the DAQ and automated reconstruction software for these programs.

The SLAC particle physics program also plays a leading role in studies of dark matter and dark energy. We are the lead DOE laboratory for constructing the 3.2 gigapixel camera for the LSST, which will probe the properties of dark energy with high precision, enabling a better understanding of this dominant component of the universe. The SuperCDMS will allow direct searches for relic dark matter candidates at unprecedented levels of sensitivity at low Weakly Interacting Massive Particle (WIMP) masses, while the complementary LZ liquid xenon experiment will provide the world's best WIMP sensitivity at higher masses. Both have been selected as next-generation direct dark matter search experiments, with SLAC playing a designated lead role in the SuperCDMS SNOLAB project. SLAC has optimized the design and production of large germanium sensors for SuperCDMS and is establishing cryogenic test facilities and TPC system test capabilities for noble liquid systems for LZ.

Meanwhile, FGST is eight years into a decade-long program of space-based gamma-ray observations, which are transforming our understanding of the high-energy universe. Recently, FGST revealed the origins of some cosmic rays and has conducted a wide variety of searches for dark matter. SLAC was the lead laboratory for construction and integration of the LAT and plays an important role supporting instrument operations.

In the areas of inflation and the early universe, SLAC and Stanford supported research with the Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment, which, in a joint analysis with the Planck observatory, has provided the most stringent limits on *B*-modes from gravitational waves in the early universe. BICEP3, deployed at the South Pole last winter, is a new instrument with a two-fold improvement in sensitivity and 10-fold improvement in survey capability over its predecessor. The ultimate experiment in this field, Cosmic Microwave Background Stage IV (CMB-S4), will build on this and other pathfinder experiments to provide definitive measurements of the universe's first light with a broad science scope that includes neutrino mass, CMB lensing and cluster cosmology.

Since its inception in 2002, the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) at SLAC has become a world-leading center for particle astrophysics and cosmology. The particle physics theory effort pursues a broad spectrum of forefront theoretical research across all areas of fundamental physics, from inflationary cosmology to Computational Quantum Chromodynamics (QCD) to dark matter to supersymmetry.

Funding for this core capability comes from DOE-HEP and DOE-NP, as well as SPP from the National Science Foundation (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).

4. Science Strategy for the Future

Overview and Summary

In September 2014, SLAC completed an institutional strategic plan informed by DOE's strategic plan, following a year-long process of engaging stakeholders and considering mission priorities. This plan was informed by the 2008 DOE-BES Grand Challenges report, the 2015 BES Transformational Opportunities report, the 2010 DOE-BER Grand Challenges report, the 2015 BER Molecular Scale Challenges report, the DOE-FES 10-year Perspective (2015-2025) report, the DOE-HEP P5 report and the 2015 Long-Range Plan for Nuclear Science. The strategic directions incorporated into the plan rest on four pillars: innovating and operating premiere accelerator-based facilities, identifying and pursuing new science enabled by our facilities and defining their future direction, performing use-inspired and translational research in energy, and defining and pursuing a frontier program in the physics of the universe. A set of core competencies in accelerator science and technology, instrumentation, X-ray science and technology and optical laser systems underpins these strategic directions. On the basis of our strategic plan, we have developed and articulated a set of future major initiatives within each of the four main thrusts.

Foremost among these major initiatives is LCLS-II, an upgrade to LCLS using a CW superconducting linear accelerator. LCLS-II will dramatically expand the FEL capabilities at SLAC and keep the U.S. at the forefront of X-ray science. The approval in March 2016 of Critical Decision (CD) 2 and 3 for this project allows us to predict its construction and commissioning timelines with confidence. As such, to take full advantage of this new capability, we have updated our strategies in ultrafast science for materials and chemistry, as well as new programs in biology and high energy density science. Our core technologies in detectors, lasers, X-ray physics and computing/data management will also be further developed to match our light source capabilities. A key integrating strategy for these growing efforts will be the opportunity to co-locate facility R&D activities and laboratory research programs in and around PSLB to develop high-impact experimental methods, techniques and instrumentation, and engage our user community. These new scientific capabilities and discoveries will naturally lead to improved approaches to addressing energy and other societal challenges, and we are refining a strategy to help connect this knowledge to practical solutions through expanded theory, synthesis, characterization and prototyping capabilities. Continued work in accelerator R&D will help to enhance the capabilities of LCLS and LCLS-II, as well as add complementary facilities, such as UED/UEM, and define pathways for compact and high-energy accelerators for future colliders and light sources, including the proposed FACET-II facility. Within the DOE-HEP program, we have leading roles in next-generation dark matter and dark energy experiments including LSST, while planning for CMB experiments probing cosmic inflation; we are growing a broad neutrino research program based on the Long Baseline Neutrino Facility (LBNF)/DUNE and next-generation neutrinoless double beta decay with nEXO; and we will be a major partner in the high-luminosity upgrade for ATLAS.

5. Mission Readiness/Facilities and Infrastructure

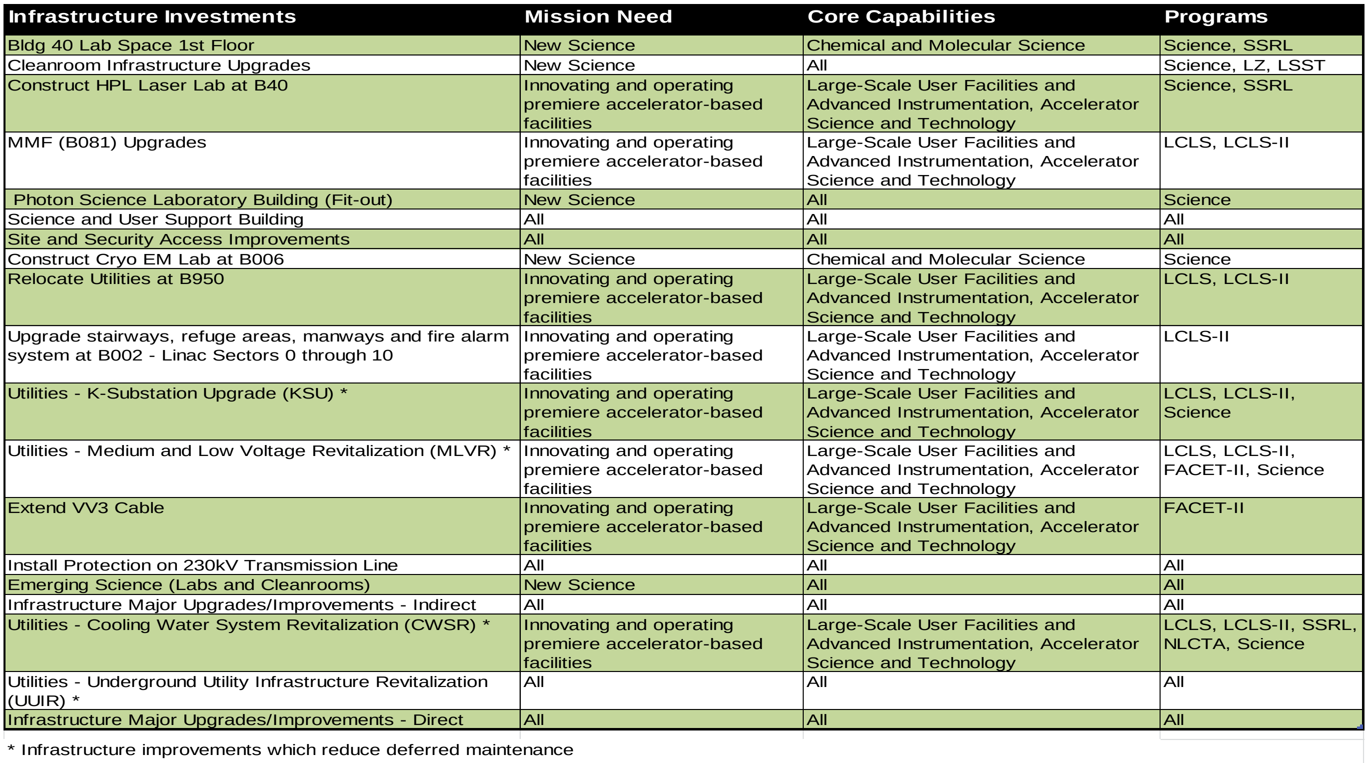
SLAC's renewed infrastructure mission readiness strategy fully aligns with the Laboratory's mission, science strategies and core competencies as defined in our strategic plan. In particular, our Infrastructure Mission Readiness (IMR) program supports the four pillars of our strategic plan by improving infrastructure reliability, operational safety and efficiency; identifying and mitigating operational risks; and optimizing infrastructure investments. The IMR program is supported by a realigned Facilities & Operations (F&O) organization, value-added operational measures and metrics, periodic infrastructure assessments and year-round planning and data analysis. In addition, periodic utility system and building assessments help us identify and understand our infrastructure gaps and risks, and are a fundamental step to mission readiness and optimizing infrastructure investments in support of the science mission.

Our goal is to reduce our infrastructure system life cycle costs while increasing infrastructure reliability, operational efficiency and safety in support of the SLAC mission. We optimize our investments using a balanced risk-based approach that considers mission; environment, safety and health; and cost and schedule aspects of proposed infrastructure investments. This process, based on DOE's Capital Asset Management Program (CAMP), results in a project ranking. This ranking is superimposed with a life-cycle cost and Return on Investment (ROI) calculations guiding an investment strategy that frees up capital funds and human resources to further reinvest, driving a cycle of increased efficiency and innovation. The resulting data is then analyzed by stakeholders and subject matter experts (SMEs) who develop an investment plan for review and approval by the Laboratory.

In addition to infrastructure investments made by SLAC and Stanford, we have proposed four infrastructure investments to support DOE's Science Laboratory Infrastructure (SLI) program: K-Substation Upgrade (KSU), Medium and Low Voltage Revitalization (MLVR), Cooling Water System Revitalization (CWSR) and Underground Utility Infrastructure Revitalization (UUIR); each of which is shown in the Infrastructure Investment Table and defined below.

Infrastructure investments identified in Figure A summarize the ongoing and planned investments that are aligned with our strategic plan and the ongoing projects and programs that are high priority, including LCLS and LCLS-II, LSST, SSRL, FACET-II, UED/UEM, ultrafast sciences, biosciences, HED, energy research and dark matter programs. With continued support from DOE and Stanford, we are refining our planning, processes and data assessments and analysis to manage our infrastructure risk and ensure a sustainable platform for our current and future science missions. When executed, we will secure a long-term sustainable basis for the operation of these facilities and programs.

Figure A: Infrastructure Investments Supporting SLAC's Mission Need and Core Capabilities



Infrastructure Investments	Mission Need	Core Capabilities	Programs
Bldg 40 Lab Space 1st Floor	New Science	Chemical and Molecular Science	Science, SSRL
Cleanroom Infrastructure Upgrades	New Science	All	Science, LZ, LSST
Construct HPL Laser Lab at B40	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	Science, SSRL
MMF (B081) Upgrades	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS, LCLS-II
Photon Science Laboratory Building (Fit-out)	New Science	All	Science
Science and User Support Building	All	All	All
Site and Security Access Improvements	All	All	All
Construct Cryo EM Lab at B006	New Science	Chemical and Molecular Science	Science
Relocate Utilities at B950	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS, LCLS-II
Upgrade stairways, refuge areas, manways and fire alarm system at B002 - Linac Sectors 0 through 10	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS-II
Utilities - K-Substation Upgrade (KSU) *	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS, LCLS-II, Science
Utilities - Medium and Low Voltage Revitalization (MLVR) *	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS, LCLS-II, FACET-II, Science
Extend VV3 Cable	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	FACET-II
Install Protection on 230kV Transmission Line	All	All	All
Emerging Science (Labs and Cleanrooms)	New Science	All	All
Infrastructure Major Upgrades/Improvements - Indirect	All	All	All
Utilities - Cooling Water System Revitalization (CWSR) *	Innovating and operating premiere accelerator-based facilities	Large-Scale User Facilities and Advanced Instrumentation, Accelerator Science and Technology	LCLS, LCLS-II, SSRL, NLCTA, Science
Utilities - Underground Utility Infrastructure Revitalization (UUIR) *	All	All	All
Infrastructure Major Upgrades/Improvements - Direct	All	All	All

* Infrastructure improvements which reduce deferred maintenance

Overview of Site Facilities and Infrastructure

SLAC's 426-acre, DOE-leased campus resides in unincorporated San Mateo County on the San Francisco Peninsula within a larger tract of land owned by Stanford. Of the 146 facilities at SLAC, DOE owns 140 and Stanford owns six. DOE currently has 1.559M gross square feet (GSF) in buildings and a replacement plant value (RPV) of $1.459B. Major utility systems include electricity, cooling and hot water, domestic water, storm sewer, sanitary sewer, gas, fire alarm, telephone and compressed air. Primary 230 kilovolt (kV) power is provided by a 5.4-mile DOE-owned tap line. The SLAC site includes tunnels and other unique experimental facilities, the largest of which are the 2-mile-long Klystron Gallery and the underground tunnel that houses the linear accelerator.

SLAC does not have any new leases of 10,000 GSF or more, and there are not any dispositions of DOE land through leasing, sale or gift in FY 2016. The terms of the most recent lease agreement between Stanford and the DOE identify up to 25 acres of land on the SLAC campus that can be returned to Stanford. The first phase includes 12.5 acres of land west of the main entry drive, shown in Figure B above; however, Stanford has not identified a timeline.

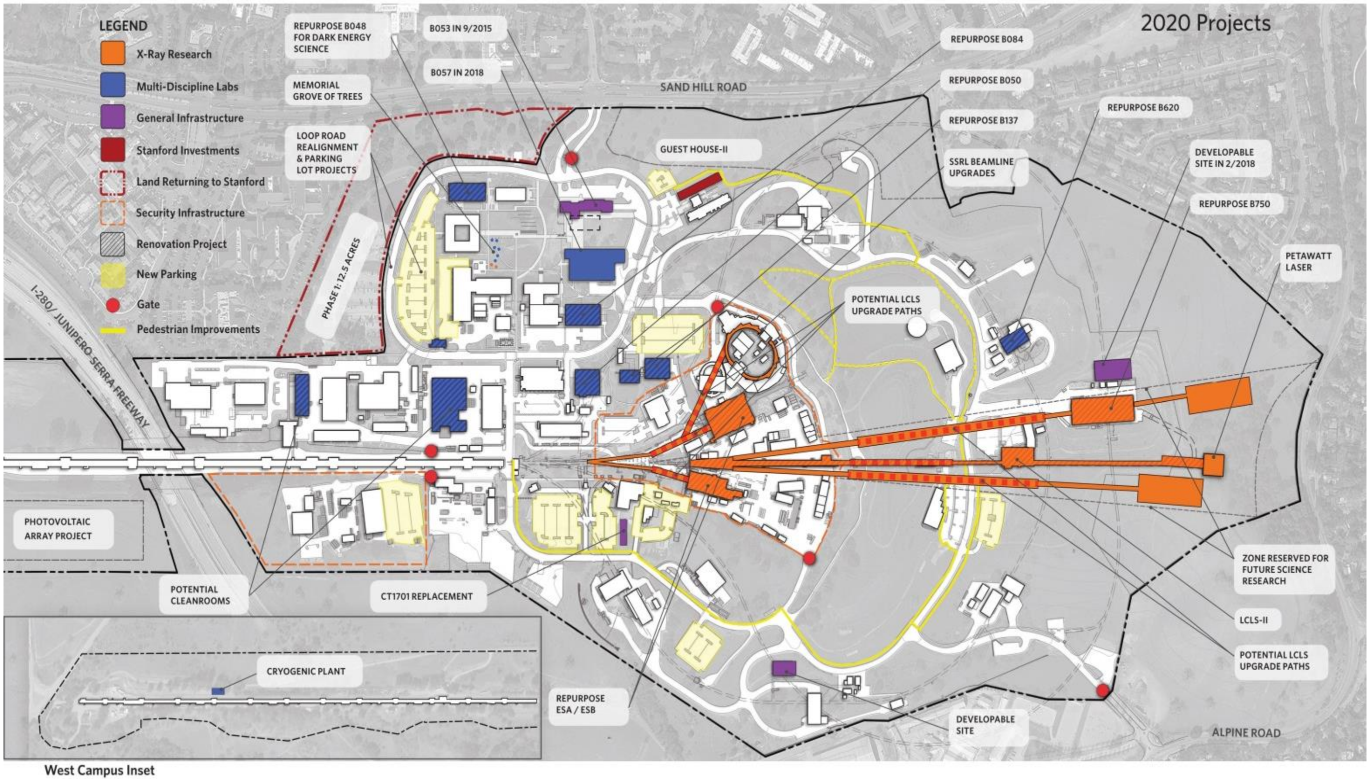
Campus Strategy

Overview

The SLAC long-range vision is a campus planning document which provides a framework for future SLAC site improvements in 2020, 2030 and beyond. It shows where future buildings are required based upon existing and planned mission needs, and it illustrates where undefined new mission programs could be placed in the future. This vision also identifies infrastructure investments necessary to meet our future objectives and realize the campus vision.

This long-range vision provides a framework for infrastructure and site improvements to support our science goals and core competencies. The high-level plan is designed to be adaptable to changing mission and funding levels to guide investment strategies. It looks beyond immediate and narrow functional issues toward broad, underlying and long-term mission goals. The SLAC long-range vision for 2020 outlines infrastructure investments as shown in Figure B below.

Figure B: SLAC Long-Range Vision for 2020



With the oldest facility at 52 years of age, 45 percent of buildings greater than 40 years old and utility distribution systems greater than 45 years old, reliability and maintenance of utility infrastructure is a critical challenge. As mentioned above, we have adopted a balanced risk-based process to prioritize our investments relative to the mission (our primary factor for investment prioritization); environment, safety and health; ROI and cost and schedule. Capital investments to address infrastructure gaps over the next 10 years are summarized in the Infrastructure Investment Table. Our current focus is on reliability of electrical, cooling water and underground utility distribution systems that have been assessed as inadequate or substandard and are associated with our high-priority facilities (LCLS, LCLS-II, FACET-II and SSRL).

Key partnerships have been a cornerstone of delivering new facilities. Along with Stanford and DOE-SC, we have funded investments totaling $228M for current and recently completed projects. Stanford investments include the PSLB shell, KIPAC, SRCC, the Arrillaga Recreation Center and the Stanford Guest House.

The 62,200 GSF Science and User Support Building (SUSB) was occupied in FY 2015. We also completed renovations to transform existing office space in Building 40 into laser and high-power laser labs in support of programs in ultrafast science; clean room infrastructure upgrades at IR-2 to support LSST and LZ; and the Magnetic Measurement Facility (MMF) upgrades at Building 81 to support LCLS-II. Stanford is scheduled to complete the PSLB “cold and dark” shell in 2016.

Leveraging our world-class light sources – LCLS and SSRL – and the PULSE and SIMES institutes at Stanford, we will be well-positioned to support the level of research of an internationally leading photon science laboratory. Our vision for PSLB is to provide an environment that fosters the development of critical research capabilities at SLAC in support of the existing and future strategic directions of our research programs and user science. PSLB will provide critical laboratory space to grow experimental programs as well as expanded synthesis and characterization laboratories.

PSLB will further this goal by providing centralized laboratory space with the necessary performance capabilities in which to grow our existing photon science research program. Co-location of laboratory capabilities and researchers will enhance science collaboration, productivity, efficiency and functionality, and enables us to expand our photon science program. PSLB's exterior and interior renderings are shown in Figure C below.

Figure C: PSLB Renderings

Collaboration is critical to the success of SLAC's multi-program science research and is supported by buildings like PSLB and by opening up our campus. The continuing security infrastructure upgrade project expands general access to a larger percentage of the site, supporting our goals of encouraging collaboration across disciplines by improving ease of movement around the campus. The ability to successfully grow and open the campus for collaboration depends largely on the completion of this project, and therefore funding the entirety of the project is important. This site security infrastructure upgrade will open up additional campus areas, including the Arrillaga Recreation Center; secure science buildings and provide a new pedestrian walkway from the Stanford Guest House to LCLS by the end of 2016.

Infrastructure Mission Readiness

As SLAC expands on our multi-disciplinary science mission in the coming decades, we need to revitalize our aging facilities infrastructure to meet current and emerging mission needs, taking available funding into consideration, while ensuring effective and efficient management and stewardship of our DOE assets. Our planned accelerator-based research expansion for LCLS-II, FACET and SSRL requires a different infrastructure support and operational mode. To further address these challenges and to support our mission, we have established an overarching campus vision of upgrading LCLS, LCLS II, FACET and SSRL capabilities and capacity, creating modern, collaborative spaces to enable emerging research and improve infrastructure mission readiness. We use the Infrastructure Mission Readiness process to identify key electrical, mechanical and control system infrastructure upgrades in support of our mission needs and our core capabilities.

The IMR program will enable us to continue to provide a sustainable platform capable of supporting current and future science. The four phase program includes:

- Assessing major infrastructure systems to understand impacts to our science mission and selecting investment projects that will address gaps and risks related to mission readiness;
- Prioritizing investments using a balanced risk-based approach to examine the mission; environment, health and safety; and cost and schedule elements of a project;

- Considering ROI and life cycle costs; and
- Reviewing the project prioritization list with stakeholders, laboratory management and SMEs to select the most critical investments.

The resulting IMR strategy includes:

- Tactically investing indirect funding based on prioritized mission needs with a focus on value and life cycle considerations;
- Constructing and renovating science buildings at SLAC to support facility users, visitors, new research and closer collaboration;
- Partnering with Stanford and other donors to innovatively improve the SLAC campus;
- Improving reliability, capability, operational safety and efficiency of electrical and cooling distribution systems associated with accelerator-based science; and
- Stabilizing and reducing operational costs by investing in infrastructure.

We are taking a value-centric and risk-based mission readiness approach to infrastructure system renewal. Instead of replacing complete systems or equipment, we are reviewing systems at the component level to determine minimum levels of renewal/replacement that are required to meet mission availability goals. For example, we are using test data to identify components that indicate a high probability of failure and only replacing those components. Equipment that tests within industry standards is not planned for replacement and is instead monitored and retested on a periodic basis. This new approach is challenging our engineers to be more creative in designing systems to meet minimum requirements while providing options for improving ROI, life cycle costs and performance goals.

We steward many high-RPV assets, including non-operational tunnels and facilities with limited future use. While some are used for storage or have been repurposed, they all require minimal maintenance and repair. As a result, a formulaic approach to determining an appropriate level of maintenance and repair investment for these assets is not generally accurate. If these assets are removed from the calculation, our maintenance and repair investment in FY 2015 was approximately 1.6 percent of the RPV.

As shown in the Integrated Facilities and Infrastructure (IFI) Crosscut table, the deferred maintenance trend is established at a 3 percent rate as directed by DOE's 2017 IFI Crosscut guidance answers. This trend is expected to improve with continued investments through multiple funding sources, including laboratory overhead, SLI funding and General Plant Projects (GPP) funded primarily from DOE-BES and DOE-HEP. The planned capital investments that reduce deferred maintenance are shown with an asterisk (*) on the Infrastructure Investment Table.

Infrastructure Gaps

Through the IMR four-phased process, we have identified infrastructure gaps – specifically in the areas of electrical, cooling water and underground utilities – and developed a comprehensive investment plan as shown in the Infrastructure Investment Table. We are leveraging multiple funding sources including SLAC Institutional General Plant Projects (IGPP), DOE-SLI and Stanford in these infrastructure investments. Incremental investments are being made each year using IGPP funds to address the most critical issues. These infrastructure investments will be used to support all of our science programs.

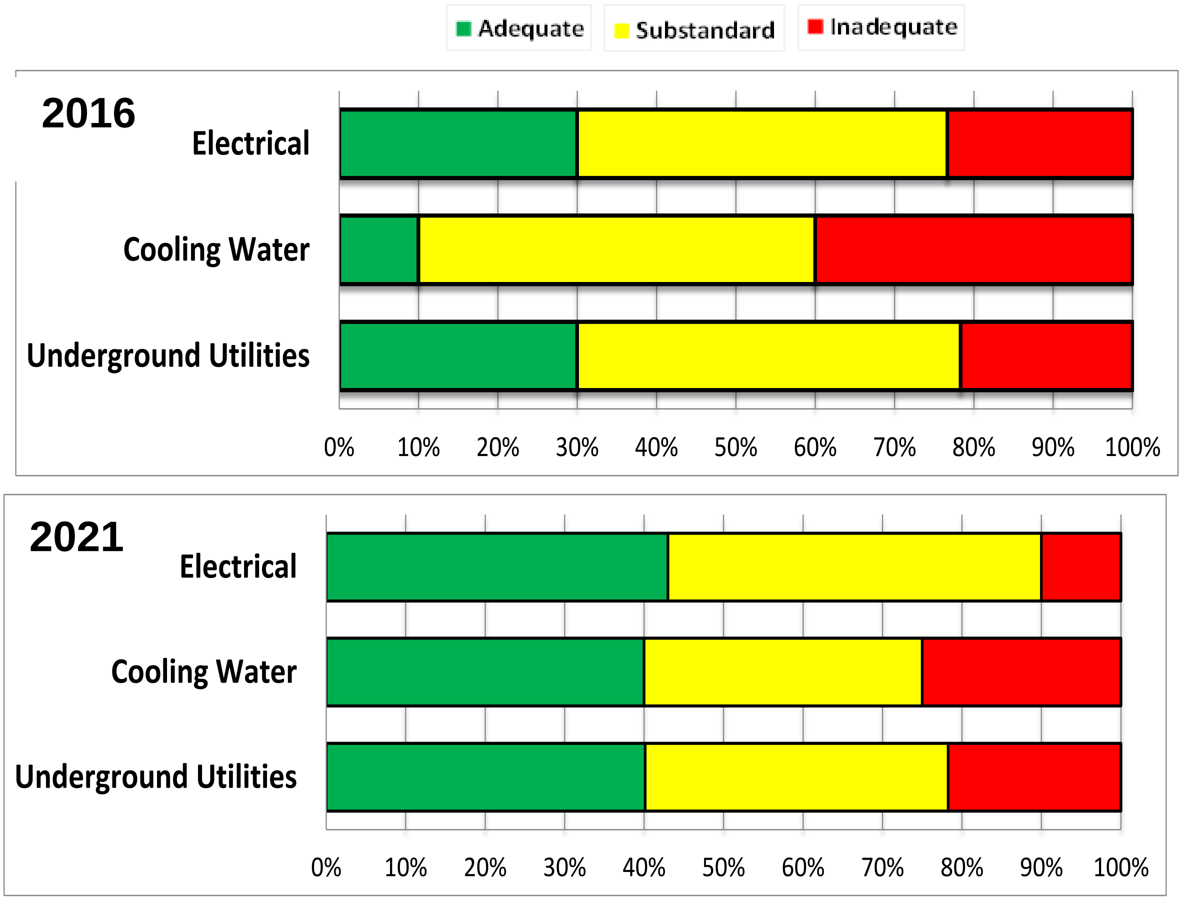
A reliable electrical distribution system is an essential component of our science mission and is a focus area for improving reliability, capability and operational safety. The linac K-substations, which are part of the medium voltage electrical system, have code and safety deficiencies and operational limitations, and in some cases are not capable of meeting current and planned mission needs. Much of the existing electrical distribution equipment is the original equipment installed 50 years ago. We have plans to replace components that have either failed or have been evaluated to have a high probability of failure. These include 12 kV substations, 480 volts AC motor control centers, distribution panels and panel boards. KSU, an FY 2016 SLI-funded GPP improvement, will upgrade substations on the first third of the linac, and MVLR, a requested FY 2017 SLI-funded GPP improvement, will revitalize the electrical system that supports the remaining two-thirds of the linac.

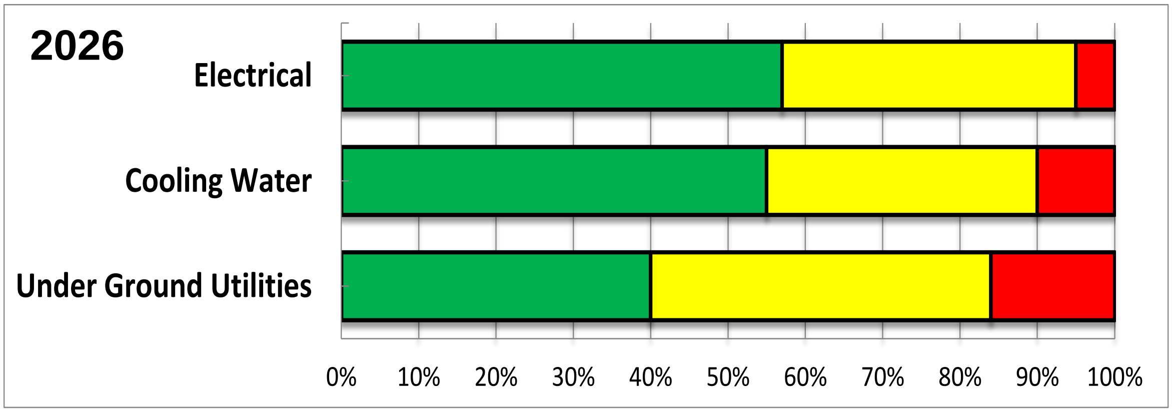
Many of the cooling water systems are more than 50 years old and original to the facility. Improvements in the cooling water systems will increase cooling water reliability and efficiency and reduce operating costs. CWSR, a requested FY 2019 SLI-funded GPP improvement, will accomplish these improvements and reduce risk to accelerator-based research.

The underground utility systems (sanitary sewer, storm sewer, domestic water and fire suppression) are also in need of attention. UUIR, a requested FY 2020 SLI-funded GPP improvement, will repair and replace this failing underground infrastructure and reduce risk of flooding and sanitary sewer discharge to the linac and environment. UUIR will also increase capacity and protect critical science and infrastructure.

Investments in these essential infrastructure systems will further support our mission to bring inadequate and substandard infrastructure on a path to adequate condition as shown in Figure D below. Substantial progress will be made over the next decade, allowing reliable operation of the existing facilities and setting up the new facilities for a long-term sustainable and cost-efficient operation without substantially increasing staff and while simultaneously reducing annual maintenance costs per facility.

Figure D: Path to Adequate Infrastructure



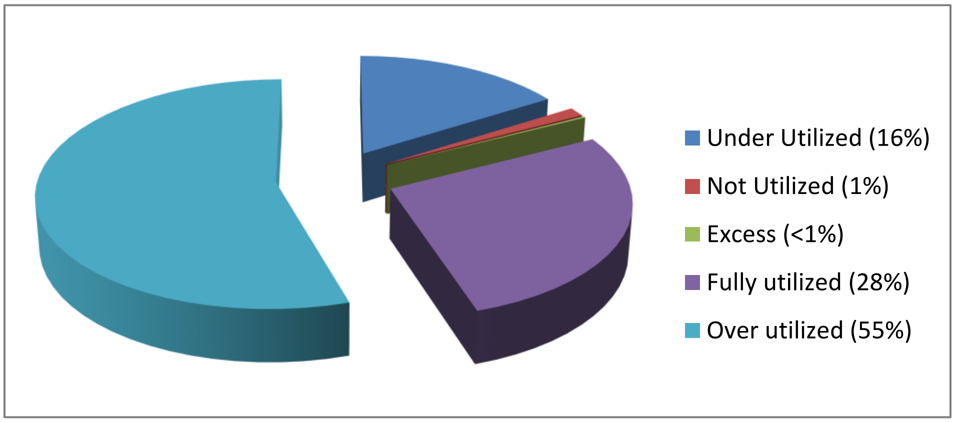


Excess Assets and Materials Plan

While none of SLAC's currently identified excess assets have been found to present an uncontrolled risk to the public or the environment, or to pose a safety risk to employees or visitors at the Laboratory, their continued presence does burden our mission due to their cumulative annual cost of maintenance. More importantly, excess assets occupy valuable land that can be redeveloped for other beneficial uses, such as laboratory and office space to support future research, research facility expansion and parking. There is an ongoing operation to remove and salvage unused trailers and seatrain storage units, rubblize concrete blocks for reuse as road base, and salvage and remove excess steel structures and frames.

Our priority is to continue our long-term plan and goal of consolidating personnel and functions from trailers into buildings, improving facility utilization rates and removing trailers and other temporary structures deemed as excess assets. The result of the Research Science Building and Infrastructure Modernization project (RSB) was a renovated and rebuilt Operation Support Building (B028: 20,000 GSF) and Administrative and Engineering Building (B041: 44,000 GSF) and a new Research Science Building (B052: 64,000 GSF). SUSB (B053: 62,200 GSF) also provides a new auditorium, conferencing center, site cafeteria and administrative offices to replace the past inadequate auditorium and cafeteria. When completed, PSLB (B057:105,000 GSF) will provide a fit-out of new laboratory and office square footage to continue this utilization improvement goal; note that current SLI funding will fit-out up to the first and second floors. The result of these new investments allowed us to vacate and prepare for the removal of inadequate buildings and trailers as these projects were completed. We are using our assets effectively with this plan as shown in Figure E below.

Figure E: Asset Utilization



The bulk of excess assets are made up of temporary structures and uninhabitable trailers which are no longer a sustainable solution for housing people, laboratories or old scientific structures. These scientific structures no longer serve the science mission and are not part of the future vision of the Laboratory. In most cases, removal of these items is not cost-effective based on ROI calculations; instead, we are developing a process for minimal maintenance on unused buildings, designating them as "cold and dark" to minimize carrying costs.

SLAC's current inventory of excess assets is summarized in the following categories:

Trailers: We have prioritized consolidating personnel and functions from trailers into buildings, improving facility utilization rates and removing trailers and other temporary structures. We have developed a demolition plan, included in our long-range vision, to address removal of these temporary structures over the next seven years, aligned with known planning timeframes to address removal of these temporary structures.

Since 2001, SLAC has removed 22 buildings totaling 46,349 square feet and 37 trailers totaling 29,727 square feet. Two facilities are currently declared as "excess" and are awaiting demolition in FY 2016: the former Security Office trailer (B235) and the SLAC Office trailer (B238). These two trailers represent 2,662 square feet and $16,000 in annual carrying costs. The estimated cost of removing these is less than $100K.

SLAC has approximately 40 remaining trailers totaling approximately 51,000 GSF that are either shut down, pending deactivation and decommissioning (D&D) or disposal; slated for removal; being used for storage or still functioning as office and laboratory space. The collective annual operational costs are $272,500 and annual maintenance costs are $87,500; however, once a trailer is closed its annual costs drop to less than $1,000 per year.

Currently staff groups are being relocated out of trailers to reduce operating and maintenance costs and to improve use of new and renovated buildings. Planning will continue site wide to increase use of newer buildings.

Buildings: SLAC has identified a number of buildings and some Interaction Region (IR) halls as excess assets. Most of the structures are not in use and do not cost us more than $1,000 each per year.

The IR halls are massive concrete structures that are partially underground. The halls' high bay structure and proximity to research facilities allow for them to be repurposed, as was done in IR-2, to create clean room space in support of the LSST camera construction, as well as the LZ test operations. We continue to evaluate repurposing IR halls for future projects to support our mission.

Other Structures and Facilities: After the conclusion of the Positron-Electron Project (PEP) and Stanford Linear Collider (SLC) operations, much of the equipment and ancillary infrastructure has remained in place. This includes two collider arcs (tunnels), beam dumps, substations and cooling systems. The collider arcs are shut down and are awaiting a decision from DOE Office of Environmental Management (EM) on funding and subsequent D&D. In 2009, DOE-EM agreed to acknowledge the collider tunnels for demolition, under a memorandum entitled "Environmental Management Transfer Decisions for Office of Science Excess Facilities and Materials." The collider arcs pose minimal safety risk, since they are inaccessible to unauthorized personnel, and there are negligible annual carrying costs. For these reasons, the vacant space is used to store irradiated equipment until funds are available for D&D.

Equipment in the PEP ring tunnel and support buildings, as well as the old beam dumps, will remain in place until they are deactivated. A number of the excess substations (e.g., those that supported PEP operations) will be candidates for removal in the next decade.

Excess Accelerator Materials: There are excess accelerator and detector components and material at many locations around SLAC that are remnants of legacy HEP research. The presence of these materials is in part a result of the DOE metal moratorium and metal suspension policy that began in 2000. With laboratory space and real estate now at a premium, and the development of programs enabling responsible management and recycling of accelerator materials, we have put a long-term plan into action to address this issue.

In order to make progress in addressing all of the key elements outlined in the moratorium policy, we developed a material release program that was approved in 2010 and extends to the entire SLAC site. Metals recycling at SLAC yielded 3,000 tons as of April 2015 and recovered $1.4M in recycling revenue. We have led the development of a DOE technical standard that will enable all DOE sites to perform similar recycling operations.

The work occurring between FY 2016 and FY 2018 will focus on the equipment removal project from linac Sectors 0–10 and the beam switch yard (BSY) that is needed to facilitate LCLS-II installation work. During the long-range period of FY 2016 through FY 2025, this program plans to recycle materials included in the more than 10,000 tons of legacy accelerator equipment that no longer supports our mission.

Decommissioning the first kilometer of the SLAC linac and klystron gallery to make room for the newly constructed LCLS-II will generate radioactive as well as non-radioactive waste. A project has therefore been put in place to manage the waste stream from LCLS-II construction efficiently and, using our approved Accelerator Material Clearance Program, recycle as much non-radioactive material on site as possible, which is expected to be up to 75 percent of excess materials. Plans for the management and disposition of excess materials from Sectors 0-10 and the BSY are described in detail in the SLAC Accelerator Materials Management Plan, a document that is approved by the LCLS-II program; Accelerator Directorate; Environment, Safety and Health and the deputy laboratory director.

In addition to the materials that can be recycled, we have large quantities of excess radioactive material on site that no longer serves our mission. In the past 10 years, we have disposed of 1,470 cubic yards of radioactive and mixed wastes and 422 excess radioactive sealed sources, and has made disposal of legacy wastes a long-term priority. The work slated to occur between FY 2016 and FY 2018 will include complete disposal of the remaining 300 radioactive sealed sources from Sectors 0-10 and the BSY. Over the next decade, we will continue the efforts to reduce the 3,367 cubic yards of legacy radioactive waste. Long-term plans include the potential for a new Radioactive Waste Management Facility that would greatly improve efficiency in the radioactive waste management processes.

Laboratory Name **SLAC National Accelerator Laboratory**

Objectives:

Objective 1 Innovating and operating premiere accelerator-based facilities
Objective 2 Identifying and pursuing new science enabled by our facilities
Objective 3 Performing use-inspired and translational research in energy
Objective 4 Pursue a frontier program in cosmology
Objective 5 Supports all or multiple objectives

Core Capabilities:

1	Large-Scale User Facilities and Advanced Instrumentation
2	Condensed Matter Physics and Materials Science
3	Chemical and Molecular Science
4	Accelerator Science and Technology
5	Particle Physics
6	Plasma and Fusion Enery Scinece

Planned Capital Investments

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
Bldg 40 Lab Space 1st Floor	**$2,396**	$2,396													IGPP	OH	3
Cleanroom Infrastructure Upgrades	**$331**	$331													IGPP	OH	1-5
Construct HPL Laser Lab at B40	**$1,112**	$64	$1,048												GPP	BES	1,4
MMF (B081) Upgrades	**$779**	$779													IGPP	OH	1,4
Photon Science Laboratory Building (Fit-out)	**$55,000**	$6,000	$25,000	$24,000											LI	SLI	1-5
Science and User Support Building	**$11,937**	$11,937													LI	SLI	1-5
Site and Security Access Improvements	**$8,900**	$2,300			$2,900		$3,700								GPP	S&S	1-5
Construct Cryo EM Lab at B006	**$3,870**		$1,250	$2,620											IGPP	OH	3
Relocate Utilities at B950	**$9,300**		$8,000	$1,300											GPP	BES	1,4
Upgrade stairways, refuge areas, manways and fire alarm system at B002 - Linac Sectors 0 through 10	**$2,920**		$280	$2,640											IGPP	OH	1,4
Utilities - K-Substation Upgrade (KSU) * [1]	**$9,800**		$9,800												GPP	SLI	1-4
Utilities - Medium and Low Voltage Revitalization (MLVR) * [2]	**$9,600**			$9,600											GPP	SLI	1,4
Extend VV3 Cable	**$677**				$677										GPP	HEP	1,4
Install Protection on 230kV Transmission Line	**$875**				$875										IGPP	OH	1-5
Emerging Science (Labs and Cleanrooms)	**$35,300**					$9,100	$14,200	$4,000	$2,000	$2,000	$2,000	$2,000			IGPP	OH	1-5
Infrastructure Major Upgrades/Improvements - Indirect	**$27,043**					$1,651	$3,483	$2,600	$4,100	$4,208	$1,500	$2,500	$3,500	$3,500	IGPP	OH	1-5
Utilities - Cooling Water System Revitalization (CWSR) * [3]	**$9,600**					$9,600									GPP	SLI	1,4
Utilities - Underground Utility Infrastructure Revitalization (UUIR) * [4]	**$7,500**						$7,500								GPP	SLI	1-5
Infrastructure Major Upgrades/Improvements - Direct	**$6,928**								$699	$679		$5,550			GPP	BES	1-5

Footnotes

[1] FIMS-90325 Sectors 0-10- LOB Condition Inadequate to Adequate
[2] FIMS-90325 Sectors 11-30 - LOB Condition Inadequate to Adequate
[3] FIMS-90330 - LOB Condition - Inadequate to Adequate
[4] FIMS-90353, 90361, 90363 - LOB Condition Substandard to Adequate

Thomas Jefferson National Accelerator Facility

1. 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 radio-frequency (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 several decades. The upgraded facility is in the commissioning phase and will begin research operations in the near future. TJNAF's current core capabilities are: experimental, theoretical and computational Nuclear Physics; Accelerator Science and Technology; and Large Scale User Facilities/Advanced Instrumentation.

The Lab has an international scientific user community of 1,510 researchers whose work has resulted in scientific data from 178 full and 10 partial experiments, 380 Physics Letters and Physical Review Letters publications and 1,292 publications in other refereed journals to-date at the end of FY 2015. Collectively, there have been more than 113,000 citations for work done at TJNAF.

Research at TJNAF and CEBAF also contributes to thesis research material for about one-third of all U.S. Ph.D.s awarded annually in Nuclear Physics (27 in FY 2015; 531 to-date; and 195 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.

1.1 2. Lab-at-a-Glance

Location: Newport News, Virginia
Type: Single-program Laboratory
Contractor: Jefferson Science Associates, LLC
Responsible Site Office: Thomas Jefferson Site Office
Website: www.jlab.org

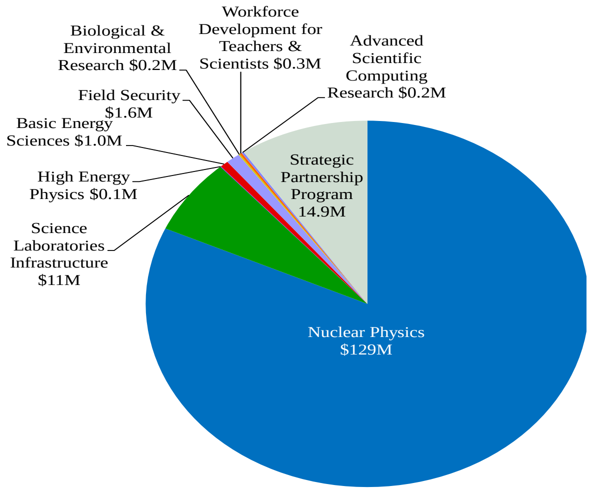
Physical Assets:

- 169 acres and 66 buildings and 4 trailers
- 876,084 GSF in buildings
- Replacement Plant Value (RPV): $397M
- 0 GSF in Excess Facilities
- 74,736 GSF in Leased Facilities

Human Capital: (period ending 9/30/15):

- 686 Full Time Equivalent Employees (FTEs)
- 24 Joint faculty
- 21 Postdoctoral Researchers
- 7 Undergraduate and 34 Graduate students
- 1,510 Facility Users
- 1,346 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs (excluding Recovery Act*):* $157.8
DOE/NNSA Costs: $142.9
SPP (Non-DOE/Non-DHS) Costs: $14.9
SPP as % Total Lab Operating Costs: 9.4%
Total DHS costs: $0.0

3. Core Capabilities

The following core capabilities distinguish TJNAF and provide a basis for effective teaming and partnering with other DOE laboratories, universities, and private sector partners in pursuit of the laboratory mission. These distinguishing core capabilities provide a window into the mission focus and unique contributions and strengths of TJNAF and its role within the Office of Science laboratory complex. Descriptions of these facilities can be found at the website noted in the Lab-at-a-Glance section of this Plan.

Each of the laboratory's core capabilities involves a substantial combination of facilities and/or teams of people and/or equipment, has a unique and/or world-leading component, and serves DOE/DHS missions and national needs. Specifically, TJNAF's three major core capabilities meeting these criteria are described below in detail:

Nuclear Physics (funded by DOE Office of Science (SC)– Nuclear Physics (NP))

Experimental Nuclear Physics

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 Continuous Electron Beam Accelerator Facility (CEBAF) electron beam can be simultaneously delivered to the experimental halls at different energies. Up to May 2012, the beam energy delivered was up to 6 GeV, and there were three experimental halls – A, B and C. Each experimental hall was 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 (1039/eN/cm2/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 now more than 1,500 users annually, of which roughly 2/3 are domestic, TJNAF supports one of the largest, if not the largest, nuclear physics user communities in the world.

TJNAF's completed 6 GeV program utilizing CEBAF has given the United States leadership in addressing the structure and interactions of nucleons and nuclei in terms of the quarks and gluons of Quantum Chromo Dynamics (QCD). The Nuclear Physics community in the U.S. has acknowledged this leadership and its potential, and indeed the 2007 NSAC Long Range Plan recommended completion of a doubling of the energy reach of CEBAF, the 12 GeV Upgrade, including construction of a fourth experimental Hall D and equipment upgrades to the existing Halls, as its highest priority. Later NSAC Subcommittees and Decadal Plans reaffirmed this priority. The highest priority of the recent 2015 NSAC Long Range Plan is to capitalize on the investments made, and first and foremost states that "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."

Recent lattice QCD 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. 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. The 12 GeV Upgrade of CEBAF will enable a worldwide unique new experimental program with substantial discovery potential to capitalize on these developments in nuclear and hadron physics.

The construction of the 12 GeV CEBAF nears completion. The accelerator commissioning has been completed and has been declared ready for operations. Hall A has seen its first continuous wave (CW) beam delivered and initiated its science program. Accelerated beam to Hall D, the newest and fourth experimental hall, was commissioned in the fall of 2014, and also Hall D, is after a stage of detector commissioning, ready for its science program. Accelerator operations sending simultaneous beam to Hall D (at 12 GeV), Hall A (at 11 GeV), and Hall B (at 2.2 GeV) have been established. Construction of experimental facilities in Halls B and C is nearing completion, with their commissioning planned for the upcoming winter period. The increased complexity of the accelerator and experimental equipment, including the introduction of Hall D, represents a substantial expansion of the scale of the operations in FY17.

Theoretical & Computational Nuclear Physics

A comprehensive theoretical effort and leadership across nuclear physics is the mission of the TJNAF Theory Center. The research program is an essential part of the national strategy for understanding the structure of hadronic matter and the worldwide effort to explore the nature of quark and gluon confinement. The broad program encompasses investigations of the hadron spectrum, hadron structure and hadron dynamics using a range of state-of-the art theoretical, phenomenological and computational approaches. These cover ab initio calculations, both in the continuum and on the lattice, of the properties of light nuclei, analyses of the nucleon-nucleon interaction, predictions for and analyses of the structure of the nucleon and its excitations, the determination of the spectrum of mesons with emphasis on their underlying quark and gluon structure, and explorations of the internal landscape of hadrons in terms of momentum, spin and spatial distributions. This internal dynamics is investigated in parallel studies using the methods of both lattice and perturbative QCD. A recent emphasis here has been on the issue of how to define and then compute the internal orbital motion of quarks and gluons. A particular strength of the theory group is the capability to meld the appropriate theoretical tools with cutting edge computational technology.

The synthesis of the latest technology with innovative theoretical tools is particularly notable in the area of High Performance Computing. TJNAF deploys cost-optimized computing for Lattice QCD calculations as a national facility for the U.S. lattice gauge theory community. Such computing capitalizes on the DOE's investment in leadership-class computing to facilitate the calculations needed to advance the understanding of nuclear and high-energy physics. To make best use of these facilities, development of a suite of novel software tools (Chroma) has allowed the calculation of observables of direct relevance to the TJNAF experimental program from the spectroscopy of baryons and mesons, including exotics, to form factors and generalized parton distributions. When combined with the power and speed of the dedicated Graphical Processing Unit (GPU) infrastructure, results of unrivaled precision for the hadron spectrum have been produced. 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. Moreover, the relation between nuclear structure at short distance scales and the underlying dynamics of quarks can be uncovered. An increasingly important part of this lattice effort is the computation of hadronic scattering amplitudes, with emphasis on providing the decay couplings of well-established mesons as a benchmark for extension to hybrid states, where the decay couplings will aid the experimental search of GlueX and CLAS12. One third of the Theory Center members is also engaged in phenomenological studies of the physics to be accessed at a future Electron Ion Collider, and are major contributors to the whitepaper that sets out its physics case. In all aspects, the Theory Center works closely with the experimental community, whether in performing crucial radiative corrections for parity-violating experiments, or in studies to constrain transverse momentum-dependent and generalized parton distribution functions from the full kinematic range of results that TJNAF will produce.

A key component in support of the 12 GeV experimental program is the Theory Center's JLab Physics Analysis Center (JPAC) working particularly closely with the CLAS12 and GlueX Collaborations. The JPAC project draws on world theoretical expertise in developing appropriate phenomenological tools and computational framework required for extracting the details of quark and gluon dynamics from experimental data of unprecedented precision and scope. Definitive answers to the basic questions of "do there exist hadrons for which the excitation of gluons is essential to their quantum numbers" and "what is the detailed internal flavor, momentum, angular momentum and spatial distribution of nucleons" require continuing engagement and collaboration between experimentalists and theorists both at TJNAF, at US universities and in the wider hadron physics community.

The Nuclear Physics Core Capability serves DOE Scientific Discovery and Innovation (SC) mission numbers 2, 4, 22, 24, 26, 27, 28, 30, 33, 34, 35 and 36 from "Enclosure 1: List of DOE/NNSA/DHS Missions."

Accelerator Science and Technology (funded by DOE SC – Nuclear Physics, High Energy Physics)

The focus of TJNAF's Accelerator Science is on superconducting, high current, continuous wave, multi-pass linear accelerators (linacs), including energy recovering linacs. Past achievements and future plans involve the lab's expertise in low emittance electron injectors, SRF niobium-based accelerating technology, and advanced electron-ion collider design. This broad suite of capabilities is complemented by world-class expertise in accelerator design and modeling.

Injector R&D

TJNAF has extensive expertise in high current photoemission sources, especially polarized sources. Over the past years, the polarization delivered to the CEBAF users has progressed from 35% (bulk gallium arsenide), to 70% (strained gallium arsenide), to 89% (multi-layer strained gallium arsenide). In addition to measurements by the experiment, the polarization is measured at the injector with a Mott polarimeter, whose precision has been pushed to the limit with dedicated R&D. A new, higher voltage DC gun has been built (200kV) anticipating the need for improved beam quality for future parity violation experiments at 12 GeV CEBAF, and a photogun capable of operation at 350 kV is being developed for the Upgraded Injector Test Facility (described in part 4 of this section) and for nuclear physics experiments at the Low Energy Recirculator Facility (LERF). Recent photogun development was partially funded by the International Linear Collider (ILC) and through the DOE program Research and Development for Next Generation Nuclear Physics Accelerator Facilities (LAB 12-632) and (LAB 14-1082). TJNAF electron sources and injectors have produced in continuous wave operation, electron beams with currents of 180 μA and 89% polarization for CEBAF and unpolarized beams of 9 mA for the ERL. For future high-current unpolarized beam applications, photoguns will soon rely on alkali-antimonide photocathodes that exhibit longer operating lifetime compared to gallium arsenide photocathodes.

SRF R&D

The SRF Institute at TJNAF can be a cost-effective R&D partner for all Office of Science projects requiring SRF expertise because of its experience and facilities. Past and current partnerships include jointly funded R&D and production of cavities for the Spallation Neutron Source (SNS) at ORNL, high-current cavities funded by ONR, crab cavities funded by the Advanced Photon Source (APS), and R&D on high Q0 cavities and new materials for future accelerator technologies funded by BES. The application of this know-how is currently being applied to projects across the DOE-SC complex.

TJNAF also carries out forefront SRF R&D including high gradient research (which led to the development of processing procedures that were applied to the 12 GeV cavities), new materials and thin film research aimed at low frequency cavities where the cost of niobium is high.

More recently, the focus has shifted to high Q0, which reduces the cryogenic losses in SRF cavities. TJNAF is producing very high Q0 cavity results with the use of Nitrogen doping of traditional solid niobium cavities. Current work continues exploring process refinements and extending the process to various types of cavities. Additionally, TJNAF is studying the possibility of reacting tin on the internal surfaces of Niobium cavities to create a film of Nb3Sn. The initial results are encouraging and could lead to superconducting cavities with significantly lower cryogenic losses than the niobium cavities that are the state of the art today. TJNAF is also engaged in understanding the impact of these very high Q0 cavities on the requirements for cryostat and component designs in cryomodules. This technology has been adopted for the LCLS-II project at SLAC.

TJNAF is also pursuing a program to improve the performance of cryomodules installed in CEBAF by reworking the oldest or weakest cryomodules with new state of the art cavities while reusing most of the cryomodule hardware. This may be the most cost-effective way to maintain the gradient needed for high-energy operations.

TJNAF is studying new materials, notably ingot niobium, which improves the Q0 while reducing the material costs. Studies of niobium with increased tantalum content (reduced purification) are also demonstrating promise of higher Q0 at lower cost. These two effects are not mutually exclusive and together provide a low-cost strategy to reach the performance required by CW accelerators at a more affordable cost.

Advanced 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 Laboratory Electron Ion Collider (JLEIC). A pre-conceptual design report for JLEIC was published in 2012, which fulfills 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 now working towards a pre-Conceptual Design Report (pre-CDR) in 2 years with a CDR to follow in ~4 years. A first cost estimate was submitted to the NSAC Subcommittee on EIC cost in January 2015: technical choices and costs were endorsed by the Subcommittee and formed the basis for the NSAC Long Range Plan discussions. The JLEIC is a collider that uses the existing 12 GeV CEBAF as an injector for the electron ring. The ion ring requires a brand new ion complex to produce, accelerate and collide the ions with the electrons. The injector complex consists of a source, ion linac, booster, and collider ring. The electron ring and ion ring are stacked in a common ~2.2 km long figure-8 tunnel. The innovative figure-8 design allows proton and light-ion polarization well above 70%. The optics for the main accelerator components has been designed, and the focus now has turned to studying the correction systems and planning the R&D to validate key needed technologies. The most critical R&D item is high-energy bunched-beam magnetized electron cooling, and we plan to establish feasibility of this novel technology with a series of studies, simulations and targeted experiments that leverage our competence and capabilities and those of our collaborators. Other components of the JLEIC R&D portfolio include innovative superconducting magnets for arcs and interaction regions, and SRF technology for storage and crab cavities. Completing design and R&D towards a conceptual design report consistent with the critical decision timeline for the EIC project and with the requirements for DOE order 413.3 will require appropriate resources to be identified.

The Accelerator Science Core Capability serves DOE Scientific Discovery and Innovation mission numbers 25, 26, and 30 from "Enclosure 1: List of DOE/NNSA/DHS Missions."

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 7/8 mile racetrack and was built to deliver precise electron beams to three experimental End Stations or Halls simultaneously. Hall A houses two high-resolution magnetic spectrometers of some 100 feet length and a plethora of auxiliary detector systems. Hall B has been the home of the CEBAF large-acceptance spectrometer (CLAS) with multiple detector systems and some 40,000 readout channels. Hall C boasts an 80 feet long high-momentum magnetic spectrometer 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.

The expertise developed in building and operating CEBAF has led to an upgrade that doubled the maximum beam energy (to 12 GeV) and provided a unique facility for nuclear physics research that will ensure continued world leadership in this field for several decades. The $338M project, known as the 12 GeV CEBAF Upgrade, received Critical Decision 0 (CD-0) approval in March 2004 and started construction (CD-3 approval) in September 2008. Approval of CD-4A (Approve Accelerator Project Completion and the Start of Operations) was received in summer 2014, approximately five months ahead of schedule. This upgrade has added one new experimental facility, Hall D, dedicated to the operation of a hermetic large-acceptance detector for photon-beam experiments, known as GlueX. In Hall A, with the existing equipment, and new Hall D the initial 12 GeV science operations have started. The remaining 12 GeV upgrade work, nearing completion, will add a new magnetic spectrometer in Hall C, and convert the Hall B apparatus to allow for the higher-energy and higher luminosity operations. Unique scientific opportunities exist in Hall A with the new Super BigBite Spectrometer (SBS) under construction and with additional dedicated apparatus. This encompasses one-of-a-kind experiments, such as the foreseen MOLLER apparatus to measure the weak charge of the electron and provide a fundamental precision test of the Standard Model. Also foreseen is a general-purpose apparatus such as SoLID, that will allow unprecedented 3D imaging of nucleons in momentum space in the valence quark region, a search to new physics in the 10-20 GeV range complementary to the LHC but unique to a lepto-phobic Z' of 100-200 GeV, and access to the QCD conformal anomaly. Accelerator instrumentation is installed to deliver beams to all four Halls simultaneously.

To enable the experimental program, TJNAF staff is a world leader in the development and operation of high-power cryogenic target systems, and highly-polarized gaseous and solid-state target systems, such as polarized 3He, H and D solid-state polarized target systems, and frozen-spin H and HD-Ice targets. Many of these targets have demonstrated world record performance. In addition, to facilitate a modern and efficient data acquisition system, TJNAF staff have designed and developed an ultra-fast fully pipelined electronics system, with components finding their way into other user facilities such as Brookhaven National Laboratory. This development of advanced data acquisition instrumentation allows for spin-offs such as that described in the bio-medical applications below. TJNAF staff is at present envisioning how with foreseen trends in advanced scientific computing and ultra-fast electronics, we can define the next generation of data readout of large-scale advanced instrumentation, as e.g. relevant for the envisioned SoLID apparatus and a future Electron-Ion Collider.

Nuclear Physics Detector Technology (funded by DOE SC – Nuclear Physics)

Developing and implementing novel detector techniques for the next-generation of nuclear physics experiments supports the main mission of TJNAF. Such techniques allow the development of large-scale particle identification, high-rate tracking and electromagnetic calorimetry systems. Some examples are the Ring-Imaging Cherenkov (RICH) kaon identification detector under construction in collaboration with INFN/Italy, the high-rate Gas Electron Multiplier (GEM)-based tracking systems in collaboration with University of Virginia, and the lead-tungstate (PbW04) based calorimeter development in collaboration with Orsay/France and Catholic University of America. TJNAF is also instrumental in testing position sensitive photomultiplier tubes and the exploration of advance photon detectors such as the silicon photomultipliers (with their first-time ever applicability in a large-scale experiment in GlueX) and a recently initiated collaboration with ANL on development towards an early application of the large area picosecond photon detector. This expertise has contributed to the technology transfer efforts of TJNAF, as described in Section V, such as commercial breast-imaging systems, the development of a new hand-held camera based on silicon photomultipliers and used as an imaging aid to cancer surgeons during surgical procedures, the advance of a SPECT-CT system that has been used in brain studies on awake, unrestrained mice, and development of PhytoPET, a PET imaging methodology for plant research.

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 has been increased from three to four. The experimental program is very flexible and dynamic. The simultaneous execution of experiments requires that CEBAF be capable of delivering beam with a large dynamic range in beam currents (nA → 100s of µA) or bunch charge (0.004fC → 0.4pC). Additionally, the experimental user can request beam energies that correspond to 1, 2, 3, 4, 5 or 5.5 pass recirculation. The electron beam is polarized and spin alignment can be optimized for a single user.

Presently, CEBAF is transitioning from the 12 GeV commissioning effort into the "initial years" Physics program. Up to this point, an opportunistic Physics program has been supported during periods when the accelerator commissioning efforts allowed. Extensive superconducting radio frequency (SRF) cavity maintenance was performed during the summer of 2015. Following this maintenance, CEBAF delivered the first 12 GeV to Hall D in December 2015. In addition to achieving the design energy, the beam transverse and longitudinal properties were measured to be within the Physics specification for the initial year's program. Additionally, the 5-th pass RF separator was operated at full design energy simultaneously delivering 50µA of CW beam to Hall A and 100nA CW beam to Hall D. With 418 installed SRF cavities, CEBAF operations represent a significant fraction of the world SRF operating cavity-hour 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.

Additional research and development activities include beam diagnostics, emphasizing non-invasive techniques to monitor and maintain delivery of beams with up to a 1MW of beam power. CEBAF operations also support and enable R&D in Accelerator Physics and efforts from the Engineering and Physics Divisions.

TJNAF staff has developed a substantial ability to conceive and design large accelerator facilities, building upon 6 GeV CEBAF operations and augmented with the ongoing 12 GeV Upgrade. With the completion of the 12 GeV Upgrade, TJNAF will continue its role of the world's premier experimental QCD facility. The ability to use the TJNAF 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 mutual beneficial cross-fertilization between the TJNAF LERF and Nuclear Physics.

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.

Using SRF technology based on CEBAF, TJNAF has constructed and operated an advanced Free Electron Laser (FEL). The development of this machine enabled TJNAF to pioneer new Energy Recovery Linac (ERL) technology. In the ERL, the electron beam is re-cycled back through the accelerator out of phase with the accelerating field so the beam energy is returned to the SRF cavities. This power, which would normally be dumped, can represent 90% of the beam power in a high power linear accelerator. TJNAF was the pioneer in developing this technology and the TJNAF FEL remains the highest power system extant. A number of other laboratories are adopting this technology, and ERL technology is likely to become an important contribution to sustainability initiatives at DOE labs.

This IR FEL has demonstrated up to 14 kW of CW average power, making it the most powerful free electron laser in the world. Funds were obtained from the Commonwealth of Virginia to upgrade the beam energy by refurbishing one of the cryomodules. This cryomodule has been completed, met specifications in the test cave, been installed and commissioned in the FEL.

TJNAF is developing a new plan for the future use of this valuable asset. The Lab is using the term LERF (Low Energy Recirculator Facility) to refer to this facility to reflect a broad potential. The present range of the discussion includes future nuclear physics experiments (DarkLight is one example, with construction already partially funded by an NSF MRI grant), characterization of materials using low energy positrons, and R&D on production of medical isotopes using the (gamma, n) reaction. There is also substantial potential for facilitation of commercial development of free electron laser technology, and TJNAF is pursuing this option as well. Overall, TJNAF is developing a plan for future utilization of this facility, which would be of maximum benefit to the mission of the laboratory and of the nation.

TJNAF is also 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). Representing a major upgrade in international X-ray Free Electron Laser capabilities for study of atomic interactions, condensed matter physics, warm dense plasmas, and biological physics, the system will provide intense, coherent 50 fs long photon pulses at up to 5 keV in energy with repetition rates up to 1 MHz. The heart of this facility is a state-of-the-art SRF linac replacing the first 1/3 of the SLAC copper linac providing 4 orders of magnitude improvement in average laser beam intensity. Expertise at TJNAF will facilitate successful construction, installation, and operation of this first SRF-based linac at SLAC. TJNAF will be responsible for construction of half (2 GeV) of the superconducting accelerator as well as the two cryogenic refrigerators. The system will utilize an entirely new nitrogen surface processing to raise the cavity quality factor above 3 x 1010 for substantial savings in electrical power and refrigeration required. Cavities will be fabricated by industry based on the successful XFEL production model but testing and assembly of the cavities into cryomodules, and testing of the cryomodules will be performed by TJNAF and FNAL before installation at SLAC. Once operational, beams from both the existing LCLS accelerator and the new superconducting accelerator will be able to drive two advanced undulators providing exceptional experimental flexibility and doubling the number of users that can utilize the facility simultaneously. The project has obtained CD2/3 approval from DOE.

Another SRF application under consideration is the development of an EUV (Extreme Ultraviolet) FEL for semiconductor lithography. There is increasing industrial interest in this technology, and TJNAF is pursuing the possibility of strategic partnerships with industry to perform the physics and engineering design of an FEL suitable for such an application.

SRF Accelerator Construction (funded by DOE SC, Nuclear Physics)

TJNAF has developed and installed state-of-the-art infrastructure for the design, development, fabrication, chemical processing, and testing of superconducting RF cavities. This complete concept-to-delivery capability is among the best in the world. All of these capabilities have been essential to the development, deployment, commissioning and operation of the 12 GeV CEBAF Upgrade and continue to be essential to refurbish cryomodules from CEBAF which is critical to maintaining the gradient needed to support the Physics programs. The completion of TJNAF’s Technology and Engineering Development Facility (TEDF) Project, provided about 40,000 additional square feet of space. This additional space combined with the renovated existing space, also completed as part of the TEDF Project, enhanced and enabled all SRF operational elements to be co-located. The new facility also includes additional experimental assembly space. Integral to the new facility is configurable space that can be adapted to work on different kinds of SRF cavities as TJNAF’s portfolio of projects expands. Essential to the SRF program at TJNAF is a five-year plan to progressively update the SRF processing tools to optimally leverage the building infrastructure to improve processing and achieve a safer and ergonomically better work environment.

The SRF Facility will be used to assemble the cryomodules for the LCLS-II project. Modifications have been made to the configurable space to adapt the Facility for the production of LCLS-II cryomodules. New assembly tooling has been added and integrated with existing tooling to provide a unique and efficient approach to assembling cryomodules for the LCLS-II project. Additionally, new RF capability is being added to the SRF Cryomodule Test Facility (CMTF) to enable acceptance testing of the LCLS-II cryomodules. The new tooling and the upgraded CMTF will first be used to assemble and test the LCLS-II prototype cryomodule in late FY16. Construction of the production cryomodules is planned to start in late FY16 and continue into early FY19.

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 an important resource for the US 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) 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 Masters theses to ensure the continuity of this expertise in the coming decades.

TJNAF's cryogenics group's highly-skilled staff operates and improves the laboratory's three large 2K cryogenic plants (Central Helium Liquefier (CHL) 1 & 2 and the Cryogenic Test Facility (CTF)) that support CEBAF operations and SRF production. Including the existing Endstation Refrigerator (ESR), the overall refrigerator count has increased to five operational plants (adding CHL2 and Hall D) as the 12 GeV Upgrade came on-line. The large 2K plants utilize patented cryogenic cycles developed by TJNAF that increase efficiencies by up to 30% as compared to what has traditionally been available from industry. Extensive operational experience has allowed the group to develop controls technologies and techniques that permit year round, unattended operations that drastically decrease staffing needs required for operations of this magnitude. Additionally, stepwise improvements have been made on the mechanical systems, primarily the warm compressors, which significantly extend their lifetimes between major maintenance cycles and decrease input power needs. The combination of cycle and mechanical improvements has decreased the input power requirements for equivalent refrigeration at 2K by 1.4MW for CHL2 as compared to CHL1.

The 12 GeV Upgrade has benefitted from improvements that were first demonstrated at NASA's Johnson Space Center where both the cycle technology and improvements on the warm compressor system were applied to a 12.5kW refrigerator at 20K for a space effects chamber to test the James Webb telescope. Prior to this, the cycle technologies were applied to other DOE facilities, notably to the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.

The group is presently responsible for designing, specifying, procuring and commissioning the CHL for FRIB, based on the successful CHL2 design for the 12 GeV Upgrade. Additionally, responsibilities for specifying and procuring the two LCLS-II refrigerators have been undertaken by the group.

Nationally, this group is a premier source of cryogenic engineering and design for large helium refrigerators, filling a void in commercially available services. TJNAF's cryogenics group is consulted when project needs for a large helium refrigerator system arise (>2kW @ 4K or equivalent capacity) to ensure effective design results and highly efficient operation.

The Large Scale User Facilities/Advanced Instrumentation Core Capability serves DOE

Scientific Discovery and Innovation mission numbers 24, 26 and 30 from Enclosure 1: List of DOE/DHS Missions.

4. Science Strategy for the Future

With the imminent completion of its 12 GeV upgrade project, TJNAF is well positioned to continue its world leadership in hadronic nuclear physics. The upgraded CEBAF along with the enhancements in experimental equipment offer many opportunities for major advances in our understanding of the substructure of the nucleon, the fundamental theory of the strong force QCD, aspects of nuclear structure relevant to neutron star physics, and the (lack of?) completeness of the standard model of particle physics. The new capabilities will enable unique 3D mapping of the valence quarks and extend the earlier studies to comprehensively describe the valence quark momentum and spin distributions in nucleons and nuclei. New opportunities to discover heretofore unobserved hadron states predicted by quantum chromodynamics will become available. Higher precision measurements of the weak couplings of elementary particles will be accessible through measurements of parity violating asymmetries. Full exploitation of the upgraded facility will require construction of new experimental equipment, and TJNAF has two proposed MIE projects (MOLLER and SoLID) that have received strong endorsement from the nuclear physics community.

The 2015 NSAC Long Range Plan (LRP) strongly supports the robust operation of CEBAF necessary to deliver the long-awaited science program: “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.” In addition, the LRP recommends “increasing investment in small-scale and mid-scale projects and initiatives” and we hope this can help realize the new MIE projects at TJNAF.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

Thomas Jefferson National Accelerator Facility is located on a 169 acre federal reservation. North of the DOE-owned land is an eight acre parcel referred to as the Virginia Associated Research Campus (VARC) which is owned by the Commonwealth of Virginia and leased to SURA which, in turn, sub-leases five acres of this property for $1 dollar per year to DOE for use in support of the Lab. SURA owns 37 acres adjacent to the TJNAF site, where it operates a 42-room Residence Facility at no cost to DOE. At the close of FY 2015, approximately 686 Staff FTEs, 24 Joint Appointments, 21 Postdoctoral Researchers, 7 Undergraduate, and 37 Graduate Students were occupying site facilities. Each day, TJNAF hosts on average, 100 users from the United States and around the world.

As of September 30, 2015, TJNAF consists of 66 DOE-owned buildings (867,028 SF), and four real-property trailers (9,056 SF) totaling 876,084 SF, plus roads and utilities. Additionally, the Lab leases office and shop buildings (37,643 SF) from the Commonwealth of Virginia, office and lab space (26,869 SF) from the City of Newport News located in the Applied Research Center (ARC) adjacent to the TJNAF campus, a temporary office trailer (469 SF), and 9,755 SF of off-site leased storage space totaling 74,267 SF of leased space. The Lab continues efforts to consolidate leased and trailer office space with the elimination of 8,964 SF or leased and owned trailers in FY 2015 and the planned elimination of 6,596 SF of trailers in FY 2017.

Table 1 shows the results of recent Lab Operations Board (LOB) sponsored condition assessment. The Lab has completed the condition assessment of all facilities. A total of 60 of the 70 DOE owned and leased buildings were found to be adequate, 9 substandard, and one (1) inadequate. Of the 5 owned and leased trailers assessed, four were found to be substandard and one (1) inadequate. Of the 36 other structures and facilities (including OSF 3000 series assets) assessed, 30 were found to be adequate, 5 substandard, and one (1) inadequate. A total of 4,920 SF of real property trailers are currently underutilized and plans are being developed to eliminate this space. There are currently no excess facilities at the Lab and none are expected within the next 10 years. Currently, there are 55 aged shipping containers (17,000 SF) used for storage, a reduction of six containers over the last year. An additional 17 shipping containers are scheduled to be removed by the end of FY17.

Table 1: Facility Assessments and Excess Facilities

	Adequate		**Substandard**		**Inadequate**	
	Count	**SF**	**Count**	**SF**	**Count**	**SF**
Other Structures and Facilities (OSFs)	25	N/A	5	N/A	1	N/A
Mission Unique Facilities	37	328,650	0	0	0	0
Non-Mission Unique Facilities	29	322,183	12	291,673	2	4,157
	Count	**SF**				
Number and square footage of excess facilities	0	0				
Square footage of underutilized space in non-excess facilities.	2	4,920				

A current copy of the Land Use Plan can be can be found on the TJNAF Facilities Management website. The Lab has leased 9,275 SF of warehouse space in FY16 in support of Lab efforts on the LCLS2 project at SLAC. The lease for the Service Support Center (34,739 SF) and Facilities Shops building (2,904 SF) was extended in FY15 from September 30, 2017 to September 30, 2045. The current lease of 26,869 SF in Applied Research Center expires September 30, 2017 and will be renegotiated in FY16.

Campus Strategy

The objectives for the 2026 TJNAF Lab Campus plan are:

- Construct and upgrade facilities and utilities to fully support mission objectives.
- Replace substandard temporary and leased space with permanent facilities.
- Increase energy efficiency and support DOE sustainability goals and requirements.
- Accommodate a Jefferson Lab Electron Ion Collider (JLEIC)

Infrastructure investments over the last ten years have provided more than 264,000 SF of new facilities (Experimental Hall D, Technology and Engineering Development Building, CEBAF Center Wing F, General Purpose Building, and Experimental Staging Building. This construction includes the Technology and Engineering Development Facility project was completed providing the Lab a new 74,000 SF Technology and Engineering Development (TED) Building, a 47,000 SF Test Lab Addition, as well as a renovated Test Lab, (a 50 year-old previous NASA facility), funded by the Science Lab Infrastructure (SLI) program. In addition the Accelerator Site electrical distribution system primary and secondary feeders and cooling towers have been replaced as part of the SLI funded Utilities Infrastructure Modernization (UIM) project. The remaining portions of the UIM project work will be completed in FY17. Through these projects, the campus has been transformed into a walking-campus, with many sustainability features incorporated. Current critical infrastructure gaps shown in Table 1 below have been identified through the latest Lab condition assessment. These gaps need to be closed to enable a fully mission-capable campus.

Infrastructure Gaps

Infrastructure Component	Gaps and Impacts
Cryogenics	Hall and Cryogenics Test Facility cryogenics are unreliable due to age of equipment
Office and meeting and collaboration space	Temporary / leased office space for scientists, engineers, and support staff is substandard or inadequate Lack of modern meeting capabilities negatively impacts collaboration
High bay fabrication/experimental equipment assembly	High bay fabrication space is over-utilized Layout of existing experimental equipment assembly space is not functional and is not fully utilized for its intended purpose due to storage and other functions occupying the space
Shipping, Receiving, and Warehouse	Permanent warehouse space is over-utilized Temporary / leased storage space is substandard or inadequate Shipping and receiving functions currently occupy space which was intended for experimental equipment assembly
Sustainability	Numerous facilities are currently inefficient and do not meet HPSB or sustainability guiding principles
Site Utilities	Fire protection potable water, sanitary sewer, and storm water systems all lack capacity to support operations

Prioritized Infrastructure Needs

- **Cryogenics** (SLI/SLI-GPP /Lab GPP) - The Lab’s highest priority is to upgrade its cryogenic infrastructure to ensure reliability and capacity for future mission needs. Operation of the Cryogenics Test Facility (CTF) is critical to support testing for the cryomodule cavity components produced by the Superconducting Radio Frequency (SRF) Institute for Jefferson Lab, other Labs in the Office of Science complex as well as SPP. Installation of a new 4K cold box and controls under the UIM project will provide additional CTF 4K capacity. The new cold box will arrive in FY16 with installation complete in FY17. Additional investments are needed to increase 2K capacity and overhaul/replace aging equipment related to 2K operations. These investments are planned by the Lab following delivery of LCLS2 cryomodules in support of anticipated future SRF projects for the DOE National Lab complex.
  A separate and unrelated issue of reliability of the 40+ year old End Station Refrigerator (ESR) plant serving three of the four experimental halls exists due to the lack of critical spare parts that are no longer manufactured or available. The replacement of the ESR will consist of a refurbished and installed surplus 4K refrigerator from the Superconducting Super Collider (SSC) project with the associated distribution system, utilities and controls.

- **Communications** (SLI) –Subsurface communications systems have insufficient capacity to meet existing and future needs. The UIM project currently underway will correct both of these identified gaps. Estimated completion is in FY 2016.

- **Computer Center Efficiency Upgrade and Consolidation** (SLI and Lab GPP) – Computer Center cooling and power improvements are now underway under the UIM project and will provide needed data center cooling and uninterruptable power utility capacity to support lab computing needs. This project is scheduled for completion in FY16. HVAC improvements under the UIM project will provide core computing hot and cold aisle configuration to allow consolidation of the Lab computer and data centers. A Lab funded GPP project will provide high performance computing hot and cold aisle configuration to reduce the Power Utilization Efficiency (PUE) to assist in the Lab meeting DOE Computer Center power efficiency goals. Estimated completion is in FY 2017.
- **EHS&Q Offices** (Lab GPP) – Construction of 12,000 SF of energy efficient office and technical space to house the EHS&Q Division will consolidate the staff currently residing throughout the Lab in a combination of overcrowded, aging trailers and leased space. Project will allow elimination of a trailer and reduction of long term leased space. Construction is underway and is scheduled for completion in FY 2017.

- **CEBAF Center Renovation** (SLI-GPP) – The condition of the 1988 original structure has been rated as substandard. The mechanical system in this portion of the building has exceeded its service life and has experienced multiple failures. Replacement of major pieces of HVAC equipment is required in the near future. Replacement of the HVAC system will require vacating the portion of the building under renovation and removal and replacement of the ceilings. Lab staff is currently overflowing into common areas such as corridors, storage rooms, and copy areas creating egress issues and safety concerns. Reconfiguration of the affected spaces is needed to alleviate many of these conditions. Renovation will meet high performance building standards. The renovation will be executed one wing per year plus the atrium/auditorium in the fourth year using a combination of Lab GPP and facility maintenance funds.
- **CEBAF Center Office Expansion & Modernization** (SLI) – The current site at TJNAF accommodates the staff needed for ongoing operations. However, existing office facilities are inadequate, and impede progress. Currently over 22,200 SF of office space and meeting rooms are leased in the Applied Research Center owned by the City of Newport News to accommodate staff. A portion of this leased space is occupied by the Center for Advanced Studies of Accelerators (CASA). It is important for CASA to be co-located with Theory, Physics, and Accelerator divisions. The scientific community is growing and there is limited flexible, reliable, and efficient collaboration space: large meeting rooms have to be rented off-site for large meetings and collaborations. In addition, with the Auditorium and storage space for TJNAF's educational program located in other buildings across the site, work-flow from one building to another is inefficient. The ARC building is also rated as substandard and needs a sustainability renovation to reduce energy consumption towards DOE goals. A long term infrastructure initiative is to house Lab staff and operations within DOE owned space. These functions would fit well within an office addition to CEBAF Center. The Lab also lacks adequate meeting space to host numerous Lab meetings and collaborations. Inclusion of meeting space along with office space is the proposed SLI project. The scope includes 83,000 SF of office and meeting space. Construction will meet high performance building standards. The preliminary cost and time estimate for this element of work is $66M and three years including design. The project could eliminate up to 55,000 SF of leased space while providing the needed meeting space to support ongoing programs.
- **Physics Technical Support Building** (Lab GPP) **-** Currently technical staff and equipment supporting the operations for all four experimental halls are spread among several buildings on the campus and accelerator site. This project will provide 12,000-14,000 SF of technical and high bay space for fabrication and improves efficiency by consolidating these functions and locating them in closer proximity to the experimental halls. Additionally, the project resolves space shortages of Engineering Division technical and high bay fabrication space as well as provides swing space required to conduct the EEL Renovation project. Construction will meet high performance building standards.

- **Water Reuse Capture and Tank** (Lab GPP) – Installation of rain water collection system and storage tank for use in cooling towers and for limited irrigation to reduce potable use to assist in meeting water sustainability goals.
- **Shipping and Receiving/Property Warehouse/Facility Operations** (Lab GPP) - Existing high bay and technical space in the Experimental Equipment Lab (EEL) is not fully utilized due to its required use for storing materials and equipment and for conducting shipping and receiving activities. Construction of a shipping, receiving and modern warehouse would allow improved use of the much needed high bay and technical space and allow elimination of 61 shipping containers for storage. Completion of this project is needed to create necessary swing space for the renovation of the EEL and to provide long term experimental setup and support space. The facility will also house the facilities maintenance shops currently in the (2,904 SF) Forestry Building leased from the Commonwealth of Virginia. This building is in substandard condition and needs to be replaced. The project will be constructed in phases based on Lab annual GPP funding. The facilities operations and maintenance shop will be the first phase. The project will be constructed in phases beginning with expansion of the Central Material Storage Area.

- **Experimental Equipment Lab Renovation** (GPP Cross-cut) - Renovation of the Experimental Equipment Lab building is needed to increase the functionality and utilization of the high bay space as well as to correct inadequate mechanical systems, improve efficiency of the building envelop and correct code deficiencies. The scope of the work will require vacating large portions of the buildings during the periods of construction. Functions will be temporarily relocated to the newly constructed Shipping and Receiving Warehouse to minimize the impact on operations.

- **Road Improvement** (Lab GPP) Reconfiguration and improvements of Lab entrance roads to improve site coordination with adjacent land development.

- **Site Storm Water Management** (Lab GPP) – Installation of a storm water retention pond to meet increasing regulatory requirements.
- **Accelerator Storage Building** (Lab GPP) – Currently storage to support SRF and other accelerator operations is scattered in numerous storage containers as well as off site in leased space. Onsite efficient storage will improve efficiency in accessing and management of materials. Project provides 6,000 to 8,000 SF of storage space for accelerator specific materials and assemblies and will reduce use of shipping containers and offsite leases.

The $29.9M FY 2014 UIM project will, among other things, resolve the above process cooling gaps with the replacement of aging cooling towers and electrical distribution and communication through the replacement of electric cabling and the installation of additional data cabling and equipment. The UIM project will eliminate more than $2.7M of deferred maintenance. The remaining gaps can be closed through a combination of SLI, SLI-GPP, and NP-GPP funding totaling $85.3M over the next ten years. These projects will eliminate more than $3.7M of deferred maintenance. Additional estimated funding of $2.5M is expected through a Utility Energy Services Contract to implement energy conservation measures.

The Lab's Asset Condition Index is 0.985, a rating of excellent. The Lab has averaged 1.5% maintenance and repair expenditures over the last 5 years. During this period the deferred maintenance has decreased from $15.8M to $5.9M through SLI and GPP capital investment and elimination of temporary facilities. Electrical and mechanical preventative maintenance costs have decreased through the conversion from contract to in-house resources. Enclosure 2 is the Integrated Facilities and Infrastructure Crosscut Data Table showing planned Lab maintenance and deferred maintenance projections. Through the planned investments we project a continued decrease in the values of deferred maintenance.

The Campus Land Use Plan is shown as Enclosure 3. Enclosure 2 shows the investments needed to implement this Campus Plan. The plan consists of a mix of SLI, infrastructure crosscut, NP- GPP, and alternative financing. NP-GPP funding levels shown were based on the annual NP budget guidance. It is not anticipated there will be any inadequate facilities at the end of the period.

The fully executed campus plan supports:

- 4 Experimental Halls fully operational
- 4-Hall multiplicity
- 35 weeks of research
- CEBAF reliability >85%
- Partner/lead on major SRF-based accelerator construction projects
- Ability to exploit/leverage capabilities of the Low Energy Recirculator Facility (LERF) (Isotopes, Dark Light, Industry and University-led research)

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

;

Objectives:		
	Objective 1	Construct and upgrade facilities and utilities to fully support mission objectives
	Objective 2	Replace substandard temporary and leased space with permanent facilities
	Objective 3	Increase energy efficiency and support DOE sustainability goals and requirements

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
EHS&Q Building	**2,150**	2,000		150											GPP	NP	EI
Core Computing Sustainability	**2,250**		2,000	250											GPP	NP	EI
Cryogenics Equipment Upgrade	**5,650**			1,600	2,250	1,800									GPP	NP	LSUF
Physics Technical Support Building	**5,000**					1,450	3,300	250							GPP	NP	LSUF
Central Material Storage Area Expansion	**1,800**							1,800							GPP	NP	LSUF
Shipping & Receiving Building	**2,120**							950	1,170						GPP	NP	EI
Facilities Operations Building	**4,000**								1,150	2,000	850				GPP	NP	EI
Water Reuse Capture & Tank	**2,000**									390	1,610				GPP	NP	EI
Lab Road Improvements	**2,000**											2,000			GPP	NP	EI
Property Storage Building	**2,535**											535	2,000		GPP	NP	LSUF
Site Stormwater Management	**2,000**												610	1,390	GPP	NP	EI
Accelerator Storage Building	**1,300**													1,300	GPP	NP	AST
Cryogenics Infrastructure Modernization – Exp. Halls *	**8,000**			8,000											GPP	SLI	LSUF
CEBAF Center Renovation - Wings A, B, C *	**9,800**				9,800										GPP	SLI	NP
EEL Modernization *	**9,900**								9,900						GPP	SLI	LSUF
CEBAF Center Office Expansion &	**62,000**				4,700	30,000	27,300								--	SLI	NP
UESC	**2,500**		2,500												--	--	EI

Core Capabilities

EI	Enabling Infrastructure
LSUF	Large Scale User Facilities/Advanced Instrumentation
AST	Accelerator Science and Technology
NP	Nuclear Physics

Idaho National Laboratory

1. Mission and Overview

The Idaho National Laboratory (INL) missions are to discover, demonstrate, and secure innovative nuclear energy solutions, other clean energy options, and critical infrastructure. The lab will achieve these mission objectives and technical outcomes and execute INL's vision to change the world's energy future and secure our critical infrastructure through:

- Focus on research, development, demonstration, and deployment (RDD&D) on grand challenges in energy and national security
- Designing, building, and operating world class and unique research, development, and demonstration (RD&D) infrastructure
- Working toward creating a global nexus of world-class scientific talent
- Building and sustaining global strategic partnerships.

To execute the INL mission, INL integrates and applies distinctive core capabilities and unique RD&D facilities with signature strengths in nuclear energy, clean energy deployment, and modernizing and securing critical infrastructure. The outcome will be transformational innovations in energy and security concepts.

In operation since 1949, INL is the nation's leading RD&D center for nuclear energy, including nuclear nonproliferation and physical and cyber-based protection of energy systems and critical infrastructure, and integrated energy systems RDD&D. INL is managed and operated by Battelle Energy Alliance, LLC (BEA), a wholly owned company of Battelle, for the Department of Energy (DOE) since 2005. BEA is a partnership of Battelle; BWX Technologies, Inc.; AECOM; the Electric Power Research Institute (EPRI); the National University Consortium (Massachusetts Institute of Technology, The Ohio State University, North Carolina State University, University of New Mexico, and Oregon State University); and the Idaho University Collaborators (University of Idaho, Idaho State University, and Boise State University).

2. Lab-at-a-Glance

Location: Idaho Falls, ID
Type: Multi-program Laboratory
Contractor: Battelle Energy Alliance
Responsible Site Office: Idaho Operations Office
Website: www.inl.gov

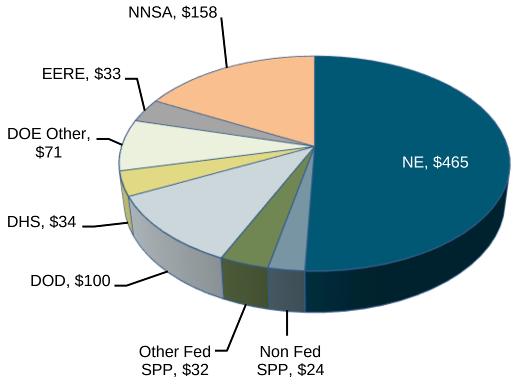
Physical Assets:

- 569,180 acres and 500 real property assets
- 2.3M GSF in buildings
- Replacement Plant Value (RPV): $4.8B
- 115k GSF in 13 Excess Facilities
- 1M GSF in Leased Facilities

Human Capital:

- 4,005 Full Time Equivalent Employees (FTEs)
- 18 Joint faculty
- 32 Postdoctoral Researchers
- 220 Undergraduate and 86 Graduate students
- 49 Facility Users
- 472 Visiting Scientists

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs (excluding Recovery Act): $917
DOE/NNSA Costs: $727
SPP (Non-DOE/Non-DHS) Costs: $156
SPP as % Total Lab Operating Costs: 21%
Total DHS costs: $34

3. Core Capabilities

Of the 24 core capabilities distributed across DOE's science and applied energy laboratories, INL has 13 DOE-acknowledged core capabilities and two DOE-acknowledged emerging core capabilities, indicating the exceptional breadth of its scientific and technological foundation. This represents a science and engineering skillset that extends across a continuum, connecting basic and applied research to testing and deployment. INL offers a broad array of capabilities in both fundamental sciences and engineering sciences in support of the DOE mission and delivers critical outcomes in nuclear, clean energy deployment, and critical infrastructure protection. Appendix B provides a mapping of INL core capabilities to DOE programs.

INL's core capabilities span nuclear engineering and related scientific disciplines, such as applied materials science, chemical and molecular science, condensed matter physics and materials science, nuclear and radiochemistry, chemical engineering, systems engineering, decision analysis, and probabilistic risk assessment, as well as purpose-built research infrastructure for nuclear energy, at-scale clean energy and environmental technology deployment studies, and critical infrastructure protection. Each core capability is a substantial combination of knowledge, people, equipment, and facilities, having unique and/or world-leading components, and is employed to respond to the INL mission challenges for DOE, NNSA, DHS, Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and other INL customers. Capability synergies enable INL to address research challenges posed by DOE's missions to carry out the transformative research required to accelerate the delivery of energy, environment, and security solutions to the marketplace, with an emphasis in RDD&D. INL's RD&D capabilities, resources, and unique geography enable the integration of scientific discovery, innovation, engineering, operations, and controls into complex/large-scale testbeds for discovery, innovation, and demonstration of at-scale transformational clean energy and security concepts, strengthening INL's leadership as a demonstration laboratory.

INL Core Capabilities

- Advanced computer science, visualization, and data
- Applied materials science and engineering
- Biological and bioprocess engineering
- Chemical and molecular science (emerging)
- Chemical engineering
- Condensed matter physics and materials science (emerging)
- Cyber and information sciences
- Decision science and analysis
- Environmental subsurface science
- Large-scale user facilities/advanced instrumentation
- Mechanical design and engineering
- Nuclear and radiochemistry
- Nuclear engineering
- Power systems and electrical engineering
- Systems engineering and integration

Created as the National Reactor Testing Station, INL pioneered the first nuclear-generated electricity to power an American community (Arco) and demonstrated the Navy's first nuclear propulsion systems. INL is where the nation's best and brightest researchers come to advance the promise of nuclear energy, the most reliable and cost-effective energy source to enable national objectives for addressing climate change. Since its creation, INL's RD&D portfolio has expanded. Today, INL is the lead national laboratory for nuclear energy RDD&D supporting the long-term operations of commercial light water reactors (LWRs), developing advanced nuclear reactors and associated fuel cycles and nuclear fuels. INL is home to some of the world's most unique facilities that support innovations across all aspects of nuclear energy and national security. In addition to nuclear energy, INL is a globally-recognized RDD&D leader in control systems cyber security and makes important contributions to secure and modernize the nation's critical infrastructure.

INL's 890-square-mile laboratory and testing complexes represent a synergistic integration of co-located and networked nuclear and national security facilities. INL hosts unparalleled assets, such as Materials and Fuels

Complex (MFC), Advanced Test Reactor, (ATR), Transient Reactor Test (TREAT), a utility-scale electric power grid for improving grid reliability and security; a wireless communications testbed supporting commercial and government-sponsored research; key capabilities for performing cyber and control system research, explosives and ballistic threat analysis, and armor development and production; and safe and secure locations for accelerating protective solutions development and testing, as well as for facilitating first responder training experiences in nuclear forensics, real-world contamination scenarios, and incident response. Combined with its internationally-recognized critical infrastructure protection and nuclear nonproliferation scientists and engineers, the INL resembles a city/region where challenging energy and security questions can be answered at scale. INL is addressing energy production challenges by facilitating discoveries and innovations to advance energy and security technology and enable clean energy deployment. INL has also made significant contributions in renewable energy grid integration and transportation system transformation. INL is addressing challenges in water utilization and energy-critical materials, assembling biomass feedstock, and optimizing the efficiency of advanced manufacturing processes. INL is deploying technologies that are increasing the balance, diversity, efficiency, affordability, and accessibility of domestic sources of energy and supporting the national transition to industrial competitiveness through energy security.

INL applies core capabilities to non-DOE sponsor needs through SPPs and other mechanisms that contribute to DOE’s investment results in RDD&D. SPPs also strengthen INL capabilities and sustain the ability to deliver on DOE missions.

Applied Computer Science, Visualization, and Data

INL’s strategic intent is sustained leadership with advances in applications in computational science and engineering, specifically focused on applications in nuclear energy, clean energy deployment, and critical infrastructure protection. INL’s computing success has been the rich internal and external collaboration centered on the Multiphysics Object Oriented Simulation Environment (MOOSE) framework. INL created MOOSE, an open-source, high performance computing (HPC)-based simulation framework (*54, 55*). The framework was built on a unique computational science approach, combining computer science with the mathematical description of the physics. MOOSE enables domain scientists to rapidly obtain fully coupled, fully implicit solutions of multiphysics problems using state-of-the-art nonlinear/linear solvers and takes full advantage of massively parallel computing. Many MOOSE-based simulation tools have been developed to predict the behavior of nuclear fuels and materials undergoing irradiation for both nuclear reactor normal operating and accident conditions. National and international laboratories and universities have developed more than 40 MOOSE-based applications.

INL focuses MOOSE-based software applications on nuclear power, materials, structural dynamics, multiphase flow, waste analysis, and geophysics. Nuclear power applications include: radiation transport, reactor physics, nuclear plant safety and systems analysis, growth and effects of corrosion and wear products (e.g., rust and particles), and multiscale nuclear fuels performance. Materials applications include materials development, effects of corrosion, damage and aging evolution, and irradiated material analysis. Over the years, MOOSE has evolved as a general-purpose, multiscale, multidomain simulation framework in many fields, including subsurface reactive transport modeling (*14*) and coupled hydro-thermo-mechanical-chemical processes. As such, INL is a recognized leader in the development of models to better understand fractures and fluids in tight rock formations, safe long-term stewardship of chemical and nuclear waste disposal in the subsurface (numerical simulation of contaminant fate and transport), risk analysis, and performance assessment. Geophysics applications include: seismic, geothermal, geochemistry, and isotope transport. MOOSE’s unified computational framework is also ideally suited for the development of next-generation earth system models, which require multidomain, multiscale, multiphysics coupling among hydrological, biological, and geochemical processes across both the subsurface environment and terrestrial ecosystems. INL will enable an increasing number of MOOSE-based applications, coupling experimental studies with modeling and simulation, and enhanced validation of these predictive capabilities through investment in a Collaborative Computing Center (C3)[12].

INL's risk-informed safety margin characterization is supported by the validated MOOSE-based safety analysis tool and supports management of uncertainty, nuclear reactor design, and improved decision making for nuclear power plants. ATR modeling and simulation (M&S) advances computational methods for nuclear reactor design/analysis and integrated reactor experiments and M&S are achieved through the TREAT simulator.

Approximately 80 researchers, including four joint appointees and 13 postdocs with expertise spanning physics, applied mathematics, materials engineering, mechanical engineering, risk analysis, computer science, computational science, and nuclear reactor engineering support this core capability. INL's Scientific Computing group provides computing and visualization resources to develop new capabilities, build tools, foster collaboration, and support external users. HPC systems run application codes from three primary categories: user-developed and open-source codes, such as MOOSE; DOE-controlled nuclear software, such as MCNP, ORIGEN, SERPENT, and MC21; and commercial engineering and scientific codes, such as STAR-CCM+, Abaqus, and VASP, which are used in research involving computational fluid dynamics, structural analysis, and materials modeling.

Computer modeling and simulation, when appropriately validated and coupled with experiments, extend our understanding beyond some of the limitations of experiments. In complex systems, such as a nuclear reactor or a power distribution grid, the theory that governs the behavior of individual components becomes interconnected in complex ways that both theory and experiment struggle to fully capture, predict, or explain. In these instances, computer modeling and simulation can provide critical insights and help accurately develop the understanding needed to engineer, design, research, and operate very complex systems. Nuclear energy development efforts have historically relied largely on theory and experiment, but in the future will rely increasingly on computer modeling and simulation. The field of big data analytics and data-intensive computing is a relatively new core capability that has significant applicability to many INL areas, such as knowledge management and validation, national security programs, cyber security research, and Earth and environmental sciences.

INL has leveraged this capability to support programs for the Office of Nuclear Energy (NE), Environmental Protection Agency (EPA), DoD, EPRI, Westinghouse, AREVA, Geothermal Technologies Office, the Office of Energy Efficiency and Renewable Energy (EERE)'s Bioenergy Technology Office, DHS, and NNSA. This capability advances DOE's goals in science and energy and nuclear security as articulated in the DOE Strategic Plan *(66).*

Applied Materials Science and Engineering

Applied materials science and engineering is a core competency and an area in which INL is recognized as an international leader in the nuclear energy generation research community and for critical infrastructure protection. An integrated set of capabilities, spanning nanoscale discovery to code case qualification, allows INL researchers to apply this capability to fabricate, characterize, examine, and store experimental quantities of nuclear fuels and materials; support applications in nuclear reactor systems, fuel cycle separation, used fuel disposition, isotope production, nuclear forensics, and post-irradiation examination (PIE); determine effective

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[12] See Section 6 for discussion of C3.

protections for the nation's critical infrastructure assets against environmental and man-made hazards; and manufacture Abrams A1 tank armor (INL is recognized as the U.S. Army's Armor Center of Excellence for heavy armor systems). INL's research expertise is in advancing nanoscale chemistry, dislocation dynamics, and nucleation and growth phenomena; characterizing materials and interpreting complex mechanisms to understand structure/property relationships and the role of defects in controlling properties; and improving performance of deployed materials in the most hostile environments. The capabilities are often used in conjunction with irradiation testing in the Advanced Test Reactor (ATR), providing researchers the opportunity to conduct irradiation experiments and develop an advanced understanding of its effects on fuels and materials performance. The U.S. Navy utilizes this capability to advance fuel designs that will allow a ship to never refuel.

Increasingly, research and experimental efforts are strongly coupled with INL's M&S capabilities at macro- and meso-scales, utilizing the MOOSE framework along with other sophisticated equilibrium and kinetic modeling tools. INL is integrating M&S with comprehensive experimental efforts to accelerate research productivity and predict fuel and materials performance along with the development and qualification of structural materials for emerging nuclear reactor systems. INL's next-generation fuel performance code is being used by various researchers across the DOE complex, universities, and industry. The MOOSE-BISON-MARMOT platform (referred to as MBM) relies on a multiscale, multiphysics, three-dimensional finite element, transient, and steady state framework and allows easy development of application software with emphasis on fuel performance. The BISON code is a thermo-mechanical, engineering-scale fuel performance code that runs under the MOOSE framework. It can be coupled to empirical, algebraic closure models to represent the fuel and cladding properties at different irradiation stages. For a more fundamental understanding of the fuel behavior at the meso-scale, BISON can also be coupled with the MARMOT code, which is another application under the MOOSE framework. MARMOT solves the phase-field equations to investigate the microstructural evolution in fuels and materials, along with the various transport phenomena inside and across the fuel grain boundaries. Together with the experimental capabilities at ATR and MFC, MBM provides a predictive fuel performance code with less reliance on empirical models. INL is also in the process of restarting the Transient Reactor Test (TREAT) Facility to support the type of transient testing needed to develop and prove the critical safety basis of advanced reactor fuels. TREAT will allow the investigation of fuel behavior under off-normal conditions, such as large power increases and loss-of-cooling events.

The strategic intents are to: (1) enable use of improved fuels and materials in advanced reactors; (2) facilitate refinement of international evaluations and test standards; (3) develop coupled testing and characterization approaches to decipher property evolution; (4) enable intelligent design of alloys through the process-microstructure-property link; (5) enhance the capability through advanced instrumentation that allows in-reactor measurement of materials response during irradiation; (6) advance materials science instrumentation and techniques for application to radioactive and highly radioactive materials in hot cell or glove-box operations; (7) identify and design advanced remote sampling manipulation equipment for both in-cell and out-of-cell sampling handling operations, including sorting, cataloguing, preparation, and transport; (8) build new capabilities for in-canal experiments; (9) integrate with computational techniques for verification and validation of predictive models; (10) develop the next generation of verification, signatures, and observables for safeguarding of nuclear and radiological materials; and (11) generate irradiated materials data in support of existing LWR fleet life extension.

Approximately 481 staff members and 12 postdocs support the development of new fuels and materials to enable emerging nuclear technology. Their work provides a technical basis for materials behavior to meet established and predicted performance requirements for a range of nuclear reactor systems, such as modeling and simulation, innovative lightweight materials for armor protection applications, hardening of critical infrastructure, the development of advanced materials to vastly improve many aspects of emerging energy systems, and the qualification of new materials systems and processes to optimize end-use performance through a multiscale understanding of physical and mechanical properties.

The combination of ATR, MFC, and TREAT, with complementary capabilities at the Center for Advanced Energy Studies (CAES), Energy Innovation Laboratory (EIL), and Specific Manufacturing Capability (SMC) make for world-class fuels and materials characterization, irradiation, PIE, and testing capabilities to support this core capability.

Primary sponsors for this capability are NE, EERE, Office of Electricity Delivery and Energy Reliability (OE), SC, NNSA, and DoD. Other sponsors include EPRI, TerraPower, Westinghouse, Office of Naval Reactors (NR), the Korea Atomic Energy Research Institute (KAERI), and the intelligence community. In addition, INL is working toward sponsorship from the Nuclear Regulatory Commission (NRC), DHS, Basic Energy Sciences, the Department of State, and ARPA-E.

Biological and Bioprocess Engineering

INL's core capability spans bench-top analysis through scale-up and integration to address challenges in biomass preprocessing solutions, logistics, feedstock supply/specification, supply chain development, and demonstration challenges. INL focuses on innovation in feedstock and bioproducts to incorporate bioenergy as a viable part of an energy portfolio. INL performs independent testing, development, and scale-up of preprocessing systems with producers of biomass feedstock and bioproducts to reduce variability and produce high-quality feedstock from grass, wood, and agricultural residues. Biomass variability makes it a uniquely challenging feedstock compared to other energy feedstocks, such as coal and crude. Over the last decade, INL has built expertise in characterizing chemical and mechanical properties, decontamination process technology, trace detection, and process system design. INL is recognized by EERE's Bioenergy Technology Office in supporting two areas: (1) feedstock preprocessing scale-up and integration and (2) feedstock production and supply.

The strategic intent is to develop innovative, intelligent, and adaptive control solutions for integrated preprocessing of biomass materials. This will dynamically adapt processing conditions to produce consistent feedstocks from variable and diverse starting materials. INL combines system integration, chemical engineering, analytical chemistry, agricultural science, and materials science to assess supply chain design and provide understanding of cost, quality, and risk tradeoffs for economic viability of biofuels. INL increases biomass efficiency to enable a successful supply chain. INL combines operational data and field trials, physiochemical characterization data, and lab and full-scale conversion data to: (1) inform feedstock development and selection, (2) improve conversion process development and selection, (3) streamline supply chain processes, (4) assess the value of domestic and export trade, (5) develop U.S. biomass standards, and (6) utilize a large-scale, fully integrated pilot facility for process development, scale-up, and toll processing.

INL plans to expand this capability by developing particle mechanics and solids flow capabilities with expanded computational science tools, such as computational fluid dynamics and finite element modeling supported by HPC capabilities. Enhanced characterization tools (e.g., nuclear magnetic resonance, microscopy, and quantitative 3D x-ray), mechanical testing tools (e.g., flowability testing and shear testing) and large-scale validation using the process demonstration unit (PDU) will also be used to support the research. As the capabilities are developed, they will be available through the Biomass Feedstock National User Facility (BSNUF) to support collaborative projects with industry, universities, and other federal agencies.

Approximately 114 staff members, including experts in chemical engineering, materials science and engineering, systems science, data mining, computational intelligence, and cognitive learning approaches support this capability. INL's enduring physical asset, PDU, is a one-of-a-kind, fully integrated pilot facility. PDU is the associated characterization capability at the Biomass Feedstock National User Facility (BFNUF), and the other components of this capability make INL the most complete feedstock preprocessing R&D and pilot facility in the world.

The primary sponsor for this capability is EERE for the cost reduction, performance improvement, technology validation, and risk reduction goals for bioenergy, as identified in EERE's strategic plan.

Emerging: Chemical and Molecular Science

Over the years, INL has developed expertise in understanding, predicting, and controlling physical and chemical transformations, and has created a rich and robust knowledge of chemical process technologies in several niche areas, including critical materials. Specifically, this expertise includes chemical separation, electrochemical separation, separation science, membrane science, radiochemistry, actinide chemistry, catalysis, and trace analytical measurements to support lowering energy consumption, securing supplies of critical energy materials, and reducing waste.

INL has applied this capability to develop scientific advancements to ensure a sustainable domestic supply of critical materials, secure resource supply, reduce waste, improve catalysts and catalytic processes, and save energy by delivering efficient approaches that improve energy- and resource-intense processes. Facilities that support this capability include: the CAES[13] laboratories, CAES Materials and Characterization Suite (MaCS), EIL, and Energy Systems Laboratory (ESL). Most recently, INL has developed capabilities in Temporal Analysis of Products (TAP) for catalysis research-kinetics of gas-solid interactions and Switchable Polarity Solvent Forward Osmosis (SPS-FO) for water purification. SPS-FO provides a new way to purify water that can be operated using waste heat or cheap high-grade thermal heat from sources such as natural gas. By removing the need for significant electricity inputs, the cost of water treatment can be significantly lowered using SPS-FO in place of more traditional processes, such as reverse osmosis. The TAP capability is unique in the DOE complex and one of three in the U.S. It will be used to assess steps of elementary reactions on complex materials (as opposed to single crystal surfaces) for development of multi-step microkinetic reaction mechanisms. TAP requires specialized expertise for design, execution, and interpretation of experimental data. INL has such a team.

The capability is supported by approximately 105 staff members with expertise in materials science and chemical engineering, and is expanding capabilities in: (1) process design and scale-up; (2) carbon conversion; (3) biomass characterization; (4) chemical composition and analysis; (5) thermochemical feedstock properties; (6) rapid screening techniques; (7) microscopy and imaging; (8) particle characterization; (9) PIE; (10) nondestructive

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[13] CAES (55,000 ft^2) fosters multi-institution, collaborative energy research programs important to the nation; attracts students and faculty to the Idaho universities; promotes informed energy policy dialogue across Idaho and the nation; and acts as a catalyst for technology-based economic development in Idaho. CAES houses: (1) radiochemistry laboratory, (2) advanced materials laboratory, (3) analytical chemistry laboratory, (4) advanced transportation laboratory, (4) microscopy and characterization suite, (5) fluids lab, (6) advanced visualization laboratory, (7) analytical instrumentation laboratory, and (8) human performance simulation laboratory. These laboratories support materials science, advanced visualization and modeling, actinide sciences, analytical chemistry, and carbon management. The capabilities are made available to CAES partners through collaborative research activities in nuclear science and engineering, bioenergy, carbon management, energy efficiency, and advanced materials.

analyses; (11) actinide chemistry; (12) advanced molecular battery electrolysis; (13) decontamination technologies; and (14) geochemical modeling, subsurface fate, and transport.

Primary sponsors for this capability are NE, EERE, OE, and DoD. INL is working to increase its SC collaborations and partnerships.

Chemical Engineering

INL has a long history of chemical engineering achievements related to nuclear fuel separations, radioactive waste treatment, chemical transformation of energy-intensive industrial processes, catalysis, securing supplies of critical energy materials, and transformation to clean transportation. Separation of used fuel constituents to recover fissile material and prepare long-lived radioactive elements for disposal is usually accomplished by either aqueous solvent extraction technology or by non-aqueous electrochemical means. In the area of solvent extraction, INL has engineering-scale pilot plants to perform testing with all three major extraction equipment types (pulse columns, mixer-settlers, and centrifugal contactors). INL is the only laboratory in the U.S. that has pilot facilities and expertise for all three equipment types. These pilot facilities currently support development of separation technologies for nuclear energy, critical materials, environmental management, and homeland security missions.

The Laboratory's history and expertise in reprocessing spent nuclear fuel requires unique capabilities in process chemistry and process development for separation of highly radioactive chemicals. The applied chemical research performed at INL bridges a range of scales from molecular studies to large-scale process and system design and seeks to discover and develop unique chemical-based solutions for complex energy and national security problems. INL maintains a large number of laboratories and process development facilities dedicated to generating these innovative solutions.

INL is the only facility in the U.S. that has an engineering-scale electrochemical separations facility, utilizing an electrorefiner in a shielded hot cell facility, for the processing of used nuclear fuel. INL engineers have successfully demonstrated the scale-up of electrochemical processing by three orders of magnitude. This facility continues to serve a key role in the exploration of safeguarded and advanced separations processes and is an important element of U.S. cooperation with the Republic of Korea.

In the area of non-nuclear chemistry, INL is a technical leader in the development of solid oxide cells for the production of hydrogen and synthesis gas ($CO+2\ H_2$) using heat and electricity. INL currently has six test stands for long-duration (24 hours a day, 7 days a week) unattended experiments on single cells and stacks containing 3–25 cells to support this work. The longest duration stack test to date has been 2,500 hours. INL's largest test to date has been the Integrated Laboratory Scale experiment, with 720 cells and 18 kW. INL's expertise in identifying and characterizing chemical constituents in extremely harsh environments is used to understand how materials withstand highly corrosive, high-temperature environments typical of those required for thermochemical production of hydrogen, production of synthetic fuels, and removal of carbon dioxide from chemical processes and power plant exhaust.

INL's chemical engineering talent actively develops new and efficient methods for densifying biomass; safe, high-energy storage lithium batteries; novel biochemical routes to renewable fuels; durable storage materials for nuclear processing waste; and efficient recycling of energy-critical materials. To achieve these new technologies, bench scale and pilot plant testing is performed in partnership with U.S. industry, regional universities, and other national laboratories.

INL's expertise in applied chemical and industrial process modeling, systems engineering, and system control theory provides a unique ability to integrate complex chemical operations. INL is applying this capability to develop a hybrid energy system composed of renewable, nuclear, and fossil energy production coupled with energy-intensive industrial processes, such as petroleum refining, oil shale retort, and methanol and ammonia production, as well as high-capacity energy storage to provide a balanced approach to energy production and use.

In the area of catalysis, INL has unique capabilities with the recent addition of the TAP reactor system and supporting expertise. This instrument is the centerpiece for the development of a new catalyst design paradigm based on understanding the link between surface composition and microkinetic details. INL is working toward establishing a "user-facility"-type center where the TAP capability can be made more accessible to collaborators from industry and academia.

Radioactive waste treatment is a strong INL capability with niche applications for DOE. INL has decades of experience in the design, scale-up, and operation of fluidized-bed calciners and steam reformers for the solidification of waste.

The strategic intent is to lead market transformation through advanced chemical separation and heterogeneous chemical and electrochemical catalysis, as well as advance process engineering by bringing fundamental research to scale. Approximately 119 staff members and RD&D facilities, including MFC, Bonneville County Technology Center (BCTC), Chemical Processing Plant (CPP-653) Material Recovery pilot plant, Moran Plant[14], Remote Analytical Laboratory CPP-684. MaCS, CAES, ESL, EIL, and TAP support this capability at INL. INL has leveraged this expertise to support programs for NE, Office of Environmental Management (EM), NNSA, DHS, and DoD.

Emerging: Condensed Matter Physics and Materials Science

INL has a growing core capability in condensed matter physics and materials science that underpins INL's nuclear energy mission. Areas of research include: (1) energy carrier transport in actinide-bearing materials, (2) mechanical properties of materials with respect to extremes in radiation, stress, and temperature, and (3) radiation-induced defect formation, clustering, and elemental redistribution. Currently, INL has considerable capability to characterize all aspects of the structure-property relationship in a post-irradiation environment. However, because of annealing of point defects and damage caused by auto-irradiation during cool down, further progress in mapping of the structure-property relationship will require a step change in the capability to characterize materials in-reactor. Accordingly, future areas of research will include: (1) high throughput combinatorial materials science to develop sensor materials that are resistant to radiation, chemical diffusion, and thermal and mechanical stresses, (2) new sensor designs and advanced manufacturing technologies that will enable measurement of physical properties with high spatial resolution, and (3) identifying specific measurements and measurement parameters (e.g., measurement viability, measurement accuracy, length scale, and time scale) that can be best used to validate state-of-the-art computational materials science models.

INL uses this capability to evaluate longevity, economics, and safety of nuclear reactors; advance the understanding of radiation response of nuclear fuels and materials through microstructural characterization and evaluation of length-scale-dependent thermal and mechanical properties; and conduct research in materials design, development, and testing for innovative energy concepts that address current nuclear and non-nuclear

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[14] Refiners and suppliers of unbranded transportation fuels, heating oil, and petrochemical feedstocks.

energy market needs. INL leads in the characterization of nuclear fuels and materials focusing on the relationships between radiation-induced microstructural evolution and physical, thermal, and electronic properties; the use of multiscale simulation tools to understand and design new material systems; and the application of information to fabricate new materials and material systems.

Approximately 90 staff members, including two joint appointees and five postdocs, support this capability to address challenges in nuclear fuels and materials innovations in understanding: (1) thermal transport phenomena in nuclear fuel, (2) mechanical behavior of structural materials, (3) radiation effects in fuels and structural materials, and (4) multiscale characterization of radiological material using advanced microscopy. Primary facilities include MFC, CAES, MaCS, laser-based materials characterization, and Carbon Characterization Laboratory. INL has leveraged this expertise to support programs for NE, NNSA, NR, EPRI, NASA, and nuclear reactor fuel vendors. INL is also expanding industry cooperation through the GAIN, Office of Fossil Energy, and EERE programs.

Cyber and Information Sciences

The strategic intent of cyber and information sciences is securing the nation’s critical infrastructure to improve its resiliency; the nation’s critical infrastructures become more instrumented and vulnerable as they are continuously connected to information and wireless communication systems. INL is a leader in and internationally recognized for industrial control systems security at the confluence of cyber security, wireless, embedded protocols, and threat assessments. The critical infrastructure protection facilities utilize specialized environments spread across the INL landscape. INL also maintains strong ties with control systems vendors and infrastructure owners/operators.

INL’s R&D capabilities and long-standing operational support of the DHS Industrial Control Systems Cyber Emergency Response Team (ICS-CERT) is an example of how INL’s expertise in vulnerability discovery, malware analysis, incident response, risk assessments, reverse engineering, and hardware exploitation support control system security needs to the nation. In addition to this support, INL advances tools and approaches utilized by ICS-CERT, such as the Automated Vulnerability Assessment, which increases the scalability of critical infrastructure assessments and enables the development of a catalog of critical systems for rapid evaluation. These capabilities are also applied to other DHS programs supporting activities in regional resilience, infrastructure situational awareness, and infrastructure dependencies/interdependencies.

INL’s capabilities in this area extend to nuclear operations and nuclear security. INL’s framework for enhancing the cyber security of nuclear facilities includes cyber-informed engineering, advanced malware detection, analysis, and reverse engineering and mitigation strategies. INL leads the innovation in cyber-informed engineering of control systems and re-prioritizing R&D and mitigation activities based on risk-based analysis of cyber-physical consequence. Innovations in cyber-informed engineering include: (1) new and systematic methods and tools that are threat-informed and consequence-driven to provide engineering-based mitigations, (2) new threat analysis techniques to baseline cyber threat actors according to specific technical capabilities for high consequence events and not just “intent,” (3) discovery and remediation of new cyber-physical effect modes and gaps in physics-based modeling and simulation tools (e.g., cyber-induced water-hammer and appropriate transient analysis in fluid dynamics codes), and (4) discovery and definition of limits for quantitative risk tools based on purely physical failure modes. Innovations in intelligent monitoring and control include: (1) cyber state awareness in trusted control loops, (2) cyber monitoring techniques for unique and fragile protocols in operational layers of controls systems, (3) techniques and tools for embedded control systems forensics and verification, and (4) out-of-band sensors, operational process modeling, and fusion of sensors/state models into operational cyber situational awareness.

At the request of the International Atomic Energy Agency (IAEA), INL cyber security subject matter experts have assisted in updating Design Basis Threat guidance, conducted in-field technical training, and teamed with other international experts to produce direction related to conducting cyber security training and assessments of nuclear facilities. INL provides international and domestic leadership in nuclear cyber security across the commercial fuel cycle (non-weapons).

INL established multidisciplinary technical teams to address the protection of the nation's critical infrastructure against all hazards with an emphasis on cyber/physical threats and inherent interdependencies. The teams are at the forefront of supporting DOE and other U.S. Government agencies faced with protection of the nation from increased critical infrastructure threats from both domestic and international actors. Team members represent the top talent for evaluation of technical threats and threat actor analysis, vulnerability assessment, interdependency and impact analysis, solution development, prototypes/demonstrations, technical training, and innovative and deployed products.

INL's critical infrastructure protection and cyber security capabilities and related applications are internationally recognized in areas of energy, national security and industrial process security, optimization, and control. INL offers unique and extensive capabilities in control systems security that can be broadly grouped into three main R&D areas: information and decision-making systems, cognitive science and human-computer/machine interaction, and cyber security.

In the area of information and decision-making systems, INL has world-class expertise in innovation of intelligent monitoring and control systems for both energy and national security research applications. INL has over 175 staff members with expertise spanning critical infrastructure testing and analysis, control systems cyber R&D, infrastructure resiliency, cyber-informed design, and disaster recovery. This team is dedicated to industrial control cyber security projects sponsored by national security customers, including DoD, DHS, DOE, and the Department of Justice.

In addition, INL's cyber information capability supports DOE's mission by developing technologies using computational intelligence methods that address complex engineering issues. For example, INL introduced innovative monitoring and decision-making technologies for: effectively integrating complex energy systems and increasing their energy conversion efficiency, decreasing environmental impact, exploiting low-quality energy sources, enabling efficient grid introduction of intermittent renewable, managing variability, enabling resiliency behavior, improving safety, and accommodating reliable and stable dynamic operation. To improve national security, INL has likewise developed predictive techniques that can best utilize collected information for the prompt detection, diagnostics, prognostics, and control of anomalies and health conditions of equipment, unit operations, processes, systems, and systems-of-systems under observation. INL provides leadership and expertise for both private industry and federal programs, as illustrated by the success of Resilience Week, an annual INL-sponsored symposia dedicated to transforming the resilience of cognitive, cyber-physical systems.

Primary facilities include ICS-CERT watch floor, training facilities, full-scale control systems and grid; Wireless Testbed; infrastructure for full-scale testing (e.g., power, wireless, water, transportation, control systems); and the Critical Infrastructure Test Range Complex (CITRC), a national proving ground for multiple government agencies and industry.

Decision Science and Analysis

Decision science and analysis is a subdiscipline of systems engineering that 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, and to assess the impact of market dynamics, human behavior, and regulations, policies, or institutional practices on their decisions. This capability provides credible, objective information to assist DOE and other customers with strategic planning and program direction, policy formulation and implementation, and efforts to remove market barriers to deployment and to improve engagement with stakeholders. INL has built leadership in data-driven methods, probabilistic modeling, complex systems analysis, and tools for creating knowledge and insights that support INL in managing and developing understanding of impact of nuclear operations of existing nuclear power plants around the world. INL has expertise in advanced reactor concepts (non-LWR technologies), hybrid energy systems, applied mathematics, thermal hydraulics, reactor physics, HPC, modeling and simulation, and cyber-informed risk and vulnerability assessment methodologies for cyber-physical systems including infrastructure dependencies/interdependencies, and next-generation control loop theory. INL has extensive experience planning, organizing, and conducting trade studies. These often take advantage of a suite of recognized commercial off-the-shelf and internally developed tools and processes to aid the decision-making and risk management process and to help programs, projects, and organizations better understand, manage, and solve complex challenges.

In an environment of ever-increasing technical, regulatory, and political complexity, any decision requires decision makers to: (1) understand the complexity and interrelationships associated with pending challenges and how those challenges integrate with other enterprise elements, (2) resolve large and varied opinions on solutions to such challenges, (3) understand the precedence and interrelationships of their decisions, and (4) establish a risk-informed, defensible path forward for viable solutions. INL leverages decision science and analysis capability to meet decision-making challenges.

INL has a deep and rich history in the development of probabilistic risk assessment (PRA) methods, tools (including nationally recognized and used computer models), and in the application of those models to evaluate complex nuclear systems for commercial nuclear power, space, and defense. The NRC's risk-informed regulatory framework is based, in part, on insights derived from PRA. Risk-informed plant safety performance measures, risk models used in the reactor oversight process, and the internationally recognized SAPHIRE code for risk evaluation were all developed by INL. INL's PRA professionals, with a strong focus on nuclear power plant risk and safety, is likely the largest such group in the U.S. Complementary capabilities in plant operating data analysis and human reliability analysis round out INL capabilities in this important area of nuclear safety.

With over 110 highly trained professionals, INL has built leadership in: (1) risk management, risk-informed decision-making, risk-informed safety margin characterization (RISMC), uncertainty analysis, PRA, and human performance and reliability; (2) operating experience and data management; (3) statistical analysis and trending; (4) regulatory decision making and risk-informed regulation technical support; (5) nuclear cyber, critical infrastructure protection, and grid security; and (6) advanced energy systems, hybrid energy systems, renewable energy systems integration, waste disposition, critical materials resource expansion, and vulnerability reduction. This core group of highly trained professionals applies organized, interdisciplinary approaches to solve a variety of operational, organizational, programmatic, and research problems. This capability integrates the technical skills necessary to provide reliable, quality products, processes, and services specifically targeted at helping organizations make informed decisions. In short, INL provides the rigor and understanding necessary to help organizations and projects make logical, defensible, data-driven, and risk-informed decisions.

This capability provides leadership and expertise for both private industry and federal programs, including NE, NRC, DHS, EERE, Office of Intelligence and Counterintelligence, DoD, the Transportation Security Administration, NNSA, NASA, EPRI, Canadian Nuclear Safety Commission, Norwegian Research Council, Halden Reactor Project, NuScale, TerraPower, EDF Energy, and the UK Nuclear Decommissioning Agency.

Environmental Subsurface Science

Our nation's rich history in nuclear energy research helped advance nuclear technologies and made nuclear power production a reality. However, these advances also produced waste, which together with defense-related nuclear wastes resulted in contamination across the DOE Complex. Concern over the potential migration of waste constituents into the underlying aquifer and national waterways spurred extensive R&D examining subsurface contaminant fate and transport. Expertise in examining reactor materials, fuel design and performance, fuel cycle separations, and environmental analyses supported newer capabilities in biogeochemistry, reactive transport modeling and experimentation, actinide and lanthanide chemistry, materials science and engineering, and advanced computational methods. INL's environmental subsurface science research is focused primarily on developing predictive understanding of: (1) the fate and transport of metal and radionuclide contaminants under natural and far-from-equilibrium conditions and (2) the geomechanical responses of the subsurface associated with extraction of energy resources (e.g., fossil, geothermal) and waste storage. These research areas support cleanup efforts at INL and across the DOE complex and INL's clean energy mission.

This capability is supported by approximately 140 researchers and technical staff with expertise in hydrology, geochemistry, environmental microbiology, molecular biology, materials science, analytical chemistry, and computational science. Close integration of these multiple disciplines is a hallmark of INL. The Laboratory has a long history of collaborations between microbiologists, molecular biologists, and geochemists to study geomicrobiology and microbial interactions with metals and radionuclides (*1-13*). In addition, multidisciplinary INL research teams are recognized for conducting intermediate-scale experiments in reactive transport with mineral precipitation in porous media, integrated with reactive transport modeling from pore to continuum scale (*14-18*), as well as geophysical sensing of the evolving biogeochemistry (*19-22*). The studies have contributed significantly to fundamental understanding of the coupling and feedbacks between transport, mixing, and the propagation of biogeochemical reaction fronts in heterogeneous porous media.

A distinctive INL strength is the physics of multiphase flow dynamics in the deep fractured vadose zone. INL's commitment to this topic is derived from its unique hydrogeologic setting atop thick (varies from ~100 ft to ~2,000 ft), fractured, variably saturated basalt. This hydrogeologic setting is characterized by abnormally rapid downward migration of water and contaminants over a large vertical distance, for which models built on the conventional flow and transport theory of unsaturated porous media fail.

Over the last two decades, funded mostly through EM and SC, INL has led multi-laboratory teams in a large number of unsaturated fracture flow tests of increasing scale and complexity, ranging from Hele-Shaw cells of ~cm size, to bench-scale (~1 m) simplified analog fracture experiments, to field-scale 100-meter diameter infiltration tests (*23-32*). INL also led the development of a suite of unique physics-based flow and reactive transport codes for predicting multiphase fluid dynamics in fractures and fracture networks (*33-41*). The close integration of experimental and modeling studies has significantly advanced fundamental understanding of how gravitational, viscous, inertial, and capillary forces and fluid-fluid-solid contact line dynamics interact with fracture intersections and low-permeability sedimentary inclusions. Such interactions in a deep fractured vadose zone lead to highly nonlinear, even chaotic multiphase flow dynamics including features such as flow focusing, spontaneous flow path switching and episodic flow, avalanching, and cascading.

This capability is supported by state-of-the-art laboratories for materials characterization and preparation, flow and transport experiments, and chemical and elemental analysis (including isotopic analysis). In keeping with its primary nuclear energy mission, INL also maintains extensive radiochemistry laboratories and irradiation facilities. Unique within the DOE complex, INL operates a 2m radius geocentrifuge with a 50 g-ton capacity. The ability to conduct geocentrifuge experiments instrumented with direct (e.g., moisture sensors, pressure transducers) and indirect (e.g., miniaturized electrical resistivity tomography) flow monitoring devices enables rapid unsaturated flow and transport experiments with real-world scaling. INL offers a myriad of locations and options for field studies (e.g., Vadose Zone Research Park) and possesses the expertise and equipment needed for extended field mobilizations.

INL recognizes that subsurface energy resources are critical to the nation's low-carbon and secure energy future. Funded primarily by the Geothermal Technologies Office. industry, and indirect funds, INL has developed physics-based multiscale and multiphysics geomechanical models for better predictive understanding, across all relevant scales, of changes in stress and strain fields, fracture nucleation, propagation, and coalescence in complex heterogeneous media, as well as reactivations of natural fractures/faults because of thermal, hydraulic, and mechanical perturbations. These phenomena are associated with applications such as recovery of unconventional fossil fuels from shale, engineered geothermal systems, CO_2 injection, and geologic disposal of nuclear and other wastes (*37, 42-48*). INL's environmental subsurface team is positioned at the frontier of understanding the physics of fracturing stressed heterogeneous rocks, the fundamental thermodynamic laws that drive the complex and often self-organized, hierarchical patterns of fracturing, nonlinear interactions among propagating fractures, and between heterogeneities ranging from mineral grains to natural fractures and faults, causal mechanisms of induced seismicity, and fracturing energy release because of fluid injection.

This capability supports INL's strategic science priorities under the Laboratory's clean energy missions and environmental stewardship of nuclear wastes and chemicals and include: (1) developing further predictive fundamental understanding of subsurface biogeochemical transformations and collateral effects on macroscopic material properties, using integrated theoretical and experimental studies and innovative multiscale modeling; (2) adaptive monitoring of coupled processes and property changes in heterogeneous subsurface environments; and (3) development of unifying multi-domain, multiscale, and multiphysics computational frameworks and interoperable models for linking the subsurface environment and terrestrial ecosystems.

INL will be working with the Environmental Molecular Sciences Laboratory to advance fundamental understanding of physics of nanoporous geomaterials and coupled biogeochemical and mechanical processes at the molecular scale to nano and subnanoscale. INL is currently pursuing collaborative research through a CRADA with the Chinese Academy of Sciences on subsurface fate and transport modeling, geomechanics and fracturing driven by chemical/hydraulic/thermal perturbations. INL strategic partnerships include CAES, other national laboratories (e.g., Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory [ORNL], Pacific Northwest National Laboratory, and ANL) and other DOE programs (Critical Materials Institute) and offices (i.e., SubTER, EERE, NE-Used Fuel Disposition, EM, Basic Energy Sciences, ASCR, Office of Fossil Energy), as well as industrial partners.

This capability has been developed through programs in the DOE's Office of Biological and Environmental Research, EM (groundwater and soil and nuclear materials disposition), Office of Fossil Energy (carbon sequestration), EERE (geothermal technologies), and the DoD Air Force Center for Engineering and the Environment. This capability advances DOE's missions in scientific discovery and innovation and environmental cleanup as articulated in the DOE Strategic Plan.

Large-Scale User Facilities/Advanced Instrumentation

Table 3.1: User facilities at INL.
Nuclear Science User Facilities (NSUF)
Biomass Feedstock National User Facility (BFNUF)
Battery Performance Laboratory
Wireless National User Facility (WNUF)

Table 3.1 provides a list of the user facilities at INL. INL has end-to-end nuclear fuel cycle RD&D capabilities, including the highest concentration of nuclear expertise and the greatest single-location suite of nuclear research capabilities in the U.S. In 2007, DOE designated ATR and associated PIE capabilities at MFC as user facilities available for access by other scientific users—from universities, other national laboratories, the international research community (with U.S. partners), and industry. INL has the most complete and advanced complement of fabrication, irradiation and PIE capabilities, and advanced instrumentation for study of radioactive and highly radioactive nuclear fuels and materials under in-reactor and out-of-reactor conditions. INL developed procedures and mechanisms for access to ATR, the ATR-C facility, the experiment library, and INL facilities with PIE capabilities for work on fuels or materials experiments. INL implemented a peer review selection process for award of DOE-sponsored experiments for university and other nonproprietary users. INL established a pricing policy consistent with DOE requirements on cost recovery for industry and proprietary users. As the program evolved, INL secured partnerships with capabilities at other laboratories and universities that are relevant to understanding the behavior of irradiated fuels and materials as part of a user facility network.

NSUF is managed and funded under the DOE Nuclear Energy Enabling Technologies Program. In addition to advancing an understanding of technical issues that are of NE interest, NSUF contributes to the training of a new generation of nuclear energy experimentalists. As a set of large-scale user facilities, NSUF provides access to facilities that are unique in the world. The NSUF program encourages teaming among universities, industry, and national laboratories, and allows for sharing of research capabilities among universities, national laboratories, and international research organizations.

ATR is a world-unique materials test reactor that supports the irradiation needs of multiple users. As a highly versatile irradiation facility, ATR has supported the development of the Navy's nuclear propulsion program for decades, including the ability to produce lifetime cores. Over the last 10–20 years, the use of ATR has expanded to include many other missions, such as development of gas reactor fuels and actinide bearing fuels for NE and low enrichment fuels for the NNSA U.S. High Performance Research Reactor Program within the Office of Material Management and Minimization. Transient testing capabilities are being restarted and enhanced with TREAT to provide an upcoming and unique, world-class capability available to users worldwide. Anticipated to begin in fiscal year (FY) 2018, transient testing will screen advanced fuel concepts, including accident-tolerant fuels, by allowing for early identification of the limits of fuel performance. It will also focus on fuel development from various viable options, ultimately reducing the time and cost required to develop new fuels. TREAT is capable of conducting tests on full-size fast reactor fuel and 36-in. segments of LWR fuel. The NRC will use data from TREAT tests as part of the process for granting licenses for new fuel types. The data will also be important for the validation of multi-scale, multi-physics modeling and simulation tools.

To guide ATR in meeting its research customers' requirements and ensure that it is sustained through investments as a viable research asset, the ATR Program has developed an out-year health improvement strategy. Key to this strategy is the recognition that ATR must provide predictable and reliable days of irradiation, which ensures availability to support its customers' experiment objectives. ATR developed an internal process to regularly evaluate the condition of all major or critical equipment and the relative risk and impact to the plant of that equipment's failure. This evaluation ranks equipment condition and considers regulatory impact, safety impact, and programmatic impact to arrive at an aggregate numeric score that represents the system or equipment's relative health. The ranking process allows ATR (i.e., Plant Health Committee) to objectively prioritize the equipment or systems that require repairs, refurbishment, or replacement. ATR and ATR experimental loops are equally considered. The output of the plant health process guides the priorities of the plant health strategy and supports its annual funding. This investment in the ATR as a national asset has been supported by the sponsors as necessary to meet their irradiation objectives. The process to allocate experiment positions in ATR works through the ATR Users Working Group. This process establishes understanding of the irradiation objectives of each of the experiment customers and then allocates and schedules positions in ATR to meet those objectives as nearly as possible, considering the demand for the key irradiation positions. The Users Working Group, with representatives from INL's nuclear S&T, ATR Programs, Naval Reactors, and DOE-ID, approves an Integrated Strategic Operating Plan for the current fiscal year along with notional out-year plans. The Integrated Strategic Operating Plan provides the plan and schedule by position in the reactor for the experiment customers. As the experiment customer base increases as a result of GAIN, the issue of limited experiment positions will become more pronounced. ATR is undertaking efforts to increase the predictability, reliability, and availability of the reactor, along with improvements in the experiment process. These will improve the efficiency of the irradiation process (from experiment development through irradiation) and the overall ability to support an increased number of experiment customers.

A full suite of capabilities for fabrication and characterization of fresh fuels and PIE on irradiated fuels (both destructive and non-destructive examination) are housed in MFC facilities such as Hot Fuel Examination Facility (HFEF), Fuels and Applied Science Building (FASB), Environmental Monitoring Laboratory, and Analytical Laboratory. They support NE missions, NNSA missions, and are operated as user facilities. For example, HFEF's precision mill enables non-destructive, higher-fidelity PIE for TerraPower. The Neutron Radiography Reactor (NRAD), located inside HFEF, allows use of neutron radiography for non-destructive examination of irradiated fuels, a unique capability in the U.S. Since 2005, DOE and INL have made a significant investment in new, state-of-the-art materials characterization equipment, such as the electron probe micro-analyzer, local electrode atom probe, focused-ion beam, micro-X-ray diffraction, transmission electron microscopes, and scanning electron microscopes, with the objective of tailoring their use to irradiated fuels and materials. The IMCL houses and operates highly sensitive equipment in shielded cells for irradiated fuel characterization. The facility provides capabilities that are unique in the U.S. to investigate the effects of irradiation at micro- and nano-scales. The FASB houses state-of-the-art hot cells and chemistry control systems dedicated to irradiation assisted stress corrosion cracking and fracture toughness of full size, highly irradiated reactor internal material specimens. In addition to the material characterization capabilities at MFC, the CAES facility, located at the Research and Education Campus (REC), provides access to INL advanced characterization capabilities for materials at low doses and is also operated as a user facility. Owned by the Idaho universities, the facility operates under an NRC license.

Over the last decade, with DOE investment, INL has expanded its capabilities and leadership in material characterization and PIE that are being applied to all NE programs. In addition, these capabilities are offered to universities, other laboratories, and the international research community as user facilities. INL also provides direct support to industry on fuels and materials for existing reactors. The capabilities are integrated and used in a complementary fashion with ATR and TREAT.

INL has created and maintains the Nuclear Energy Infrastructure Database and Nuclear Fuels and Materials Library of irradiated samples and the Knowledge and Validation Center to accumulate and preserve knowledge for use by nuclear professionals and organizations to validate codes for modern nuclear plants, fuel cycle analyses, and development of advanced nuclear energy systems. This is an integral part of the GAIN initiative.

The research sponsored and funded by the NSUF links directly to NE mission accomplishment, as well as to the Nuclear Energy University Program. The NSUF program is the Laboratory approach of the future, matching the research to the right capabilities, regardless of where the capabilities are located. NSUF also serves as a gateway to INL and is expanding opportunities for access to additional capabilities of the Laboratory, including capabilities in other disciplines of clean energy development and national security, including BFNUF, Battery Performance Library, WNUF, and HPC Center.

DOE is reactivating TREAT to support development and qualification of advanced fuel forms for the U.S. research program and to operate as a user facility for domestic and international users. TREAT previously performed more than 2,800 transient tests over a 35-year period. It was designed and operated to study the effects of both sudden (pulse) and steady rises of reactor power on fuel specimens. It is the only transient test reactor in the U.S. with adequate space for testing partial length light water reactor fuel and full- length fast reactor fuel over a wide range of neutronic and thermal-hydraulic conditions under transient operation conditions, up to conditions simulating severe reactor accidents. Once restarted in 2018, it will enable U.S. researchers to investigate the behavior of nuclear fuels (and their cladding) under severe transients, understand the failure mechanisms, and quantify failure thresholds. INL also provides direct support to industry on fuels and materials for existing reactors. The capabilities are integrated and are used in a complementary fashion with the ATR and TREAT.

INL's REC provides state-of-the-art laboratories and administrative facilities to support multiple Laboratory mission. REC is very conducive to collaboration with business and university partners, while providing diverse laboratories and office spaces. It includes EIL, CAES, ESL, National Homeland Security Research Facilities, Energy Research Office Building, INL Research Center, Radiological Environmental Science Laboratory, BCTC, and the HPC Data Center.

INL's WNUF applies extensive wireless expertise, laboratories, and a full-scale wireless test bed to enable the development of innovative, technical solutions to meet the emerging national wireless communications challenges that connect the nation's technology, which drives our national economy and enables government, military, emergency and public safety operations. In addition to our integrated team of wireless experts from government, military, academia, vendors, and telecommunication providers, INL's unique wireless infrastructure includes: (1) multiple laboratories equipped with experimental transmission, receiving, and analysis systems and chambers; (2) an isolated geographical terrain with relatively radiofrequency-free environment; (3) authorization from the National Telecommunications and Information Administration to operate as an experimental radio station for testing advanced technology system performance, and interference testing and training; (4) full-scale, deployed second, third, and fourth generation technology and networks for sophisticated signal, reliability, and encrypted messaging research and testing; (5) multiple network operation centers for simultaneous testing of on- and off-site communication systems; and (6) physics-based radiofrequency modeling and simulation. In addition to providing industry, academia, and national laboratories access to extensive wireless expertise and infrastructure for nonproprietary testing, the WNUF enables users to structure more complex user facility tests that could include industrial-scale testing centered on INL's wireless testbed.

At INL's BFNUF, researchers help overcome key technical barriers facing the U.S. bioenergy industry by investigating advanced feedstock supply and logistics, analysis and sustainability, preprocessing, and characterization. BFNUF provides customized technical support to leading U.S. feedstock, bioenergy, and technology companies. BFNUF includes: (1) a full-scale biomass feedstock PDU, a unique flagship capability, which helps bioenergy companies find the best way to convert feedstock to fuel; (2) a characterization laboratory to analyze feedstock and feedstock storage performance to aid customers in the development of high-quality product; and (3) a feedstock development, scale-up, and integration capability—helping to develop feedstock specification, process, and supply chain. BFNUF also offers lab and pilot-scale testing for industrial feedstocks during process, scale-up, and integration, helping customers to accelerate commercialization and overcome costly delays during commissioning and start-ups.

INL's Battery Test Center is EERE's primary center for battery technology testing. The facility is equipped with tools that allow testing of several hundred batteries at the same time, ranging from small coin cells to full-sized battery packs used in current light-duty vehicles. Testing equipment includes more than 650 test channels for advanced energy storage testing at the cell-, module-, and pack-level. In addition to testing battery performance, INL has a vibration test station to test mechanical durability based on accepted standardized test protocols. INL researchers have developed protocols for testing energy storage devices. Data collected, analyzed, and reported from the laboratory is recognized as some of the most reliable and accurate data for researchers, designers, industry, elected officials, and taxpayers.

INL possesses high-performance computing capabilities necessary to support advanced modeling and simulation of nuclear systems as well as other energy and industrial control systems. INL's primary HPC system is FALCON, an SGI ICE-X distributed memory system with 19,200 cores, 100 TB of memory, and a LINPACK rating of 570 TFlops. FALCON was ranked 97th on the November 2014 TOP500 list. INL also leverages an immersive visualization Computer-Assisted Virtual Environment facility and two PowerWall display systems for large format visualization research, nuclear facility virtual tours, nuclear reactor visualization, materials science study, chemistry/physics visualization, molecular modeling, volume visualization, LiDAR visualization, and other energy-related 3D imaging programs. These systems are sized and configured to support INL's unique mission in nuclear, and they provide scientific computing capabilities to support efforts in modeling and simulation in partnership with the NSUF. Collectively, these tools have enabled unprecedented insight into the behavior of nuclear fuels and materials during irradiation.

With over 829 staff, including two joint appointments and 10 postdocs, INL provides leadership and expertise for both private industry and federal programs, including NE, NR, and DoD. It has leveraged this expertise to support programs for DOE, NR, DoD, NNSA, EPRI, NRC, Crocker Nuclear Laboratory, and the Drug Enforcement Agency.

Mechanical Design and Engineering

INL maintains mechanical design and engineering capabilities that are used for nuclear system design, other energy and industrial processes, and development of technologies for evaluations of materials behavior in support of national defense programs. This capability combines advanced materials and fabrication knowledge to achieve complex design solutions. Mechanical design and engineering is a crosscutting capability specifically for the nuclear energy and defense programs and for the Laboratory in general. Mechanical engineers support the design and engineering of components, systems, subsystems, plant-scale prototypes, or other facility needs across the entire Laboratory.

This capability has a foundation of fundamental and applied engineering research that provides a solid expertise base for the engineering of highly complex systems. This foundation is applied to design, development, testing, and demonstration of components, systems, and subsystems, extending to plant-scale prototypes. The design and engineering of products includes many diverse individual capabilities, in addition to classical mechanical engineering, including modeling and simulation; sensing and controls; structural, thermal, and fluids analysis and design; static, kinematic, and dynamic analysis; and extensive experimental validations. INL conducts mechanical design and engineering work to applicable standards, codes, and regulatory requirements, and conducts innovative unique work in support of research requirements where standards, codes, and regulatory requirements do not yet exist. In addition to direct application of mechanical design and engineering, this capability is a major supporting element of the Laboratory's systems engineering and integration capability.

INL is defined by its ability to scale up and test systems from bench scale to pilot and engineering scales, leading up to full-scale prototype development, demonstration, and product manufacturing. Of more than 50 reactors built at INL, each represented a new design or demonstrated the operating safety envelop for deployment purposes. This included the reactor and fuel cycle facilities, as well as other components to move and convert energy, robotics for remote material handling, instrumentation and controls, and computer codes to predict behavior. INL utilizes its capabilities in mechanical design and engineering to support design of new energy-related projects; to develop innovative and novel solutions for warfighters to maintain U.S. battlefield superiority; to analyze, design, test, and validate unmanned vehicles; to develop advanced transportation; to drive renewable energy transmission; and to develop and use modern computational tools for engineering design and analysis.

More than 142 engineers and scientists and two postdocs support the mechanical design and engineering capability. Expertise includes mechanical engineering, electrical engineering, systems engineering, materials engineering, computer-aided design/computer-aided manufacturing drafting, machining, and highly experienced technician support. An extensive Laboratory infrastructure for designing, building, testing, and validation include INL's research center and associated laboratories in the REC and INL personnel at CAES, the ATR Complex, MFC, and SMC. These facilities are supported by general-purpose engineering-scale prototype facilities, chemical and radiological laboratories, and materials development and research laboratories.

INL continues to build leadership in: (1) advanced neutronic/thermal/structural design and analysis; (2) design of complex processes, systems, and hardware for investigating in-reactor material and fuel performance; (3) micro-grid support and analysis with renewable energy generation and penetration; (4) system design and development integration considerations; (5) testing and verification/validation for components, and system integration at scale; and (6) advanced armor applications, energetic material development, and explosives testing.

The end users, or the ultimate customers for these capabilities are the RD&D sponsors, that is, NE, EERE, OE, NNSA; other agencies, such as DoD; and industrial entities like EPRI, TerraPower, NRC, European Grup de Recerca en Radiacions Ionitzants, and KAERI.

Nuclear and Radiochemistry

INL has a long history and deep expertise in the unique chemistry and analysis of radioactive materials. Predicting the effects of radioactive decay and transmutation on chemical and material behavior in applications such as energy production, waste management, and nuclear nonproliferation is an essential part of INL's mission. INL has extensive research and operations experience with nuclear and radiochemical separations technologies at bench and engineering scale. In the 1980s, INL built and operated the only U.S. second-generation aqueous reprocessing facility and developed broad experience in nuclear and radiochemical separations on various used nuclear fuel types, including aluminum, zirconium, stainless steel, and graphite fuel. INL designed, built, and operates the only engineering-scale, electrochemical separations R&D facility in the U.S. The Laboratory's access to used fuel, in combination with the expertise and facilities for used fuel handling, affords unique capabilities in all aspects of radiochemistry.

Given INL's expertise in solvent extraction and radiochemistry, INL leads NE science and technology (S&T) research in nuclear and radiochemical separations technology. Today, INL scientists and engineers are applying this expertise to address challenges in: (1) climate change and clean energy, by vastly improving fuel cycle separations for mitigating nuclear waste issues and developing predictive and manipulative capabilities for safer, more efficient handling of radioactive material; (2) environmental protection, by developing separations and measurement technology for eliminating the nuclear waste legacy and isotope ratio measurements for fate and transport; and (3) national security, including advancing nuclear forensics, reducing the stockpile of nuclear material, and isotopic trace standard production. In addition, INL has extensive university and international collaborations and is leveraging available academia capabilities while helping to prepare a new generation of radiochemists.

The radiochemistry laboratories support experimentation with actinide and activation product elements (*56*). Experiments on the effects of high radiation fields on the properties of solutions (*57, 58*) and solid materials are conducted using irradiation facilities at INL (Radiation Test Loop, NSUF). Measurement of trace levels of radioisotopes in environmental matrices (*59, 60*) using specialty mass spectrometry, including an accelerator mass spectrometer and mass separators, allow rapid detection of extremely low concentrations of rare isotopes. Another INL research focus is the evolution of matrix chemistry during continued radiolysis (*57*), which is evaluated by measuring transient radical as well as ionic species in solution (*61-63*) and the gas phase (*64*). These experiments are important for monitoring nuclear waste separations (*65*) and storage, and for predicting the performance of long-term containment measures.

INL provides leadership in radiochemistry relative to solvent extraction technologies and free radical chemistry, thermodynamics and kinetics of liquid-liquid extraction process chemistry, solvent extraction process chemistry, nuclear nonproliferation verification, and forensics. These applications leverage capabilities in chemical and materials sciences; irradiation services in ATR for plutonium-238 isotope production; and detection science, special nuclear materials trace gas standards, and mass spectrometry.

Approximately 110 experts, including one joint appointment and three postdocs, support the nuclear and radiochemistry capability. Extensive Laboratory infrastructure in support of this capability include the Radiochemistry Laboratory (RCL), FASB radiolysis/hydrolysis test loop and gamma irradiator, EIL, Fuel Manufacturing Facility, and ATR. The end users, or the ultimate customers for these capabilities, are the sponsors of RD&D (i.e., NE, NNSA, NASA, and SC) and other agencies within DoD and DHS.

Nuclear Engineering

Nuclear engineering is the core expertise of INL rooted in INL's historical role as the reactor test station where more than 50 reactor prototypes were built, operated, and tested, and where many large-scale reactor safety experiments have been conducted. Similar activities are ongoing today as the Laboratory supports the primary mission of NE, through supporting nuclear systems design, analysis, and operation; advanced fuel development and testing; high-temperature chemical and electro-chemical separations; engineering-scale pyroprocessing treatment facilities; highly enriched uranium to low enriched uranium (LEU) reactor conversion; radioisotope power system fueling, testing, transport and ground operations; hybrid energy systems; nuclear nonproliferation, international safeguards, and emergency response technology RD&D and training; global threat reduction; and nuclear fuels performance M&S, RD&D of technologies involving high-temperature chemical and electro-chemical methods for separation, purification, and recovery of fissile elements from used nuclear fuel.

INL's nuclear engineering expertise draws upon the multiple disciplines required to analyze, design, demonstrate, deploy, and operate nuclear systems. These include capabilities in neutronics, thermal hydraulics, and structural design analyses for small- and large-scale experiments, mechanistic and probabilistic safety analyses, as well as development of nuclear grade instrumentation and control systems, and development of destructive and non-destructive nuclear materials detection and safeguards technologies. INL nuclear experts understand the complex processes and facilities associated with the nuclear fuel cycle, the attributes and economics of the various fuels cycles, and the implications for safeguarding special nuclear material. Nuclear engineering capabilities include identifying, modeling, and evaluating proliferation vulnerabilities in the nuclear fuel cycle and then developing and testing techniques and the supporting instrumentation needed to counter these vulnerabilities. Interdisciplinary teams with researchers apply their expertise in critical infrastructure protection, robotics, cyber security, and physical protection to resolve broad challenges that impact national and international nuclear security.

INL has substantial experience with the application of modern software to perform integrated neutronics, thermal-hydraulics, and structural analyses for nuclear systems for the commercial nuclear power industry, defense, space, and regulatory community. INL also has decades of leadership in the development of reactor safety analysis codes through the development and maintenance of the Reactor Excursion and Leak Analysis Program (RELAP) code series. INL researchers are working on the next generation of reactor safety codes by incorporating state-of-the-art software engineering and two-phase flow solution algorithms. INL also has a deep and rich history in the development and use of PRA, including development of the leading codes that are in use today (see Section 3.1, 3.8). In addition to analytical capabilities, experimental and testing capabilities are in place to support the development, verification, and validation of complex nuclear safety analysis codes. For example, thermal hydraulic experiments that support nuclear system design studies and safety analysis.

In addition, INL nuclear engineers support the safe and reliable operation of the ATR and the ATR-C facility (a low power version of ATR located in an extension of the ATR canal) as well as NRAD at MFC. INL's nuclear engineers are involved in developing state of the art instrumentation and control systems for ATR to enable better experimental control and data acquisition, as well as for deployment in other nuclear systems and upgrades to the primary coolant system. The nuclear engineering staff is involved in the design, fabrication, and monitoring of ATR experimental test trains that support NE and NR's testing needs for ATR experiments and ATR-C criticality safety tests.

INL nuclear engineering is developing new nondestructive assay methods for quantifying plutonium in whole commercial spent fuel assemblies with the aim to develop revolutionary, order-of-magnitude improvements in INL's ability to use technical safeguards to quantify and track plutonium in domestic and international nuclear fuel cycles. INL's nuclear engineering assets assess the proliferation risks of advanced fuel cycle input and associated material streams and use this information to improve safeguards approaches and instrumentation to address identified vulnerabilities. The large-scale processing and nuclear materials handling capabilities located at the MFC enable development and testing of these new technologies. On behalf of DOE, DHS, other federal agencies, and industry, INL also provides engineering capabilities related to testing and evaluation of radiation detection and measurement instrumentation.

Approximately 427 technical experts, including three joint appointments and 10 postdocs, are dedicated to nuclear systems design, reactor physics, nuclear nonproliferation, and mechanistic and probabilistic safety analysis. An extensive Laboratory infrastructure supporting these activities includes Space and Security Power Systems Facility at MFC; Fuel Conditioning Facility, containing remote material handling capabilities for highly irradiated materials, as well as engineering-scale molten salt uranium recovery and purification equipment; TREAT; ATR/ATRC, NRAD, HFEF capabilities. MFC is the only known location in the world with remotely operated, engineering-scale pyroprocessing equipment deployed in an inert hot cell. The end users or the ultimate customers for these capabilities are the RD&D sponsors, that is, DOE NE, SC, NR, NNSA programs; other agencies such as NASA and DoD; and industrial entities including EPRI, KJRR, EDF Energy, Westinghouse, NuScale, TerraPower, and B&W.

Power Systems and Electrical Engineering

INL's power and electrical engineering team's scientific experts and leading power engineers with industry experience conduct RD&D using the nation's largest high power and evaluation test range. INL leads research in clean energy systems design, analysis, and integration; state awareness diagnostics, prognostics and control data analysis; process system state analysis; mitigation of damaging effects of natural and man-made hazards (most notably geomagnetic disturbance and electromagnetic pulse); energy system and defense applications; electrical/economic modeling analysis; and performance design requirements development. The unique combination of resources, including a real-time, high-fidelity physics-based power modeling and simulation system, allows INL to deliver advanced energy systems security research and testing. Design, integration, and evaluation expertise are combined to realize renewable energy system-wide solutions that also optimize full-scale grid control, stability, reliability, and security.

INL focuses on system level applied engineering to enable industry and government in optimizing renewable energy and hybrid energy systems through grid integration of electric power while addressing other technical issues, such as variable generation and energy storage. These innovations deliver non-dispatchable electricity production onto the grid, provide power flow control into and through the grid, and optimize energy storage size and location in the electrical supply chain.

INL's campus and Site boundaries provides access to isolated, secure, industrial-scale facilities and infrastructure for conducting comprehensive interoperability, vulnerability, and risk assessment activities. These assets include: (1) National Electric Grid Test Bed, which includes an isolatableand customizable utility-scale 138kV transmission system and 13.8kV meshed distribution areas with multiple concurrent test areas; (2) CITRC; (3) Wireless Test Bed; (4) Water Security Test Bed; and (5) Control System and Cyber Security Innovation Labs. INL's power grid operates under a full range of climatic conditions (i.e., temperature, wind, snow, ice). With the highly instrumented grid, INL can safely isolate grid sections and associated testing infrastructure to conduct full-scale testing and validation of technology components, grid security and resilience, systems, and processes. Industry can use this capability to test owner-specific equipment.

In addition to operating and maintaining the country's largest wholly-owned power grid test infrastructure, INL has leading infrastructure protection programs that develop and use advanced modeling and simulation technologies to provide quick and reliable analysis of complex infrastructure interactions and interdependencies. INL's real-time digital simulator (RTDS) provides high fidelity power systems simulation technology for fast, reliable, accurate, and cost-effective study of power systems. It is a physics-based transient power system simulator that operates in real time, allowing the user to test physical devices (i.e., hardware-in-the-loop, grid-in-the-loop, and controller-in-the-loop) and validate energy system performance models. RTDS also enables assessing power flow management both to and from the grid and matches real-time supply to demand within network constraints. INL has the largest investment of RTDS in the laboratory complex.

INL emphasizes a holistic resilient systems approach to the grid that integrates cyber and physical security with efficiency and stability as performance constraints to optimize power system operations and mitigate threats. By developing and maintaining robust full-scale cyber and physical security analytical capabilities, INL ensures that legacy and current generation control systems have the best available defenses to protect grid operations. With an eye toward the next generation of control architectures, INL conducts interdisciplinary instrumentation, control, and intelligent systems research to enhance power systems and grid resiliency.

INL's power and electrical engineering staff and capabilities support areas such as cyber security and critical infrastructure protection research as subject matter experts in the instrumentation, control, and operation of electrical grids, integrated energy systems and advanced vehicle programs, assessment of geomagnetic disturbance effects on grid, and assessment of cascading and escalating impacts across and among lifeline sectors including power, water, telecommunications, and transportation. The staff also performs work for others in the area of energy security and grid reliability for the DoD.This includes assessments of available renewable resources on and near military bases, microgrid development to ensure an uninterruptable supply of electricity under various situations, and smart grid development for increasing energy efficiency on the base and putting energy information into the hands of base commanders.

The core power grid used for INL's full-scale testing and evaluation is primarily used to power INL site operational facilities; therefore, the grid is supported under operational funding from NE. Specific test configurations are funded directly by the projects under test and evaluation at INL, including projects for DOE, DHS, DoD, and other government and industry agencies. Approximately 29 technical experts, including one joint appointment, bring together expertise in power and control systems and engineering combined with cyber expertise. The end users or the ultimate customers for these capabilities are the RD&D sponsors, that is, NE, OE, NNSA, and EERE; other agencies such as DoD, CES-21, and Florida Power and Light; and industrial entities.

Systems Engineering and Integration

INL is a recognized leader in the area of energy and critical infrastructure security systems engineering, integration, testing, and demonstration. The roots of INL are grounded in the conceptualization, design, operation, and analysis of prototypic complex systems, a competency developed and maintained today to help industry reduce the time and cost of energy and security technology deployment, help regulatory agencies set appropriate standards, and assist policy makers in establishing the viability of advanced technologies. This capability base incorporates components of each of the other INL core capabilities and is what makes INL distinctive as a national laboratory. INL's expertise is in holistically addressing problems or challenges, from mission analyses through verification and validation, to enable optimal solutions. INL has demonstrated expertise integrating technical resources, systems, elements, and people.

Expertise initially developed to characterize the viability, safety, and operational characteristics of nuclear reactor designs are still in operation today. This expertise includes associated energy conversion and control technologies, which has expanded to the development, design, and deployment of fuel cycle technologies, hybrid energy systems, resilient design and recovery of critical infrastructure; consequence-driven cyber-informed engineering integration of high fidelity physics-based modeling, full-scale experiments, the most instrumented industry-scale test grid; and testing of related components, subsystems, and systems that play a critical role in national security.

INL retains systems engineering capabilities that support design and fabrication activities, experiment design and development, instrumentation controls, data analyses, and quality assurance. These capabilities are comprised of a strong combination of research engineering and operations skills, leadership-class infrastructure, and educational partnerships.

Responding to national needs over last 15 years, INL has built additional and substantial capability for testing of prototype renewable/clean energy systems, advanced vehicle testing and analyses, battery performance testing, sensor and detector networks, and electrical transmission systems. These energy systems and related advanced integrated (hybrid) energy systems that combine nuclear, renewable, and fossil energy, grid scale energy storage, and related grid management are increasingly tapping this capability base and will be important areas of application and capability enhancement in the future.

Other examples of systems engineering and integration that resulted in the development of testing and demonstration capabilities are the large PDU for conversion of biomass feedstocks into commodity grade standardized fuel pellets and a full-scale prototype waste package cell. Both examples utilized teams of engineers and scientists assembled from across the Laboratory to solve a complex engineering problem. This approach highlights breadth of capabilities at the Laboratory to assemble multidisciplinary teams (consisting of a few personnel to hundreds) to perform highly complex engineering projects efficiently and effectively.

Approximately 58 technical experts, including one joint appointment, join expertise in systems engineering and integration to conduct problem identification and management of technical, functional, and operational requirements and project risks; identify viable technology alternatives, and conduct R&D to mature the alternatives; and select and implement optimal and defensible solutions for energy, environment, and security systems. These experts also help ensure the modern smart grid incorporates secure smart communications and distributed generation resilience to geomagnetic storms, electromagnetic disturbances, and cyber/physical attacks with interdependent/cascading consequences. An extensive Laboratory infrastructure supporting these activities include those listed above and a wide range of general-purpose engineering-scale prototypes, chemical and radiological laboratories, materials development, grid, and research laboratories. These expertise and physical capabilities are increasingly deployed as national user facilities where industry, government, and academic researchers can engage INL staff to carry out research, development, integration, testing, and demonstration.

The systems engineering and integration capability is applied to programs of national and international importance, including those for NE, EERE, OE, and NNSA; other agencies such as DoD, DHS, and the Drug Enforcement Agency; and industrial entities including NuScale, TerraPower, and EDF Energy. The national capability deployment by INL is also the basis of U.S. technical engagement with other countries (e.g., UK Nuclear Decommissioning Agency).

4. Science Strategy for the Future

INL's strategic initiatives to achieve critical outcomes are listed in Table 4.1 They are designed to advance the scientific and technological capabilities and sustain and build INL's core capabilities and leadership positions to provide for national-scale energy and security solutions for DOE in critical mission areas. As an applied energy laboratory with unique geography, INL retains core competencies and capabilities to develop, test, and demonstrate advanced concepts for proof of concept and technical and economic viability.

INL's capabilities and partnership networks in nuclear S&T and research provide unprecedented opportunities for rapidly building an expanded understanding of the challenges and for developing and delivering solutions to address these challenges. These include innovative nuclear reactor design, advanced accident-tolerant fuels, nuclear fuel cycle advances, long-term solutions for the management of used nuclear fuels and nuclear waste, nuclear energy applications, integration and deployment of first-of-a-kind nuclear reactors, and global security enhancement by protecting nuclear material. GAIN will make this state-of-the-art, continuously improving RD&D infrastructure available to stakeholders to achieve faster and more cost-effective nuclear energy technology innovation. The deployment of the first domestic commercial SMR can be enabled through INL's knowledge, expertise, and capabilities, and with INL Site's unique infrastructure (geography, operations, and security) to overcome technical, regulatory, operational, and first-of-a-kind constraints—hence, the second initiative.

The third initiative is focused on accelerating the pace of technology innovation and transition through regional partnership and deployment. INL will close the gap between supply and demand, address the technology deployment challenges by developing regional private-public partnerships, and focus on regionally relevant technology challenges and needs. INL has made significant contributions in addressing S&T challenges in renewable energy grid integration, transportation system transformation, water utilization, energy-critical materials, biomass feedstock assembly, and optimizing the efficiency and security of advanced manufacturing processes. These initiatives will regionally advance the clean energy economy and help meet national goals for deep decarbonization, by employing regional and national efforts with private capital and partnerships, and in creating a Regional Clean Energy Innovation Partnership (RCEIP).

In addition to clean energy S&T, INL is a globally-recognized RDD&D leader in control systems cyber security; it makes important contributions to secure and modernize the nation's critical infrastructure. INL's 890-square-mile laboratory and testing complexes represent a synergistic integration of co-located and networked nuclear and national security facilities. INL hosts unparalleled assets, such as a utility-scale electric power grid for improving reliability and security; a wireless communications testbed supporting commercial and government-sponsored research; key capabilities for performing cyber and control system research and explosives and ballistic threat analysis; safe and secure locations for accelerating protective solutions development and testing; and first responder training experiences in nuclear forensics, real-world contamination scenarios, and incident response. These capabilities will solve complex global security challenges in the areas of critical infrastructure protection, nonproliferation, and national and homeland security. Each of the four initiatives is discussed in the following subsections.

Strategic partnership and collaboration are key elements in executing all four strategic initiatives. INL will continue to develop partnerships with other national laboratories, universities, and industry (both domestically and internationally) to support mission objectives and advance capabilities, pool capabilities and resources, accelerate innovation, support demonstrations, accelerate deployment of technology advances, and build INL's science and engineering pipeline. As capabilities expand, the Laboratory will continue to make its distinctive research facilities and expertise available to the scientific user community on a competitive basis. To facilitate mission growth and partner engagement, INL will lease additional facilities to support opportunities in GAIN and critical infrastructure protection.

INL uses its discretionary resources to strengthen its core capabilities and to advance the Laboratory's mission and agenda. The annual LDRD budget is developed after careful consideration of investment needs and overall INL indirect budget. The final LDRD budget request is developed and approved by INL's laboratory director. The

LDRD program benefits INL and DOE by providing the Laboratory with resources for developing new R&D capabilities to better meet DOE and the nation's needs, seed innovative research, and attract and retain research staff to maintain the vitality of the Laboratory.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

INL is located in southeastern Idaho with assets and capabilities residing in Idaho Falls and on the INL Site (see Figure 6.1). INL's RDD&D capabilities are consolidated around several research areas on the desert site: the ATR Complex is the primary location to conduct thermal irradiation; MFC provides shielded hot cells to handle highly irradiated materials, glove boxes to handle special nuclear material and the TREAT facility for transient testing; CITRC primarily serves the N&HS mission, including critical resilience and nonproliferation testing; SMC houses unique assets underpinning N&HS and DoD missions; Idaho Nuclear Technology and Engineering Center (INTEC), currently owned and operated by EM, is home to several facilities that support INL's spent nuclear fuel capabilities and may also support future INL customer needs; Central Facilities Area (CFA) is the main site-wide services and support area for the on-site campuses. Idaho Falls is home to REC, where primary focus is on non-radiological laboratory-based research to support NE research, at-scale clean energy systems integration and demonstration, N&HS capabilities, and Laboratory administrative functions.

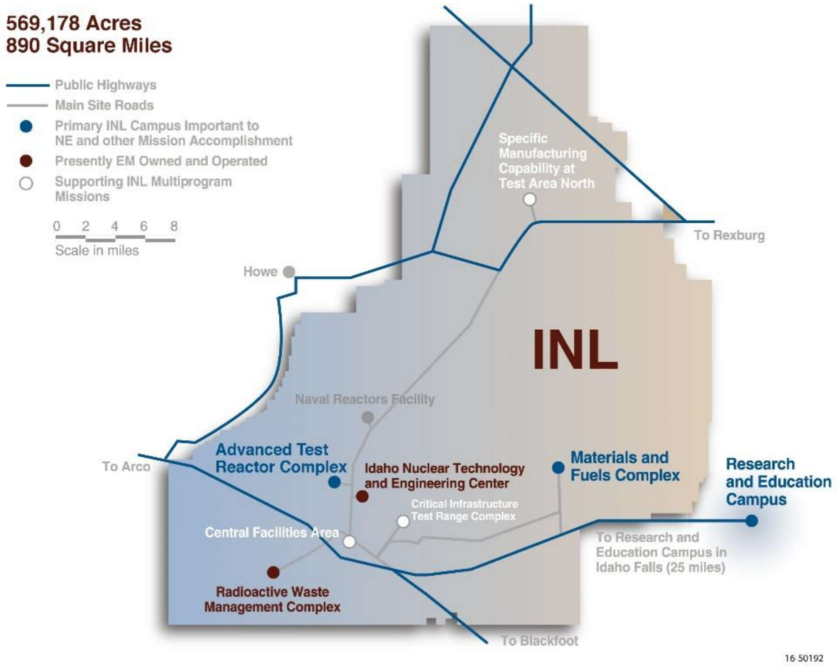

Figure 5.1: INL facilities and infrastructure.

INL real-property infrastructure includes 500[15] NE-owned and operated real property assets[16] with a total replacement value of $4.8 billion. These assets include 296 operating buildings (totaling 2.3 million gross ft^2), 200 non-programmatic other structures and facilities, and four "programmatic" real property assets that fall into the 3,000-series Facility Integration Management System (FIMS) other structures and facilities (OSFs) usage code category, as well as ATR, its cooling tower and vent stack, and the TREAT. The inventory includes 24 mission-critical assets. The facilities accommodate approximately 4,000 people on a daily basis, including employees, facility users, subcontractors, and others. Site-wide utilities and supporting infrastructure consisting primarily of roads, railroads, power distribution systems, and communication systems are maintained and operated to serve and connect the campuses and facilities.

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[15] 24 mission-critical, 315 mission-dependent, and 161 not mission-dependent assets.

[16] Buildings, trailers, and other structures and facilities (utility systems and roads).

As documented in Table 6.1, the most recent[17] asset condition index for NE-owned and operating non-programmatic assets is above the DOE target (0.950) and has been essentially stable for the last several years. This trend is also true for mission-critical assets (ACI=0.992).

Space utilization has also improved (with average asset utilization for all facility types at 96.04) as we work to accommodate growth in programs by utilizing existing assets. Through this growth and as user facility participation increases, space strategy will continue to be evaluated.

Table 5.1: INL NE infrastructure summary.

Asset Condition Index	Mission-critical	0.992
	Mission-dependent	0.971
	Not mission-dependent	0.981
Asset Utilization Index	Office	91.49
	Warehouse	99.14
	Laboratory	97.42
	Housing	NA

INL Site is also home to EM facilities at INTEC and at the Radioactive Waste Management Complex (RWMC). EM manages the newly established Idaho Cleanup Project (ICP) Core under contract with Fluor Idaho, LLC, for the performance of ongoing Advanced Mixed Waste Treatment Project and ICP work scopes. At the conclusion of the contract, it is anticipated that all Idaho Settlement Agreement transuranic waste will be dispositioned out of Idaho and all Agreement to Implement/CERCLA Record of Decision buried waste will be exhumed from the Subsurface Disposal Area. The ICP Core contract requires that operational facilities be operated and maintained to support ongoing mission work. A breakdown of building ownership showing EM-owned buildings versus NE-owned buildings is available in the FIMS database. Spectra Tech, Inc. is under contract with EM to manage NRC-licensed facilities at INTEC: the Three Mile Island-2 spent nuclear fuel storage facility and the Idaho Spent Fuel Facility.

Naval Reactors Facility (NRF) is also one of INL Site's Primary facility areas that will continue to fulfill its currently assigned missions for the foreseeable future. NRF is operated by Bechtel Marine Propulsion Corporation, under contract with and direct supervision of the Naval Nuclear Propulsion Program; their facility information is not available in FIMS. INL provides support services to NRF, ICP Core, and DOE NRC-Licensed Facilities per formal agreements.

Campus Strategy (Overall Approach to Infrastructure Sustainment)

Improved stewardship of assets across the laboratory is a priority. We employ a comprehensive strategy that includes adequate maintenance and sustainability improvements of enduring facilities, construction of sustainable new facilities where needed, and disposition of unneeded assets. To achieve this, INL leverages the "Reduce the Footprint" and "Freeze the Footprint" initiatives to champion real property stewardship practices that support the Department's Real Property Efficiency Plan and overall Asset Management Plan. INL also leverages a robust maintenance program focused on ensuring real property assets are maintained in a condition suitable for intended use. The maintenance program includes condition assessments, a work control system, management of deferred maintenance, a method to prioritize maintenance projects, and cost accounting systems to budget and track maintenance expenditures. INL's infrastructure sustainment strategy has five main focus areas or initiatives (Figure 6.2 provides an overview of investment and timeline):

Leverage existing and establish new capabilities necessary to fully achieve mission objectives.

Sustain key campuses.

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[17] FY 2015 FIMS Snapshot taken on October 1, 2015, for Federal Real Property Council/Profile Reporting.

Optimize space and land use decisions – Strategically target space and INL land resources for development to ensure we can meet growth needs, while maintaining a focus on nuclear energy research first.

Upgrade computing infrastructure – Upgrade communications infrastructure to increase information technology (IT) functionality across the laboratory.

Enhance site sustainability – Take action to maximize energy and water efficiency, minimize chemical toxicity and harmful environmental releases, promote renewable and other clean energy development, and conserve natural resources while sustaining assigned mission activities.

Leverage Existing and Establish New Capabilities

New research and support facility infrastructure investments over the last five years have provided more than 302,000 ft2 of new facilities (including the Radio Analytical Chemistry Laboratory, ATR Technical Support Building, Critical Infrastructure Protection and Resilience, the Energy Innovation Laboratory, Irradiated Materials Characterization Laboratory, and multiple support structures). Through these projects, the REC campus has largely been transformed, with many sustainability features incorporated. These new capabilities are now being leveraged to achieve mission outcomes in demonstrating modeling and simulation, energy and resource integration, renewable energy, critical infrastructure protection, and nuclear systems design.

Focus has now shifted to establishing state-of-the-art capabilities that enable INL's new strategic objectives:

- Enable clean energy by supporting deployment of the first U.S. small modular reactor.
- Enable the success of GAIN by delivering a U.S. nuclear test bed that includes sustaining MFC and ATR, and by restarting TREAT to design nuclear energy systems.
- Design resilient critical infrastructure, enable future defense systems, and provide innovative nuclear and nonproliferation solutions by delivering the Cybercore.

In these venues, INL is experiencing an increase in visitors and users to the various complexes, and expects this trend to continue over the next five years. To support this and the above objectives, a primary goal is to extend use of existing facilities and capabilities with world-class expertise and a full complement of capabilities that allows INL to serve as a multi-program laboratory with broad competencies in energy and national security. Both MFC and ATR will continue their support of current missions while establishing new capabilities either as part of GAIN or through other avenues; this includes reestablishing MFC as a national nuclear test bed. We will address office space congestion there and elsewhere through paradigm shifts in space management plans, metrics, and models for labs, offices, cores, and support space. Strategic infrastructure investments will revitalize, support, and advance research capabilities at these complex locations.

Likewise, infrastructure gaps limit INL's continued leadership of associated programs and deployment of critical cyber security solutions on INL campuses. Gaps include a lack of reconfigurable cyber and electronic research laboratory spaces (unclassified and classified); office space for researchers adjacent to laboratory areas; special development areas (all levels of security configurations); connections to key customer information networks; and the ability to have functional connections to private customers.

While significant improvements to INL infrastructure will be made, scalable solutions will be used in which we will design for tomorrow and enable growth and evolution. Current projects and sustainment activities that are providing new laboratory buildings, renovated facilities, and upgraded utilities are proceeding toward on-time completion within budget. Investments to address identified infrastructure gaps for the near and long-term are identified in Table 6.2. Figure 6.2 depicts major capital investments to address infrastructure needs for the near and long term

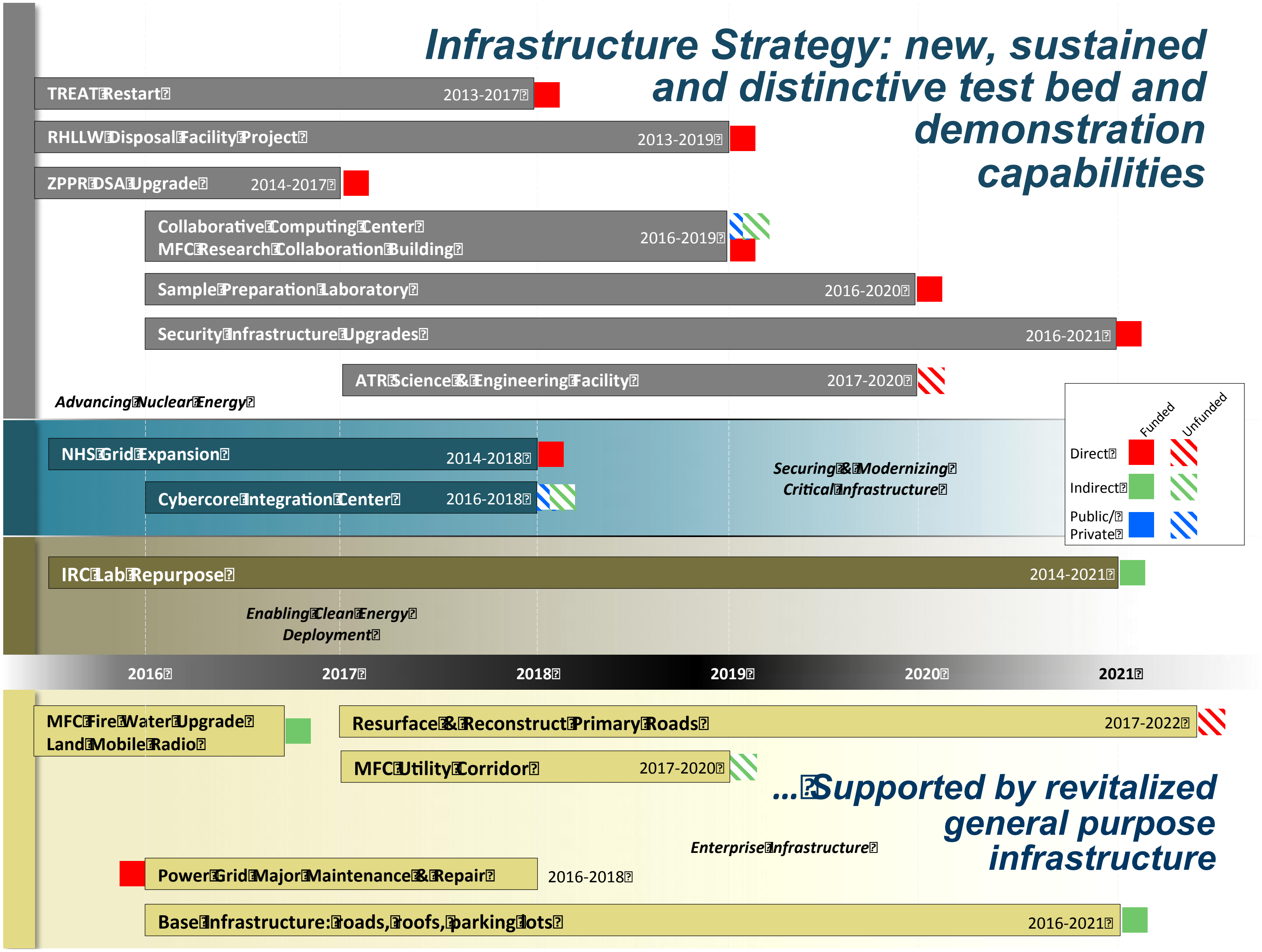

Figure 5.2: Investment overview and timeline.

Table 5.2: Infrastructure gaps, needs, and investment strategy.

Core Capability	Infrastructure Gap/Risk	Investment Strategy
Applied Materials Science and Engineering	Anticipated closure of RWMC Subsurface Disposal Area will eliminate onsite disposal capacity supporting NE and NR.	Construct Remote-Handle Low-Level Waste disposal capability
Applied Materials Science and Engineering Large-Scale User Facilities/Advanced Instrumentation Nuclear Engineering	DOE currently lacks capability to provide "stress testing" of nuclear fuels (quick, high-energy neutron pulses that mimic accident conditions) to help the industry design even more durable fuels, establish performance limits, validate design codes, and help regulators (like the NRC) define safety limits.	Restart **TREAT** at MFC to support transient testing in 2018
Applied Materials Science and Engineering Large-Scale User Facilities/Advanced Instrumentation Nuclear Engineering	As capabilities supporting the NSUF become more robust and access to the NSUF increases for national and international users, infrastructure to support research data visualization, demonstration and testing at the MFC will be required.	Build the **MFC Research Collaboration Building**
Applied Materials Science and Engineering	Lack of facilities capable of housing next-generation PIE equipment to support advanced nuclear fuel and materials research.	Construct **Sample Preparation Laboratory** at MFC Complete outfitting of IMCL
Enabling Infrastructure	Security infrastructure upgrades are necessary to ensure adequate controls in place to address identified gaps and fully support mission needs.	Implement **Safeguards & Security infrastructure** projects Complete **Live Fire Shoothouse Enhancements** (2017)

Core Capability	Infrastructure Gap/Risk	Investment Strategy
		Provide **Redundancy of intrusion detection systems at MFC** (2017) Implement Physical Security Enhancement activities (2018 – 2022)
Large-Scale User Facilities/Advanced Instrumentation **Nuclear Engineering** Applied Materials Science and Engineering	A new building is necessary to receive, prepare, stage, assemble, and test materials and equipment in support of core internal change-out activities and ongoing operations. The facility will provide direct support to activities associated with advancing and developing the next generation of nuclear reactors, fuels and materials.	Build the **ATR Science and Engineering Facility**
Applied Materials Science and Engineering Large-Scale User Facilities/Advanced Instrumentation Nuclear Engineering	High-bays, fuels and materials development laboratories, and support spaces that include scientific collaboration and turnaround office spaces are key features that do not currently exist to support experimental testing of advanced fuel manufacturing processes and developing concepts for an advanced fuel fabrication	Build the **Reactor Fuels Fabrication Facility** (Reactor fuel and structural materials support facility)
Applied Materials Science and Engineering	Rapid commercialization of innovative nuclear energy systems and technologies that cannot be developed using the existing test or research reactors (e.g., fast spectrum fuels and materials testing capability).	CD-1 for **Fast Spectrum Test Reactor**

Core Capability	Infrastructure Gap/Risk	Investment Strategy
Nuclear and Radiochemistry Nuclear Engineering	Dedicated nuclear facility R&D space is needed for classified and unclassified nuclear nonproliferation and forensics programs	Establish the **Nuclear Nonproliferation and Nuclear Forensics Laboratory**
Advanced Computer Science, Visualization, and Data Cyber and Information Sciences Decision Science and Analysis Environmental Subsurface Science Large-Scale User Facilities/Advanced Instrumentation	Computing demands will exceed existing HPC capacity by 2018 as advanced modeling and simulation techniques are applied to predict the behavior of nuclear fuels and materials undergoing irradiation for both reactor normal operating and accident conditions. Increased demand for the capability and the computing time requires additional laboratory and computer spaces to accommodate growth in staff and expansion/refreshing of the HPC.	Establish the **C3** (Lease)
Cyber and Information Sciences Decision Science and Analysis Large-Scale User Facilities/ Advanced Instrumentation Power Systems and Electrical Engineering	A robust capability to holistically address automation and control system challenges is lagging the increasing threat and demand for innovative solutions. The challenges exist across multiple agencies and across industry. Leveraging the existing expertise and capability in cyber and Information sciences and by forging key partnerships, INL will provide the nation with an enduring cyber-physical innovation capability centered on the Cybercore.	Establish the **Cybercore** (Lease) Invest in **expansion of existing infrastructure** (UB2 -4/EROB/INL Administration Building) to accommodate growing programs
Enabling Infrastructure	The need for long-term dry storage of ATR spent fuel will need to be addressed in the next five years	Develop strategy for long-term storage of ATR spent fuel
Enabling Infrastructure	As programs and user facilities grow and expand users, the need for upgrades to security technology and surety will continue. A comprehensive plan for ensuring the security and viability of INL capabilities is in place.	Implement **Physical Security Enhancement activities** (2018 – 2022)

Core Capability	Infrastructure Gap/Risk	Investment Strategy
Enabling Infrastructure	The existing location for the cyber security operations center may be inadequate to support future enhancements and may require upgrades/relocation.	**Cyber Security Operations Center**
Bold = Primary CC		

INL invests close to $50M annually in needed maintenance, repair, and upgrades of general-purpose infrastructure. These investments are from a variety of funding sources, including federal appropriations for line-item construction projects, general plant projects (GPPs), and plant health investments, as well as overhead-funded investments in institutional general plant project (IGPP) work and routine maintenance and repair. Initially defined in the response to the Laboratory Operations Board infrastructure cross cut call for high-priority general-purpose infrastructure needs, INL has maintained focus on addressing high-priority needs listed in Table 6.3.

Table 5.3: High-priority investments in basic existing infrastructure.

General Purpose Infrastructure	Cost Estimate	Infrastructure Component Gaps and Impacts	Status
Power Distribution System	$23M current/ $40M total	Replace critical components of INL site wide high-voltage power grid and complete select upgrades of data communications, fire alarm signaling, and redundant power feed.	Appropriated: FY2016- $23.2M Request: FY2016 - $23.2M FY2019 - $5M
Resurface and Reconstruct Primary Roads Pavement repair	$41.6M	This activity will prevent continued degradation and failure of primary roads surfaces and roadbeds that have not received proper road treatments in over 15 years. Repair work will avoid forecasted accumulation of more than $40M of Deferred Maintenance over the next five years. It will also address safety and drivability performance issues associated with Rutting, cracking, and roughness of ride for all vehicle traffic on these primary two-lane, multidirectional roadways. Site roads are utilized by government, employee, and commercially owned vehicles including emergency response, heavy-duty haul vehicles, and light vehicles for access and delivers to all INL site work activities. In some cases, publicly accessible roadway hazards will also be reduced. Rutting, roughness and cracking impact the effectiveness of snow removal causing ice buildup that results in safety hazards and imposes the need for speed reduction to maintain vehicle control, thus impacting emergency response times. Additionally, refurbishment of external parking surfaces that are badly deteriorated and improperly sized to meet current needs, and improve lighting for safety purposes is needed at MFC, ATR, and SMC. Pavement work will establish bus access loops, repair all access roads into and around the complexes, and correct drainage to eliminate ponding of storm water	Request: FY 2017 - $15.2M FY 2018 - $3.6M FY 2019 - $3.6M FY 2020 - $3.5M FY 2021 - $3.5M Indirect Investment: FY 2016 - $1.7M FY 2017 - 2021 - $TBD

General Purpose Infrastructure	Cost Estimate	Infrastructure Component Gaps and Impacts	Status
Modernize Essential Communications Infrastructure	$10M	Aging site fiber optic cables and equipment connecting infrastructure to INL's network ring are now undersized and becoming obsolete. There is increased risk of work interruptions and outages because of failed communications equipment that is beyond its service life and no longer supported by the vendor for spare parts and service. This infrastructure capability enhances worker safety by ensuring communication links to emergency systems and back up communication lines. It is also critical enabling infrastructure supporting research mission needs by linking complex areas with high performance computing, instrumentation and control, and collaboration.	Indirect Investment: Fy2017 – 2020 - $1.2M proposed
Replace Deferred Roofs	$20M	INL has approximately 218,000 ft^2 of failing roofs[18] on enduring buildings with an estimated replacement cost of almost $10M that accounts for $4M of roof related deferred maintenance. There is an additional 531,000 ft^2 of roof area having an estimated replacement cost of more than $25M that is projected to reach the point of failure[4] in the next 5. Impact includes risk of work interruptions and damage to building structures, and water intrusion into electrical and electronic equipment, and costly research equipment inside the buildings. Roof replacement investment is needed to mitigate this and avoid forecasted accumulation of and additional $25M of deferred maintenance over the next five years.	Program Funds: FY 2016 - $.6M (IFM) FY 2017 - $3.3M (IFM) FY 2018 - $2.7M (U.S. Army) Indirect Investment: FY 2016 - $1.5M FY 2017 - 2021 - $TBD
Revitalize INL Research Center Laboratories and Offices	$45M	Revitalize and repurpose INL research laboratories that support multiple programs and customers; this includes electrical, communications, HVAC, gas distribution systems and laboratory and office areas.	Indirect Investment: FY 2020 - $5M FY 2021 - $5M FY 2022 - $5M

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[18] Failing roofs are roofs identified by the June 2015 RAMP roof assessment as degraded to the point that it is not economical to repair.

General Purpose Infrastructure	Cost Estimate	Infrastructure Component Gaps and Impacts	Status
MFC/TREAT Utility Corridor	$8.2M	The electrical distribution system at MFC suffers from aging equipment, incomplete power distribution, and improper routing of cables. Power is transmitted through aging equipment from a single source, with no redundancy to maintain power during planned or unplanned outages. Communications cables are routed through the same manholes as power cables. This configuration violates the current electrical code, necessitates power outages to allow work on the communications system, and potentially exposes maintenance workers to electrical hazards. Security communications cables share the same duct as other communications cables, compromising the integrity of secure communications.	Indirect Investment: FY 2017 – 2021 - $TBD
Underground Storage Tanks	$5M	Emerging need: INL has at least 24 underground storage tanks that are 20–30 years old in deteriorating condition and may be out of compliance with existing and newly defined requirements. Following assessment and analysis, INL is seeking resources to remove at least eight tanks that are approaching end of life (30 years), replace seven tanks, and enhance or modify the remaining tanks to bring them into compliance by 2018.	Request for direct and indirect funding pending based upon priority established in the underground storage tank replacement program
Rail Line Upgrade	TBD	Emerging need: An engineering evaluation of the existing 144 miles of railroad will identify specific needs for repair, maintenance or replacement of rails. An increase in utilization is anticipated to support of NR mission objectives.	M&O base funding ~$420K FY 2016 –2021 - $TBD
MFC Balance of Plant		A laboratory strategy is being developed that includes laboratory investment alongside DOE-NE investment to create an overall infrastructure capable of achieving GAIN objectives and creating a more comprehensive nuclear energy test bed. This includes improvements to deteriorating infrastructure, and strategy to eliminate nearly 52,000 ft2of aging modular office space and adding modern office space [e.g., effective professional, viable configurable offices, collaboration spaces directly associated with research areas]) that will attract and retain research staff.	Indirect Investment: FY 2016 - $1.2M proposed FY 2017to 2021 - $TBD
Fire Protection	$20M-$30M	INL's fire protection system infrastructure is aging causing compliance issues, system failures, maintenance issues, and unsatisfactory performance. The primary issues include obsolete fire alarm panels, degraded fire water systems, and end-of-life systems. There is increased risk of work interruptions and outages because of failed fire protection equipment that is beyond its service life and no longer supported by the vendor for spare parts and service. These items	Infrastructure investments requests pending

General Purpose Infrastructure	Cost Estimate	Infrastructure Component Gaps and Impacts	Status
		need to be replaced to ensure reliability and reduce near-term mission risk. Integration of the Fire Protection System across INL is critical to resolve these issues in the most effective and efficient manner possible. As such, an INL Enterprise Fire Protection Technical Integration Strategy and Management Approach and an INL Enterprise Fire Protection Technical Integration Implementation Plan have been prepared and submitted to management for approval.	

Sustain Key Campuses

With a focus on critical mission outcomes, INL defined, and is implementing, five-year plans for managing mission and general-purpose infrastructure to address deferred maintenance, improve plant reliability, achieve predictable annual operation, and reduce operational risk at ATR and MFC campuses specifically. In specific support for GAIN and SMR advancements, the Materials and Fuels Complex Integrated Five-Year Strategic Roadmap (INL/EXT-16-37720) and the Advanced Test Reactor Programs 5-Year Plant Health Investment Plan Update (CCN 237712) address infrastructure needs, existing gaps, and investments required to maintain and operate our mission-critical and dependent infrastructure.

As part of the 2014 DOE Laboratory Operations Board infrastructure assessment, priority general-purpose infrastructure needs for FY 2016–2018 were identified. As a result, significant Idaho Facilities Management Program investments in general purpose infrastructure ($23.2M INL Power Distribution in 2016–2017, and $15M in roads in 2017) and in programmatic projects to improve capabilities is contributing to the projected downward trend in deferred maintenance, as shown in Figure 6.3.

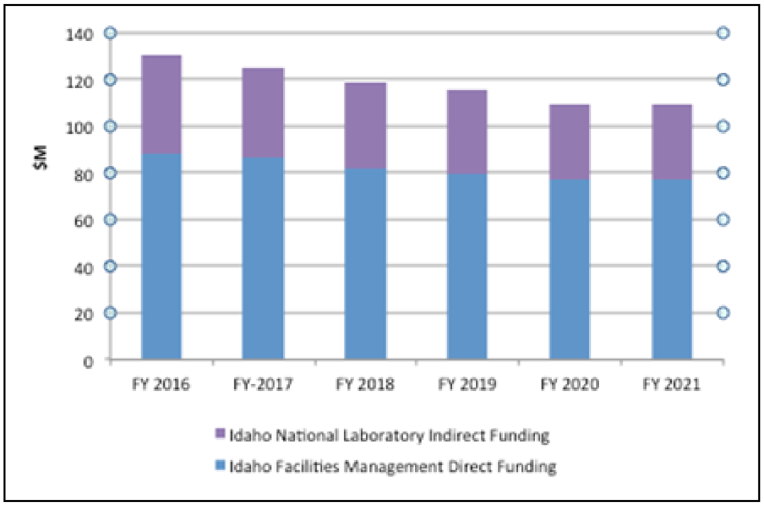


Figure 5.3: INL deferred maintenance projection.

INL is also committed to providing employees and visitors with modern, collaborative, and sustainable work environments that are safe, accommodating, flexible by design, and able to be reconfigured as necessary to meet specific program/project needs in the following ways:

Consolidating space and co-locating support functions in renovated, modern spaces enables INL staff to advance INL's vision and mission.

Improving movement about the campuses by developing a wayfinding strategy to simplify and safeguard circulation, transportation, and pedestrian pathways and gateways on our campuses.

Providing safe and reliable bus transportation from local communities to INL on-site campuses at no cost to the employee through the INL transportation system, which is considered a critical component of INL safety culture.

Optimizing existing parking lots to gain capacity, enhance efficiencies in bus transportation, and develop new parking lots to meet growth and sustainability objectives.

Emphasizing environmentally sustainable practices in campus operations and processes and as we renovate existing space.

Maintaining the security of nuclear operations is fundamental to successful mission outcomes; DOE continues to make the necessary investments to ensure compliance with security requirements.

Advanced Test Reactor Complex

Located 72 km (45 miles) west of Idaho Falls, the ATR Complex historically has supported fuel development for the Navy's nuclear propulsion program. Over the last decade, its use has expanded into other mission areas that include particle fuel development for the high-temperature gas reactor, minor actinide-bearing fuel development, and low-enriched fuel for the NNSA's Reduced Enrichment for Research and Test Reactor Program, which is part of the Global Threat Reduction Initiative.

The ATR Complex houses ATR, one of the world's most versatile materials test reactors. A low-temperature, pressurized, water-cooled reactor for steady-state irradiation, ATR supports nuclear energy research and materials irradiation for DOE, EPRI, NR, South Korea Atomic Energy Research Institute, and several university and industrial collaborators through the NSUF. The ATR has operated for 47 years, and the facility has an indefinite lifespan, because of routine, planned replacement of the entire reactor internal structure at approximate 10-year intervals. Investment needs for the remaining majority of the plant infrastructure have been defined in the Advanced Test Reactor Programs 5-Year Plant Health Investment Plan Update (CCN 237712). In addition, our focused attention to drive down deferred maintenance costs over time; the need to consolidate, refurbish, and renovate general-purpose support infrastructure; and the need for mockup and preparation space may be solved through the addition of the ATR Science and Engineering building. The proposed building will need to be in place to support the planned 2020 core internal change activities. In the next five years, INL will need to address long-term dry storage of ATR spent nuclear fuel, which may require a facility solution.

Materials and Fuels Complex

MFC is located 28 miles west of Idaho Falls; it houses unique capabilities, including engineering-scale, microstructural, and chemical characterization of irradiated fuels and materials; spent fuel processing and treatment; transient testing; radio analytical chemical analysis; fuel fabrication; component fabrication and testing; nuclear material storage and transportation; and waste handling, engineering, and support infrastructure. MFC successfully supported demonstration of EBR-II and its associated research and testing programs over a period of nearly 30 years. Reviving and improving the historical MFC capabilities to support demonstration-scale activities is an imperative for INL. This will support its mission to lead GAIN and to provide improved access to unique and valuable nuclear capabilities to national laboratory, industry, university, and international users. Previously identified gaps in transient testing and nuclear materials characterization and examination are being addressed by recent and planned investments to restart TREAT and to build the Sample Preparation Laboratory and the MFC Research and Collaboration Building. Additionally, investment in general-purpose infrastructure, as well as consolidation and modernization of existing facilities, is needed, including innovative solutions to resolve office space congestion. MFC priorities for collaboration and office space are increasing relative to other use needs as the population of the research campus grows, and as current obsolete modular office space, no longer suitable to support MFC, is removed. Need for continuing investment in the aging infrastructure has been addressed in the MFC Integrated Five-Year Strategic Roadmap (INL/EXT-16-37720, Volume 1). Hot cell refurbishment and MFC lifecycle management will be the focus of future investment.

Specific Manufacturing Complex

SMC is located 55 miles northwest of Idaho Falls. SMC has been working with the U.S. Army for over 30 years to provide innovative survivability solutions and produce armor for the Abrams A1 Main Battle Tank. The project with the support of INL and DOE-ID has grown into a national asset that has been designated by the U.S. Army as the Abrams Armor Center of Excellence. The project facility boasts 320,000 ft^2 of under-roof floor space, all located on a 25.5-acre secure footprint.

SMC is the last remaining project at the Test Area North (TAN) and is anticipating 10 to 15 years of continuing operations. The need for continuing investments in TAN's aging infrastructure is critical in keeping the SMC project going forward into the future. The primary lifecycle issues are the TAN 601 dial room, TAN potable water system, power distribution system, HVAC, roofs, and the roads and grounds. Without future investments in the TAN infrastructure, the SMC project will be forced to shut down, because of INL's inability to provide power, water, communications, and safe roadways and buildings that are structurally sound.

Research and Education Campus

REC serves as the "Gateway to INL" and provides the primary entry point for the user community to INL capabilities. INL has transformed REC to be more conductive to collaboration with industry and university partners, while providing the latest in laboratory and office efficiencies. Key research and administrative services infrastructure exists on this campus, including primary capability for advanced computer science, visualization, and data to support GAIN (including the planned addition of C3, the hub for INL's Cybercore, as well as capabilities to support clean energy security (including research and demonstration in bioenergy feedstock processing, advanced battery testing, and hybrid energy system integration). Similar to MFC, office space congestion and underutilized space on the REC campus are targeted for improvement through zoning and cleanup activities such as a Clean Sweep.

Address Excess Facilities

INL identifies unneeded real property assets excess to mission needs for reuse or disposal per federal real property disposition requirements. It is INL's goal to offset new construction through the elimination of equivalent excess facilities—especially for office or warehouse needs. Typical methods of elimination include demolition and lease termination or expiration. INL's current real property portfolio includes 115,123 ft^2 of excess facilities. The safe and secure disposition of some of these facilities requires stabilization and abatement (removal of asbestos, radioactive contamination, and equipment); deactivation and decommissioning (shut down and removal of active systems); and demolition. Because of the age and location of these assets, more often than not, the most efficient and effective method for conducting cleanup and disposition of the facilities and materials is through demolition, based on reducing risks and minimizing costs.

A major challenge to being able to decommission and demolition (D&D) several excess facilities involved five historical Naval Proving Ground (NPG) signature properties located at CFA. The challenge was met through a signed Memorandum of Agreement (MOA) between DOE-ID and the State of Idaho, completion of a Historic American Landscape report provided to DOE-ID, the State Historical Preservation Office (SHPO), U.S. National Park Service, and Advisory Council on Historical Preservation (references INL/EXT-15-35931, INL/EXT-15-35895, and INL/EXT-15-35824), and installation of an informational kiosk at the U.S. Highway 20 rest area to commemorate the history of the NPG facilities. Completion of this milestone demonstrated good faith to SHPO in the MOA and brought INL one step closer to obtaining final approval to proceed with D&D of the old buildings. On September 1, INL received approval to demolish the NPG buildings. A letter to DOE-ID from the SHPO stated: "For the purposes of the Section 106 process, we consider the relevant stipulations in the MOA to be met and therefore the demolition work at the site may proceed." Abatement of all buildings and D&D of building CF-632 and a water tower occurred ahead of schedule on September 25 and 30, 2015.

INL has been working with DOE on securing FY-17 funding to assess, remediate, deactivate, and demolish two contaminated buildings—the excess Radiological-Environmental Sciences Laboratory (RESL, CF-690) and the excess Health Physics Instrumentation Laboratory (HIPL, CF-633). These excess contaminated buildings are listed as INL site priorities 1 and 2 in FIMS and on the DOE National Laboratory Operations Board (LOB) Excess Contaminated Facilities Working Group (ECFWG) inventory. Funding ($5.1M) for demolition of these two assets (and others) has been requested in the FY 2017 Presidents budget request. The HPIL (CF-633) is one of the five Naval Proving Ground buildings approved for demolition by the State of Idaho Historical Preservation Office (SHPO) under the MOA. If D&D funding is secured as planned all NPG buildings, CF-690, associated OSFs and other shovel ready buildings will be demolished within the provided funding constraints.

Direction for completing excess facility D&D is maintained through an active building disposition strategy that includes summary of estimated costs, status, hazards, and risk ranking, and estimated year of elimination. The actual investment and disposition square-foot profile will depend on the amount of funding that is ultimately allocated to this effort. Excess assets include those with shutdown-related FIMS status codes for buildings, trailers, and OSFs (FIMS Status Codes 3, 4, 5, 11, and 12). Despite budget constraints in past years, excess facility elimination and disposition remains a real property management priority. Table 6.4 provides excess facility disposition projection over the next five years.

Table 5.4: Summary of projected excess facility elimination.

Excess Property Type	**2016**		**2017**		**2018**		**2019**		**2020**	
	No.	**Gross ft^2**	**No.**	**Gross ft^2**	**No.**	**Gross ft^2**	**No.**	**Gross ft^2**	**No.**	**Gross ft^2**
National Register Eligible	0	0	5	64,527	2	45,420	0	0	1	1,138
Non-historic	0	0	0	0	1	1,188	0	0	1	2,166
National Register Eligible OSF	0	0	0	0	0	0	0	0	0	0
Non-historic OSF	1	0	0	0	0	0	0	0	0	0
Total	**1**	**0**	**5**	**64,527**	**3**	**46,608**	**0**	**0**	**2**	**3,304**

INL Waste Liabilities

DOE-NE and DOE-EM have complementary infrastructure to support INL's waste management activities. Both organizations have waste storage pads and waste disposition infrastructures that directly support their individual missions, and both actively utilize each other's capabilities when needed to ensure minimal duplication of infrastructure. DOE-NE owns 11 waste management facilities that directly support the management or handling of newly generated waste from ongoing operations, including R&D programs. DOE-NE uses some of the 25 DOE EM-owned waste management facilities where it is not cost effective to maintain duplicative capabilities or when DOE-NE's waste stream is small compared to DOE-EM's waste volumes.

DOE-NE, with NR, is currently constructing a replacement facility for onsite disposal of RH-LLW. DOE-EM will maintain the existing onsite RH-LLW disposal capability until the existing disposal facility is full. The RH-LLW Disposal Facility will be a Hazard Category 2 nuclear facility, consisting of below-grade precast concrete vaults designed to emplace and dispose of stored and newly generated RH-LLW waste from ongoing operations, including R&D programs. To address current and future waste liability issues at INL, additional infrastructure options are being considered and include:

- Enhanced treatment capability for RH bulk reactives waste generated in future TREAT operations, future fast reactor research and in support of RWDP backlog.
- Capability for treatment of RH-MLLW RCRA metals waste (>50R) to support current and future missions.
- Waste storage, handling and characterization facilities at MFC to relieve HFEF, AL, and various research facilities of waste storage burden.
- Upgrade SCMS's capability to treat and/or prepare difficult CH-MLLW reactives waste for shipment to off-site treatment facilities.

Optimize Space and Land Use Decisions

Space and land use planning and decisions at INL are guided by the DOE Asset Management Plan, Laboratory Agenda, and INL business portfolio planning process. Hand in hand with attending to the condition of real property assets is our emphasis on ensuring the most efficient and effective space utilization while providing INL employees with a modern, collaborative, and sustainable work environment that is flexible by design to meet specific program and/or project needs. A primary tenant is to utilize existing assets to the fullest before considering an asset for excess or before proposing addition of new assets. To optimize space utilization, INL has implemented office standards and provides a variety of office and workspace types and sizes. In addition to application of the space standards, INL continues to implement a REC consolidation strategy to meet the space standards, co-locate support personnel, and divest of poorer condition assets (i.e., IORC). Strategies for accommodating anticipated growth in several INL program areas are also being implemented specifically to address the potential need for new space and to support critical outcomes in GAIN and Cybercore. In the near-term, focus is placed on accommodating the anticipated summer surge of new hire activity, which could include approximately 200 employees, 210 interns, and 100 joint appointments. To accommodate this growth while making progress toward "Freeze the Footprint" and "Reduce the Footprint" federal requirements, INL metrics indicate there is underutilized or poorly utilized space at REC, as evidenced through a number of turn-around offices, double or triple offices, and important research labs being used to store equipment.

To validate the amount of available and underutilized space, walk-downs were completed for several REC facilities. Results will be used to formulate a five-year strategic space plan that will include initiatives to optimize available space while forecasting space needs. Walk-downs of space at MFC and ATR will also be incorporated into the strategic space plan in the future.

To optimize decisions, a Land Use Committee, comprised of senior staff from organizations and companies supporting missions on INL, is chartered to look at the reasonable arrangement of the different INL Site and REC land-use areas and spatial layout to achieve desired objectives. These efforts study proposals, results of suitability evaluations, land management regulations, and potential program conflicts for purposes of advising and recommending land use positions. Goals include improving the efficiency and effectiveness of INL land use, maintaining the relative balance of the ecosystem, and achieving sustainable use of resources. The process requires dealing with many correlating factors.

When required, the *Idaho National Laboratory Comprehensive Land Use and Environmental Stewardship Report* (INL/EXT-15-00726) is updated to provide a comprehensive description of historical land use, current operations, and projected land use plans. The report examines multiple land-use options by describing site issues, capabilities, opportunities, and limitations. The land that comprises the INL Site has experienced a long and varied history that ranges from prehistoric times, when it was inhabited by nomadic groups of Native Americans, to its modern use as the location of a world-class nuclear research center. This represents unique challenges and complexities; major factors governing land use decisions include the following:

CERCLA, commonly known as Superfund, was enacted by Congress on December 11, 1980, and governs environmental remediation, including remediation of federal facilities at the Site.

INL Site was placed on the National Priorities List in November 1989. This required DOE to enter into a Federal Facility Agreement and Consent Order (FFA/CO) with the EPA and the State of Idaho for effective management of INL Site.

A Settlement Agreement was signed on October 16, 1995, to resolve issues with the State of Idaho related to spent nuclear fuel and waste management. It also recognizes DOE's commitment under the FFA/CO to complete all major environmental restoration activities for INL Site.

Operations are governed by hazardous waste and air quality permits issued by the State of Idaho.

A Candidate Conservation Agreement was made between DOE and the U.S. Fish and Wildlife Service for rangeland fire management as a critical priority for protecting, conserving, and restoring the health of the sagebrush steppe ecosystem and greater sage-grouse habitat.

Historic archaeological sites and artifacts require preservation efforts.

Proximity to nearby cities and towns, and a Native American Reservation must be considered.

An initial site assessment is being completed to determine INL's appropriateness for implementing pollinator-friendly best management practices.

Recent changes in land use at INL Site include an expansion of the Naval Reactor Facility Boundary, construction of the Remote-Handled Low Level Waste Disposal Facility, establishment of the water security and wireless testbeds, and a zone for unmanned aerial vehicle research operations. No changes have occurred on the REC campus since 2013. Proposals under current or slated for future consideration include the following:

Siting for commercial parties, such as the Carbon Free Power Project Small Modular Reactors, and federal research such as the Frontier Observatory for Research in Geothermal Energy field laboratory.

Growth on the north REC campus to accommodate the new Cybercore and C3.

Long-term stewardship of several aged federal properties on the REC campus, including the INL Research Center (IF-602/603, 30 years old, 46,512 ft^2 offices and 112,276 ft^2 adjacent wet and dry laboratory space), Information Operations and Research Center (IF-608, 47 years old, 37,299 ft^2), and the INL Admin Building (IF-606, 30 years old, 65,494 ft^2).

Expected responsibility for long-term stewardship of INL Site once the EM cleanup mission is complete.

Work to define long-term stewardship of EBR-I, such as through a foundation that could assist in operation and development of the museum.

Relocation of fabrication and machining capability from the North Holmes Laboratory.

Table 5.5 provides a summary of real estate actions FY 2015 (actual) and FY 2016 (planned), including new (or renewal) leases of 10k ft^2 or more, and disposals of DOE land via leasing, sale, or gift. Table 6.6 summarizes overall infrastructure investments. Table 6.7 summarizes the facility and infrastructure budget.

Table 5.5: Summary of land use changes or real estate actions ($K).

Category	**FY 2015 Actual**	**FY 2016 Planned**	**FY 2017 Projected**	**FY 2018 Projected**	**FY 2019 Projected**
New/renewed leases* (> 10,000 ft^2)	$340	$6	$0	$3,406.5	$7,850
New/renewed land use agreements					
Disposals of DOE land via leasing, sale, or gift					
Net reductions in footprint (ft^2)					
Land leased for grazing (total acreage managed by BLM)		340,000			
Limited, controlled hunts for elk and antelope (Idaho Department of Fish and Game)					
Total					

*Includes 2015 – BCTC and national and historic landmarks; 2016 – Willow Creek Building; 2018 – Engineering Research Office Building, IF-681/IF-682, and partial year lease for Cybercore and C3; 2019 full-year lease for Cybercore and C3.

Table 5.6: Infrastructure investment.

Objectives:

Objective 1 Leverage existing & establish new capabilities

Objective 2 Sustain Key Campuses

Objective 3 Address Excess Facilities

Planned infrastructure Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Funding	Core Capability
Institutional General Plant Projects																	
MFC Fire Water System Upgrade - TEC	7,826	5,451	2,375												IGPP	I	Enabling Infrastructure
Land Mobile Radio Upgrade - TEC	3,937	1,787	2,150												IGPP	I	Enabling Infrastructure
Underground Storage Tanks*	5,000				5,000										IGPP	I	Enabling Infrastructure
Essential Communications Infrastructure*	4,800			1,200	1,200	1,200	1,200								IGPP	I	Enabling Infrastructure
MFC Utility Corridor - TEC $8.2M	3,000			1,000	1,000	500	500								IGPP	I	Enabling Infrastructure
Repurpose INL Research Center Laboratories (IRC)*	9,000			500	500	500	500	1,000	1,000	1,000	1,000	1,000	1,000	1,000		I	Applied Materials Science & Engineering; Chemical Engineering
Reactor Fuels Fabrication Facility	9,500								9,500						IGPP	I	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Nuclear Nonproliferation and Nuclear Forensics Laboratory	9,500										9,500				IGPP	I	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
MFC Technical Support Facility	9,500												9,500		IGPP	I	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Programmatic General Plant Projects																	

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Funding	Core Capability
DOE Laboratory Accreditation Program Facility	4,380	4,380													GPP	D	DOE
MFC Research Collaboration Building - TEC	9,500		9,500												GPP	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
MFC Perimeter Intrusion Detection and Assessment System - TEC	8,281		8,281												GPP	D	Enabling Infrastructure
MFC Central Alarm System Upgrade - TEC	3,400		3,400												GPP	D	Enabling Infrastructure
ZPPR Documented Safety Analysis Upgrade - TEC	2,118		1,790	328											GPP	D	Nuclear Engineering
NHS Power Grid Test Bed - Power Line Construction Project (DOE-OE funding) - TEC	2,975		2,975												GPP	D	Cyber and Information Sciences; Decision Science and Analysis; Large-Scale User Facilities/Advanced Instrumentation; Power Systems and Electrical Engineering
INL Power Distribution System* - TEC	7,941		7,941												GPP	D	Enabling Infrastructure
Live Fire Shoothouse Enhancements - TEC	3,875			3,875											GPP	D	Enabling Infrastructure
ATR Science and Engineering Facility	9,500			9,500											GPP	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Space and Security Power Systems Facility Addition (NASA funding) - TEC	2,976				2,468	508									GPP	D	Nuclear Engineering
Cyber Security Operations Center	3,375					3,375									GPP	D	Enabling Infrastructure
MFC Perimeter Modifications - TEC	1,875					1,875									GPP	D	Enabling Infrastructure
MFC ProForce Exercise Facility - TEC	3,375					3,375									GPP	D	Enabling Infrastructure
MFC 714 Replacement - TEC	4,125							4,125							GPP	D	Enabling Infrastructure
Line item construction projects																	

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Funding	Core Capability
Remote Handled Low-Level Waste Disposal Project 13-D-905 (joint funded by NE and NR) NE - TPC	12,366	7,922	1,504	2,940											LI	D	Applied Materials Science & Engineering
Remote Handled Low-Level Waste Disposal Project 13-D-905 (joint funded by NE and NR) NR - TPC	20,005	14,990	3,640	1,375											LI	D	Applied Materials Science & Engineering
Sample Preparation Laboratory - TPC (revised Project Data Sheet currently in development, final TPC and funding profile will be established with CD-1)	95,000		3,500	8,800	TBD	TBD	TBD								LI	D	Applied Materials Science & Engineering
Other infrastructure activities																	
Cybercore - Acquisition	13,050		950	3,150	8,950										Acq	I	Cyber and Information Sciences; Decision Science and Analysis; Large-Scale User Facilities/Advanced Instrumentation; Power Systems and Electrical Engineering
Cybercore - Operation Costs	78,960				4,729	7,307	7,526	7,752	7,984	8,224	8,471	8,725	8,986	9,256	Lease	I	Cyber and Information Sciences; Decision Science and Analysis; Large-Scale User Facilities/Advanced Instrumentation; Power Systems and Electrical Engineering
C3 Acquisition Costs	7,925		850	1,400	3,500	2,175									Acq	I	Advanced Computer Science, Visualization, & Data; Cyber and Information Sciences; Decision Science & Analysis; Environmental Subsurface Science
C3 Operation Costs	53,080				558	5,170	5,325	5,485	5,649	5,819	5,993	6,173	6,358	6,549	Lease	I	Advanced Computer Science, Visualization, & Data; Cyber and Information Sciences; Decision Science & Analysis; Environmental Subsurface Science
Security Enhancements	TBD				TBD	TBD	TBD	TBD	TBD						TBD	D	Enabling Infrastructure
Maintenance and repair and D&D																	
Specific Manufacturing Capability Maintenance (Department of Defense Funded)	20,180	1,770	1,332	1,362	1,393	1,428	1,466	1,500	1,535	1,581	1,628	1,677	1,728	1,779	M&R	D	Applied Materials Science & Engineering

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Funding	Core Capability
Advanced Test Reactor Maintenance (NR Portion - NE/NR Funded)	12,858	883	891	912	898	917	940	968	997	1,027	1,058	1,089	1,122	1,156	M&R	D	Applied Materials Science & Engineering
Advanced Test Reactor Maintenance (NE Portion - NE/NR Funded)	45,563	2,252	3,067	3,145	3,260	3,346	3,429	3,532	3,638	3,747	3,860	3,975	4,095	4,217	M&R	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Material and Fuels Complex Maintenance	204,731	14,280	9,885	10,181	21,505	16,022	15,737	16,000	15,633	16,102	16,585	17,083	17,595	18,123	M&R	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
INTEC Maintenance	4,351	313	210	215	315	324	334	344	355	366	377	388	400	412	M&R	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
MFC -TREAT Maintenance	33,876		2,435	2,500	2,563	2,627	2,692	2,760	2,829	2,914	3,001	3,091	3,184	3,280	M&R	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Space Battery Maintenance (NASA Funded)	7,328	559	477	492	507	522	537	553	569	586	604	622	640	660	M&R	D	Nuclear Engineering
Advanced Test Reactor Complex Balance of Plant Maintenance	9,791	1,150	619	635	651	667	683	703	724	746	768	791	815	839	M&R	I	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Sitewide Indirect Maintenance	172,415		12,424	12,772	12,971	13,325	13,689	14,063	14,404	14,836	15,281	15,740	16,212	16,698	M&R	I	Enabling Infrastructure
Material and Fuels Complex Balance of Plant Maintenance (Indirect)	72,636	4,215	3,416	3,501	10,750	12,330	4,622	5,567	4,365	4,496	4,631	4,770	4,913	5,060	M&R	I	Enabling Infrastructure
Telephony Maintenance	785	34	50	50	54	56	59	62	65	67	69	71	73	75	M&R	I	Enabling Infrastructure
ATR Five-Year Plan Plant Health Investments	84,485		10,000	6,470	21,615	19,745	13,095	13,560							M&R	D	Applied Materials Science & Engineering; Large Scale User Facilities/Advanced Instrumentation; Nuclear Engineering
Roofs (Indirect Investment)*	10,561		1,500	1,200	1,600	2,700	855	846	1,500	360					M&R	I	Enabling Infrastructure
Roofs (Direct Investment IFM, US Army)*	6,620		600	3,320	2,700										M&R	D	Enabling Infrastructure
Primary Roads (Indirect Investment)*	9,213		1,792	2,021	1,600		1,900	1,900							M&R	I	Enabling Infrastructure
Primary Roads (Direct Investment)*	15,200			15,200											M&R	D	Enabling Infrastructure

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Funding	Core Capability
INL Power Grid (Direct Maintenance)	15,870		15,870												M&R	D	Enabling Infrastructure
D&D - All years include pre-D&D planning, characterization, and hazard remediation. FY-2017 includes $4,600K for demolition of specific facilities	10,241	779	525	5,187	750	750	750	750	750						D&D	D	Enabling Infrastructure

National Energy Technology Laboratory

1. Mission and Overview

The National Energy Technology Laboratory (NETL) is the Department of Energy's (DOE) Fossil Energy laboratory. NETL's mission and vision is to lead the nation and world in the discovery, integration, and demonstration of the science and technologies that will continue to ensure the nation's energy security, while protecting the environment for future generations. NETL will achieve this mission by:

- Maintaining nationally-recognized technical competencies in areas critical to the discovery, development, and deployment of affordable, sustainable fossil energy technologies and systems;
- Collaborating with partners in industry, academia, and other national and international research organizations to nurture emerging fossil energy technologies across the full breadth of the maturation cycle, from discovery, through development, to commercial-scale demonstration and deployment; and
- Continuing active engagement in the national and international clean energy conversation to be poised to recognize, and react to, emerging opportunities to enable transformational clean energy ideas.

For more than a century, NETL has played a significant role in ensuring domestic energy security through its focus on the safe, affordable, and increasingly sustainable production and utilization of the nation's fossil energy resources. Beginning in 1910 as a U.S. Department of the Interior Bureau of Mines laboratory in Pittsburgh, Pennsylvania, dedicated to coal and coal mine safety, NETL has expanded over the years to include other Bureau of Mines sites in Morgantown, West Virginia; Bartlesville, Oklahoma; and Albany, Oregon, adding technical breadth and capability relevant to the DOE mission. NETL was designated a DOE national laboratory in 1999.

Today, NETL's research portfolio has a total value in excess of $13 billion, including $ 8.5 billion in cost sharing investment, committed by our academic and private sector collaborators. Partners in NETL's research discovery, development, and deployment programs number in the thousands and include small and large American businesses, national research organizations, colleges and universities, and other government laboratories, including nine of NETL's sister DOE national laboratories.

NETL is the Department's only Government-Owned Government-Operated (GOGO) national laboratory.

2. Lab-at-a-Glance

Location: Pittsburg, Pennsylvania
Morgantown, West Virginia
Albany, Oregon
Sugarland, Texas
Anchorage, Alaska
Type: Single-program Laboratory
Government-Owned Government-Operated
Website: www.netl.doe.gov

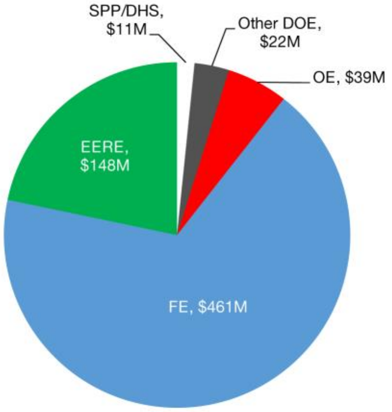
Physical Assets:

- 242 acres and 109 buildings
- 1,157,849 GSF in buildings
- Replacement Plant Value (RPV): $596.9M
- 0 GSF in Excess Facilities
- 74,736 GSF in Leased Facilities

Human Capital:

- 1,336 Full Time Equivalent Employees (FTEs)
- 47 Joint faculty
- 94 Postdoctoral Researchers
- 12 Undergraduate and 50 Graduate students
- 916 Technology Development Partner Institutions (Active Awards)

FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs (excluding Recovery Act): $234
DOE/NNSA Costs: $670
SPP (Non-DOE/Non-DHS) Costs: $11
SPP as % Total Lab Operating Costs: 4.7%

3. Core Capabilities

For over a century, NETL's core capabilities, expertise, and mission-unique facilities have delivered innovative technology solutions to significant energy and environmental-related challenges. Notable NETL successes over the decades include the production of synthetic fuels from domestic fossil resources, the mitigation of trans-boundary acid rain, and the ability to affordably achieve steep reductions in mercury and other power plant emissions. More recently, to help DOE respond to public concern about the magnitude of the Deep Water Horizon oil spill, NETL federal scientists led DOE's National Lab Response Team and were the first to calculate what was later established to be an accurate flow rate for the disaster. In addition, NETL research has stimulated the development of high-efficiency, next-generation combustion turbines; created the technology that enables the ability to identify, estimate, and economically recover our nation's abundant unconventional shale oils and gases; and generated technology solutions for effectively and safely capturing and storing carbon dioxide (CO_2).

NETL's current slate of technical core capabilities includes expertise in Decision Science and Analysis, Applied Materials Science and Engineering, Chemical Engineering, Environmental Subsurface Science, and Systems Engineering and Integration, which are described separately in the following sections. However, NETL believes strongly in a multidisciplinary approach to technology development, building teams that encompass the breadth of NETL's technical capability to conduct research, and harnessing the power of diverse thought to more rapidly conceive and deliver effective technology solutions. Utilizing this approach, NETL is addressing a variety of national challenges, including reducing greenhouse gas emissions through carbon capture and storage, developing more efficient energy conversion processes, and demonstrating novel advanced energy systems.

Decision Science and Analysis

NETL develops and utilizes a variety of multi-scale computational tools and approaches to support decision-making and provide in-depth, objective analyses. Work in this area encompasses a sophistication that enables a comprehensive evaluation of the most complex engineering systems and their related environmental risks; the delivery of information essential to guiding NETL's research path; and the ability to assess and forecast technical, economic, and environmental risks and focus investment decisions in technologies with the potential to achieve the greatest advances in efficiency, performance, cost, and life-cycle emissions.

This capability also facilitates strategic planning and technology development by providing a strong understanding of the interactions among energy markets and related policies, environmental systems, energy processes, and the capabilities of current and emerging technologies. In this manner, NETL's Decision Science and Analysis capability supports DOE's mission to ensure America's security and prosperity and address its energy and environmental challenges through the development of transformative science and technology solutions.

NETL is internationally recognized for its development and utilization of advanced process systems engineering models and computational tools to support decision- making and analysis in the context of many potentially conflicting goals. Through the Carbon Capture Simulation Initiative (CCSI), NETL researchers developed and deployed several new capabilities for integrating multi-scale models with advanced optimization, uncertainty quantification, and surrogate modeling techniques. These tools include the Framework for Optimization, Quantification of Uncertainty and Surrogates (FOQUS), which supports robust process analysis, and the Automated Learning of Algebraic Models for Optimization (ALAMO) machine learning code, which helps make sense of large, complex data sets to better support decision-making. NETL is also a leader in the development of validated, predictive process models of fossil energy systems, including those for carbon capture.

NETL is also an internationally recognized leader in life cycle analysis (LCA) to identify and quantify the risks and impacts of current and emerging technologies on environmental systems. NETL supports a team of experts in this area and maintains a unique set of software tools and datasets that include the Power Systems Life Cycle Analysis Tool (Power LCAT), a high-level dynamic model for tracking costs and environmental performance for a range of electricity generation technologies; the Grid Mix Explorer, which allows users to customize the makeup of an electricity grid specific to a particular life cycle case and mix of technologies; and the NETL Unit Process Library, which provides nearly 500 building blocks for life cycle modeling, containing qualified input and output data.

NETL has developed unique tools to understand tradeoffs between resource and technology options that ultimately feed into assessments of the impact of market dynamics, regulations, policies, or institutional practices on the development and uptake of technology. NETL customizes and uses a variety of energy-economy forecasting models such as the National Energy Modeling System (NEMS) and MARKAL to portray existing and proposed policy scenarios and differing technology assumptions in order to assess impacts on resulting electricity generation and emissions, water use, and cost of electricity. Key NETL models supporting this capability include the NETL CO_2 Saline Storage Cost Model, NETL CO_2 Model, and NETL Carbon Capture Retrofits Database, which provide site-specific estimates of CO_2 storage, and pipeline costs to enable identification of the most cost-effective resources and opportunities for carbon capture and storage (CCS); the NETL CO_2 Capture Transport Utilization and Storage (CTUS) sub-module, which integrates into NEMS to enable a comprehensive assessment of the potential role of CCS systems in forecasts; the NETL Energy-Water module, which assesses stress on water supplies caused by power generation; and the NETL-WVU Econometric Input Output Model, which enables the assessment of the impacts of research and development (R&D) and related policies on employment, gross domestic product (GDP), and income.

NETL's Decision Science and Analysis capabilities are also used extensively to support fossil energy strategic planning and program direction through technology assessment via the NETL Cost and Performance Baseline Studies and Pathway Studies, market-based goal development for the Clean Coal and Carbon Management Program, and key analysis and exercising of the above capabilities critical to the development of the Fossil Energy Rare Earth Element and Methane Quantification programs.

NETL analyses are widely disseminated and cited in national and international publications on energy (e.g., the Environmental Protection Agency's (EPA's) Carbon Pollution Standards, CCS Cost Network, and ICF International). Products developed via this capability (e.g., integration of the NETL CTUS-NEMS module into Energy Information Administration [EIA] and Office of Energy Policy and Systems Analysis [EPSA] versions of NEMS) have been deployed by supporting agencies and other stakeholders (e.g., industry licensees of the CCSI Toolset).

Applied Materials Science and Engineering

NETL is internationally recognized for its competency in the design, development, and deployment of advanced structural materials and tailored functional materials for use in energy-applications and extreme service environments. Of particular note is NETL's ability to conceive, engineer, and evaluate materials from molecular to power plant scales, with a strong emphasis on process engineering, realistic environmental testing conditions, and a feedback loop enabled by direct collaboration with practical-scale technology deployment projects. This relationship enables materials optimization, process components design, and the generation of industrially-relevant, impactful material solutions.

The Applied Materials Science and Engineering capability has been successfully demonstrated for energy applications on numerous occasions, including development of corrosion-resistant refractory brick used in nearly all slagging gasifiers world-wide, commercially-licensed sorbents for mercury removal and CO_2 capture and heat treatment profiles for large-scale nickel-base superalloy castings as part of DOE's Advanced-Ultra-Supercritical (AUSC) program. In addition to playing a critical role in energy applications, NETL's Applied Materials Science and Engineering capability has also benefited other sectors, including the development and deployment of a world-leading radiopaque alloy for medical coronary stents and ballistic-resistant armor deployed in military ground vehicles.

NETL's functional materials development focuses on the design, synthesis, physical characterization, and performance testing of the nanomaterials, polymers, porous sorbents, ionic liquids, and electroceramics required for the next generation of carbon capture, gas separation, chemical looping, solid oxide fuel cell (SOFC), chemical sensing, and fuel processing technologies. Experimental research utilizes scanning tunneling and atomic force microscopy for imaging chemical reactions and quantifying energetics; wet-chemical and vapor-growth methods to create plasmonic nanostructures for chemical sensing and energy conversion applications; spin-casting and fiber fabrication methods to produce mixed-matrix membranes for CO_2 and light gas separations; and the design of heterogeneous catalysts for power, heat, and fuel production. Computational research complements this work with a range of simulations for predicting crystallographic structures at reaction conditions; chemical reaction mechanisms and associated energetics; electronic structure, optical properties, and excited-state charge carrier behavior; and multi-scale modeling that utilizes atomistic-level simulations for predicting bulk mechanical properties. The material systems and devices resulting from this work are evaluated under realistic performance conditions such as coal power plant flue gas available at the NETL-sponsored National Carbon Capture Center (NCCC).

NETL conducts structural materials research, leveraging its substantial alloy fabrication and corrosion facilities to deliver high performance, affordable materials that can enable the development of unconventional resources, advanced combustion systems, novel power cycles, and other advanced energy systems. Researchers specialize in the design, synthesis, fabrication and manufacturing, and performance assessment of corrosion and heat-resistant alloys, and ceramics and refractories for structural and environmental protection applications. Typical objectives include development of cost-effective and, hence, deployable materials that can withstand severe mechanical stress and corrosive and erosive environments for upwards of 100,000 hours of service life. NETL maintains a complete alloy development research facility, including an alloy fabrication laboratory for prototyping alloy manufacturing (unique in the national lab complex) with capabilities for melting (vacuum induction melting [VIM], vacuum arc remelting [VAR], electroslag remelting [ERS]), casting, forging, rolling, and heat- treating materials ranging in size from a few grams to 100 kilograms; and NETL's Severe Environment Corrosion Erosion Research Facility and related laboratories for assessing materials performance in simulated fossil fuel environments at high temperatures and pressures.

Funding for NETL's Applied Materials Science and Engineering capability comes primarily from FE. Additional funding is provided by DOE's EERE and various SPP sponsors, for research that leverages NETL's unique alloy design, melt processing and fabrication capability, and that focuses on materials performance in extreme environments, and the development of magnetic materials, cores, and devices.

Chemical Engineering

Chemical Engineering is a foundational capability that supports NETL's mission to address the nation's most pressing energy and environmental challenges of today, while looking forward to the challenges of tomorrow.

As an applied laboratory, NETL's top-down perspective leverages the concept of "simulation-based engineering" closely integrated with focused experimentation. By working with models appropriate for analyses at relevant scales, backed by experiments that can produce data at those scales, researchers can accelerate the rate of discovery. This in turn accelerates the pace of maturation in order to reduce the overall investment required through the development cycle.

Advanced simulation capabilities with integrated chemical reaction, and mass-, energy-, and momentum-transport phenomena enable NETL to rapidly develop materials, devices, and processes for energy conversion. NETL integrates physical and chemical experimental research with computational sciences ranging from molecular- scale to device-scale to plant-scale with capabilities in computational chemistry, device-scale simulations, process systems engineering, and optimization. NETL uses density functional theory to understand and improve catalysts and hydrogen separation membranes, and Monte Carlo and molecular dynamics simulations to identify promising carbon capture materials such as ionic liquids. NETL's internationally recognized team of experts develops detailed, scalable, high speed single- and multi-phase computational fluid dynamics (CFD) models to assess current—and redefine future—energy conversion processes. Central to NETL's device-scale modeling capability is the laboratory's open-source suite of multi-phase CFD code—Multiphase Flow with Interphase eXchanges (MFiX)—which has over three decades of development history and more than 3,500 registered users worldwide. Through CCSI, NETL has developed computational capabilities to design and optimize the entire carbon capture process by integrating information from particle to device to systems scales that constitute the processes. To enable the development, testing, and application of the models, NETL's supercomputer "JOULE" provides 503 TFlops of floating point operational power with over 24,000 computational cores.

To complement and validate computational approaches, NETL has specialized expertise and unique facilities that enable collection of data under appropriate scales and environmental conditions. These specialized, highly instrumented experimental facilities enable the collection of detailed, high-resolution data (i.e., optical access and laser diagnostics) of reactive flows required to validate models and accelerate technology development.

Examples of NETL's unique facilities include the Laboratory's 50-kWth Pilot-scale Chemical Looping Reactor, Multi-cell Array SOFC Test Platform, High-Pressure Cyber-Physical SOFC/Turbine Hybrid Performance Project (HYPER) Facility, and Magnetohydrodynamic Power Generation Facility. In addition, NETL is equipped with a variety of cold and reacting flow experimental facilities that, in combination, enable both the optimization of modeling tools under idealized geometries and the resolution of practical problems facing industry technology developers under commercially relevant geometries.

In addition, NETL has developed and deployed several modular reactor systems, including a fluidized bed solid sorbent capture system and a membrane-based separation system, to the NETL NCCC to evaluate promising technologies on pre- and post-combustion slip streams. NETL also operates a wide variety of reactor systems for the development and evaluation of traditional thermo-catalytic processes, as well as produces novel concepts for providing activation energy for catalytic systems (i.e., microwave) and process intensification methods (i.e., integrated membrane reactors).

NETL's integrated computational and experimental Chemical Engineering capability has delivered a number of successes such as the simulation-based design of the pilot-scale gasifier at the Power System Development Facility in Wilsonville, AL; the modeling and hierarchical validation of a 1-MW scale carbon capture reactor; as leader of the National Risk Assessment Partnership (NRAP), NETL has generated several ROMs and other computational tools for assessing risk and quantifying uncertainty associated with carbon storage applications.

NETL's robust geomaterials science expertise is used to characterize natural and man-made materials in the subsurface, and to understand how they change under different in situ conditions, such as pressure, temperature, composition, biological activity, and stress. A unique combination of imaging facilities (e.g., computed tomography [CT] scanners), analytical equipment, and static and flow-through vessels allows NETL researchers to test solids and fluids under subsurface conditions over extended periods and investigate changes due to chemical, mechanical, and biological processes.

Combined theory, lab, simulation, and field approaches are used to measure and predict fluid flow in geologic media from the pore to the field scale, providing a more complete understanding of emerging issues such as the fracture-dominated flow seen in shale gas and oil applications. For example, NETL CFD experts are and the use of validated models to predict CO_2 capture efficiency with 95% confidence intervals to assist process scale up.

Funding for NETL's Chemical Engineering capability comes primarily from FE. Additional funding is provided by DOE's Office of Environmental Management and the Department of Interior's (DOI's) Bureau of Safety and Environmental Enforcement, for research that leverages NETL's chemical engineering capabilities in the analysis, modeling, and validation of residual waste processing at treatment plants, and the use of remotely operated video technology in the analysis and evaluation of submerged oil/gas leaks.

Environmental Subsurface Science

NETL's Environmental Subsurface Science capability is internationally recognized for its ability to monitor, analyze, and predict the physical, chemical, and biological structure and function of complex subsurface environments, from the field-scale down to the molecular level. These multi-scale assessments enable accurate analyses of the occurrence and distribution of in situ resources, and predictions of the performance of engineered natural systems over a range of time- and space-scales. The capability includes the development of reduced order models (ROMs) required for decision- ready science, and methods and tools used for resource estimation such as those that enabled the development of our nation's unconventional shale oils and gases. Also, that are validated by NETL's CT imaging facility, and the NETL-developed FRACGEN and NFFLOW software helps researchers better understand the behavior of unconventional systems like shale gas and oil formations.

NETL's geospatial data management and analysis capabilities include a growing suite of knowledge and tools for managing, analyzing, and interpreting data, including the ability to manage large geospatially- organized data sets and the tools to mine those data to address energy-related questions. NETL maintains both the National Carbon Sequestration Database and Geographic Information System (NATCARB) database for carbon storage reservoirs and the internationally recognized Carbon Storage Atlas. NETL's Energy Data eXchange (EDX) is a platform for data sharing and collaborative research, and has developed a suite of tools, such as the Variable Grid Method, for use in analyzing geospatial data.

Research on new and innovative monitoring technologies includes the development of new protocols and approaches for site characterization and monitoring of engineered natural systems, and statistical approaches for the design and interpretation of monitoring networks. NETL has received recognition for its perfluorocarbon tracer and remote sensing monitoring technologies, and works with its industrial partners to apply new monitoring approaches at oil and gas, carbon storage, and geothermal field sites.

Funding for NETL's Environmental Subsurface Science capability comes primarily from FE. Additional funding is provided by DOE's EERE and the DOI's Bureau of Safety and Environmental Enforcement, for research that quantifies the risks of off-shore resource development and production, develops monitoring technologies for geothermal systems, and explores new ways to enhance surface oil recovery efficiency, should a spill occur in the Arctic.

Systems Engineering and Integration

The complexities of today's fossil-based energy portfolio, and the challenges of incorporating new technology into existing or emerging systems, make NETL's Systems Engineering and Integration capability critical for managing cost and risks and for efficiently maturing technology deployment. A major obstacle to moving technology to market is the ability to effectively integrate component subsystems into a single operational system, which requires that optimization occur at the systems level and not solely on the technology platform.

NETL's Systems Engineering and Integration capability benefits from the Laboratory's experience as a full life-cycle organization to advance technology through the entire range of technology readiness levels (TRLs). NETL's unique model, which combines scientific and technical expertise with project management proficiency and a systems engineering capability, guides advances that emerge from its Decision Science and Analysis efforts, translating them into investment pathways for the development of technologies.

NETL sustains and enhances an internationally recognized capability focused on developing a portfolio of technology-based solutions. These solutions take the form of both individual sub-system components that enhance the performance of existing energy platforms, and of the more complex, capital-intensive, advanced energy systems that have achieved desired technical, cost and environmental performance goals and have been proven ready to effectively compete in the global marketplace. In some cases, technologies are developed for a single system application (e.g., to remove and capture CO_2 from gasifier syngas). In other cases, emerging technologies may have multiple uses in the energy sector, such as wirelessly sensing and transmitting data from within harsh, high-temperature environments. NETL periodically assesses technology development progress and evaluates remaining challenges as inputs to its decision-making regarding future research directions, priorities, and resource allocations. NETL's efforts are focused on ensuring optimal development of these emerging technologies, and ultimately reducing the cost and deployment risk of resulting system applications.

NETL manifests Systems Engineering and Integration efforts (as part of its FE mission) through the planning, environmental review, design, construction, operations testing, and performance assessment of a portfolio of demonstration-scale projects aimed at advancing the state-of-the-art of CCS technology. Key technical and cost performance challenges that confront the wide- scale deployment of CCS technologies in the competitive marketplace are being addressed by co-sponsoring (with private-sector partners) large-scale demonstrations of advanced, cost-effective CO_2 capture, utilization, and storage technologies integrated with power-generation and other industrial applications.

NETL's planning and assessment efforts serve to define the desired level of technology maturity at each step of development both in terms of the TRL to be achieved and the technical performance requirements to be demonstrated. The maturity of a technology is updated based on information from regular reports, independent expert peer reviews, and the conduct of Technology Readiness Assessments (TRAs) to establish that target TRLs have been reached. NETL utilizes the TRA process as a stage gate, to inform stakeholders of the status and maturity of ongoing research, and to determine future investment.

NETL has a long history of integrating early-stage research conducted on laboratory campuses with sponsored research conducted at facilities owned and operated by academic, private-sector, and utility partners. A closer look at federal investment in the research, development, and demonstration (RD&D) portfolio within the FE portion of NETL's mission finds that it is highly leveraged with partner investments, thus serving to ensure the validity, intensity, and commercial potential of the research. The total value of this portfolio is approximately $11.5 billion, $8 billion of which is provided by the private sector.

Funding for NETL's Systems Engineering and Integration capability comes primarily from FE. Additional funding is provided by DOE's EERE, DOE's Office of Electricity Delivery and Reliability, and DOD's Defense Logistics Agency, for work that leverages NETL's ability to evaluate and forecast the performance efficiency, cost, and carbon intensity of advanced energy conversion systems and to assess the potential economic, environmental, and energy security benefits resulting from their deployment in competitive markets.

4. Science Strategy for the Future

NETL's science and technology strategy focuses on catalyzing the discovery and development, and enabling the deployment, of the affordable, sustainable fossil energy technologies that are necessary to ensure quality of life, and end energy poverty, for the nation and the world. Success in this mission requires that NETL effectively integrate and manage research activities conducted by a broad range of partners in the private and public sectors across the full spectrum of maturation levels, from early development, through pilot-scale demonstration, to large-scale deployment. It also requires that NETL, again in collaboration with partners from academia and the other national laboratories, continuously feed the technology development pipeline with new concepts that have the potential to provide revolutionary solutions to the science and engineering challenges of sustainable, affordable, fossil energy production and utilization.

At the heart of NETL's science and technology strategy is a focus on building and nurturing the suite of technical core capabilities that provide the Laboratory with the scientific and technological expertise to conceive and develop innovative solutions at the bench, and to efficiently guide the most promising concepts through the development cycle to deployment and widespread commercial implementation. With a solid understanding of the requirements needed to produce affordable, real-world solutions, NETL builds multidisciplinary research teams that utilize a combination of modeling and simulation, with targeted experimental validation, to address cross-cutting technology gaps and speed new technology development.

As the Department's only GOGO national laboratory, NETL does not currently have access to laboratory-directed research and development (LDRD) -type discretionary funding and so is limited in its ability to invest in technical capabilities and research activities outside of defined program areas. However, where discretion is possible, NETL will place a priority on nurturing its technical core capabilities, to position these capabilities to continue to be major participants in the clean energy conversation, and to best serve the public interest. Targeted investments, to include investments in people as well as instrumentation and infrastructure, will be made in the areas described in the following pages with the expectation of enhancing NETL's ability to deliver substantial advances in the efficiency and sustainability of fossil energy technologies over the next decade. These investments will also better position the Laboratory to expand its SPP portfolio.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

NETL's R&D campuses are located in Morgantown, West Virginia; Pittsburgh, Pennsylvania; and Albany, Oregon. NETL also operates field offices in Anchorage, Alaska and Sugar Land, Texas, which comprise leased building space. The laboratory footprint consists of 109 buildings and 1 trailer on over 242 acres with a GSF of 1,157,849 and a replacement plant value of $596.9 million.

The age profile for NETL's facilities is similar to other DOE laboratories with over 75% of GSF being in buildings over 30 years in age and over 45% in buildings over 50 years old. NETL real property assets are assessed annually by DOE FIMS administrators who conduct walkthrough inspections to verify property type, usage code, operating status, square footage, and percent utilization to meet the requirements of the annual FIMS validation process. Based on these assessments, 77% of NETL's buildings (comprising 86% of GSF) are classified as being in good to excellent condition. Although a large percentage of NETL buildings rate as good to excellent, these ratings only reflect the condition of the building infrastructure and do not provide a good indication of the condition of research laboratories. Many of the laboratories at all three campuses are over 25 years in age and in need of investment to maintain critical core capabilities. Utilities (potable and fire water, electrical infrastructure, telecommunications network, compressed air and nitrogen, etc.) are similar in age to NETL's buildings. Over the past five years, significant investments have been made in the water and electrical infrastructure at each campus in response to system failures that threatened lab operations. As a result, these utilities at each campus have been significantly upgraded and are generally in good condition. The telecommunications networks at all three sites are at end of life and need to be replaced. Additional investments are planned over the next five-to-ten years to fully address utility needs.

The most recent Land Use Plan developed by NETL can be found in the NETL FY2015 Ten Year Site Plan that was submitted to DOE Headquarters in July 2015. This Land Use Plan has been excerpted and is included as Appendix 2. With regard to real estate transactions, NETL is in three discussions with NIOSH to transfer ownership of a building on the Pittsburgh campus. This building, in excess of NETL's needs, would require extensive modifications to meet the DOE mission, and it resides on 5.2 acres of land that is remotely located from the research plateau of the Pittsburgh campus.

Investment Planning

Infrastructure investments are targeted to maintain, sustain, and recapitalize current assets, as well as to develop new capabilities that are critical to meeting the DOE mission. Capital investments are identified, planned, and prioritized to meet specific programmatic mission requirements, to upgrade and maintain critical infrastructure, and to meet mandated sustainability goals.

Facilities and infrastructure projects less than $10 million are typically funded using the General Plant Project (GPP) funding that NETL receives annually, while projects of $10 million or more require line item appropriations. The primary program benefit, type and magnitude of the investment, and purpose of the investment are the principal factors that determine the type of capital funding used.

NETL's capital planning process begins with FE mission needs. Requirements for projects are developed based on needs identified in NETL's Science and Technology Strategic Plans and Programs and Laboratory Operations Directorates. Projects are prioritized based on organizational needs, with higher priority assigned to projects based on safety, mission need, environmental protection, and sustainability. Consideration of NETL's overall mission, programmatic needs, condition assessments, energy audit findings, deferred maintenance, and factors affecting site development are applied in developing recommendations to NETL management. Projects are then submitted to a Configuration Control Board (CCB), which is chaired by NETL's Chief Operating Officer, for final selection and implementation. Approved projects are implemented by NETL's Laboratory Operations Directorate.

The output of this planning process is a multi-year project plan, which was used to populate Enclosure 6 (see Appendix 4). The planning and implementation process provides the CCB with periodic, updated information on facility and infrastructure capital construction progress and annual investment projections.

History and Campus Strategy

NETL's three R&D Campuses have distinct core capabilities that are firmly grounded in the history of the Laboratory. These core capabilities are strongly aligned with the DOE and FE missions and form the basis for centers of excellence at the specific campuses. NETL's infrastructure investment plan builds on these core capabilities while enhancing the laboratory's capabilities for integration and collaboration among multi-disciplinary teams of scientists and engineers to focus on problems specific to the DOE mission. The research campuses are also located in close proximity to several major universities and energy sector corporations, which enable NETL to leverage facilities and resources to meet the DOE mission. For example, the structural materials research team at the Albany campus focuses on development of advanced high-temperature alloys. This team also collaborates with the Combustion Team at the Morgantown campus to access unique facilities for testing these alloys in high-temperature combustion environments. Both of these teams collaborate closely with faculty and staff at the regional universities to create multi-disciplinary teams that focus on the DOE mission.

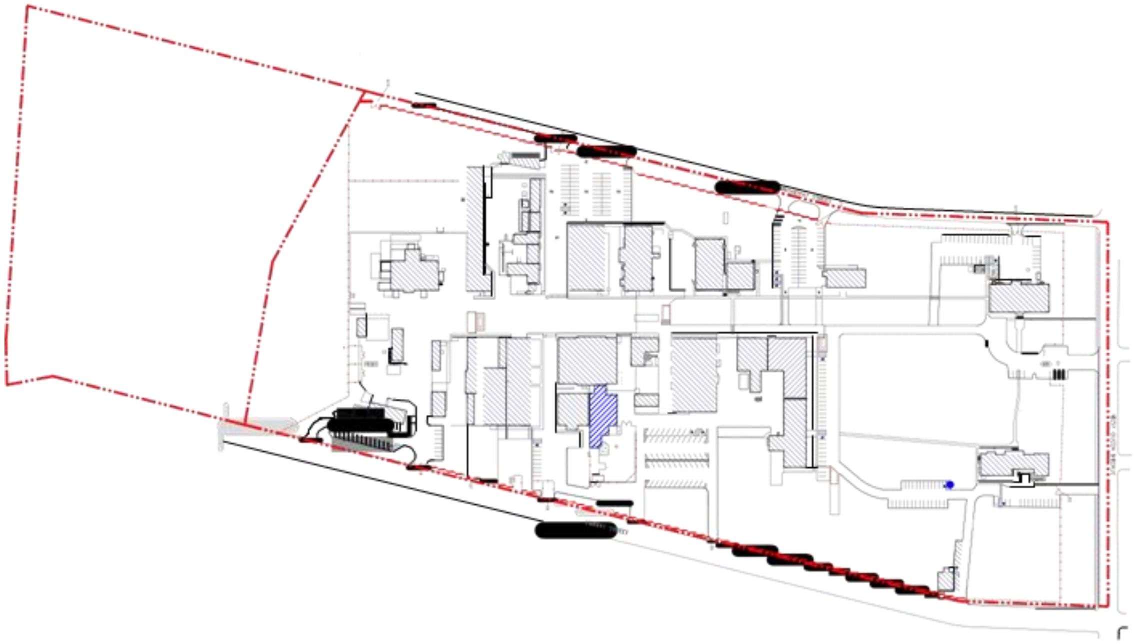


Figure 5.1 Site Map of NETL Albany Campus

The campus in Albany, Oregon is located in Linn County, in the Williamette Valley, and has 38 buildings, comprising 248,122 GSF, on 43.9 acres. The site originally served as a campus for the Albany College from 1925 through 1938. The Bureau of Mines purchased the site in July 1943, and the facilities were expanded to create the Northwest Electro-Development Laboratory, later known as the Albany Research Center. The mission of the Albany campus was and still is focused on structural materials R&D. Material processes developed at the site were utilized for the rapid deployment of light water reactors for the Navy Reactor Program. All of the zirconium used in the Nautilus and Seawolf submarines was produced at the Albany site, and the metals processing industry in the Albany area was a direct outgrowth of technology development fueled by the Laboratory. In 1996 the site was transferred to the U.S. Department of Energy, FE, and in 2006 the site was integrated into NETL. Due to the historical significance of the facilities and the research that was conducted at the site, the Oregon State Historic Preservation Office deemed the site to be eligible for the National Register of Historic Places as a Historic District in 1997.

When NETL assumed operations of the Albany campus, there were a number of legacy issues with facilities and critical infrastructure due to the age of the facilities and the nature of the R&D conducted, that compromised FE mission readiness. To address this situation, NETL conducted an assessment in 2011 to develop a "Plan for Consolidation of Core Research Operations at the NETL – Albany site," which was followed in 2012 with an implementation plan. The plan was developed to consolidate and focus R&D operations to better support the FE and DOE missions, and when fully implemented, will reduce the Albany campus footprint from 39 buildings and 2 trailers to operation of 18 buildings. NETL began implementing the consolidation plan in 2012 and has subsequently made substantial upgrades to site utilities and laboratories to better support the FE mission.

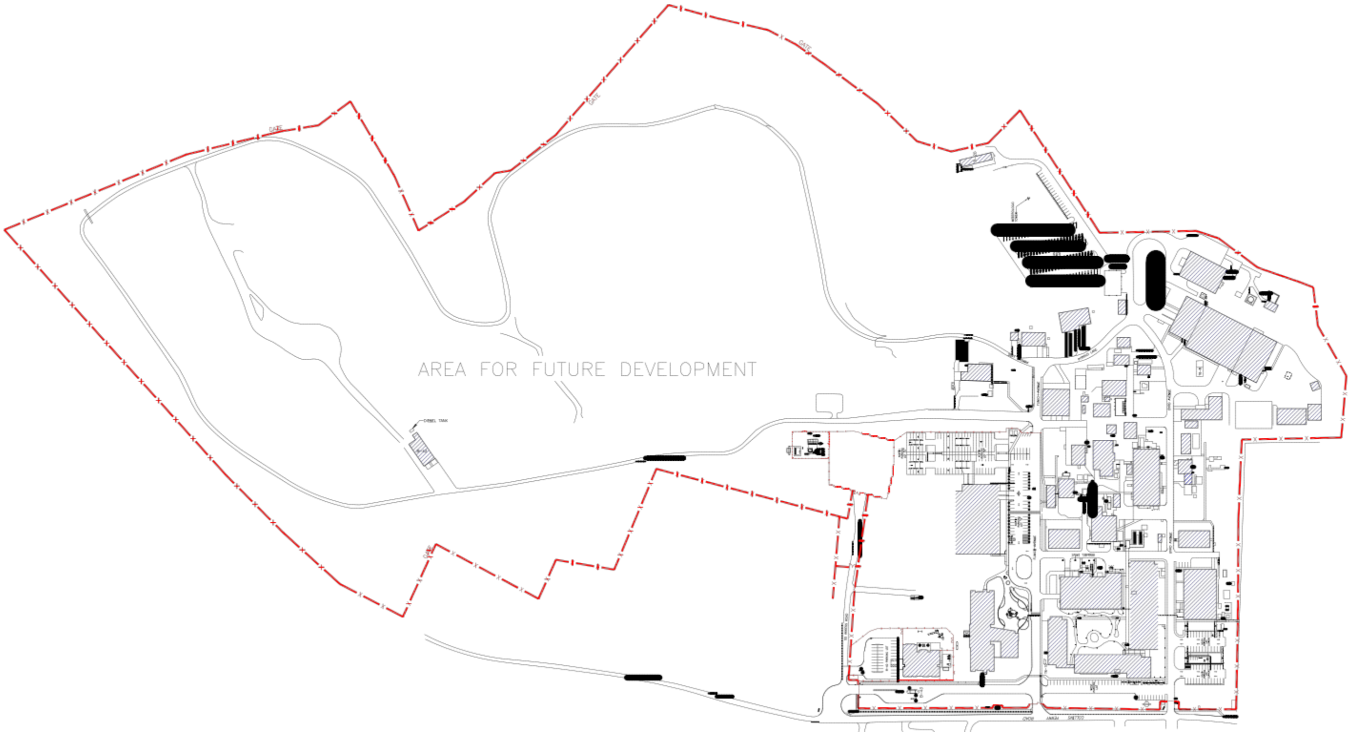


Figure 5.2 Site Map of NETL Morgantown Campus

The Morgantown campus has 45 buildings, comprising 454,654 GSF on 136 acres located in Monongalia County in northern West Virginia. Approximately 40 acres of the campus is developed for use with 54 acres of developable land available for growth to meet the DOE mission. The Morgantown campus was established as part of the U.S. Bureau of Mines in January 1946 and was originally known as the Synthesis Gas Production Laboratories. The early mission of the laboratory was focused on finding more efficient ways to gasify coal. That mission has grown to include core capabilities in chemical engineering focused on developing high efficiency energy conversion and power generation systems as well as reducing greenhouse gas emissions through efficiency, carbon capture, and storage. An example of recent success in this area is NETL's leadership in the development today's state-of-the-art 60%+ efficient gas turbine power cycles. As the DOE mission evolved, core capabilities in Environmental Sciences have been developed to include extensive resource characterization, database development for resource assessment and carbon storage, and evaluation and mitigation of environmental impacts from energy recovery and utilization. The Morgantown campus also has extensive core capabilities in Systems Engineering and Integration and Decision Science and Analysis and is known for pioneering work in integration of multiphase-flow and complex chemistry simulations into systems analysis to greatly improve the fidelity of these simulations to support the DOE mission.

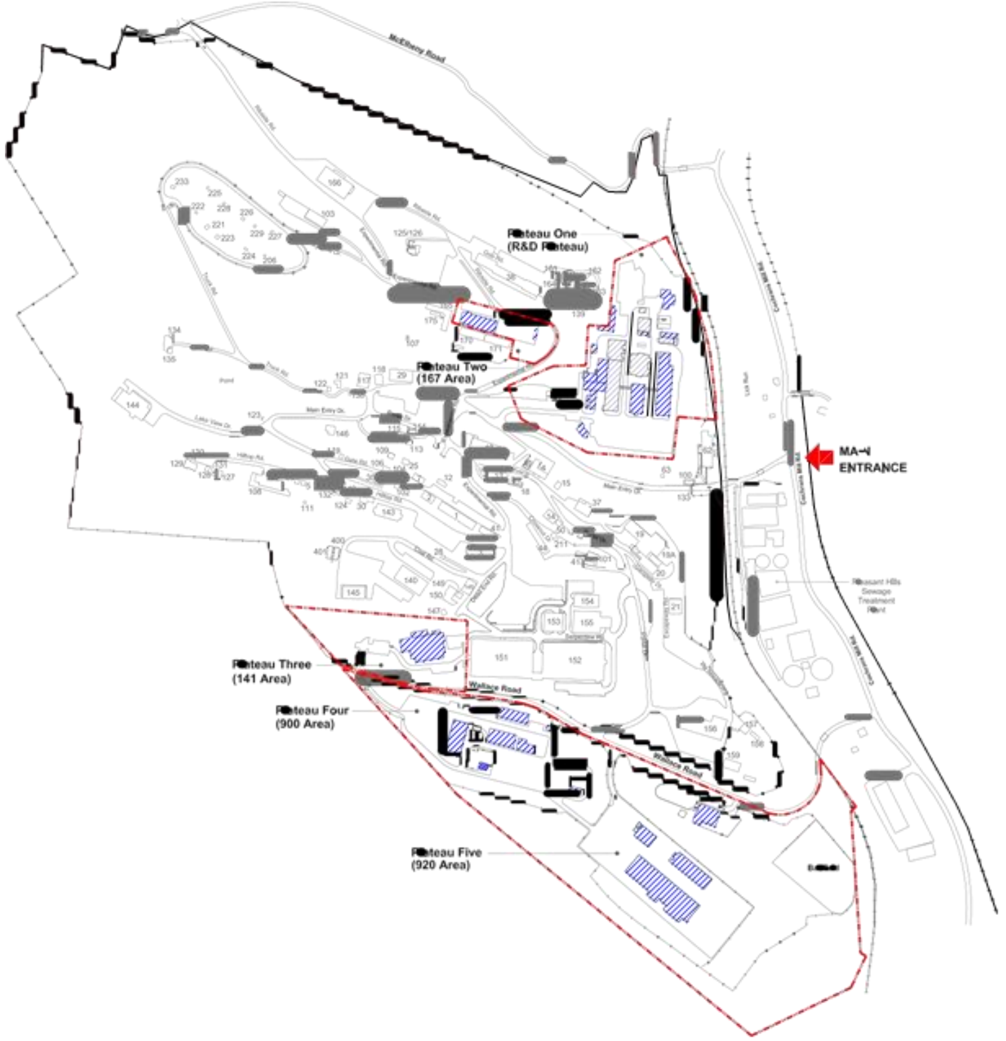


Figure 5.3 Site Map of NETL Pittsburg Campus

The Pittsburgh campus has 29 buildings and one trailer, comprising 455,821 GSF on 62.6 acres located in Allegheny County in western Pennsylvania. The campus is part of the Bruceton Research Center (BRC) comprising 239 acres of land occupied by NETL, NIOSH, and MSHA. The campus is divided into two primary parcels, which are physically separated: an R&D campus located on 15.5 acres at the northeast corner of the BRC and a program management and lab support campus located on a parcel at the south end of the BRC. The Pittsburgh campus was established by the U.S. Bureau of Mines in November 1945 as part of the Bureau's Synthetic Fuels Research Branch. The early mission of the laboratory was focused on production of liquid fuels from coal, and the laboratory has historical strengths in fuel chemistry, catalysis, and process development. That mission has evolved to include core capabilities in Chemical Engineering and Applied Materials Science and Engineering focused on intelligent materials design, synthesis and testing of functional materials to facilitate gas separations (including CO_2), mitigate pollutant emissions such as mercury and sulfur from fossil energy effluent streams, and enable sensor technologies. The Pittsburgh campus also has extensive core capabilities in Systems Engineering and Integration and Decision Science and Analysis to support the DOE mission.

Investment Strategy

NETL's investment strategy was developed to meet four primary objectives as shown in detail in Appendix 4. Objective 1 (blue section) includes projects targeted to maintain and enhance current mission critical core capabilities. These projects are primarily laboratory renovations that will ensure essential core capability is sustained into the future. These renovations in general are lower cost and can be accomplished within NETL's base budget. Objective 2 (pink section) includes major initiatives needed to ensure future mission readiness. These projects generally involve complete renovations of existing facilities or construction of new facilities that require substantial investments and cannot be fully implemented without additions to NETL's current base budget. Objective 3 (green section) includes projects targeted to maintain critical infrastructure to ensure mission readiness and manage the growth in deferred maintenance. Most of these projects can be accomplished within NETL's current base budget; however, as indicated in the cross-cut request, additional funding is needed to prevent growth in deferred maintenance. Objective 4 (purple section) includes projects targeted to maintain or enhance mission- critical IT infrastructure. As identified in the cross-cut request, some additional funding is needed to meet critical IT needs, in particular to replace an aging telecommunications network that is at end of life and to facilitate consolidation of data centers.

3–5 years

Investments in the three-to-five year timeframe are targeted to achieve two primary goals. Laboratory renovation projects are targeted to ensure critical core capability is maintained and strengthened and to ensure NETL continues to meet the DOE mission. The major initiatives planned in the three-to-five year timeframe, as described below, add capability that is essential for NETL to continue to meet the DOE mission—in particular, goals for carbon management—through 2027.

6–10 years

The major initiatives planned in the three-to-five year timeframe will ensure mission readiness through 2027. These facilities will provide the versatility needed to quickly refocus R&D efforts as program needs change over time. The Energy Conversion Technology Center, for example, will provide a highly versatile capability for high-pressure, oxy-fuel, and supercritical CO_2 cycle development that can be aligned to address a range of advanced concepts. The focus of NETL's investment plan during the six-to-ten year timeframe will expand some of these capabilities, but the primary focus will be on a systematic upgrade of R&D laboratories to ensure future mission readiness. These renovations will include upgrades to building ventilation and controls and alarm infrastructure to meet Labs 21 and sustainability goals for DOE buildings, thus reducing carbon emissions, energy usage, and operation and maintenance costs for the Laboratory. A secondary focus in the six-to-ten year time frame will be on the removal of surplus aging infrastructure that no longer meets the future mission.

Laboratory Name **NETL**

Objectives:

Objective 1: Maintain and Enhance Current Mission Critical Core Capability
Objective 2: Implement Major Initiatives to ensure future mission readiness
Objective 3: Maintain facilities and critical infrastructure to ensure mission readiness and manage deferred maintenance
Objective 4: Sustain, enhance and develop computing infrastucture to ensure mission readiness

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
															Select from Drop Down Menu		
High Pressure Combustion Laboratory (B-6-M) - Replace	191	191													GPP	FE	7. Chemical Engineering
Materials Characterization and Performance Testing	1,845	1,845													GPP	FE	Crosscuts 3, 7, and 15
REaction Analysis and Chemical Transformation	1,873	1,873													GPP	FE	7. Chemical Engineering
Decommision B-84-P High Bay - Prep for future use	287	287													GPP	FE	Crosscuts 3 and 7
Cross Cutting Research and Innovation Center (B-25-M)	5,180	180	3,000	2,000											GPP	FE	Crosscuts 3, 7, and 15
Functional Materials Development Laboratory (B-94-P	4,500		500	2,500	1,500										GPP	FE	Crosscuts 3 and 7
Severe Errosion Corrosion Evaluation Facility (B-28-A	5,200				500	2,200	2,500								GPP	FE	Crosscuts 3 and 7
Fluidization Engineering Research Lab (B-22-M)	1,000				1,000										GPP	FE	7. Chemical Engineering
Institute for the Design of Advanced Energy Systems -	4,200				2,800	1,400									GPP	FE	Crosscuts 3 and 7
Center for Advanced Subsurface Imaging and	1,812					1,812									GPP	FE	15 Environmental Subsurface
Center for Intelligent Alloy Manufacturing - Adv	2,750							2,750							GPP	FE	3 Applied Materials S&E
Future Laboratory Renovations	57,534							5,130	8,111	8,355	8,600	8,858	9,110	9,370	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Strategic Alignment of R&D (B-58-P) Office Renovations	4,000		2,200	1,800											GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Energy Conversion Technology Center (B-20-M Reno)	8,250		250		8,000										GPP	FE	7. Chemical Engineering
Advanced Alloy Development Laboratory	7,750		250	7,500											GPP	FE	3. Applied Materials S&E
*Simulation Based Engineering Center (B-7-M Reno)	7,000				7,000	0									GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Parking Garage for Pgh campus R&D plateau	3,000					3,000									GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Materials Forensics Lab (B-93-P reno)	45,000					45,000									LI	FE	Crosscuts 3, 7, 15
Simulation Based Engineering Center Phase II - Model	8,000									8,000					GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Energy Conversion Technology Center Phase II - Cycle	7,000								7,000						GPP	FE	7. Chemical Engineering
Fire and Water Line Replacement - Mgn Site	2,412	873	1,540												GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Roof Replacements B-32-A and B-922-P	1,258	1,258													GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Construction of Salt Storage bldg Morgantown site	281	281													GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Water and Gas Metering (Alb Site) EISA-2007	233	233													GPP	FE	
HVAC Upgrades - Sustainability (B-33-M and B-58-P, B-	843	843													GPP	FE	
Door Replacement (Mgn site) Energy Mgmnt-Safety	287	287													GPP	FE	
Bottled Gas Storage and Receiving Bldg B-65-P	1,097	1,097													GPP	FE	Crosscuts 3, 7 and 15
Bottled Gas Storage and Receiving Bldg B-37-A	663	663													GPP	FE	Crosscuts 3, 7 and 15
Demolition of B-30-M Aging Infrastructure - Excess	124	124													GPP	FE	
Office Space - Life Safety upgrades B-1-A	2,796	296	2,500												GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Office Space - Energy Management - Life Safety B-922-P	1,060	1,060													GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Replace Failing Fire and Potable water lines (Pgh site)	3,634	34		3,600											GPP	FE	
Installation of Lab Access Controls (security)	2,935	1,895	1,040												GPP	FE	
Renovate Primary Power Distribution System - Mgn	1,700			1,700											GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Chemical and Waste Handling Facility (B-35-A) Fire	400				400										GPP	FE	Crosscuts 3, 7 and 15

Planned Capital Investments: (Asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Activity Type	Funding Program	Core Capability
															Select from Drop Down Menu		
Demolition of B-2 Albany - Aging infrastucture - Safety	1,067	67		1,000											GPP	FE	
Demolition of B-99, B-59, B-93 Aging infrastrucre prep for	1,200						1,200								GPP	FE	
*Demolition of B-30 tower at Albany site	1,200				1,200			0							GPP	FE	
Office Renovations - life safety, HPSB, facilitate mission,	38,645			430	4,350	2,000	2,100	710	4,500	4,635	4,775	4,915	5,050	5,180	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Demolition of Excess/Aging Infrastructure	3,634	124			1,550	0	0	0	300	310	320	330	345	355	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Electrical Infrastructure - Life Safety	15,188		180	200	4,620	2,750	350	713	1,000	1,025	1,050	1,075	1,100	1,125	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Fire and Water Line Replacement	1,798				1,030	0	0	100	103	106	110	113	116	120	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
HVAC Replacement - Sustainability-Maintenance	10,180		330	200	1,200	1,175	1,150	800	825	850	875	900	925	950	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Roof Repair/Replacement	14,255		1,200	400	400	1,250	3,045	250	1,200	1,235	1,270	1,300	1,335	1,370	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Building Exteriors/Windows Repair/Replace	10,940				1,500	700	850	130	1,200	1,235	1,275	1,310	1,350	1,390	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Design studies and des document mgmnt	7,163	325	400	500	515	530	550	565	580	600	618	640	660	680	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Misc Facilities Maintenance and Construction Mods	6,340		605	600	650	200	600	445	500	515	530	550	565	580	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Site Utilities Maintenance	4,045			125		250	1,150	250	350	360	370	385	395	410	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Misc Energy Management Projects - Sustainability, EO's,	2,785			100	220	750	380	30	200	205	210	220	230	240	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Safety and Security Projects	2,945			150	1,785	50	280	50	100	100	105	105	110	110	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Roads and walkways Maint/Repair	7,860		450	250	1,170	150	800	990	650	650	675	675	700	700	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Technolgy refresh - Joule supercomputer	75,000			16,500			18,000			19,500			21,000		GPP	FE	Crosscuts 3, 7. 13, 15, and 24
A/V conference room technology refresh	4,162	427		260	450	850			375	500	900			400	GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Data Center Consolidation/Relocation B-1-A	1,875	175	1,500	200											GPP	FE	Crosscuts 3, 7. 13, 15, and 24
Data Center PDU-UPS installation (B-39-M)	265	265													GPP	FE	Crosscuts 3, 7. 13, 15, and 24
IT Infrastructure - Cable plant design and infrastructure	1,189	189				1,000									GPP	FE	Crosscuts 3, 7. 13, 15, and 24
IT Infrastructure Design-Strategy Dev (Data center	841	841													--	FE	Crosscuts 3, 7. 13, 15, and 24
*Data Center Reconfiguration/Consolidation	2,325		75	250	2,000	0									GPP	FE	Crosscuts 3, 7. 13, 15, and 24
*Telecommunications Network Replacement (VOIP)	3,250				3,250	0									GPP	FE	Crosscuts 3, 7. 13, 15, and 24
	0																
	0																

National Renewable Energy Laboratory

1. Mission and Overview

From breakthroughs in fundamental science to new clean energy technologies to integrated energy systems that power our lives, NREL researchers are transforming the way the nation and the world use energy.Founded in 1977 as the Solar Energy Research Institute (SERI), NREL is the only federal laboratory solely dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies. The Alliance for Sustainable Energy manages NREL under a performance-based contract to the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE).

In the first chapter of NREL's history, its research was instrumental in enabling the emergence of a national and global renewable energy industry, particularly evident in solar, wind, and biofuels. NREL's solar research yielded advances in thin-film PV materials and high-efficiency, multijunction solar cells, helped launch several successful companies and helped make solar photovoltaics one of the fastest-growing energy sectors. NREL's wind turbine design codes, innovations in components and blades, and its capabilities in validating performance of prototype blades and turbines have supported the wind industry in lowering the cost of electricity to 4-7 cents per kilowatt hour (kWh). NREL's research in biofuels led to a greater understanding of photosynthetic systems for hydrogen, fuel, and chemical production as well as genetic and pathway engineering of micro-organisms. Its knowledge and know-how supported the emergence of the first integrated biorefineries in the United States. As the market began to mature and the uptake of first generations of technologies began to scale up, NREL added systems integration research to its portfolio with an initial focus on the important topic of grid integration. The relevance and impact of NREL's research has been acknowledged with 58 R&D 100 awards since 1982. NREL continues to lead the national laboratory system in partnerships through which NREL innovations and knowledge are transferred to the market. Partnering to achieve market impact is an essential part of NREL's DNA.

2. Lab-at-a-Glance

Location: Golden, Colorado
Type: Single-program Laboratory
Contractor: Alliance for Sustainable Energy, LLC
Responsible Site Office: Golden Field Office
Website: www.nrel.gov

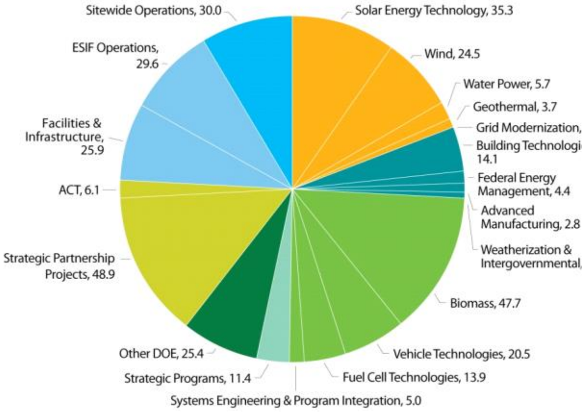
Physical Assets:

- 628.7 acres and 60 buildings and 4 trailers
- 1,160,647 GSF in buildings
- Replacement Plant Value (RPV): $517.6M
- 0 GSF in Excess Facilities
- 182,827 GSF in Leased Facilities

Human Capital:

- 1,706 Full Time Equivalent Employees (FTEs)
- 7 Joint faculty
- 92 Postdoctoral Researchers
- 32 Undergraduate and 33 Graduate students
- 53 Facility Users
- 1 Visiting Scientists

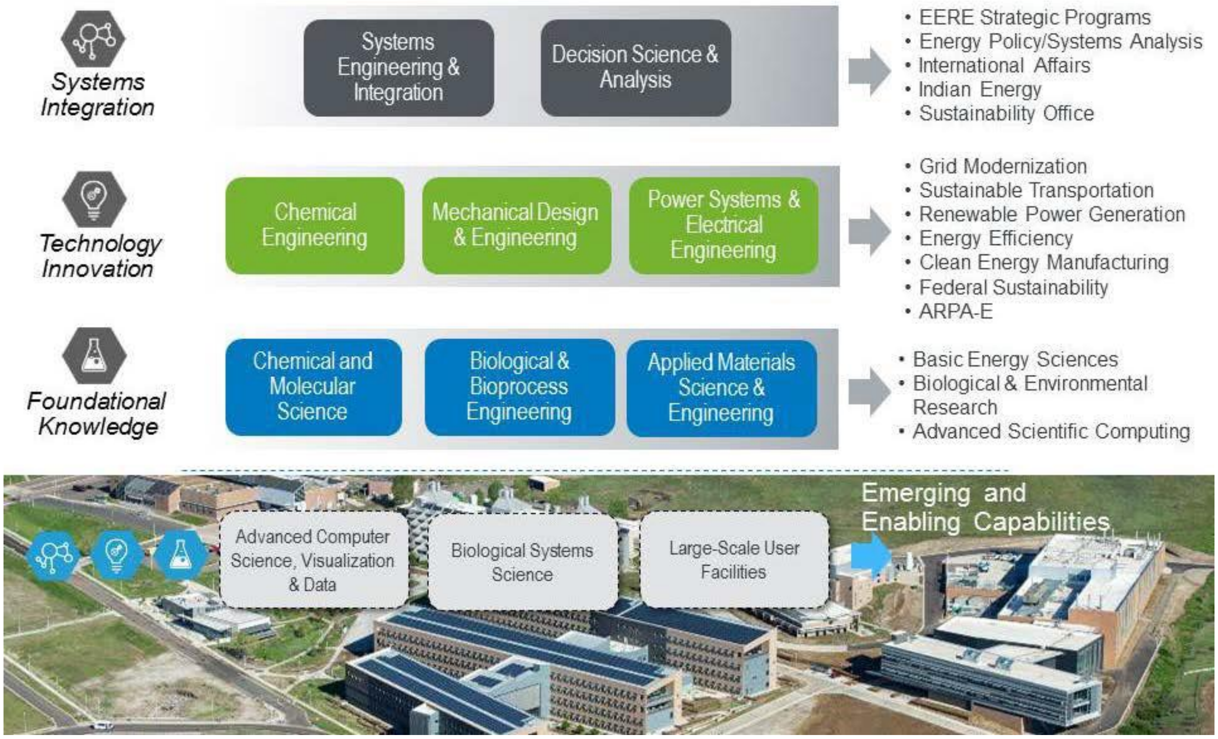
FY 2015 Funding by Source (Costs in $M):



Total Lab Operating Costs
(excluding Recovery Act): $386.3M
DOE/NNSA Costs: $343.5
SPP (Non-DOE/Non-DHS) Costs: $44.1M
SPP as % Total Lab Operating Costs: 11.4%
Total DHS costs: $404k

At this time, the key question is what is next for NREL? With the early commercial successes, some might suggest that the mission has been accomplished. However, we are only at the very early stages of an energy transition. The agreements reached at the Conference of the Parties (COP) 21 in Paris point the way to the significant transformation that is required to achieve the long-term vision of keeping the global temperature rise this century well below 2 degrees Celsius and driving efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels. This will require market uptake of clean energy technologies at an unprecedented pace and scale and new system operating strategies. It will require more than deployment of today's technology to achieve scale at an acceptable cost and with the performance and resiliency required to sustain reliable operation. A much deeper understanding of the systems of systems that surrounds and interacts with engineered energy production and use systems is needed both to guide technology and system innovation and the areas of scientific discovery that will provide the foundation for transformative innovation as well as to create a viable roadmap that ensures the fidelity of actions toward the vision. With these factors in mind, Alliance has set a course for NREL that will reinvigorate its science culture and position NREL as the focal point for innovation in this next phase of clean energy research and development.

3. Core Capabilities



Integrated approach to market-relevant solutions

NREL's core capabilities bring deep understanding of markets and policy, as well as existing and emerging renewable energy and energy efficiency technologies. They also create an understanding of energy systems that supports the laboratory's mission. Together, these capabilities provide the technical foundation to comprehensively understand national energy challenges and opportunities. They also guide the focus of the laboratory's underlying science toward gaining knowledge, supporting technology innovations, and developing integrated systems that will address these challenges. NREL's eight core capabilities derive their uniqueness from this market-facing system solution perspective and experience in clean energy:

- **Decision Science and Analysis**
- **Systems Engineering and Integration**
- **Power Systems and Electrical Engineering**
- **Chemical Engineering**
- **Mechanical Design and Engineering**
- **Applied Materials Science and Engineering**
- **Chemical and Molecular Science**
- **Biological/Bioprocess Science and Engineering.**

NREL's core capabilities integrate scientific knowledge, innovations, and insight to transform clean energy technologies, systems, and markets, while advancing DOE strategies, missions, and goals.

It is important to understand that the value that NREL provides is in the integration of the capabilities along with the deep knowledge of the domain (renewable energy and energy efficiency) that focuses the laboratory's work. By doing this, we can gain a full understanding of the context that the ultimate solution must address, access the ability to use those insights to guide research and development, and provide focused science capabilities that deliver knowledge relevant to key technology challenges.

The following summaries highlight the unique attributes for each of NREL's core capabilities.

Decision Science and Analysis

This capability provides insights across all NREL research and development programs. NREL analysis, across energy pathways, assesses interactions among technologies and the implications for the economy and the environment. The laboratory's work in this area provides credible and objective information to guide research, energy investment, and policy formulation. Nearly 300 scientists, engineers, and analysts at NREL are working to bridge the gap between technologies and the market.

Deep energy system and market understanding, NREL's work informs energy transformation

NREL's analysts have a deep knowledge of renewable energy and energy efficiency and the integration of technical, economic, and environmental aspects of technologies, systems, and supply chains under changing policy and market scenarios. They focus on integrated analysis across the full energy spectrum and all energy pathways. The laboratory's market-facing activities provide critical data and insight around market dynamics.

The analysis work includes sustainability metrics (e.g., energy/water/land use) and climate change implications included in life-cycle analyses. NREL analysts also provide insights to guide research toward outcomes. NREL has worked with research partners – and led – key studies such as *Renewable Electricity Futures*, *Transportation Energy Futures*, and *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis*.

Significant uptake of data, tools, and insights by broad range of decision makers

NREL's science has helped inform DOE programs, the investment community, regulators, and local/state/federal policy and public/private decision makers. Analyses supported the first *Quadrennial Energy Review* (QER) and contributed to the second *Quadrennial Technology Review* (QTR). The laboratory's foundational data and analysis informed regulatory and policy formulation and reduce implementation risk. For example, NREL's analysis insights helped countries define Intended Nationally Determined Contributions (INDCs) as part of the

Conference of the Parties (COP21) negotiations, and it provided objective assessment of various production tax credit scenarios as requested by Congress.

NREL's Clean Energy Manufacturing Analysis Center (CEMAC) provides detailed understanding of supply chains. Our popular *Renewable Energy Data Book* received 12,300 downloads during FY 2015, while many others accessed more than 130 journal publications and technical reports.

Research assets

NREL's unique data, models, and tools include geospatially detailed resource data and models (e.g., Regional Energy Deployment System, Biomass Scenario Model, System Advisor Model). The laboratory is a recognized source for key state-of- the-art and projected data (RE resource, technology cost, and performance).

The Joint Institute for Strategic Energy Analysis (JISEA), hosted by NREL and its founding university partners, has worked with national and global collaborators to extend its research capabilities to put RE and EE technologies in context with fossil and nuclear energy and to enable comprehensive analysis of the environmental impacts of energy systems on earth systems.

Funding sources include most EERE offices, Energy Policy and Systems Analysis (EPSA), Department of Defense (DOD), Department of the Interior (DOI), Department of State (DOS), U.S. Agency for International Development (USAID), Environmental Protection Agency (EPA), Treasury, General Services Administration (GSA), Department of Homeland Security (DHS), Department of Commerce (DOC), U.S. Department of Agriculture (USDA), Department of Transportation (DOT), states/local/tribes, foundations, private sector.

Systems Engineering and Integration

NREL integrates a deep understanding of technologies and how they operate in systems across all resource pathways. This capability helps create renewable and efficient energy systems solutions that are relevant to market, policy, and economic and environmental constraints. Nearly 125 engineers and analysts at NREL have this deep domain knowledge in energy technologies and markets.

Leading capabilities to integrate and optimize future energy systems

NREL is a leader in the systems engineering discipline as applied to design, practice, and validation of complex energy systems. The laboratory has provided techno-economic assessment of hybrid energy systems, e.g., Natural Gas-Renewable and Nuclear-Renewable systems that can provide desired energy services (comfort, function, mobility, etc.) across multiple domains (electricity, thermal, fuel, water), and provide new opportunities for utilities and

Its demonstration of water-cooled high-performance computing (HPC) with full use of waste heat received an R&D 100 Award in 2015. NREL provided expertise in integration of high-pressure hydrogen vehicle refueling with on-site electrolysis. NREL also helped with the conversion of excess renewable electricity to synthetic natural gas, longer-C hydrocarbons. The laboratory also led analysis and hardware testing for water technologies to provide electric grid services.

NREL's systems engineering expertise supports EERE program offices by providing a structured approach to assessment and validation of early-stage technologies and their developing markets.

Enabling investments to achieve resiliency and deep carbon reductions

An area of excellence for NREL is our knowledge in rebuilding communities after disaster with resilience and greenhouse gas (GHG) reduction. The laboratory's successes include New Orleans (Katrina); Greensburg, Kansas (tornadoes); and New York/New Jersey (Hurricane Sandy)

Through this unique capability, NREL has enabled federal agencies to meet energy mandates and executive orders throughout their complexes. NREL has designed reliable and secure energy systems for the Department of Defense (DOD) forward and base installations. Laboratory experts also assist remote villages, island nations, and developing countries with low-carbon development strategies.

Research assets

The Energy Systems Integration Facility (ESIF) provides a contained and controlled integrated energy system platform, which the research community and commercial partners can use to develop and evaluate both individual technologies as well as integrated systems approaches. The NREL campus itself can function as an integrated energy system test bed.

The laboratory has developed models, tools, and web-based applications to predict future system cost, performance, and operability. Our high-performance computing and visualization capabilities enable the exploration of interfaces among complex systems.

These capabilities have helped us forge deep engagement with public and private partners for field testing and validation.

Funding sources include the Federal Energy Management Program (FEMP), Weatherization and Intergovernmental Program (WIP), Energy Transitions Initiative, DOE Indian Energy, state and local governments, U.S. Department of Defense, U.S. Department of State, USAID, industrial partners.

Power Systems and Electrical Engineering

NREL uses its significant expertise in electrical and power systems engineering and the laboratory's unique facilities to help modernize the nation's power grid and accelerate the deployment of clean energy systems. NREL has nearly 100 scientists and engineers focused on innovative research in the integration of clean energy technologies into power grids.

Leading capability to enable grid operations with RE at scale

This capability supports several elements of the DOE Grid Modernization Initiative (GMI) including development and characterization of devices and integrated systems; application of resource and grid sensors, measurements, and forecasts; power systems operations and control; and design, simulation, and studies for power grids. This work is done at a variety of scales including bulk power systems, distribution, microgrids, and customer-sited grids. . In addition, NREL has new capability in understanding security and resilience approaches for energy infrastructures, particularly the electricity distribution grid. In addition, NREL engages in institutional support via analysis and simulation of electricity markets, regulations, and policies.

Key innovations and knowledge that reduces barriers to large-scale RE penetration

NREL has been instrumental in organizing and providing technical leadership for the Grid Modernization Laboratory Consortium (GMLC), a multi-laboratory collaborative that conducts research in support of the GMI, which meets the DOE goals regarding reliability, resilience, security, flexibility, sustainability, and affordability of the power system.

NREL has developed improved power electronic and local controls for wind and solar systems that enable higher penetrations of renewable energy (RE) while maintaining power system stability. NREL has also developed advanced wind and solar resource measurement and forecasting techniques to improve power system operations.

NREL also works closely with industry to accelerate deployment of innovative ideas. NREL has partnered with SolarCity and Hawaii Electric to enable 250% higher integration of PV on distribution circuits through better understanding of PV inverter characteristics and grid conditions. NREL staff also worked with Duke Energy and Alstom to develop advanced distribution management systems that integrate controls for RE systems and voltage regulation.

Our expertise has resulted in more than 100 peer-reviewed publications and technical reports during the past year. NREL staff also served as journal editors for several Institute of Electrical and Electronics Engineers (IEEE) publications.

Research assets

The Energy Systems Integration Facility (ESIF) is a one-of-a-kind user facility, which features a ~1MW distribution grid for “plug and play” testing of whole system experiments, hardware-in-the-loop testing, and integration with HPC capabilities for grid modeling and simulation. The ESIF has welcomed 70+ users in its first two years of operation and received an R&D 100

Award for “Lab of the Year” in 2014. The laboratory has acquired field data and experience from working at hundreds of sites nationally and internationally and fostered nearly 100 partnerships in this area.

Additionally, the National Wind Technology Center (NWTC) showcases multiple MW-scale wind turbines, storage, PV systems, and a large controllable grid. These unique capabilities allow for complete system testing up to 7 MW of combined system power.

Funding sources include EERE, including the Solar Energy Technologies Office (SETO), Wind and Water Power Technologies Office (WWPTO), Building Technologies Office (BTO), Vehicle Technologies Office (VTO), and Fuel Cell Technologies Office (FCTO); Office of Electricity (OE), including Smart Grid (SG) and Transformer Resilience and Advanced Components (TRAC); EPSA; Advanced Research Projects Agency-Energy (ARPA-E); and strategic partnership projects (SPP).

Chemical Engineering

NREL is using chemical engineering for thermochemical conversion of biomass to fuels and chemicals, fuel cell development, validation, and techno-economic analysis. More than 100 chemists and engineers at the laboratory specialize in catalysis, process engineering, and fuel cells.

Leader in applying ChE to RE and EE technologies and chemical processes

NREL has expertise in biomass to fuels/chemicals technology development and integration, as well as integrated fermentation and catalysis for bioproducts.

Our researchers cover the full spectrum of R&D from concept to pilot-scale demo, are publicly recognized for providing a benchmark for bioenergy techno-economic analysis, and are leaders in electrochemical engineering.

NREL is also known for providing unbiased data to guide the biodiesel industry in establishment of specifications and its ability to conduct high throughput fuel cell membrane electrode assembly (MEA) testing.

Impact on bioenergy market and community

The laboratory has partnered with Petrobras and Ensyn to validate biofuel production to the Environmental Protection Agency (EPA) from co-processing of pyrolysis oil with refinery streams. NREL has established a multiyear CRADA with the National Biodiesel Board to investigate critical biodiesel properties and performance, along with several CRADAs and industrial partnering on fuel cell performance and durability.

The laboratory's work is represented in more than 100 peer-reviewed publications annually, including high-impact journals such as *Science, Nature,* and *Proceedings of the National Academy of Sciences* (PNAS).

Research assets

The Thermochemical Conversion Process Development Unit, the Biomass Catalyst Characterization Laboratory, the Ignition Quality Tester, the Renewable Fuels and Lubricants Laboratory, and the Integrated Biorefinery Research Facility are key components of this core competency.

The laboratory also provides support for bench/pilot-scale pyrolysis, gasification, and catalysis; as well as fuel cell MEA fabrication and testing.

Funding sources include EERE, including the Bioenergy Technologies Office (BETO) and Fuel Cell Technologies Office (FCTO); strategic partnership projects (SPP).

Mechanical Design and Engineering

NREL uses its mechanical design and engineering capabilities to develop design tools and advanced technologies/systems in wind turbines, vehicles, buildings, and solar power systems. Nearly 350 engineers and scientists possess deep domain knowledge in thermal sciences, thermodynamics, fluid flow, aerodynamics, simulation and modeling, and structural analysis and design.

Leader in applying systems approach to technology

NREL's leading thermal management capabilities have improved design of batteries, power electronics, and buildings. Our design tools have enabled successive generations of wind turbines, advanced vehicles, concentrating solar power, geothermal energy, and buildings.

Our technical knowledge has assisted industry in developing codes, standards, specifications, and testing protocols for wind turbines and blades, marine hydrokinetics, energy efficiency, vehicle designs, and geothermal energy.

Recognized Impact in innovations that advance a wide range of EE and RE technologies

NREL has helped improve the hydrogen-fuel economy through fueling infrastructure, standards, data integration, and benchmarking. Laboratory staff have been recognized through diverse R&D 100 awards, for expertise in areas such as the demonstration of utility-scale renewable energy production.

Our expertise has also been demonstrated through work to benchmark a catalytic converter, the image-processing occupancy sensor, Isothermal battery calorimeters, desiccant-enhanced evaporative air-conditioning, and the SkyTrough solar concentrating collector.

This capability has netted 288 partnerships and 62 intellectual property agreements.

Research assets

NREL has unique facilities that enable a systems approach to innovation in renewable generation, sustainable transportation, and energy efficiency. These capabilities have also led to significant industry partnerships at the NWTC, Thermal Test Facility (TTF), Hydrogen Infrastructure Testing and Research Facility (HITRF), and Renewable Fuels and Lubricants (ReFUEL) Laboratory.

Key collaborations have included H2USA/Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST), US DRIVE/United States Council for Automotive Research (USCAR), 21st Century Truck, Institute for Advanced Composites Manufacturing Innovation (IACMI), and Power America. Industry-guiding design tools include Computer Aided Engineering for Batteries (CAEBat), Building Energy Optimization (BeOpt), Energy Design Assistance Program Tracker (EDAPT), and the Simulator for Wind Farm Applications (SOWFA). Accreditation by the American Association for Laboratory Accreditation

(A2LA) has allowed NREL to perform blade testing to the IEC 61400-23 blade test standard. The HPC (Peregrine) also enables dynamic simulations and physics-based modeling of systems.

Funding sources include DOE-EERE (VTO, WWPTO, BTO, FCTO, SETO, Geothermal Technologies Office – GTO, FEMP), DOT, DOD, utilities, state agencies, original equipment manufacturers (OEMs), and Tier I suppliers.

Applied Materials Science and Engineering

NREL focuses on functional materials, processes, and devices to develop new and/or significantly improve renewable energy conversion, storage, and use that spans from materials discovery to device and system performance and reliability. Nearly

100 scientists and engineers at the laboratory are experts in synthesis/processing, devices/systems, and characterization.

Leader in materials and device fabrication, characterization, and reliability

The laboratory’s capabilities in applied materials science and engineering are used for research in PV materials/device fabrication, characterization, performance, and optimization. We also work with novel thin-film synthesis, characterization, and applications. Researchers work to improve materials by design-coupling theory, synthesis, and characterization (Energy Frontier Research Center – EFRC).

Other major focus areas for the laboratory include interfacial science, PV device certification, and PV device and module reliability. NREL has been a leader in research of advanced coatings, e.g., ALD for battery electrodes; and also excels in the area of fuel cell materials, components, and durability.

Recognized impact in advancing RE and EE technologies

NREL's work has led to record efficiencies for PV cells (e.g., III-Vs, thin films). Laboratory researchers work on next-generation PV devices and materials processing including Si-based tandems, perovskites, and solution processing.

The laboratory also partners with industry to strengthen our work in PV, PV processing, fuel cells, electrochromic windows, LEDs, solar fuels, and batteries. NREL developed a predicted properties database: materials.nrel.gov to share information with others.

NREL has been recognized for its work on international PV reliability standards (e.g., PVQAT), as well its contributions to international collaborations such as the Global Alliance of Solar Energy Research Institutes (GA-SERI) and SERIIUS. Researchers in this area produced nearly 200 publications in 2015.

Research assets

This capability is supported by the Solar Energy Research Facility and the Science and Technology Facility, which enable integration from science to systems. The Outdoor Test Facility supports work in PV reliability, and the high-performance computer (Peregrine) supports theory, simulation, and modeling from molecules to engineered systems. NREL's facilities also support work in advanced characterization for optoelectronic properties, surface science, microstructure, dynamics, advanced materials synthesis and processing, advanced device reliability, and durability.

Funding sources include Office of Science-Basic Energy Science (SC-BES), EERE (SETO, FCTO, BTO, VTO), ARPA-E, DOD, SPP.

Chemical and Molecular Science

NREL has expertise in the understanding, design, and control of chemical and molecular systems and processes for energy conversion and storage, and catalytic designs to hydrogen production. Nearly 50 scientists and engineers work in synthesis/processing, devices/systems, and characterization.

Leading fundamental research that enables advances in RE and EE Technologies

NREL works in fundamental photochemistry and photophysics of molecular and nanoscale systems, and also is a leader in spectroscopic probes of transport and interfaces. Laboratory scientists work with properties and processing of nanostructured systems, especially quantum dots and nanotubes.

Laboratory research focuses on fabrication and characterization of PV devices based on novel materials and processes, as well as theory and molecular design of new chromophores. NREL works with reaction pathway modeling as well as electrochemistry and photoelectrochemistry. Our researchers also look at new materials and coatings for battery and fuel cell electrodes; and we're leaders in catalyst design, synthesis, and optimization.

Foundational science insights enable innovating next-generation technologies

NREL's experts in chemical and molecular science have a fundamental understanding of primary exciton dynamics in nanoscale structures, as well as energy and charge generation and transport. They also work with high efficiency photo- electrochemical water splitting and next-generation concepts for photovoltaics e.g., excitonic systems (EFRC); our insights have also helped improve catalysts for biomass conversion.

The laboratory has also established industrial collaborations in organic PV and PV windows, and increased our outreach through nearly 100 publications, which include 12 articles in high-impact journals *Nature* or *Science* in 2015.

Research assets

The Solar Energy Research Facility and Science and Technology Facility capabilities support basic research and integration with development. The chemical and molecular science capability is also supported through an atmospheric processing laboratory, and NREL's high-performance computer (Peregrine) supports theory, simulation, and modeling.

Work in this area is supported by ultrafast and time-resolved laser spectroscopy, along with microwave conductivity and transient terahertz spectroscopy, atomic resolution scanning probes, advanced synthesis of molecular and nanostructured system, and automated catalyst testing laboratories.

Funding sources include SC-BES, EERE (SETO, FCTO), SPP.

Biological and Bioprocess Engineering

NREL uses its significant expertise in biological systems science and engineering to convert biomass into fuels, chemicals, and materials. Nearly 100 biologists and chemists specialize in pretreatment, enzymolysis, micro-organism development, and fermentation.

Leader in biofuels and biochemicals R&D

NREL's capabilities in this area strengthen understanding and help improve photosynthetic systems for H2, fuel, and chemical production. Our experts also focus on genetic and pathway engineering of micro-organisms as well as computational and molecular modeling capabilities for rational design of enzymes.

Our researchers are also leaders in biomass compositional analysis and surface characterization as well as biomass to fuels and chemicals technology development and integration expertise.

Impact on bioenergy market and community

NREL has also provided external influence through partnerships with DuPont, Abengoa, and POET to develop, integrate, and scale-up first-of-a-kind cellulosic ethanol technologies. Laboratory researchers have had international reach in next- generation biofuels through collaborations with EcoPetrol and IOC.

NREL engages in bioenergy-related R&D ranging from fundamental science funded by an Office of Science Bioenergy Research Center and multiple Energy Frontier Research Centers, to more applied research in its core portfolio funded by the EERE BioEnergy Technology Office. NREL also has a critical leadership role for DOE in coordinating large research efforts – including Co-Optima, Feedstock Interface Consortium, Separations Consortium, and ChemCatBio – across other national laboratories.

Laboratory researchers have received R&D 100 Awards for their work in enzyme and micro-organism development, and shared their findings in the biomass area through nearly 100 peer-reviewed publications annually in high-impact journals (*Science, Nature, PNAS*).

Research assets

The laboratory's work in biological and bioprocess engineering is supported through the Photobiology Research Laboratory and the Integrated Biorefinery Research Facility. Their work is also supported in the Biomass Surface Characterization Laboratory and through Advanced Imaging and Microscopy.

The work is supported through bench/pilot scale, batch, and continuous pretreatment reactors and dozens of fermenters, as well as photobioreactors (500mL to 8,000L) NREL's high-performance computer (Peregrine) enables fundamental understanding of biological mechanisms

Funding sources include EERE (BETO, FCTO); Office of Science Biological and Environmental Research (SC-BER); ARPA-E, SPP.

4. Science Strategy for the Future

NREL's vision is to be the world's preeminent scientific institution that delivers foundational knowledge, technology and systems innovations, and analytic insights to catalyze a renewable and sustainable energy future. The scale of the transformation required cannot be overstated. NREL will play a leadership role in innovation, in technical integration among leading institutions that will provide important contributions, and in bringing deep insights to define what is required from science, technology, and systems engineering. Many of the building blocks to achieve this vision are already in place, but investments must be made to enhance and integrate across these core capabilities and to create a work environment and culture that catalyzes innovation.

Earlier this year, NREL submitted a white paper to EERE that outlined a strategy to reinvigorate the science culture of the laboratory. As a key part of this strategy, Alliance intends to double the investment in the Laboratory Directed Research and Development (LDRD) Program during the next five years (**see Appendix 4 for a list of proposed investments**). The LDRD Program allows the laboratory to conduct research that establishes proof of principle for leading-edge concepts and to develop and sustain core capabilities. This effort provides a mechanism to change research direction or develop emerging areas that have potential for high impact; it also provides a flexible resource to attract talent to the laboratory. Alliance partitions the LDRD portfolio in four key areas to enable these strategies (see box at right).

Alliance will revitalize NREL's innovation culture, strengthen and integrate its core and emerging capabilities, and deliver research outcomes with significant impact through six major transformational initiatives:

- **Functional Materials and Processing for Clean Energy**
- **Bioengineering for Advanced Materials and Chemistry**
- **Hydrogen at Scale**
- **Grid Integration**
- **Next-Generation Wind**
- **Clean Energy System Design.**

The Grid Integration initiative is a mature transformative investment that will transition from this part of the portfolio in FY 2017. The other initiatives represent emerging areas that will provide new platforms for innovation and impact and where we expect to continue to invest over a multiyear period. They also will help develop the necessary capabilities and demonstrate the promise of these new concepts. Each of these initiatives, in addition to elevating NREL's science, embodies key strategies to ensure relevance and impact:

- Drive research with insights from analysis and a systems perspective -- "connecting systems to science"
- Establish strong collaborations within the laboratory system and leading universities to field strong teams
- Elevate partnerships with industry to create channels to market impact.

5. Mission Readiness/Facilities and Infrastructure

Overview of Site Facilities and Infrastructure

DOE-owned facilities at NREL are situated on the South Table Mountain (STM) site and National Wind Technology Center (NWTC). Alliance also operates in leased facilities at the Denver West Office Park (DWOP), the Joyce Street Facility (JSF) in Jefferson County, the Renewable Fuels and Lubricants (ReFUEL) Laboratory in Denver, and in office space in Washington, D.C. Ultimately, Alliance aspires to move all research operations to its main campuses, unless there is a clear value to having an off-site presence.

In FY 2016, the real property inventory at NREL included 69 buildings totaling 1,160,647 square feet (plus 7,372 in trailers) and had a DOE Asset Condition Index (ACI) of 0.99. This is the highest (most favorable) rating category. 2 Included are:

- 5 leased facilities (182,827 square feet, average age – 32 years)
- 28 STM site buildings (999,796 square feet, average age – 18 years)
- 31 NWTC site buildings (81,415 square feet, average age – 17 years)
- 4 NWTC site trailers (7,372 square feet, average age – 15 years)

The current facilities on the STM and NWTC sites are shown in Figure 5-1 and Figure 5-2.

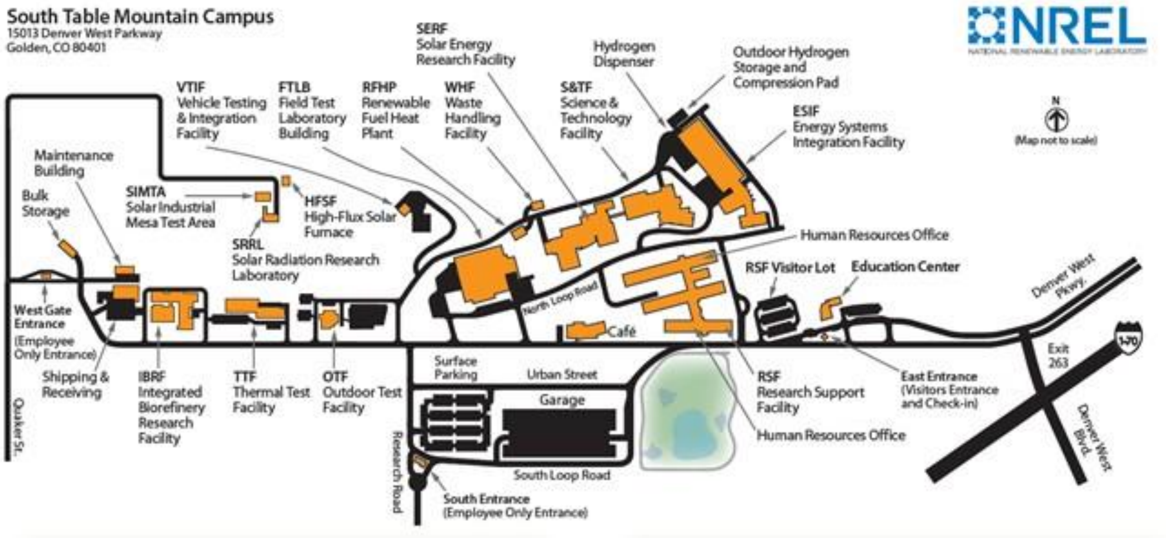


Figure 5.1 South Table Mountain Campus

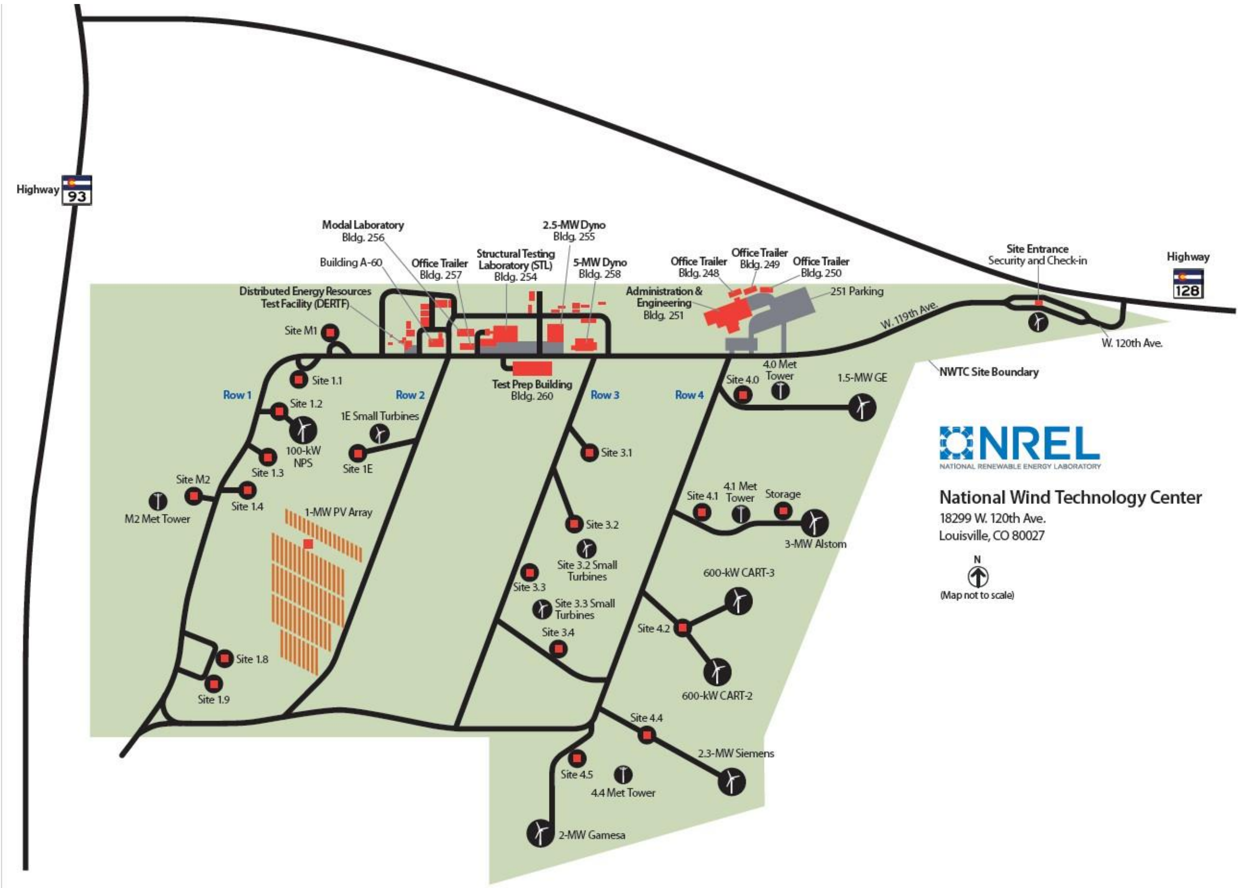


Figure 5.2 National Wind Technology Center

Campus Strategy

Alliance's development strategy for the NREL campus is articulated in the *2011 South Table Mountain Campus Master Plan* (August 31, 2011). Targeted investments are made to evolve the fixed campus infrastructure (buildings, on-site and grid power supply) and transportation systems to support scientific excellence, innovation, and market impact; to attract talent, research collaborators, and partners; and to serve as a test bed for integrated, sustainable energy systems research.

Upgrades to NREL's infrastructure align with supporting current research programs and with creating the capabilities required to address emerging areas of research while maintaining safety and ensuring protection of the environment. Alliance campus strategy places a priority on preserving limited campus space for research. It aims to develop any new facilities in a way that minimizes impacts on the environment and ensures the safety of the staff and the surrounding community. Each new development is used as an opportunity to showcase clean energy technologies and to push the efficiency of the design – within budget constraints – to provide a model for others.

Alliance prioritizes the use of capital budgets to sustain the value of existing assets, create new research capabilities, and improve safety and operations. Generally, budget proposals reflect year-to-year cost escalations linked to overall replacement plant value (RPV); maintenance, repair, and replacement schedules; and general inflation. The funding for the projects represented in this section is proposed in the Facilities and Infrastructure (F&I) budget requests or within individual programs to support specific research activities. The following sections identify infrastructure gaps and outline Alliance's proposed plan for investing F&I budgets.

Infrastructure Gaps

Infrastructure gaps at the NREL campus reflect the need for research assets that will significantly increase innovation and market impact or enhance operational capabilities to increase safety or protect the environment. The major challenges NREL faces include:

- Inadequate fire protection, particularly in older facilities. An assessment of NREL facilities identified 541 findings and 155 observations that have been evaluated on a risk basis to inform the development of a mitigation plan, which requires facility modifications.
- Inadequate waste treatment capabilities. The current waste-handling facility is of insufficient scale to address the growth in research on the campus, and its design makes it difficult to comply with state and federal hazardous waste regulations efficiently and effectively.
- Limited ability to expand work with market participants both to commercialize NREL-originated inventions, but also to create market pull for the clean energy innovation pipeline.
- NREL facilities have limited flexibility to quickly respond to changing research priorities or directions, or to accommodate expanding collaborations with universities and students. In addition, laboratories in leased space are not suitable for many types of scientific and engineering experimentation due to restrictions on ventilation, vibration, and handling of hazardous materials.
- Modernizing the technical foundation at the National Wind Technology Center to provide the technical foundation that will lead to improved design and operations of wind plants and effective integration of wind with the grid. This also includes research on advanced materials and processing research and demonstrations that enable cost reductions in the manufacturing supply chain.

In addition to these gaps, a recent real property research and development (R&D) asset evaluation concluded that a number of laboratory facilities and supporting infrastructure are in need of critical upgrades because key assets/equipment are well beyond their useful life. An ongoing general purpose equipment approach to sustain the value of the R&D assets, facilities, and infrastructure is needed to sustain the relevance and long-term value of these assets. Property management records for R&D assets valued at greater than $10,000 serve as the starting point for evaluating equipment. Individual R&D assets are evaluated to determine on a case-by-case basis whether an asset requires replacement. If replacement is warranted, a recommendation is made regarding whether it should consist of the same or similar R&D capability, or if replacement with a new capability is more appropriate. Recommended replacements are prioritized by facility/capability, identified by costs for installation, and evaluated for their value to Alliance and DOE. Alliance prioritized a list of pending GPE investments totaling approximately $5 million. These investments are above and beyond what is presented later in this section.

Infrastructure Investment Summary

Alliance maintains an ongoing process to identify and prioritize infrastructure and equipment needs across the laboratory. These planning activities include both current and strategic outlooks for the laboratory through annual planning with the NREL General Purpose Investments (GPI) System, which is made up of both the GPE investments and GPP investments, as well as strategizing for larger investments and facilities that propel current core capabilities to achieve farther reaching impacts. On the whole, these investments are intended to establish or reposition unique institutional capabilities that will create NREL roles in new programs or initiatives. Generally, these investments are coupled with one or more strategic initiatives. Alliance's investment also includes plans to recapitalize existing facilities and equipment that have outlived their useful lives and have gone into disrepair.

General Purpose Investments

Alliance places a priority on sustaining mission impact and on maintaining safe, secure, and effective operations that enable research. During the next five years, Alliance will focus on fewer, larger GPPs with multiyear goals. Projects that are already underway include the addition of advanced manufacturing capabilities and general site improvements. These include Americans with Disabilities Act (ADA) improvements at the National Wind Technology Center, build-out of a clean room capability in the S&TF, upgrading HVAC systems and renovating labs within the Field Test Laboratory Building (FTLB), and upgrading the electrical infrastructure at the NWTC. Recognizing the difficult path for capital projects, Alliance proposes to work with EERE to increase the laboratory's annual GPP funding during the next five years, which would enable larger projects that support incremental capability development. Above and beyond the GPP baseline, Alliance is proposing a few large GPP projects that are *at or above* the current annual budget of $7.8 million, but still below the $10 million GPP threshold limit. These large investments are necessary for site safety and environmental protection. These larger investments are difficult to implement as they absorb most of – or the entire – annual GPP budget and place mortgages on future years' budgets, leaving little room for baseline priorities. The current large GPP investments that have been identified to support the NREL infrastructure and mission space are:

- **Fire Protection Assessment Response** - This phased investment will respond to the fire protection assessment findings through a multiyear program based on a graded risk matrix. The plan will aggregate similar work across facilities, which will achieve cost efficiencies and address highest-risk areas first. This investment also meets the criteria for the FY 2018 crosscut proposal in the area of *facility improvements*.
- **Waste-Handling Facility Upgrades** - This investment would expand the current Waste-Handling Facility (WHF), which was built in 1991 and occupies 1,000 square feet. NREL is proposing an expansion to 5,000 square feet to accommodate current and anticipated future needs of the campus. This expanded facility would be used for packaging and short-term storage of hazardous waste and other special wastes before being shipped off-site for proper management and disposal/recycling. Building upgrades would include modification to the existing loading dock height and a pedestrian ramp to provide much-improved ergonomic material-handling capabilities. Further engineered safety systems may include a snorkel vent for use during the consolidation of flammable organic solvent waste, which would eliminate the need for respiratory protection. The new WHF building design would help NREL comply with state and federal hazardous waste regulations in a more efficient and effective manner. These rules mandate that containers be segregated while in storage to prevent the potential for comingling of incompatible materials. This investment also meets the criteria for the FY 2018 crosscut proposal in the area of *facility improvements*.

Priorities for GPE investments focus on two categorical investment types: Multi-programmatic Support Equipment and Information Technology Infrastructure Support. The multi-programmatic support equipment priorities would enhance and expand the current capabilities of the laboratory. The priorities for information systems infrastructure would provide a laboratory-wide capability for enduring mission-related project data stewardship, storage, and application support beyond that funded directly in project scope.

Major Construction Projects

Alliance has prioritized major capital projects that would expand capabilities of the laboratory to accelerate its research and impact on energy system transformation and climate change mitigation. These projects are described briefly below:

Clean Energy Design and Collaboration Center. To keep the United States at the forefront of clean energy research, development, and deployment, there is an immediate need for a capability that will support the Department of Energy (DOE) goal to increase national and regional impact. The goal of the Clean Energy Design and Collaboration Center (CEDACC) is to provide the capabilities required to accelerate the uptake of DOE-derived clean energy technologies in the marketplace and create market pull for innovations that are in the development pipeline. The CEDACC supports EERE's "DOE Lab Impact" initiative by providing access to laboratory capabilities that will enable local and regional entities to define and realize their local aspirations. These efforts can be realized while contributing to global efforts that stem the effects of carbon at the pace and scale that will have a material impact. Specifically, CEDACC capabilities will enable: 1) virtual experimentation with technology options to explore alternative system designs, their operational characteristics, and their impacts; 2) conceptualization and validation of alternative roadmaps for realizing a system design; 3) more rapid transition of innovations from lab to market and adoption at scale; and 4) more robust feedback from the market to guide early-stage research toward market outcomes. It will offer a means for stakeholders to explore opportunities to adopt novel and emerging technologies in existing systems, evaluate new market structures, and assess tradeoffs. It will bridge between new technology developers and the market. The capabilities of the CEDACC will also catalyze a higher level of collaboration among private companies, local and regional stakeholders (energy planners, infrastructure owners, and regulators), and national laboratory researchers.

Clean Energy Materials and Processing Innovation Laboratory. This project would provide a flexible laboratory capability to support expanded research programs at NREL that will accelerate with functional clean-energy materials and processing research that will underpin technology and manufacturing innovations that will advance expanded research in solar, hydrogen, fuel cells and storage. The laboratory will support expanded experimentation and exploration of bio-derived molecules as functional replacements for chemicals and molecules and their application to clean energy technologies. The capabilities of the CEMPIL will: 1) accelerate the discovery and development of new materials, devices, processes, and tools for deployable low-cost reliable renewable energy and energy efficiency applications and their rapid evolution into deployable technologies; 2) accelerate the development of materials processing science to enable new, scalable, high- throughput low capital manufacturing technologies**,** 3) conduct initial experiments to apply new materials processing advances to manufacturing processes in partnership with commercial partners. This project will support the laboratory and office space associated with the growth in research talent in the following NREL core capabilities: biological and bioprocess engineering; biological systems science; applied materials science and engineering; chemical engineering; and computer science, visualization, and data.

Wind Innovation Research Laboratory. This project will provide leading research and engineering capabilities that will enable the design and optimization of wind systems. This effort will lower the cost of unsubsidized wind energy from 35%-50% of today's levels as well as enable reliable operation in grids of various scales. The project will convert the NWTC into a flexible research platform that integrates existing and new research infrastructure. It will be used to conduct research that

transforms the state of the art in wind plant design, operations and manufacturing. The Wind Innovation Research

Laboratory (WIRL), a 112,000 gsf facility, will include:

- A flexible controls research platform to support experimentation and validation of controls and advanced electrical and mechanical system interfaces with a goal of improving power output at the turbine and plant level.
- Grid interface simulation and experimentation capabilities to provide modeling, simulation, and visualization laboratories to research operations at the interface of dynamic controllable plants with the grid. Real-time plant optimization through plant operations can significantly reduce levelized cost of energy for wind plants.
- Manufacturing science, engineering, and demonstration capabilities to enable research on novel materials for raw- material or system sub-component for on-site manufacturing. The laboratories will be flexible to accommodate components or systems that scale from small turbines that support island/community applications to larger systems typical of installations on the plains or offshore. This work is aligned with EERE/Wind and EERE/Advanced Manufacturing Office (AMO) goals and leverages existing Institute for Advanced Composites Manufacturing Innovation (IACMI) research at NREL that is conducted in collaboration with ORNL.
- Supporting laboratories, conference space, and offices for research staff, visiting scientists, and industry partners that will use these capabilities to conduct the research to increase wind plant output and reduce costs through new materials and manufacturing methods.

Energy Systems Integration Facility Expansion. The U.S. Department of Energy established the Energy Systems Integration Facility on the NREL campus as a unique, new national integrated energy system platform. The facility

enables users to conduct integrated energy system experiments for developing and evaluating individual technologies as well as integrated systems approaches. A key limiting ESIF research infrastructure is the Research Electrical Distribution Bus (REDB). The original design of ESIF anticipated six elements of the REDB: three AC busses at 250, 1,600, and 2,500 amps (corresponding to 250 kW, 1 MW, and 2 MW maximum power, respectively); and three DC busses at 250, 1,600, and 2,500 amps (corresponding to 250 kW, 1 MW, and 2 MW maximum power, respectively). Only the 250 amp and 1,600 amp busses have been constructed (both AC and DC), but with few laterals into ESIF laboratory spaces, which limits functionality. Space has been preserved for the 2,500 amp busses, but no physical infrastructure is present. A single, large (~1 MW) experiment involving the REDB effectively precludes others from using it elsewhere at ESIF, which significantly limits the capability of ESIF to support future user experiments at megawatt scale.

A full build-out of originally planned REDB infrastructure would add a second 250A AC and DC bus, which would provide additional capacity for users to conduct integrated system experiments at the <500 kW-scale, construct

“B laterals” sections for the existing 250A and 1,600A busses to extend access to the REDB to additional ESIF labs. This would also allow NREL to acquire and connect the necessary fixed equipment (grid simulator, load bank, DC power supplies, etc.) in ESIF labs, which would enable additional experiments on these new laterals and busses. A second phase would add a new 2,500A AC and DC bus and the associated equipment to expand ESIF capabilities to host integrated systems experiments as large as 2 MW. In addition, a house power upgrade to 10 MW will be needed in FY 2021 to support the simultaneous conduct of multiple 1-2 MW experiments, once all six REDB busses are built out and operational. The project would also enhance the sensing and communications infrastructure of the ESIF as well as its thermal, fuels, and water integration capabilities.

Deferred Maintenance

Individual pieces of real property equipment – such as electrical panels, water chillers, elevators, and sewer pipe – are tracked in the DOE Condition Assessment Information System (CAIS). CAIS identifies required maintenance and repair (M&R) tasks based on standard maintenance guidelines. Items that are past their useful service life are included on the deferred maintenance (DM) list. Because much of the equipment in a given building is put into use at the same time and has the same service life, CAIS-required maintenance (as well as deferred maintenance) shows significant projected variability from year to year for the overall site. This lack of a clear trend in deferred maintenance is normal.

To measure maintenance performance and a laboratory’s ability to maintain its real property assets, DOE uses the Asset Condition Index (ACI), a metric that relates the laboratory’s deferred maintenance to its replacement plant value (RPV) using the following formula:

ACI = 1 - (DM/RPV)

The goal is to minimize deferred maintenance and keep the ACI as close to 1.0 as possible. In FY 2015, NREL’s ACI was 0.999. Even with the variability in deferred maintenance projections, NREL’s projected ACI does not drop below 0.985 over the planning horizon. NREL sustains this favorable ACI with DOE’s assistance in providing NREL annual general purpose M&R and site-wide funding. Site-wide funding covers, in part, building real property preventive maintenance tasks, which directly limit the growth of deferred maintenance lists. The general purpose M&R funding was created to control real property deferred maintenance. NREL has the processes and project management plans in place to ensure that the infrastructure impacts of these important funding sources are maximized.

Planned Capital Investments: (asterisk denotes infrastructure crosscut proposed project)

(Dollars in Thousands)

Project	Total	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Type	Core Capability
Clean Energy Design and Collaboration Center (CEDCC)	**26,000**				2,000	24,000									CLI	Decision Science and Analysis; Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering
Clean Energy Materials and Processing Innovation Lab (CEMPIL)	**230,000**				30,000	200,000									CLI	Chemical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering; Systems Engineering and Integration
Wind Innovation Research Laboratory (WIRL)	**130,000**				15,000	35,000	35,000	25,000	20,000						CLI	Systems Engineering and Integration; Power Systems and Electrical Engineering;

																Mechanical Design and Engineering
Energy Systems Integration Facility Infrastruct. Expansion	**75,000**					20,000	20,000	20,000	15,000						CLI	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
Chemical Fume Hood	**90**	90													GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
FTLB 113/115 Renovation and Flammable Gas	**1,900**	400			1,500										GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical Engineering
FTLB 118 Renovation	**606**	606													GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical

																Engineering
Fuel Synthesis Lab Upgrade	**1,350**	1,000	350												GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical Engineering
Nanoscale Dry Etch	**892**	892													GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
NWTC Site-Wide Data Acquisition	**340**	340													GPP	Decision Science and Analysis; Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering
PDIL Cleanroom - Phase 4	**1,197**	1,002	195												GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and

																Engineering
SERF 209 Phosphorous Recovery Safety Upgrade	**129**	129													GPP	Chemical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
SERF Photo-electro-chemistry Lab Refurb - Phase 2	**775**	775													GPP	Chemical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
Wireless Charging Capability	**988**	988													GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering
Management Labor	**2,595**	-	644	644	644	663									GPP	Supports a crosscut of all core capabilities and infrastructure
York Boiler (IBRF)	**1,600**		1,600												GPP	Biological and Bioprocess Engineering; Chemical and

																Molecular Science; Chemical Engineering
NWTC Advanced Composite Manufacturing Facility	**735**		735												GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering
ESIF High-Perf. Computer 5MW Upgrade	**2,300**			950	1,350										GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
FTLB Lab 136 Demolition	**225**		225												GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical Engineering
Gloveboxes for Synthesis of Advanced Materials	**175**		175												GPP	Chemical Engineering; Mechanical Design and Engineering;

																Applied Materials Science and Engineering
Solution Processed and Nano Materials Glovebox System	**200**		200												GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
NWTC Power Generation Upgrade*	**8,183**		3,500	4,683											GPP	Infrastruc. crosscut
NWTC Water and Utility Corridor	**4,000**		100	1,511	2,389										GPP	Infrastruc. crosscut
Fire Protection Assessment Response - Phase I *	**7,000**				7,000										GPP	Infrastruc. crosscut
FTLB Lab 155 Renovation	**1,337**				1,337										GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical Engineering
Synthetic Molecular Biology Lab (IBRF)	**813**				813										GPP	Biological and Bioprocess Engineering; Chemical and Molecular Science; Chemical Engineering

Advanced Manuf. Equipment Expansion	**1,020**				1,020										GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
Atlas Copco Air Compressor System	**330**				330										GPP	Chemical Engineering; Biological and Bioprocess Engineering; S28Applied Materials Science and Engineering
Waste-Handling Facility Upgrade *	**7,800**				5,667	2,133									GPP	Infrastruc. crosscut
Backup Generator NWTC DERFT & B-254 & B-257	**550**				550										GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
Integrated Crane Scale System for NWTC	**160**					160									GPP	Systems Engineering and Integration; Power Systems and

																Electrical Engineering; Mechanical Design and Engineering
Distributed In-Line Oil Debris Monitoring System	**490**					490									GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
Distributed Vibration Analysis System	**630**					630									GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering; Applied Materials Science and Engineering
Indoor Bathrooms for NWTC Dynos and CGI Facilities*	**980**					980									GPP	Infrastruc. crosscut

Vibration Stress Testing System	**460**					460									GPP	Systems Engineering and Integration; Power Systems and Electrical Engineering; Mechanical Design and Engineering
Anti-Reflection Coating System	**660**					660									GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
Dilatometer	**120**					120									GPP	Chemical Engineering; Mechanical Design and Engineering: Applied Materials Science and Engineering
NWTC 251 Conference Room Upgrade*	**310**					310									GPP	Infrastructure crosscut
NWTC 251 Restroom Remodel*	**460**					460									GPP	Infrastructure crosscut
Aggregate Outyear Investment Levels	**72,000**						9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	GPP	Supports a crosscut of all core capabilities and infrastructure

Total	584,400	6,222	7,724	7,788	69,600	286,066	64,000	54,000	44,000	9,000	9,000	9,000	9,000	9,000	-	Supports a crosscut of all core capabilities and infrastruc.

Integrated Facilities and Infrastructure (IFI) Crosscut Data

(Dollars in Thousands)

Maintenance and Repair (For Federally Owned Facilities)	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Predictive, Preventive and Corrective M&R (incl. DM Reduction)													
Direct Funded	10,240	12,693	10,983	11,313	11,652	12,002	12,362	12,733	13,115	13,508	13,913	14,331	14,761
Indirect Funded	2,351	1,200	1,200	1,200	1,236	1,275	1,311	1,350	1,391	1,435	1,475	1,520	1,565
Total Predictive, Preventive and Corrective M&R	12,591	13,893	12,183	12,513	12,888	13,277	13,673	14,083	14,506	14,943	15,388	15,851	16,326
Operation, Surveillance & Maintenance (OS&M) of Excess and Unutilized Facilities													
Direct Funded	0	0	0	0	0	0	0	0	0	0	0	0	0
Indirect Funded	0	0	0	0	0	0	0	0	0	0	0	0	0
Total OS&M of Excess and Unutilized Facilities	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Maintenance and Repair	12,591	13,893	12,183	12,513	12,888	13,277	13,673	14,083	14,506	14,943	15,388	15,851	16,326
Deferred Maintenance Projection	766	1,421	396	6,800	8,510	2,675	1,422	770	2,318	2,170	1,083	399	356

Other	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Replacement Plant Value Projection ($000)	517,639	533,168	549,163	565,638	582,607	600,085	618,088	636,631	655,730	675,401	695,664	716,533	738,029
Building Area (Thousands GSF)	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967	1,073,967
Excess and Unutilized Facilities (Thousands GSF)	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 1
Science and Energy Core Capabilities

The Programs reporting to the Under Secretary for Science and 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 1. Distribution of Core Capabilities across the Science and Energy Laboratories

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF	INL	NETL	NREL
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 Engineering		✓	✓		✓	✓	✓				✓	✓	✓
8	Chemical and Molecular Science	✓	✓	✓		✓	✓	✓		✓				✓
9	Climate Change Science and Atmospheric Science		✓	✓		✓	✓	✓						
10	Computational Science		✓			✓	✓	✓						

	Core Capabilities	AMES	ANL	BNL	FNAL	LBNL	ORNL	PNNL	PPPL	SLAC	TJNAF	INL	NETL	NREL
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**					✓	✓	✓				✓	✓	
16	**Large Scale User Facilities/Advanced Instrumentation**		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
17	**Mechanical Design and Engineering**					✓	✓		✓			✓		✓
18	**Nuclear Engineering**		✓				✓	✓				✓		
19	**Nuclear Physics**		✓	✓		✓	✓				✓			
20	**Nuclear and Radio Chemistry**		✓	✓		✓	✓	✓				✓		
21	**Particle Physics**		✓	✓	✓	✓				✓				
22	**Plasma and Fusion Energy Science**						✓		✓	✓				
23	**Power Systems and Electrical Engineering**					✓	✓	✓	✓			✓		✓
24	**Systems Engineering and Integration**		✓	✓		✓	✓	✓	✓			✓	✓	✓

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. ***New*** 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 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.

8. 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.

9. ***New*** 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; and (4) integrated analyses of climate change, from causes to impacts changes, including impacts on energy production, use, and other human systems, (2) understanding and predicting future extreme weather as the climate evolves, that in turn introduces risk and vulnerability to energy and related infrastructures, (3) understanding the carbon cycle, with focus on the interdependence of a changing climate and terrestrial ecosystems, and (4) 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. ***New*** 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. ***New*** 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. ***New*** 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 sustainabile 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 Facilties/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. ***New*** 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. ***New*** 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.

19. 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.

20. ***New*** 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.

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. ***New*** 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.

Appendix 2
List of DOE/NNSA/DHS Missions

Scientific Discovery and Innovation (SC)

Advanced Scientific Computing Research

1. To develop mathematical descriptions, models, methods, and algorithms to accurately describe and understand the behavior of complex systems involving processes that span vastly different time and/or length scales.

2. To develop the underlying understanding and software to make effective use of computers at extreme scales.

3. To transform extreme scale data from experiments and simulations into scientific insight.

4. To advance key areas of computational science and discovery that further advance the missions of the Office of Science through mutually beneficial partnerships.

5. To deliver the forefront computational and networking capabilities to extend the frontiers of science.

6. To develop networking and collaboration tools and facilities that enable scientists worldwide to work together.

Basic Energy Sciences

7. Discover and design new materials and molecular assemblies with novel structures, functions, and properties, and to create a new paradigm for the deterministic design of materials through achievement of atom-by-atom and molecule-by-molecule control

8. Conceptualize, calculate, and predict processes underlying physical and chemical transformations, tackling challenging real-world systems – for example, materials with many atomic constituents, with complex architectures, or that contain defects; systems that exhibit correlated emergent behavior; systems that are far from equilibrium; and chemistry in complex heterogeneous environments such as those occurring in combustion or the subsurface

9. Probe, understand, and control the interactions of phonons, photons, electrons, and ions with matter to direct and control energy flow in materials and chemical systems

10. Conceive, plan, design, construct, and operate scientific user facilities to probe the most fundamental electronic and atomic properties of materials at extreme limits of time, space, and energy resolution through x-ray, neutron, and electron beam scattering and through coherent x-ray scattering. Properties of anticipated new x-ray sources include the ability to reach to the frontier of ultrafast timescales of electron motion around an atom, the spatial scale of the atomic bond, and the energy scale of the bond that holds electrons in correlated motion with near neighbors

11. Foster integration of the basic research conducted in the program with research in NNSA and the DOE technology programs, the latter particularly in areas addressed by Basic Research Needs workshops supported by BES in the areas of the hydrogen economy, solar energy utilization, superconductivity, solid-state lighting, advanced nuclear energy systems, combustion of 21st century transportation fuels, electrical-energy storage,

geosciences as it relates to the storage of energy wastes (the long-term storage of both nuclear waste and carbon dioxide), materials under extreme environments, and catalysis for energy applications.

Biological and Environmental Research

12. Obtain new molecular-level insight into the functioning and regulation of plants, microbes, and biological communities to provide the science base for cost-effective production of next generation biofuels as a major secure national energy resource
13. Understand the relationships between climate change and Earth's ecosystems, develop and assess options for carbon sequestration, and provide science to underpin a fully predictive understanding of the complex Earth system and the potential impacts of climate change on ecosystems
14. Understand the molecular behavior of contaminants in subsurface environments, enabling prediction of their fate and transport in support of long term environmental stewardship and development of new, science-based remediation strategies Understanding the role that biogeochemical processes play in controlling the cycling and mobility of materials in the subsurface and across key surface-subsurface interfaces in the environment enabling the prediction of their fate and transport.
15. Make fundamental discoveries at the interface of biology and physics by developing and using new, enabling technologies and resources for DOE's needs in climate, bioenergy, and subsurface science
16. Operate scientific user facilities that provide high-throughput genomic sequencing and analysis; provide experimental and computational resources for the environmental molecular sciences; and resolve critical uncertainties about the role of clouds and aerosols in the prediction of climatic process

Fusion Energy Sciences

17. Advance the fundamental science of magnetically confined plasmas to develop the predictive capability needed for a sustainable fusion energy source
18. Support the development of the scientific understanding required to design and deploy the materials needed to support a burning plasma environment
19. Pursue scientific opportunities and grand challenges in high energy density plasma science to explore the feasibility of the inertial confinement approach as a fusion energy source, to better understand our universe, and to enhance national security and economic competitiveness
20. Increase the fundamental understanding of basic plasma science, including both burning plasma and low temperature plasma science and engineering, to enhance economic competitiveness, and to create opportunities for a broader range of science-based applications

High Energy Physics

21. Understand the properties and interactions of the elementary particles and fundamental forces of nature from studies at the highest energies available with particle accelerators
22. Understand the fundamental symmetries that govern the interactions of elementary particles from studies of rare or very subtle processes, requiring high intensity particle beams, and/or high precision, ultra-sensitive detectors.
23. Obtain new insight and new information about elementary particles and fundamental forces from observations of naturally occurring processes -- those which do not require particle accelerators
24. Conceive, plan, design, construct, and operate forefront scientific user facilities to advance the mission of the program and deliver significant results.
25. Steward a national accelerator science program with a strategy that is drawn from an inclusive perspective of the field; involves stakeholders in industry, medicine and other branches of science; aims to maintain core competencies and a trained workforce in this field; and meets the science needs of the SC community

26. Foster integration of the research with the work of other organizations in DOE, in other agencies and in other nations to optimize the use of the resources available in achieving scientific goals

Nuclear Physics

27. To search for yet undiscovered forms of nuclear matter and to understand the existence and properties of nuclear matter under extreme conditions, including that which existed at the beginning of the universe
28. Understand how protons and neutrons combine to form atomic nuclei and how these nuclei have emerged during the 13.7 billion years since the origin of the cosmos.
29. Understand the fundamental properties of the neutron and the neutrino, and how these illuminate the matter-antimatter asymmetry of the universe and physics beyond the Standard Model.
30. Conceive, plan, design, construct, and operate forefront national scientific user facilities for scientific and technical advances which advance the understanding of nuclear matter and result in new competencies and innovation. To develop new detector and accelerator technologies that will advance NP mission priorities
31. Provide stewardship of isotope production and technologies to advance important applications, research and tools for the nation.
32. Foster integration of the research with the work of other organizations in DOE, such as in next generation nuclear reactors and nuclear forensics, and in other agencies and nations to optimize the use of the resources available in achieving scientific goals.

Workforce Development for Teachers and Scientists

33. Increase the pipeline of talent pursuing research important to the Office of Science
34. Leveraging the unique opportunities at DOE national laboratories to provide mentored research experiences to undergraduate students and faculty)
35. Increase participation of under-represented students and faculty in STEM programs
36. Improve methods of evaluation of effectiveness of programs and impact on STEM workforce

Energy Security (ES)

1. Supply - Solar
2. Supply - Nuclear
3. Supply - Water
4. Supply - Wind
5. Supply - Geothermal
6. Supply - Natural gas
7. Supply - Coal
8. Supply - Bioenergy/Biofuels
9. Supply - Carbon capture and storage
10. Distribution - Electric Grid
11. Distribution - Hydrogen and Gas Infrastructure
12. Distribution - Liquid Fuels
13. Use - Manufacturing Technologies (including efficiency and conservation)
14. Use - Advanced Building Systems (including efficiency and conservation)

15. Use – Transportation Technologies (including efficiency and conservation)
16. Energy Systems Assessment/Optimization

Office of Fossil Energy (FE)

1. Develop cost effective carbon dioxide capture technologies applicable to power generation and industrial sources
2. Develop and demonstrate safe, permanent, cost effective carbon dioxide storage and reuse options.
3. Develop advanced fossil based energy conversion technology, such as oxy-combustion, fuel cells, gasification, supercritical carbon dioxide brayton cycles.
4. Develop crosscutting technologies such as sensors, severe environment material development, and computation modeling tools that support the mission
5. Secure and environmentally sound energy future through responsible production and delivery of our nation's diverse oil and natural gas resources.

Environmental Management (EM)

1. Facility D&D
2. Groundwater and Soil Remediation
3. Waste Processing

Nuclear Energy (NE)

1. Improve the reliability and performance, sustain the safety and security, and extend the life of current reactors by developing advanced technological solutions
2. Meet the Administration's energy security and climate change goals by developing technologies to support the deployment of affordable advanced reactors.
3. Optimize energy generation, waste generation, safety, and nonproliferation attributes by developing sustainable nuclear fuel cycles.
4. Enable future nuclear energy options by developing and maintaining an integrated national RD&D framework.
5. Maintain U. S. leadership at the international level by engaging nations that pursue peaceful uses of nuclear energy

National Security (NNSA)

1. Stockpile Stewardship and Nuclear Weapons Infrastructure
2. Nonproliferation
3. Nuclear Propulsion

Homeland Security (DHS)

1. Border Security
2. Cargo Security
3. Chemical/Biological Defense
4. Cyber Security
5. Transportation Security

6. Counter-IED
7. Incident Management
8. Information Sharing
9. Infrastructure Protection
10. Interoperability
11. Maritime Security
12. Human Factors

Office of Technology Transitions (TT)

1. Expand the commercial impact of DOE’s research, development, demonstration and deployment portfolio in the short, medium and long-term in order to advance the economic, energy, and national security interests of the country.
2. Increase the commercial impact of DOE investments through the transition of national laboratory-developed technologies into the private sector.
3. Increase the commercial impact of DOE investments through private sector utilization of national laboratory facilities and expertise.

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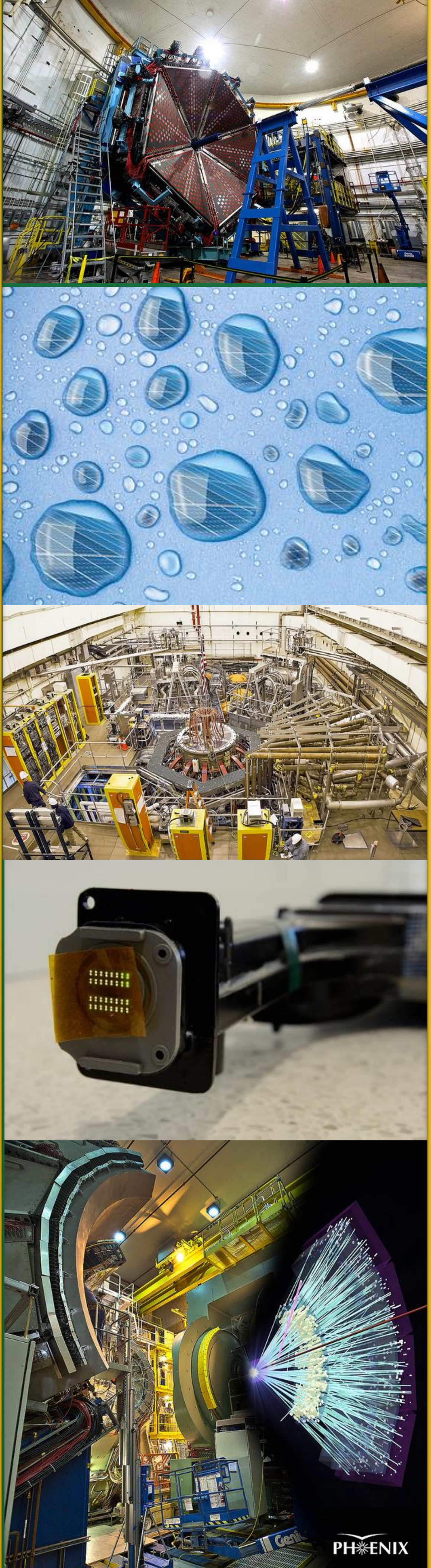

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