U.S. Federal Research and Development Infrastructure

A Foundation of the Nation's Global Scientific Leadership and Economic and National Security

May 2024

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The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the federal research and development enterprise. A primary objective of the NSTC is to ensure science and technology (S&T) policy decisions and programs are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at www.whitehouse.gov/ostp/nstc.

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About the NSTC Subcommittee on Research and Development Infrastructure

The Subcommittee on Research and Development Infrastructure (RDI) coordinates federal investments in infrastructure supporting research and development (R&D) across the nation under the auspices of the NSTC's Committee on Science and Technology Enterprise. This coordination ensures that U.S. R&D infrastructure and the scientific and engineering workforce it supports remain preeminent, relevant, and ready to address the nation's economic and national security priorities.

About this Document

Consistent with Section 1007 of the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act, the National Science and Technology Council is required to "produce a report identifying and prioritizing the deficiencies in research facilities and major instrumentation located at federal laboratories and national user facilities at academic institutions that are widely accessible for use by researchers in the United States." This document fulfills that requirement by providing an assessment of issues facing the United States' research and development infrastructure (RDI) and their impact on the nation's status as a global leader in S&T. It aims be a tool for agencies to assess and address RDI concerns based on individual needs and resources. The assessment identifies four major issues affecting U.S. RDI: aging and inadequate research infrastructure; cascading impacts from substandard facilities; a widening gap in global S&T outcomes; and challenges in recruiting and retaining top talent. This assessment also offers four opportunities for agencies to meet future S&T needs: strategic planning, identifying gaps, benchmarking, and interagency collaboration).

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Abbreviations and Acronyms

AI	Artificial Intelligence
ALMA	Atacama Large Millimeter-Submillimeter Array
AOML	NOAA Atlantic Oceanographic and Meteorological Laboratory
ARS	Agricultural Research Service
CERN	European Organization for Nuclear Research
DoD	Department of Defense
DOE	Department of Energy
ECMWF	European Centre for Medium-Range Weather Forecasting
EIC	Electron-Ion Collider
EOP	Executive Office of the President
EPA	Environmental Protection Agency
FAST	Five-hundred-meter Aperture Spherical radio Telescope
FY	fiscal year
FFRDCs	federally funded R&D centers
NIST	National Institutes of Standards and Technology
IT	information technology
JWST	James Webb Space Telescope
LBNF	Long Baseline Neutrino Facility
NAIRR	National AI Research Resource
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NIH	National Institutes of Health
NIST	National Institute for Standards and Technology
NMNH	Smithsonian National Museum of Natural History
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSTC	National Science and Technology Council
OSTP	Office of Science and Technology Policy
PRC	People's Republic of China
R&D	research and development
RDI	research and development infrastructure
RDT&E	research, development, test, and evaluation
SC	DOE Office of Science

S&T science and technology

STEM science, technology, engineering, and math

USDA U.S. Department of Agriculture

Executive Summary

President Biden is delivering an "Infrastructure Decade" that will unlock access to economic opportunity, create good paying jobs, boost domestic manufacturing, and grow America's economy from the middle out and bottom up. As the President has said, "To have the best economy in the world…you have to have the best infrastructure in the world." That starts with investing in America and building on our leadership in American research and development (R&D).

The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act of 2007 ("the Act") requires that the National Science and Technology Council (NSTC) produce an annual report "identifying and prioritizing the deficiencies in research facilities and major instrumentation located at federal laboratories and national user facilities at academic institutions that are widely accessible for use by researchers in the United States."[1]

This report focuses on the Act's charge to address the growing deficiencies at federal and national laboratories. This report provides an overview of those deficiencies and (short of additional appropriations) makes suggestions about practices that could be more widely adopted throughout government agencies. The report builds on the 2021 National Strategic Overview for Research and Development Infrastructure,[2] which provided a broad overview of the management and policy tools used in the development and management of federal research and development infrastructure (RDI).

In spite of the challenges facing the federal RDI ecosystem, since the last report was written there have been several major developments in U.S. research and development infrastructure. For example, on December 25, 2021, the James Webb Space Telescope (JWST) launched and has sent back unparalleled insight into exoplanets, the origins of our universe, and more. The National Ignition Facility announced that on December 5, 2022, it achieved fusion ignition for the first time. Major construction projects like the Electron-Ion Collider (EIC) and Long Baseline Neutrino Facility (LBNF) have hit critical milestones and announced significant international partnerships. On the planning and competition front, both the Department of Energy (DOE) and Department of State have engaged in global surveys of international RDI capabilities to help inform our future competitive landscape, and the DOE advisory committees are undertaking a broad-based prioritization effort to identify critical capabilities through the next decades. Significant progress has been made through community planning processes in all fields relevant to research and development infrastructure (RDI), supported by our federal advisory committees and the decadal planning processes undertaken by the National Academies of Sciences, Engineering, and Medicine (NASEM).

This report identifies four trends that can be found across federal research agencies. They are as follows:

- Aging and Inadequate Research Infrastructure
- Cascading Impacts from Substandard Facilities

[1] America COMPETES Act of 2007. Public Law 10-69, Section 1007. https://www.govinfo.gov/app/details/PLAW-110publ69

[2] "National Strategic Overview for Research and Development Infrastructure" October 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/NSTC-NSO-RDI-_REV_FINAL-10-2021.pdf

- Widening Gaps in Global Science and Technology (S&T) Outcomes
- Challenges in Recruiting and Retaining Top Scientific and Engineering Talent

To address these, the report identifies four areas that agencies can currently use within their existing budgets and legal authorities to help address these deficiencies:

- Strategic Planning
    - Agencies should develop processes to communicate the need for RDI investments to budget planners, Congress, and other stakeholders, and include the potential impact if such investments in R&D infrastructure are not realized. Specific and measurable impacts to mission execution are more persuasive than general impacts that are difficult to attribute.
    - The need for RDI investments should be documented with thorough assessments of facilities' maintenance and modernization needs, including both costs and well-defined prioritizations developed by each agency, and these assessments should be updated regularly.
- Identification of Gaps
    - Agencies should utilize decadal surveys, workshops, and other community planning efforts to identify and prioritize the long-term federal RDI needs of the U.S. research community, including elements that must be maintained to support U.S. researchers in academe, industry, and government.
    - Agencies should remain cognizant of the ways in which facility closures may result in U.S. dependence on international facilities and weigh the consequences if those capabilities are no longer possessed by the United States or its allies.
- Benchmarking International RDI and Identifying Collaborations
    - Agencies should regularly assess the competitive position of U.S. capabilities in their respective mission areas through benchmarking activities, such as those conducted by DOE's Office of Science (SC) federal advisory committees, the State Department's survey of international facilities, and through the decadal survey process.
    - To facilitate collaborations, agencies should pursue existing mechanisms (e.g., the Florence Agreement Program[3] and S&T agreements) and identify new ways to facilitate both national and international cooperative activities, as well as reduce barriers for in-kind contributions, materials exchange, contract and intellectual property terms, and technologies importation.
- Sharing RDI Strategies
    - The NSTC Subcommittee on Research and Development Infrastructure will coordinate an interagency working group focused on ensuring the competitive position of U.S. RDI, with activities to include sharing information on long-term strategic planning efforts,

[3] Statutory Import Programs," (International Trade Administration, n.d.). www.trade.gov/statutory-import-programs

identifying gaps in capabilities, and facilitating opportunities for national and international collaborations in facilities.

Being a science superpower carries the burden of supporting and maintaining the advanced underlying infrastructure that supports the research and development enterprise. Congressional appropriations have not kept pace with maintenance needs across multiple administrations, resulting in multibillion dollar maintenance backlogs across multiple government agencies, forcing government managers into a position where they must choose between executing science missions or maintaining their facilities.

These challenges come at a time when the People's Republic of China (PRC) and other parts of the world are able to provide newer, state-of-the-art facilities offering improved access that attracts U.S. and other international researchers.[4] Without action to remedy the situation, deferred maintenance will only increase in both cost and impact to the U.S. taxpayer and to many of the nation's critical S&T programs.

Finally, to support the continued development of a robust federal RDI ecosystem, agencies should continue to support the opportunities mentioned in the 2021 National Strategic Overview:[5]

- Maintaining Strong and Integrated RDI Planning and Coordination
- Ensuring RDIs Support a Flexible and Agile R&D Enterprise
- Advancing RDI Capabilities to Support the Convergence of Disciplines and Sectors
- Balancing RDI Openness with Security Needs

[4] "Can the U.S. Compete in Basic Energy Sciences? Critical Research Frontiers and Strategies" (A report by the BESAC Subcommittee on International Benchmarking, 2021), 3. https://science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf

[5] "National Strategic Overview for Research and Development Infrastructure" October 2021, vi. https://www.whitehouse.gov/wp-content/uploads/2021/10/NSTC-NSO-RDI-_REV_FINAL-10-2021.pdf

Introduction

> "The race for technological dominance is inextricably intertwined with evolving geopolitics and is increasingly shaped by broader political, economic, and societal rivalries, particularly those associated with the PRC's rise.
>
> Amassing the resources to sustain broad technology leadership, including the concentration of human talent, foundational knowledge, and supply chains, requires decades of long-term investment and visionary leadership. Those focusing their resources today are likely to be the technology leaders of 2040."
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> "Global Trends 2040: A More Contested World," National Intelligence Council, 2021, 56. http://www.dni.gov/files/ODNI/documents/assessments/GlobalTrends_2040.pdf

The United States has a rich history of investing heavily in its S&T enterprise, its S&T workforce, as well as RDI, including laboratories, specialized facilities, and equipment. A focus on S&T expanded during the 1950s as the Cold War escalated. Under the GI Benefits Bill, thousands of returning veterans were trained as scientists and engineers to establish the nation's leadership in S&T, and this growth continued as the generation of baby boomers, who grew up during the Sputnik era, pursued careers in S&T. During the 1950s and 1960s, the federal government greatly expanded research programs across multiple agencies to catalyze growth in research and development (R&D). Concurrently, the U.S. government invested millions of dollars in building laboratories and other facilities to accommodate the nation's growing R&D enterprise. These facilities, constructed at federal agencies and federally funded R&D centers (FFRDCs), included new laboratory buildings and specialized facilities and equipment, such as accelerators, ground- and space-based telescopes, reactors, and X-ray sources, to study fundamental and applied science. This investment helped build the nation's research and development infrastructure (RDI), which is defined as the "facilities or systems used by scientific and technical communities to conduct R&D or foster innovation."[6]

These substantial investments propelled the United States to global science leadership and led to technology breakthroughs that served as a foundation for the nation's economic growth and national security. Even under the Congressionally-authorized levels in the CHIPS and Science Act of 2022, Federal RDI construction and maintenance has not seen the same level of prioritization as in prior decades. One result has been an aging of the infrastructure at federal research laboratories and facilities that is reducing scientific output and, in some cases, impacting the ability of departments and agencies to meet their mission needs.

The existing federal scientific infrastructure served the nation well in the 20th century, enabling the United States to become a global leader in scientific discovery, talent development, and innovation. Having reached that pinnacle, however, many U.S. scientists and engineers are now faced with conducting 21st century R&D in many facilities designed in the 1950s that cannot support modern research and current laboratory practices in health and safety. Many do not have sufficient, clean, reliable, and secure electrical power necessary to support today's instrumentation and high-performance computers. Some also lack modern information technology (IT) capabilities needed to

[6] "National Strategic Overview for Research and Development Infrastructure," Subcommittee on Research and Development Infrastructure of the National Science and Technology Council, October 2021, iii. www.whitehouse.gov/wp-content/uploads/2021/10/NSTC-NSO-RDI-_REV_FINAL-10-2021.pdf

protect against data loss and cyberattacks (assuming such networking capabilities are even present). Older HVAC systems are inefficient and costly to operate, and buildings were not designed to allow the strict environmental controls needed for today's laboratory operations. In many cases, infrastructure has reached end-of-life for systems that manage water and sewage, steam and chilled water distribution, and electrical networks.

Departments and agencies have reported that the average age of their facilities exceeds the 40- to 50-year design life of most facilities, with half rated to be in poor or critical condition. Because these facilities are operating well beyond their expected lifetimes, the risk of failures is high. The risk is further compounded by aging water, steam, gas, electrical, and other types of distribution systems that are often inefficient, difficult to repair, and do not meet modern safety codes. Failing infrastructure is causing interruptions in research activities lasting weeks or months and has resulted in significant setbacks due to lost work time, loss of samples, and damaged equipment, as well as increased costs to research programs. Another critical issue facing federal RDI is that facilities built in the mid-20th century generally cannot support the needs of modern research, which requires clean, reliable electrical power, strictly controlled environments, robust internet networks, and integrated cybersecurity infrastructure, among other requirements not found in older facilities. Further, investments in new scientific user facilities are needed to provide U.S. researchers with world-leading capabilities. Without RDI designed for advancing critical and emerging technologies, such as quantum information S&T, engineering materials, biotechnologies, sensors, and microelectronics, U.S. leadership in these areas will be seriously and adversely impacted.

The challenges that the U.S. RDI enterprise is experiencing are not new and reflect decades of inadequate funding due to deprioritizing maintenance at existing facilities, development of new facilities, and decommissioning of outdated facilities. Further, these challenges are occurring simultaneously with intensified S&T competition with other nations. This is especially true of the PRC, which is vying to become the preferred partner on large RDI projects for other nations. For instance, the PRC has invested in new RDI outside of its borders, building supercomputers,[7] earth observing satellite constellations,[8] telescopes,[9] and even biosafety labs[10] in Africa and South America. In 2022, PRC President Xi Jinping committed to increase the number of international laboratories built in countries participating in the Belt and Road Initiative to 100 over five years.[11] As the PRC develops such novel capabilities, the pressure for U.S. scientists to seek partnerships in order to utilize those capabilities in order to say at the top of their fields correspondingly increases.

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[7] High speed computer donated to Tunisia's scientific research field. China Global Television Network, retrieved from YouTube, June 25, 2019. https://www.youtube.com/watch?v=VzLJ8qi_XGk

[8] Special Report: China's Space Collaboration with Africa: Implications and Recommendations for the United States. U.S. Institute of Peace, September 2023. https://www.usip.org/sites/default/files/2023-09/sr-524_china-space-collaboration-africa-implications-recommendations-for-us.pdf

[9] South America is embracing Beijing's science silk road. Nature, May 8, 2019. https://www.nature.com/immersive/d41586-019-01127-4/index.html

[10] Africa CDC and China CDC Commit to Deepen their Cooperation. Africa Centres for Disease Control and Prevention. https://africacdc.org/news-item/africa-cdc-and-china-cdc-commit-to-deepen-their-cooperation/

[11] China's Belt and Road Initiative is boosting science — the West must engage, not withdraw. Nature, October 24, 2023. https://doi.org/10.1038/d41586-023-03299-6

Some international facilities possess certain advantages due to their structuring as international organizations or state-supported commercial enterprises with stable, multiyear funding. Europe, in particular, has substantial experience leveraging investments from multiple countries through organizations like the European Organization for Nuclear Research (CERN), the European Southern Observatory, and the European Clinical Research Infrastructure Network. While many of these facilities, like CERN, provide open research platforms that mirror the U.S. model of facility access based on merit, other international facilities either require membership in an international treaty or fee-based access for outsiders. Others, like the European Centre for Medium-Range Weather Forecasting (ECMWF) and COSMO-SkyMed satellite constellation charge for access to products and services. This has direct consequences for broad U.S. access to and utilization of significant RDI capabilities. The challenges associated with U.S. participation in such facilities (to include limitations due to the appropriations process and Anti-Deficiency Act) often means that the United States does not have a seat at the table when setting the rules for international RDI governance, providing an opening for competitors like the PRC and Russia to have greater say in the governance of platforms that may require the development of novel or dual-use technology.

In addition to buildings and facilities, other capabilities factor into the way the United States conducts research. High-performance computers, combined with new modeling and data analysis techniques, such as artificial intelligence and machine learning, allow large sets of diverse data to be assimilated, analyzed, and modeled, accelerating the pace of discovery and development. For example, computational tools can be used in conjunction with multiple types of structural data combined with measured material properties to yield insight into the relationship of a material's structure with its properties. Such an approach would expedite the discovery of new materials critical to emerging technologies, including electronics, quantum materials, and engineering materials. Similarly, data from infrastructure distributed across the nation, such as multiple types of air, water, and soil monitors and satellite data, could be rapidly analyzed and modeled to provide more complete and timely assessments of ecosystems.

While the United States continues to lead the world in many fields of S&T at present, urgent efforts must be made to ensure that federal RDI is ready to serve the nation's research community in the future. Numerous efforts to develop world-leading R&D capabilities have been deployed or are underway. These include the successful commissioning and deployment of JWST[12] and major R&D facilities construction projects like the EIC[13] and LBNF hitting critical milestones[14] and announcing international partnerships. Designed to facilitate a shared national research infrastructure for responsible artificial intelligence (AI) discovery and innovation for the broad research and education community, the National AI Research Resource (NAIRR) launched its pilot on January 24, 2024, with 10 government

[12] "NASA's Webb Telescope Is Now Fully Ready for Science." (NASA. July 11, 2022). https://blogs.nasa.gov/webb/2022/07/11/nasas-webb-telescope-is-now-fully-ready-for-science/

[13] "Electron-Ion Collider Set to Begin Long-Lead Procurements." (Brookhaven National Laboratory, April 2, 2024). https://www.bnl.gov/newsroom/news.php?a=121812

[14] "Excavation of colossal caverns for Fermilab's DUNE experiment completed." (Fermi National Accelerator Laboratory. February 9, 2024). https://news.fnal.gov/2024/02/excavation-of-colossal-caverns-for-fermilabs-dune-experiment-completed/

agency partners and 25 nongovernment partners.[15] DOE/SC's federal advisory committees have released international benchmarking studies comparing RDI capabilities of the United States with those in other parts of the world. The Department of State conducted a survey assessing planned RDI capabilities issued to all diplomatic and consular posts.

Major prioritization and assessment efforts, such as the 2023 Particle Physics Projects Prioritization Panel report[16] have been released. Agencies continue to actively commission RDI prioritization exercises from their relevant federal advisory committees and through the decadal survey process, where agencies seek community input via NASEM. Within the context of the RDI subcommittee, the Interagency Working Group on Scientific Collections on November 29, 2023 released the "The Unique Role of Federal Scientific Collections," assessing the varied ways that federal scientific collections have served the nation in diverse areas of American life.[17] Historically, these activities have focused primarily on addressing the immediate scientific needs of the community; additional effort could be given to assessing and enhancing the competitive position of the United States.

To sustain world S&T leadership, the United States must continue to make strategic investments to maintain and renew federal facilities and supporting infrastructure, as well as phase out and decommission federal RDI that is no longer needed. These critical investments in new, modern facilities will underpin S&T innovation well into the future. These investments are also vital for training the next generation of U.S. scientists and engineers who will conduct research, develop new technical innovations, and manufacture new products. The challenge is to maintain a consistent and intentional revitalization of the U.S. RDI while balancing competing needs and ensuring well-coordinated prioritization decisions.

Status and Outlook for U.S. Federal Research and Development Infrastructure

The Act requires that the National Science and Technology Council produce an annual report "identifying and prioritizing the deficiencies in research facilities and major instrumentation located at federal laboratories and national user facilities at academic institutions that are widely accessible for use by researchers in the United States." This report answers that requirement.

Four issues put the future success of the nation's R&D enterprise at risk: Aging and Inadequate Research Infrastructure, Cascading Impacts from Substandard Facilities, Widening Gaps in Global S&T Outcomes, and Challenges in Recruiting and Retaining Top Scientific and Engineering Talent. Together, these issues present a serious threat to the country's continued scientific innovation, output, and global leadership in S&T. Understanding the context and consequence of these issues can shape action plans for revitalizing the nation's RDI.

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[15] "Democratizing the future of AI R&D: NSF to launch National AI Research Resource pilot." (National Science Foundation, January 24, 2024). https://new.nsf.gov/news/democratizing-future-ai-rd-nsf-launch-national-ai

[16] "Exploring Our Quantum Universe." (Report of the 2023 Particle Physics Project Prioritization Panel, December, 2023). https://www.usparticlephysics.org/2023-p5-report/assets/pdf/P5Report2023_121023-DRAFT_single-pages.pdf

[17] "The Unique Role of Federal Scientific Collections: Infrastructure Generating Benefits, Serving Diverse Agency Missions" (A report of the Interagency Working Group on Scientific Collections). https://smithsonian.figshare.com/articles/book/The_Unique_Role_of_Federal_Scientific_Collections_Infrastructure_Generating_Benefits_Serving_Diverse_Agency_Missions/24559996/1

Aging and Inadequate Research Infrastructure

Outdated and deficient RDI across the federal government is threatening U.S. leadership in R&D and impeding technology breakthroughs.

Aging infrastructure in many federal research laboratories and facilities is impacting the ability of federal agencies to meet their current missions. Many facilities are rated as being in very poor condition.

- A 2023 survey of Department of Energy (DOE) facilities at its 17 national laboratories showed that the average age of these facilities was 46 years, close to the end of the planned 40- to 50-year design life. This study further stated that nearly 40 percent of DOE facilities have been rated as substandard or inadequate to serve DOE's mission.[18]
- A survey of research facilities at the National Institute of Standards and Technology (NIST) showed that 73 percent of facilities are 60 to 70 years old, and over 60 percent of the square footage is classified as in "poor to critical condition."[19]
- A 2019 report noted, "The buildings and facilities at the National Institutes of Health (NIH) Bethesda Campus are in need of significant improvement and upgrading to sustain their current mission and ongoing functionality. The 12 million facility square feet have an average Condition Index of 83.3, which is considered poor."[20]
- In an annual report to Congress in 2024, the Department of Defense's (DoD) unfunded research, development, test, and evaluation (RDT&E) infrastructure requirements were shown to have grown significantly since annual reporting began in 2018, putting the military at risk of losing its technological superiority.[21]
- A 2024 National Aeronautics and Space Administration (NASA) report stated that 75 percent of its facilities are beyond their designed lifetime, and as of 2022, had an estimated deferred maintenance backlog of $3 billion.[22]
- The United States Department of Agriculture (USDA) Agricultural Research Service (ARS) has approximately 3,000 facilities and structures in its inventory, with an average age of over 48 years, and a $1.6 billion deferred maintenance backlog.

Failures due to aging RDI can result in costly and significant interruptions in research activities lasting weeks or months. For example, failures over a nine-month period that led to inadequate back-up power and power conditioning at one NIST research facility cost an estimated $9 million and loss of 47,000

[18] Science Laboratories Infrastructure (SLI) Program. science.osti.gov/opm/Science-Laboratories-Infrastructure

[19] Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology, National Academies Press eBooks, 2023, 31. https://doi.org/10.17226/26684

[20] Managing the NIH Bethesda Campus Capital Assets for Success in a Highly Competitive Global Biomedical Research Environment, National Academies Press eBooks, 2019. https://doi.org/10.17226/25483

[21] U.S. Department of Defense Fiscal Year 2025 Unfunded Requirements for Laboratory Military Construction Projects. February 2024. Office of the Under Secretary of Defense for Research and Engineering. Report to Congress on Section 2806 of the National Defense Authorization Act for Fiscal Year 2018 (Public Law 115-91).

[22] NASA's FY 2024 Volume of Integrated Performance. www.nasa.gov/wp-content/uploads/2023/03/fiscal-year-2024-volume-of-integrated-perfomance.pdf

researcher hours.[23] These failures can be compounded by the need to repair outdated equipment with scarce replacement parts as well as a lack of personnel familiar with older components and systems. These older systems also lack modern safety and security protection features that are standard in equipment purchased and installed today. For example, modern electrical switchgear often incorporates optical arc flash reduction systems, and today's natural gas distribution systems have built-in safety features absent in older systems. Moreover, the configurations of old steam, chilled water, natural gas, compressed air, sewer, and other types of support systems make it difficult to maintain sections of pipe or valves without extended outages. Another looming issue is that older buildings do not meet today's more stringent seismic standards, and the failure of susceptible buildings could indefinitely halt research activities. Finally, many of these older buildings are contaminated with materials that pose significant environmental and health concerns, including radioactive materials, beryllium, asbestos, and lead.

Today's research is vastly different than that conducted when these buildings were designed in the mid-20th century; thus, even well-maintained facilities do not meet the requirements of modern research. First, older buildings were designed with laboratories that accommodate a lead investigator and a few support staff, whereas today's science is most often conducted by larger, collaborative teams of investigators who require flexible space that can be readily reconfigured to meet changing research directions. Second, research today is governed by robust environmental, health, and safety standards that were not in place when these buildings were designed. For example, 50 years ago, nearly all experiments were conducted at open laboratory benches, and laboratories included only a limited number of ventilation hoods. Today, research standards require hoods for nearly all chemistry, molecular biology, materials, and nanoscience experimental procedures. Also, updated fire codes restrict the types and quantities of chemicals and gases that can be stored and used in a single fire zone; older buildings were designed with a limited number of fire zones, and some have only one designated fire zone for an entire building encompassing thousands of square feet. Further, modern research has very different demands for utilities and other infrastructure that were not anticipated even a decade ago. For example, outdated and inefficient HVAC and electrical systems are incapable of controlling temperature and humidity within the exacting requirements of sensitive equipment, such as ultra-fast laser systems and microscopes used in materials science and biology studies. Often, this type of sensitive equipment also requires specialized environments with low vibration and electromagnetic interference.

In addition to these concerns, the cost to maintain aging facilities, even without bringing them up to modern standards, continues to grow. For example, in annual DoD reports to Congress on RDT&E revitalization, these costs were estimated to be $4.7 billion in 2019, growing to $7.7 billion in 2024.[24] Similarly, a 2019 study commissioned by the NIH and led by NASEM reported that the backlog of

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[23] Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology, National Academies Press eBooks, 2023, 44. https://doi.org/10.17226/26684

[24] Report to Congress on Unfunded Requirements for Laboratory Military Construction Projects. February 2019. Office of the Under Secretary of Defense for Research and Engineering. Section 2806 of the National Defense Authorization Act for Fiscal Year 2018 (Public Law 115-91)

maintenance and repair for NIH's Bethesda campus was $1.3 billion and growing rapidly.[25] At the end of fiscal year (FY) 2023, the Bethesda backlog had grown to $3.4 billion and, taking into account all NIH sites in Maryland, Montana, and North Carolina, the backlog was reported to be $3.8 billion at the end of FY 2023. The NASEM study triggered Congressional interest, which resulted in increases in NIH's Buildings and Facilities appropriation from $200 million in FY 2019 to $350 million in FY 2023. However, even at the higher investment amount, the backlog continues to increase.

Construction and renovation of research infrastructure provides the opportunity to incorporate agile, efficient, and resilient designs that can adapt to new technologies, new operating standards, new work environments, and changing missions. Effective modernization and design will lead to savings in energy, cost, and space while improving laboratory functionality and capability (see sidebar "Modern Chemical and Materials Science Building").

A successful renovation of an older building is exemplified by Building 1 on the NIST campus in Boulder, CO, a structure that was dedicated by President Eisenhower in the 1950s. After renovation, a wing of this building became the new home to quantum information science and technology research, supporting experiments that demonstrated quantum entanglement of microresonators, an innovation recognized as the Physics World 2021 Breakthrough of the Year. This research could never have been accomplished in the original laboratory, which lacked necessary environmental controls for these sensitive experiments.[26]

Some agencies have already taken steps and devised innovative solutions to address inadequate RDI. For example, DOE's Office of Science (SC) instituted the Science Laboratories Infrastructure program, which invests over $300 million annually to transform and modernize foundational infrastructure at its national laboratories. To facilitate this strategic program, the DOE Laboratory Operations Board,[27] which includes federal and national laboratory representatives, assesses facilities and infrastructure across the DOE national laboratory complex. These enterprise-wide assessments result in a rigorous and consistent analysis of the condition, utilization, and functionality of the facilities and infrastructure that are most critical to accomplishing the mission. Building on these assessments, SC works with each of its laboratories to develop comprehensive campus strategies used to establish infrastructure priorities.

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[25] National Academies of Sciences, Engineering, and Medicine. 2019. Managing the NIH Bethesda Campus Capital Assets for Success in a Highly Competitive Global Biomedical Research Environment. Washington, DC: The National Academies Press. https://doi.org/10.17226/25483

[26] Technical Assessment of the Capital Facility Needs of the National Institute of Standards and Technology, National Academies Press eBooks, 2023, 34, https://doi.org/10.17226/26684.

[27] Science Laboratories Infrastructure (SLI) Program. science.osti.gov/opm/Science-Laboratories-Infrastructure

Modern Chemical and Materials Science Building

Chemical and Materials Sciences Building constructed in 2011 at Oak Ridge National Laboratory. [Courtesy ORNL]

With more than 300,000 square feet, Building 4500S at DOE's Oak Ridge National Laboratory was built in the 1960s to house dozens of materials science and chemistry laboratories with associated offices. As was typical during this era, the labs in this facility were constructed with only one or two chemical hoods and a handful of electrical circuits. HVAC systems were designed to condition outside air and exhaust it through the chemical hoods, turning over the entire volume of air in the building at a rate of 30 times per hour; this made the building exceptionally expensive to operate.

A new Chemical and Materials Sciences Building was constructed in 2011 and received Gold LEED certification by employing many energy saving innovations, such as reducing air flow in hoods not being actively used. To meet modern research requirements, these laboratories contain up to six hoods for use by teams of researchers and many electrical circuits and internet connections to accommodate modern laboratory equipment and computers. Compared to the single fire zone in the old building, the new building was designed with multiple fire zones and special storage rooms on each floor to facilitate high chemical loading and reduce fire hazards caused by storing chemicals in the laboratories.

These features allowed lab space to be consolidated with a 30 percent savings in space compared to the old facility, while adding new functionalities, such as highly controlled environments required for laser spectroscopy and imaging. The labs were also designed to be readily reconfigurable to accommodate changing programs, with all benches equipped with wheels and special utility hook-ups enabling their easy removal. Importantly, the building was also designed with features that support collaborations across disciplines that are critical for today's scientific enterprise. As a result, an influx of both student and staff researchers have joined the research programs of the organizations in this modern laboratory building.

Similarly, the DoD has a variety of authorities to assist in the modernization and revitalization of its RDI. One of these, 10 U.S.C § 4123, also known as "FLEX-4," authorizes laboratories to allocate between two percent and four percent of their total RDT&E funds toward workforce development, basic research, technology transition, and repair of laboratory infrastructure and equipment. DoD laboratories can use revitalization and recapitalization projects to adapt facilities and infrastructure to support new technology missions. Since the inception of the FLEX-4 Program in 2009, DoD laboratories have invested more than $4 billion across the four categories, funding improvements not possible otherwise.

Since 2012, USDA ARS has reviewed its laboratory RDI and developed a long-term plan for future capital investments, as outlined in "Capital Investment Strategy" (CIS) reports. Since 2013, ARS has adopted the U.S. Corps of Engineers BUILDER assessment program[28] to conduct assessments and assign a condition index to each facility assessed. This index takes into consideration facility age, capacity, safety and health issues, security, time since last repair/renovation, new capabilities needed, and current and future research priorities. Since 2015, ARS has received funding to modernize 30 projects of the 138 outlined in the most recent ARS CIS update.

Many other agencies, such as the Environmental Protection Agency (EPA) have developed plans for building renovations, but due to the lack of funds are unable to complete needed renovations at many of their laboratory sites.

In summary, aging infrastructure can cause research setbacks due to lost work time, loss of samples, and damaged equipment, as well as increased costs to research programs. Further, outdated RDI impedes research that requires specialized infrastructure for sensitive experiments and equipment to advance tomorrow's technologies. Some agencies have taken steps to address these issues by developing processes for prioritizing needs and by funding facility modernization and revitalization; however, more fully addressing these needs will require strategic planning across the federal R&D enterprise, as well as increased budgetary planning.

Cascading Impacts from Substandard Facilities

Aging and inadequate federal facilities can impact research efforts of government, universities, and industry.

Federal laboratories are home to many types of RDI that provide unique capabilities needed to sustain the United States as a world leader in S&T. In addition to research facilities that support specific agency missions, federal agencies also host specialized facilities that serve the nation. These critically important facilities are not found in the private sector or academia due to their high construction and maintenance costs, as well as their support of highly specialized equipment. Such equipment includes the world's largest vacuum chamber at NASA Glenn Research Center, radiation measurement and calibration laboratories at NIST, DOE's suite of scientific user facilities, and the National Science Foundation's (NSF) Antarctic research stations (see sidebar "Improving Antarctic Infrastructure").

Many of the nation's unique federal research assets are operating well beyond their design lifetimes and RDI failures can have a serious impact on the nation's research enterprise. For example, in the summer of 2022, the underground utility distribution system failed on the NIST campus in Gaithersburg, MD, along with HVAC systems, resulting in a shutdown that lasted 14 days and impacted nearly all 1,700 campus laboratories. The effects of this shutdown lasted much longer, compromising NIST's ability to provide measurement standards and support to multiple federal agencies, the private sector, and universities. In turn, the research conducted by these customers, who require standards for quantum

[28] BUILDER Sustainment Management System. https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/476728/builder-sustainment-management-system/

science and technology, radiation physics, and other important traceable measurements, were significantly delayed.

National laboratories have long documented the broader impact of facilities investments on local economies.[29] While it is generally acknowledged that certain facilities have developed reputations as training grounds for scientists and engineers in specific fields, relatively less attention has been paid to the impact of facility degradation, incidents, and changes in facilities' reputation on local universities, business, and other stakeholder communities. Given the importance of RDI to local economies, as well as their distribution around the country in diverse communities, greater attention to that relationship may be warranted.

Impact of Investment on the U.S. National Collections

Helianthus annuus [Courtesy NMNH]

The United States National Herbarium is one of the world's largest and most diverse botanical collections, accounting for more than 4 million specimens. The Smithsonian National Museum of Natural History's (NMNH) multi-year, approximately 7-million-dollar effort to digitize the herbarium resulted in 3.8 million new specimen images, 2.8 million new label transcriptions, and over 80,000 new taxonomic names added to the data catalog. This provides full access to the collection using digital technology and shared online platforms. Full digitization also improves management and enhances the long-term preservation of these fragile collections. Reliance on an industrial approach rather than specimen by specimen actions reduced the average cost per specimen of digitization from $3.32 and 555 seconds to $1.85 and 102 seconds. Deep learning tools have already been used to identify past specimen preservation methods that are hazardous prompting remediation efforts. The 500 percent increase in the past five years in web inquiries demonstrates that digital accessibility is serving research: in 2015, 14 million botanical records were queried via the online page. In 2020, during the COVID-19 pandemic, this number exploded to 70 million records queried.

29 "Fermilab drives economic growth in Illinois and South Dakota." (Fermi National Accelerator Laboratory, March 28, 2024). https://news.fnal.gov/2024/03/fermilab-drives-economic-growth-in-illinois-and-south-dakota/

Improving Antarctic Infrastructure

Amundsen-Scott South Pole Station at dawn. [Courtesy Raffaela Busse and the National Science Foundation. Reused under CC BY-NC-ND 4.0.]

The National Science Foundation (NSF) oversees three facilities in Antarctica that support important and unique experiments sponsored by multiple U.S. agencies, ranging from astronomy to environmental studies. However, maintaining and operating infrastructure at these facilities present unique and costly challenges due to the harsh environment in Antarctica. For example, buildings are in danger of becoming buried in snow, resulting in structural damage, and even collapse. Environmental satellite grounds systems, which are crucial for weather forecasting, flight planning, aviation safety, station operations, and science support, are beyond their end-of-life timelines and in danger of failure. Even fuel transport to the South Pole Station has become more challenging due to aging and increasingly unreliable equipment for traverses that carry 100,000 gallons of fuel annually.

A 2012 NSF report noted that "U.S. activities in Antarctica are very well managed but suffer from an aging infrastructure, lack of a capital budget, and the effects of operating in an extremely unforgiving environment. …when the…[NSF]…and its contractors must choose between repairing a roof or conducting science, science usually prevails. Only when the science is seriously disrupted because the roof begins to collapse will it be replaced; until then, it is likely only to be repaired. ...The status quo is simply not an option ...Failure to [recapitalize]... will simply increase logistics costs until they altogether squeeze out funding for science. A ten percent increase in the cost of logistics will consume 40 percent of the remaining science budget."

NSF established a recapitalization program of $60 million a year that comprises a portfolio of investments to mitigate aging infrastructure, assure safe working conditions, enhance operational efficiencies, and support continued U.S. science leadership on the continent.

More and Better Science in Antarctica Through Increased Logistical Effectiveness: Report of the U.S. Antarctic Program Blue Ribbon Panel, 2012. www.nsf.gov/geo/opp/usap_special_review/usap_brp/rpt/antarctica_07232012.pdf

Widening Gaps in Global S&T Outcomes

Lagging U.S. RDI investment compared to other nations can erode U.S. leadership and influence in science and technology.

Significant investments in specialized RDI catalyzed U.S. scientific innovations in the 20th century. These investments included large particle accelerators, wind tunnels, X-ray and neutron sources, and large outdoor test ranges, as well as state-of-the-art research laboratories. With these capabilities, the United States dominated for decades innovations that fueled the American economy, increased security, and improved quality of life—including advances in computers and personal electronics, breakthroughs in healthcare, and development of electric vehicles, among others. Today, however, increasing investments in RDI in other nations, if unanswered, may lead to loss of U.S. global leadership.

An example of the threat to U.S. S&T leadership is clearly seen in the area of high-performance computing and computer science over the last decade. As shown in Figure 1, in 2015, the United States contributed the most supercomputers[30] to the Top500 list globally, backed by strong support from the federal government for the development of leading high-performance computers. However, only seven years later, in 2022, the PRC surpassed the United States in number of supercomputers on the Top500 list, due in part to the PRC's increased investment in R&D. The impact of the PRC's investment is readily apparent when comparing research output: the PRC is the top overall producer of S&E publications and international patents and has the greatest knowledge- and technology-intensive (KTI) manufacturing output.[31] The United States remains the world leader in KTI services.

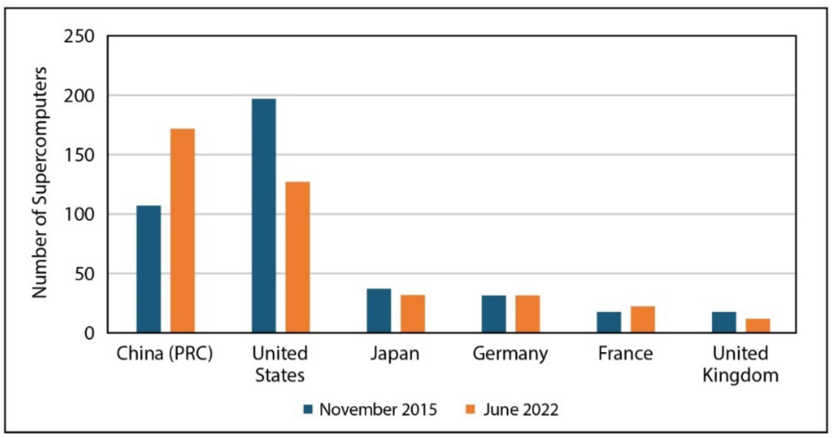

Figure 1. Comparison of the 500 most powerful commercially-available supercomputers per country (from www.top500.org).

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[30] Supercomputers are used to model and simulate complex, dynamic systems that would be too expensive, impractical or impossible to physically demonstrate. Supercomputers are changing the way scientists explore the evolution of our universe, biological systems, weather forecasting and even renewable energy. See more at https://www.energy.gov/supercomputing-and-exascale

[31] "Translation: U.S. and Global Science, Technology, and Innovation Capabilities." The State of U.S. Science and Engineering 2024. Figures 21, 25. https://ncses.nsf.gov/pubs/nsb20243/translation-u-s-and-global-science-technology-and-innovation-capabilities

Maintaining and improving U.S. computing infrastructure is critical for many applications. For example, accurate and timely climate and weather models are critical to missions that protect and support the U.S. economy and national security. However, evidence shows that the National Oceanic and Atmospheric Administration's (NOAA's) Global Forecast System lags behind the capabilities of systems developed by other countries, such as the ECMWF.[32]

A 2021 NOAA Advisory Board report noted the lack of investment in computing power "indicates that not only are we underserving the American public, but also that the United States has the potential to provide more accurate and reliable weather information. The public benefits of NOAA regaining a leadership role would be increased forecast accuracy, longer lead times, and finer-scale detail for severe weather, flooding and hurricanes."[33] Further, many agencies including NOAA[34] and DOE[35] have highlighted the growing demand to provide expanded and updated computing infrastructure to complement experimental capabilities to facilitate efficient data sharing, integration, and analysis.

In August 2023, the Defense Science Board reported in its briefing to the Office of Science and Technology Policy (OSTP) on *Balancing Openness and Security,* "China (the PRC) is outpacing the U.S. in global competition for key emerging technologies, leading in 37 out of 44 critical and emerging technologies (e.g., electric batteries, hypersonics, quantum computing, and others). Western democracies risk losing the global competition for research output and technological innovation."[36] Leadership in this competition is enabled by state-of-the-art RDI, such as X-ray and neutron sources, nanoscience facilities, biotechnology centers, accelerators, and specialized testing facilities, among others (see sidebar "Broader Impacts of Accelerator Science and Technology").

Proactively planning and prioritizing federal infrastructure improvements and modernization can benefit from benchmarking with other countries. For example, the Basic Energy Science Advisory Committee, tasked by DOE/SC with benchmarking U.S. capabilities in basic research, concluded that "advanced research facilities in the United States funded by DOE's Office of Basic Energy Sciences are world leading … largely because of long-range strategic planning, ongoing stewardship, and investments."[37] This type of planning can protect the nation's research enterprise and have far-reaching effects. If DOE failed to develop and maintain capabilities at its five X-ray sources, the impact could affect the 10,000 users served annually, which include scientists from universities, government, and

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[32] "A Report on Priorities for Weather Research" (NOAA Science Advisory Board, December 2021), 72. sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf .

[33] "A Report on Priorities for Weather Research" (NOAA Science Advisory Board, December 2021), 22. sab.noaa.gov/wp-content/uploads/2021/12/PWR-Report_Final_12-9-21.pdf

[34] "NOAA 'Omics Strategy: Strategic Application of Transformational Tools" (NOAA, February 2020). sciencecouncil.noaa.gov/wp-content/uploads/2022/08/2020-Omics-Strategy.pdf

[35] "Basic Energy Sciences Network Requirements Review Final Report" (DOE/SC, November 2023). science.osti.gov/-/media/bes/pdf/reports/2023/ESnet-Report.pdf

[36] "Balancing Openness and Security Across the DoD Academic Research Enterprise" (Defense Science Board, July 2023), 11, apps.dtic.mil/sti/trecms/pdf/AD1212739.pdf

[37] "Can the U.S. Compete in Basic Energy Sciences? Critical Research Frontiers and Strategies" (A report by the BESAC Subcommittee on International Benchmarking, 2021), 3. science.osti.gov/-/media/bes/pdf/reports/2021/International_Benchmarking-Report.pdf

industry. For example, the pharmaceutical industry is highly dependent on X-ray crystallography for the development of new drugs, and more than 30,000 samples are characterized annually on just a single beamline at the DOE Advanced Photon Source.

Broader Impacts of Accelerator S&T

Accelerators broadly impact science, industry, medicine, defense, and other sectors. Annually, particle accelerators are used to treat more than 5 million cancer patients; ion implantation is used to produce $300 billion worth of semiconductors; and e-beam irradiation is used to manufacture over $85 billion worth of consumer products, such as tires and insulation.

Advances in accelerator technologies are also critical for maintaining the nation's leadership in many high energy and nuclear physics experiments, as well as X-ray and neutron sources used broadly by the scientific community in studies on nanomaterials, vehicle batteries, pharmaceuticals, and more.

For years, the United States has been a major supporter of accelerator technology advances, but its leadership position is being surpassed now by other nations. For example, growth in ultra-high intensity lasers, an accelerator-based technology, has been stagnant in the United States while development has increased significantly in Europe and Asia in the last several years.

Maintaining leadership in this area requires investing in new accelerator infrastructure that can be used to develop new capabilities and applications. Investment is also needed in training and retaining experts who can create, operate, and further advance these technologies.

"Ultra-High Intensity Lasers Facilities Across the Globe Over Time," 2020. www.icuil.org/downloadss/laser-labs.html

In some cases, optimizing RDI investments may include establishing international collaborations that benefit the U.S. S&T enterprise. For example, NSF partnered with S&T funding agencies from Europe, Japan, and Chile to build the Atacama Large Millimeter-Submillimeter Array (ALMA)—the most powerful telescope at these wavelengths in the world. Similarly, NASA partnered with the European and Canadian space agencies and 14 additional countries to build the JWST. Additionally, such collaborations offer untapped opportunities to enhance U.S. leadership.

Proactive planning and prioritization of new and upgraded RDI is needed to ensure the nation's global S&T leadership is not eclipsed. Strategies are needed to plan for and prioritize future RDI investments, including forming collaborations with domestic and international partners.

Challenges in Recruiting and Retaining Top Scientific and Engineering Talent

The declining state of infrastructure is affecting the United States' ability to recruit and retain scientific talent.

Departments, agencies, and federal advisory committees report that sub-optimal research infrastructure and project cancellations are factors that contribute to the loss of S&T talent in the federal workforce, impacting researchers at every stage of their careers.[38] These conditions affect

[38] "Can the United States Maintain its Leadership in High Performance Computing? (A report by the ASCAC Subcommittee on International Benchmarking, 2021). 49. https://science.osti.gov/-/media/ascr/ascac/pdf/charges/2023/Report_20230627.pdf

students and post-doctoral researchers when they cannot achieve an acceptable rate of productivity due to aging RDI, which limits their career opportunities. More established researchers are affected when their productivity and impact declines, preventing them from advancing their agency's mission and reaching their career goals. Together, these factors can affect the morale of researchers and drive them away from the federal research arena.

The research and often awe-inspiring technologies at the center of our federal laboratories have inspired generations to pursue technical careers and to push the boundaries of human knowledge, contributing to U.S. S&T leadership. For instance, NASA supports approximately 2,000 interns, annually, at all NASA facilities. DOE/SC hosts thousands of students, accounting for about one third of total unique users at scientific user facilities each year. In 2023, the Smithsonian Institution hosted 510 interns and 355 fellows at its science units. Altogether, federal RDI facilities make up an important contribution to developing STEM talent around the country.

Despite this, external assessments of some federal laboratories have identified major concerns in the workforce due to recruitment and retention problems which are straining existing staff to their limits. This can affect the nation's ability to attract and retain a strong federal S&T workforce, which can in turn impact leadership and innovation in critical and emerging technologies, such as artificial intelligence, biotechnology, quantum information S&T, and microelectronics, particularly as other countries develop similar or more advanced capabilities. Breakthroughs in these areas are imperative for the development of new products and jobs that fuel the nation's economy. Solving the RDI problem should help maintain the federal S&T workforce and R&D leadership to produce innovations critical to the nation's economy, security, and well-being.

One example of how aging infrastructure is impacting the ability to attract and retain researchers is NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). This laboratory, housed in a building that opened in 1973, is responsible for real-time hurricane-related measurements and associated activities that include hurricane science, model development, sustained observational platforms, and maintaining the global oceanographic climate data record. However, the 2019 AOML Laboratory Review Summary Report stated, "AOML's physical infrastructure is no longer sufficient to support cutting-edge science and to attract a world-class scientific workforce."[39] (see Figure 2).

[39] "2019 AOML Laboratory Review Summary Report" (National Oceanic and Atmospheric Administration, November 19, 2019), 17, www.aoml.noaa.gov/wp-content/uploads/2020/07/AOML-2019-Review-Summary-Report-FINAL-.pdf

Figure 2. "When AOML started [in 1973], keypunch cards seemed cutting edge, and leisure suits seemed appropriate for the office." [Courtesy NOAA]

Foreign RDI investments are also prompting some U.S. researchers to leave the country to build state-of-the-art facilities and to find longer-term employment. For example, U.S. diplomats reported in 2018 that numerous fusion energy researchers and technologists began traveling to the PRC following the shutdown of several U.S.-based magnetic confinement fusion facilities. U.S. scientists, technologies, and companies often engage with international facilities where the U.S. government is not present, such as the Extreme Light Infrastructure (ELI) in Czechia, Hungary, and Romania and the Square Kilometer Array (SKA) in South Africa to stay on the leading edge of their respective fields.

The importance of planned investments in maintaining, upgrading, and building (where warranted) new RDI cannot be overstated, particularly given that many infrastructures may require decades of planning for successful execution. Such efforts require the development of specialized workforces around individual projects. Likewise, unexpected cancellations and inadequate communication with foreign partners can affect the reputation of the United States as a reliable partner, limiting the willingness of foreign experts to provide their unique expertise to major undertakings.[40] Without significant efforts to address these issues, the nation risks losing the S&T workforce that is critical for maintaining its role as a global leader in S&T and innovation, which will have far-reaching impacts on the future economy and security of the United States.

Opportunities

Agencies must continue to revitalize RDI critical to the nation's S&T enterprise, otherwise U.S. RDI will continue to deteriorate while costs for maintenance and replacement will continue to escalate. Although agencies need to plan and prioritize investments based on individual needs and budgets, the following four opportunities—Strategic Planning, Identification of Gaps, Benchmarking International RDI and Identifying Collaborations, and Sharing RDI Strategies—represent high-level steps required to ensure the nation's RDI is prepared to meet future U.S. S&T needs.

[40] "The Path to Global Discovery: U.S. Leadership and Partnership in Particle Physics." (A report of the High Energy Physics Advisory Panel. https://science.osti.gov/-/media/hep/hepap/pdf/202203/International_Benchmarking_HEPAP_2023112.pdf

Strategic Planning

Assessment and prioritization of investments are necessary to maintain and renew legacy facilities, as well as establish new infrastructure to realize future S&T advances.

It is clear that the overall state of federal research facilities will continue to require substantial investments to meet future research needs. Federal agencies and departments must prioritize and develop short- and long-term strategies for addressing their RDI needs, including sufficient recapitalization, operations, and maintenance investments in facilities, and disposition of excess facilities, along with a strong workforce. As part of strategic planning for RDI, agencies should also develop and maintain standards for assessing total facility and infrastructure costs, including construction, annual operating costs, maintenance, and renovations, and regular recapitalization. For example, modernization efforts should address updated requirements for safety (e.g., changes in building codes), security, and specialized research. Where applicable, agencies should ensure a proactive lifecycle approach to real property management that aligns with the federal Real Property Reform Act of 2016, the associated Government Accountability Office framework. Agencies can also look to external resources, strategies, and best practices like the 2023 NASEM report titled "Strategies to Renew Federal Facilities." The specific approaches employed may differ for the various agencies and their specific RDI requirements. For instance, planning for construction and lifecycle costs of a conventional laboratory building is quite different than the planning needed for a high-energy accelerator-based facility that serves thousands of users annually.

- Agencies should develop processes to communicate the need for RDI investments to budget planners, Congress, and other stakeholders, and include the potential impact if such investments in R&D infrastructure are not realized. Specific and measurable impacts to mission execution are more persuasive than general impacts that are difficult to attribute.
- The need for RDI investments should be documented with thorough assessments of facilities' maintenance and modernization needs, including both costs and well-defined prioritizations developed by each agency, and these assessments should be updated regularly.

Identification of Gaps

Agencies and departments should identify gaps in RDI needs and opportunities for collaborations with other federal, industrial, academic, and international partners.

Effective planning for RDI first requires input from the federal and non-federal research community, as well as RDI managers, to help reveal or underscore serious gaps and to identify the potential impact of these gaps on the U.S. federal S&T enterprise and agency mission execution. This input can be gathered by various means, such as surveys, requests for information, workshops, and other avenues. For example, federal research agencies frequently convene researchers from the national and international communities to identify needs in research infrastructure, such as electron and X-ray sources, computers, distributed measurement networks, sequencing centers, and other key areas. This gap analysis could also be used to identify potential partnerships—with other agencies and departments, the private sector, universities, and international partners—that could provide opportunities for cost-sharing and result in more impactful RDI that serves a larger research community.

- Agencies should utilize decadal surveys, workshops, and other community planning efforts to identify and prioritize the long-term federal RDI needs of the U.S. research community, including elements that must be maintained to support U.S. researchers in academe, industry, and government.

- Agencies should remain cognizant of the ways in which facility closures may result in U.S. dependence on international facilities and weigh the consequences if those capabilities are no longer possessed by the United States or its allies.

Benchmarking International RDI and Identifying Collaborations

Regular benchmarking should be performed to assess the global position of U.S. RDI and to identify opportunities for international collaborations.

Understanding the nation's global standing in S&T is critical for prioritizing RDI investments and identifying areas for international collaboration. Benchmarking studies should include documented data on relevant topics, such as global development of large-scale and mid-scale research facilities, research outputs and impact, and workforce trends. These assessments would provide foundational data for the Quadrennial Science and Technology Review and National Science and Technology Strategy, as well as for other reports and activities related to global competitive assessments.

These benchmarking studies will also identify opportunities to develop new collaborations and enhance existing partnerships as well as highlight strategic investments to restore and preserve U.S. leadership in critical areas while strengthening federal RDI and the scientific workforce. For international collaborations, processes must be established to reduce the administrative burdens often associated with developing cutting-edge scientific capabilities, including the importation of materials and technologies. Efforts should also be made to welcome the participation of international scientific experts in these benchmarking studies.

- Agencies should regularly assess the competitive position of U.S. capabilities in their respective mission areas through benchmarking activities, such as those conducted by DOE's SC federal advisory committees and the State Department's survey of international facilities.
- To facilitate collaborations, agencies should pursue existing mechanisms (e.g., the Florence Agreement Program and S&T agreements) and identify new ways to facilitate both national and international cooperative activities, as well as reduce barriers for in-kind contributions, materials exchange, contract and intellectual property terms, and technologies importation.

Sharing RDI Strategies

Establishing an interagency working group would support the modernization of RDI for the future.

RDI planning would greatly benefit from having regular meetings where representatives from federal agencies discuss RDI strategic plans and needs at both the agency level and across the federal government. These discussions would catalyze collaborations and cost-sharing on upgrading or establishing new RDI. Although federal agencies and departments have unique business practices and operating principles, they share common issues facing RDI modernization. Therefore, establishing an interagency RDI working group could also be a platform for sharing best practices and ensuring access to state-of-the-art RDI across the federal government.

- The NSTC's Subcommittee on Research and Development Infrastructure should coordinate an interagency working group focused on ensuring the competitive position of U.S. RDI, with activities to include sharing information on long-term strategic planning efforts, identifying gaps in capabilities, and facilitating opportunities for national and international collaborations in facilities.

Additionally, departments and agencies should continue to look to the policy opportunities identified in the National Strategic Overview on RDI, released in 2021:

Maintaining Strong and Integrated RDI Planning and Coordination

- Adopt a cohesive definition of RDI that encompasses experimental, observational, as well as knowledge- and cyber-infrastructure, in federal planning processes
- Identify complementary RDI—and their capabilities—across the federal government and external R&D communities to inform agency priority-setting processes.
- Plan for, invest in, and deploy the necessary knowledge infrastructure and research cyberinfrastructure to keep pace with the rate of growth of data acquisition in research, as well as published research data, to ensure the efficiency and trustworthiness of scientific pathways and pipelines.
- Ensure consistent, sufficient, and timely RDI capabilities, strategically addressing episodic efforts that can undermine the ability to meet long-term needs
- Regularly review and document RDI needs and develop planning processes that encompass repurposing, reusing, or decommissioning low-priority RDI.

Ensuring RDIs Support a Flexible and Agile R&D Enterprise

- Foster R&D community engagement to inform federal RDI planning and prioritization, for instance through assessments and cross-sector coordination.
- Seek input from Federal Advisory Committee Act (FACA) and NSTC committees, as these committees are capable of providing valuable insight on future RDI needs and coordination possibilities.
- Integrate agile design and decision processes in planning and maintaining RDIs so that capabilities keep pace with the growth in data and advancements in computing and analytics.
- Support remote access to RDI capabilities, tools, and platforms, where appropriate.
- Build strategic, long-term relationships with contractors and suppliers to enable agility in procurement, development, design, and portability of RDI systems.
- Incorporate lifecycle considerations, such as upfront costs of construction, operation, and maintenance, and anticipate future modernization needs for planned and existing RDIs.
- Incorporate lifecycle resourcing considerations to ensure RDIs sustain or enhance privacy and other legal protections.
- Ensure large or complex RDI projects are managed by staff with appropriate design and project management experience to safeguard delivery on schedule and within budget.
- Continue to create and promote STEM education programs that directly engage with and support the use of RDIs as education and training platforms.

- Ensure processes that allow the nation's R&D enterprise to thrive by fostering the participation of talent that reflects the diversity of America.

Advancing RDI Capabilities to Support the Convergence of Disciplines and Sectors

- Invest in RDIs that complement core disciplinary needs while identifying opportunities to enhance connections across disciplines and sectors.
- Consider the potential use of RDIs beyond a single agency's mission context in developing coordination efforts, especially for the Nation's largest RDI investments.
- Ensure RDIs foster convergence through partnerships and research information exchange.

Balancing RDI Openness with Security Needs

- Seek international collaborations for the development of RDIs as appropriate to foster international cooperation
- Operate RDIs using research security frameworks that balance open science with appropriate levels of vigilance and that uphold U.S. principles of integrity
- Ensure proper protections for RDIs that are vital to competitiveness, public health and safety resilience, and national security (e.g., intellectual property, certain classes of research data, implications from climate change)

Conclusion

Just like the investments in research facilities that were built during the Cold War, investments in modern federal RDI will support the development of new technologies and generate new jobs. Revitalizing federal RDI will also ensure the development of a workforce trained to discover, develop, manufacture, and use next-generation technologies.

The nation can take immediate action to revitalize RDI and support a vibrant research enterprise for years to come. Federal departments and agencies should develop actionable strategic plans with priorities for RDI investments. These plans should be informed by input from the S&T community across government, university, and private-sector institutions, and from international benchmarking. This input can also identify opportunities to partner with both domestic and international institutions. An RDI working group can share approaches and identify where collaborations can be forged to provide enhanced capabilities to a broader research community. The time to act is now; prioritizing federal RDI will support generations of future researchers and allow the United States to maintain global leadership in science, technology, and innovation.