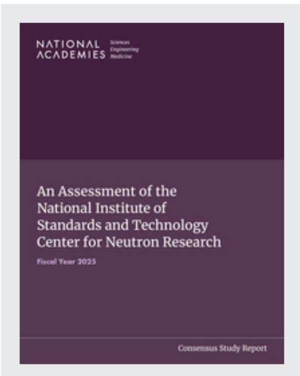

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Fiscal Year 2025

Panel on Assessment of the National Institute of Standards and Technology (NIST) Center for Neutron Research (CNR)

Physical Sciences, Systems, and Infrastructure Program Area

Center for Advancing Science and Technology

Consensus Study Report

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PANEL ON ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) CENTER FOR NEUTRON RESEARCH (CNR)

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **DAVID W. JOHNSON, JR. (NAE),** Bell Laboratories (retired), and **DAVID A. WEITZ (NAS/NAE),** Harvard University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Acronyms and Abbreviations

AFL	Autonomous Formulation Laboratory
AI	artificial intelligence
AM	additive manufacturing
BT	Beam Tube
CANDOR	Chromatic Analysis Neutron Diffractometer or Reflectometer
CHRNS	Center for High Resolution Neutron Scattering
FY	fiscal year
LNP	lipid nanoparticle
MACS	Multi-Axis Crystal Spectrometer
ML	machine learning
mRNA	messenger ribonucleic acid
NCNR	NIST Center for Neutron Research
NG	neutron guide
NIST	National Institute of Standards and Technology
NNS	NIST neutron source
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
PML	Physical Measurement Laboratory
QMS	Quantum Materials Spectrometer
RFO	Research Facilities and Operations
ROADMAP	Reflectometry-driven Optimization and Discovery of Membrane Active Peptides
SANS	Small Angle Neutron Scattering
SPINS	Spin Polarized Inelastic Neutron Spectrometer
ν-NSE	New Neutron Spin Echo Spectrometer
VSANS	Very Small Angle Neutron Scattering

Summary

This 2025 assessment of the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) addresses the research, expertise, facilities, and dissemination work of NCNR. The review builds on past National Academies of Sciences, Engineering, and Medicine assessments of NCNR, including the most recent in fiscal years (FYs) 2018, 2021, and 2023. The National Bureau of Standards Reactor first went critical in 1967, and NCNR has since become a world-leading user facility for neutron science to study the structure of materials. This is especially relevant for biotechnology, soft and hard materials, quantum information, energy storage, superconductors, advanced manufacturing, and engineering materials, in service to industry, academia, and government. NCNR advances NIST's mission of U.S. innovation and industrial competitiveness through fundamental, experiment-driven knowledge that supports U.S. companies in global leadership across a range of technology sectors.

The NCNR reactor has not operated for scientific experiments since late 2020 because of a refueling incident on start-up in 2021. Reactor cleaning and corrective action enabled a restart at low power in early 2023. However, further debris was detected, requiring additional cleanup and mitigation. This panel's review took place in May 2025 while the reactor was shut down and was being prepared to restart operations in early 2026. The panel was tasked to assess (1) NCNR's scientific and technical programs, including how it compares to other world-class neutron facilities, the quality of instrumentation, and the plan for cleaning the reactor and resuming scientific operations; (2) the portfolio of expertise within NCNR, including whether it has world-class expertise in reactor operations and advanced neutron instrumentation, and whether this expertise adequately supports NCNR's programs; (3) the adequacy of the budget, facilities, instrumentation, and human resources; and (4) the effectiveness of program dissemination, including responsiveness to stakeholder needs, access to the broad range of the scientific community, and monitoring the use and impact of the facility.

NCNR TECHNICAL PROGRAMS

NCNR maintains several research programs based on the capabilities of neutron science, including crystallography, reflectometry, scattering, spectroscopy, and magnetic and nuclear property studies. NCNR hosts major partnerships with the National Science Foundation; it hosts an industrial consortium for neutrons in soft materials; and it supports the NIST Physical Measurement Laboratory and Material Measurement Laboratory for standards, measurement science, and fundamental research. There are important research programs in soft materials and biological research, especially in collaboration with the pharmaceutical industry; in hard matter research examining electronic and magnetic behavior of materials; in neutron physics enabling NIST's metrology, calibration, and standards for nuclear units and sources; in engineering materials, particularly in collaboration with the transportation sector; and in artificial intelligence (AI), machine learning (ML), and automation.

NCNR staff are of extremely high caliber, as evidenced by national and international recognition and standing in the scientific community. Through their dedication and creativity, they have maintained an active scientific and technical program during the NCNR shutdown, both internally and in partnership with the user community by competitively obtaining beamtime at other neutron facilities. NCNR disseminates its program outputs by supporting its user community, training new students and professionals in neutron science, publishing the work of the staff and user community in high-impact journals, and partnering with the NIST Physical Measurement and Materials Measurement Laboratories in developing standards and calibrations using nuclear methods. NIST has started the *n*Mat consortium to expand its industrial engagement. NCNR has continued to host educational programs during the reactor shutdown, including the oldest summer school on neutron science in the United States. It also runs several programs for visiting scientists, postdoctoral researchers, kindergarten through grade 12 teachers and students, and the public. The impact of NCNR's work is evident in scientific publications; patents; calibrations and standards; and new technologies and understanding, particularly developed by industry.

The budget and staffing for NCNR are not keeping up with the facility's role in neutron research in the United States and globally. NCNR's FY 2025 budget is a 19 percent increase over FY 2018; however, inflation has risen 27 percent in that period, and costs at NCNR have risen even further because of reactor operations and management, an expanded safety program, and compliance costs. Staffing has similarly not kept pace with needs, with the ratio of instrument staff to instruments being 4–4.5, much lower than other U.S. and international neutron facilities. Limited staffing means that in 2026, NCNR will only be able to operate 12 of 17 scattering instruments. The reactor operations team currently lacks licensed operators to support operations 24 hours per day, 7 days per week. The panel found several challenges and opportunities for NCNR in its technical programs.

- NCNR provides the highest quality of user support for researchers. The biggest challenge is to ensure sufficient financial and human resources to continue this excellent work at a scale commensurate with NCNR's national importance.
- NCNR is proposing not to operate several instruments to continue to provide sufficient support to the remaining active instruments. The panel found that the proposed instrument choice was reasonable but will limit research in areas of quantum materials, thin-film magnetism, soft matter and biology, and advanced materials and geology, among others.
- The demand for high-throughput and multimodal measurement creates a significant need for technical and computing expertise. The panel recommends that NCNR prioritize automation campaigns on account of their initial success. (Recommendation 5-3)
- Another challenge is supporting the user community in the transition back to full reactor and instrument facility operations. The panel recommends NCNR leadership reengage the user community in the restart process through the NCNR Users Group, including in decisions driven by prioritization, such as strategic idling or upgrading of instruments. (Recommendation 3-1)
- The panel outlines several specific challenges and opportunities in soft matter, hard matter, neutron physics, engineering and imaging, AI and ML, and automation. (Chapter 3)

NCNR REACTOR

Reactor operations continue to be dominated by the cleanup and shift in safety culture required after the February 2021 incident. A Corrective Action Plan was developed and implemented and a safety culture monitoring panel is working with NCNR staff on continuous improvement. The shift in safety culture has been embraced by the operations staff and will take considerable time, effort, and resources to fully achieve. Significant advances have been made in the safety culture, including encouraging an environment open to questioning without blame, and to improving communications and issue identification to find solutions. Preparations for a mid-2025 readiness review were well underway at the time of the panel's site visit, and demonstrated the improved safety culture.

The NIST research reactor has been a safe and reliable neutron source for decades, but it is an aging reactor and needs special attention for operation. NCNR took the opportunity to implement upgrades and essential maintenance while the reactor was shut down for the second decontamination in early 2025, including a repair of the refueling plug, refurbishment of vent valves, planning and acquisition of the components for the cold source upgrades, and planning for eventual conversion to low-enriched uranium fuel. Restart of the reactor relies on the training and qualifications of reactor operator staff. NCNR is committed to meeting its goal of 15 licensed reactor operators to staff five shifts; however, the current job structure within the government can create a challenge to pay and reward reactor operators at a level that is competitive with the power industry. The reactor cleanup, upgrades, and training program appear on track to return to normal operations in 2026.

Even when NCNR returns to full operations, U.S. neutron capabilities are insufficient, and a new NIST neutron source (NNS) would provide important new capabilities. NCNR hosted a workshop in late 2023 to introduce a preconceptual design of the NNS and evaluate the need and a future path forward for neutrons in the United States. The NNS would host about 50 instruments and double the number of scientists and engineers served at NCNR.

NEUTRON INSTRUMENTATION

Neutron instruments probe materials using neutrons. NCNR has 29 beam instruments, several of which represent cutting-edge capabilities in the field and have been developed to address NIST's mission and leverage the unique strengths of NCNR's continuous thermal and cold neutron sources. NCNR's instrument portfolio has been designed to respond to the needs of the user community, emphasizing NIST's mission to serve industry. NCNR has developed instruments with enhanced performance, improved data rates, and expanded experimental capabilities. Key accomplishments include continued leadership in three-axis spectrometry to advance quantum materials physics, programming of neutron guide upgrades, development of the autonomous formulation and measurement facilities, and development of the octostrain platform. Challenges and opportunities include developing a written restart plan for each instrument; implementing the proposed upgrade plans for the cold source, low-enriched uranium conversion, and quantum materials spectrometer; and improving the instruments that support neutron science for manufacturing.

The multiyear reactor shutdown has led to significant loss of both scientific and technical personnel, which will need to be rebuilt. However, NIST management has continued to support activities that ensure maintenance of scientific expertise and continued development of research capabilities. One example is the continuation of the NCNR postdoctoral program during the outage. The current budget allocation presents a major concern and challenge, as it is insufficient to operate the entire instrument portfolio upon return of operations and does not enable technical programs such as in-house detector development.

NCNR shared three responses to the FY 2023 panel's recommendations to inform the current assessment. These responses can be found in Chapter 6, and they address upgrades to the Beam Tube (BT)-1 powder diffractometer and the BT-4 triple-axis/Filter Analyzer Neutron Spectrometer, upgrades to the Spin Polarized Inelastic Neutron Spectrometer instrument, and capital investment for better utilization of the instrument suite.

KEY RECOMMENDATIONS

The panel developed four Key Recommendations based on its review of NCNR's technical programs, expertise, budget and facilities, and program dissemination across the instrumentation, reactor, and scientific program areas.

Key Recommendation 6-1: The National Institute of Standards and Technology (NIST) leadership should support the NIST Center for Neutron Research at inflation-adjusted pre-COVID levels, supplemented by additional budget to support full reactor operations staffing. There is an urgent need to reinstate the financial support for instrumentation, staff, and science programs, in addition to full reactor

operations, to fully restart this cornerstone of neutron science and support the U.S. industrial and scientific competitiveness it enables.

Key Recommendation 6-2: The National Institute of Standards and Technology (NIST) leadership should seek congressional approval and funding to design and build a new state-of-the-art research reactor at the NIST Center for Neutron Research consistent with U.S. interest to sustain scientific competitive advantage.

Key Recommendation 6-3: The National Institute of Standards and Technology (NIST) Center for Neutron Research should develop and pursue a strategy that leverages its distinguishing instrument capabilities and science programs. The strategy should align with the NIST mission, national initiatives, and a longer-term vision for the new research reactor.

Key Recommendation 6-4: The National Institute of Standards and Technology Center for Neutron Research should augment its reactor operations and safety procedures to include expectations for continuous improvement.

1
Introduction

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) has served as one of the nation's premier resources for neutron-based research since its establishment in 1967 as a high-flux source for advanced scattering experiments (Rush and Cappelletti 2011). Together with the two neutron facilities at Oak Ridge National Laboratory—the Spallation Neutron Source and the High-Flux Isotope Reactor, NCNR forms one of only three large scale U.S. facilities enabling world-class neutron science (RTI International 2024). This constellation of capabilities is a national asset that underpins scientific discovery, technological competitiveness, and U.S. industrial leadership.

NIST's mission—to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life—directly contributes to this strategic advantage. The fundamental, experiment-driven knowledge generated at NCNR supports U.S. companies in maintaining global leadership across a range of technology sectors. Drawing a clear line from foundational scientific discovery to advanced metrology, industrial innovation, product development, and ultimately national competitiveness underscores the essential role of this facility. Sustained access to world-class characterization tools—capable of probing materials, soft matter, and buried interfaces with exceptional precision—is indispensable for progress in drug discovery, semiconductor manufacturing, artificial intelligence (AI) hardware, sensing technologies, and other long-term technology platforms.

Over the past decade, however, U.S. investment in neutron science has not kept pace with that of allied nations and the needs of U.S. industry and other neutron users. Europe and Asia continue to expand and modernize their neutron-scattering portfolios, creating a widening gap between U.S. capabilities and international benchmarks (European Spallation Source n.d.; Institute of High Energy Physics Chinese Academy of Sciences n.d.). Failure to reinvest in domestic infrastructure risks creating long-term structural dependencies in facilities and human capital and placing the United States at a strategic disadvantage in key technology domains.

NCNR functions primarily as a user facility, supporting industry, academia, and government researchers through its thermal and cold neutron beams generated by a 20 MW reactor. The facility's 29 instruments enable a wide range of scattering, imaging, activation analysis, and fundamental physics experiments. Complementary resources include sample preparation laboratories, diverse sample environments, and advanced data analysis tools. NCNR personnel span reactor operations and engineering, neutron condensed-matter science, and research facility operations, collectively supporting both user research and NIST's metrology mission—including the development of documentary standards and reference materials. As one of six major NIST laboratories, NCNR frequently provides critical research capabilities to the broader NIST enterprise.

NCNR has been offline for neutron experiments since a refueling incident in February 2021, which resulted in fuel debris contamination of the reactor vessel and elevated radiation levels in the helium sweep and ventilation exhaust systems. Following two extensive rounds of cleanup to ensure safe and reliable operations, the facility was preparing for restart during this assessment, conducted in May 2025. Full reactor operational capability is anticipated in 2026, though several instruments will not be restarted due to lack of sufficient staffing. The shutdown at NCNR has led to a major strain in the U.S. neutron science capabilities. A working NCNR reactor is a cornerstone in a resilient national neutron research source portfolio that in turn supports a healthy, broad, and productive neutron scattering community.

STATEMENT OF TASK

In 2025, at the request of the Director of NIST, the National Academies of Sciences, Engineering, and Medicine convened the Panel on Assessment of the National Institute of Standards and Technology (NIST) Center for Neutron Research (CNR), hereafter referred to as "the panel." The panel was established to carry out the responsibilities outlined in the statement of task, which is reprinted below.

The National Academies shall appoint a panel to assess independently the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Center for Neutron Research (CNR). The panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of the Center for Neutron Research. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in closed sessions and will prepare a report summarizing its assessment findings and recommendations.

NIST has requested that the laboratories be assessed against the following broad criteria:

1. Assess the NCNR's scientific and technical programs.
   - How does the quality of the research performed at the NCNR compare to that of similar world-class neutron facilities?
   - Is the quality of reactor operations, neutron instrumentations and scientific utilization of the NCNR adequate for it to reach its stated objectives? How could it be improved?
   - Does the NCNR's plan for cleaning the reactor and then resuming scientific operations offer a reasonable prospect for the NCNR to return to its previous high level of performance in 2026?
2. Assess the portfolio of scientific expertise within the NCNR.
   - Does the organization have world-class expertise in reactor operations and the development and utilization of advanced neutron instrumentation? If not, in what areas should it be improved?
   - How well does the organization's scientific and technical expertise support the research programs and the organization's ability to achieve its stated objectives?
3. Assess the adequacy of the NCNR's budget, facilities, instrumentation, and human resources.
   - How well do the facilities, instrumentation, and human resources support the NCNR's technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the NCNR disseminates its program outputs.
   - How well are the NCNR's instrument development activities and research programs driven by stakeholder needs?

- How effective are the mechanisms by which the NCNR provides access to its instrument suite by a broad subset of the scientific community? Are these mechanisms sufficiently comprehensive?
- How well does the NCNR monitor the scientific use and impact of the facility? How could this be improved?

CONDUCT OF THE ASSESSMENT

The panel comprised 12 volunteers with subject-matter expertise aligned with the scientific and technical work conducted at NCNR, and convened in Gaithersburg, Maryland, from May 13 to 15, 2025, to conduct an in-person assessment of NCNR. During the review, the panel engaged with NCNR leadership and staff, who delivered comprehensive presentations detailing the center's research activities, operations, and strategic priorities. These sessions were complemented by guided tours of NCNR facilities and substantive, interactive discussions between panel members and NCNR personnel.

In formulating its evaluation, the panel drew upon the collective technical acumen, disciplinary breadth, and professional experience of its members. The assessment employed a qualitative methodology, grounded in the materials submitted by NCNR, as well as the content of presentations, poster sessions, facility tours, and associated discussions. While the report does not address every individual research project or program, the omission of specific topics should not be interpreted as an indication of negative judgment. Rather, the panel focused its commentary on areas it considered most salient based on the information made available. The resulting report emphasizes NCNR's ongoing scientific and technical work, identifying key opportunities and challenges as observed during the site visit.

It is important to underscore that NIST maintains a distinct advisory entity, the Visiting Committee on Advanced Technology, which is charged with addressing broader questions related to strategic direction and research alignment across the agency's laboratories. Accordingly, this review does not include an evaluation of whether NCNR is pursuing the "appropriate" lines of research, as such determinations fall beyond the purview of the panel's mandate.

STRUCTURE OF THE REPORT

Following this introductory chapter, the report is organized into five subsequent chapters. Chapter 2 presents an overview of NCNR, including its current status and its critical role within the broader neutron research community. Chapter 3 discusses the technical program and operational activities at NCNR. Chapter 4 focuses on the NCNR reactor, and Chapter 5 examines the center's neutron instrumentation. Last, Chapter 6 summarizes the panel's conclusions and presents both overarching and chapter-specific recommendations.

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2
Overview of the National Institute of Standards and Technology Center for Neutron Research

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) is a world-leading user facility that provides both thermal and cold continuous neutron beams and instruments to the neutron science community, which includes researchers in the private sector, academia, and government (NCNR 2024a), and supports development of documentary standards and reference materials foundational to NIST's metrology mission. NCNR relies on the 20 MW research reactor, neutron guides, and instruments and provides a range of other services such as sample preparation laboratories, various sample environments, and data reduction and analysis. It has a history of high-impact neutron research in areas such as biotechnology, soft and hard materials, quantum information, energy storage, superconductors, advanced manufacturing, and engineering materials. Work done at NCNR has supported many significant scientific and technical publications and more than 1,200 patents throughout its existence. The average in recent years has been approximately 50 patents per year.

The NCNR reactor underwent an unplanned shutdown in February 2021 after a refueling accident, which is described further in Chapter 4. While the reactor has been shut down, NCNR reduced gas leaks from the reactor vessel (helium leak mitigation), installed a filtered drain (flange remediation), and upgraded three neutron guides (guide installation). Figure 2-1 shows the high-level schedule for cleaning and remediation activities from mid-2025 through early 2026 (NCNR 2025).

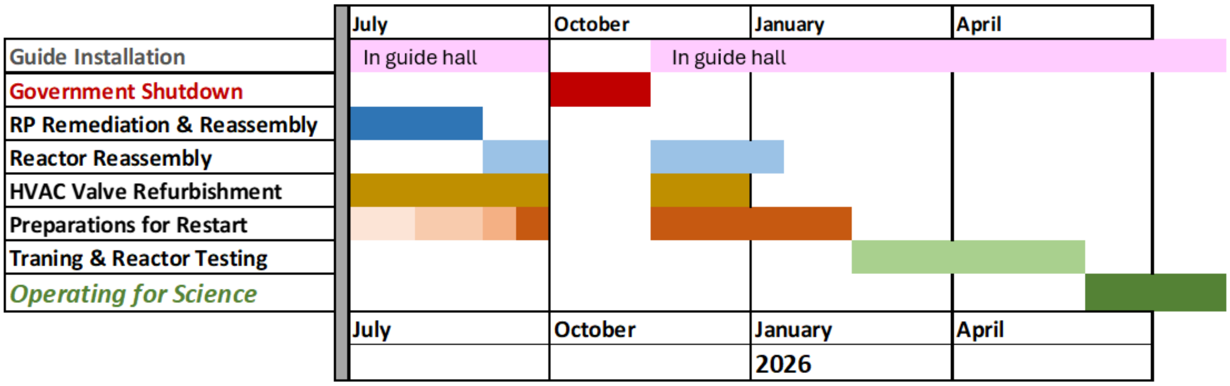

FIGURE 2-1 NCNR cleaning and remediation schedule to resume normal scientific operations. SOURCE: NIST 2025.

RESEARCH AT NCNR

NCNR manages a range of research programs. Crystallography is used to probe the structure of the atoms that comprise crystalline samples by generating neutron diffraction patterns and measuring residual stresses in engineered materials. Reflectometry generates a profile of the layers in a flat sample by grazing it with neutrons. Samples queried can include biological membranes, thin polymer films, and metallic materials structured in layers. If a polarized neutron beam is used, the magnetic and nuclear properties of thin films can be established. Small-angle neutron scattering is used to characterize materials over a scale from 1 to 1,000 nm. This technique can explore both physical and magnetic differences within samples. Neutron spectroscopy is used to probe the dynamics of materials, such as vibrations, rotations, and quantum properties, using milli-electron volt neutrons (NCNR 2019). Chapter 3 assesses NCNR's research program, and Chapter 5 assesses the instruments used for this research.

NCNR has several collaborative research activities with the National Science Foundation, industry, and other NIST laboratories. The Center for High Resolution Neutron Scattering (CHRNS) is a joint user facility with the National Science Foundation within NCNR that develops and operates state-of-the-art neutron scattering instruments. When NCNR was operating normally, it served nearly 500 scientists, postdoctoral fellows, and graduate students each year (NCNR 2019). The NIST Neutrons for Soft Materials Consortium (*n*Soft) is an NCNR research program that operates as a public–private industrial consortium whose members pay a fee and participate in a cooperative research and development agreement. The members of *n*Soft have access to NCNR's facilities to engage in neutron research for their industrial aims. Research under *n*Soft is in the public domain, and the expectation is that research results will be published. Proprietary measurements cannot be executed under the *n*Soft agreement, although proprietary research can be completed through individual agreements between companies and NCNR (*n*Soft 2025a,b).

NCNR supports the work of the NIST Physical Measurement Laboratory (PML) through the Neutron Physics and Dosimetry Groups within the Radiation Physics Division. The Dosimetry Group develops, maintains, and disseminates standards for the gray, the standard unit of radiation (PML n.d.-a). The Neutron Physics Group also develops and provides standards as well as provides measurement services and conducts fundamental research in support of NIST's overarching mission. Services include neutron imaging, development and calibration of scientific instruments, calibration of neutron sources, and work geared toward detecting concealed nuclear materials, radiation protection, and generating nuclear and particle physics data (PML n.d.-b).

NCNR also supports the work of the NIST Material Measurement Laboratory through the Nuclear Methods Team, a subset of the Chemical Process and Nuclear Measurements Group in the Chemical Sciences Division. This group generates and curates reference methods and data, disseminates Standard Reference Materials, develops standards and models, and advances fundamental chemical measurement science by conducting rigorous chemical and physical measurements at the current state of the art. Its work is focused on energy, manufacturing, national security, and the environment. Specifically in the context of this assessment, the group collaborates with other organizations, including NCNR, to use nuclear methods for elemental analysis (MML n.d.)

The breadth of topics impacted by the scientific work conducted at NCNR is shown in Figure 2-2.

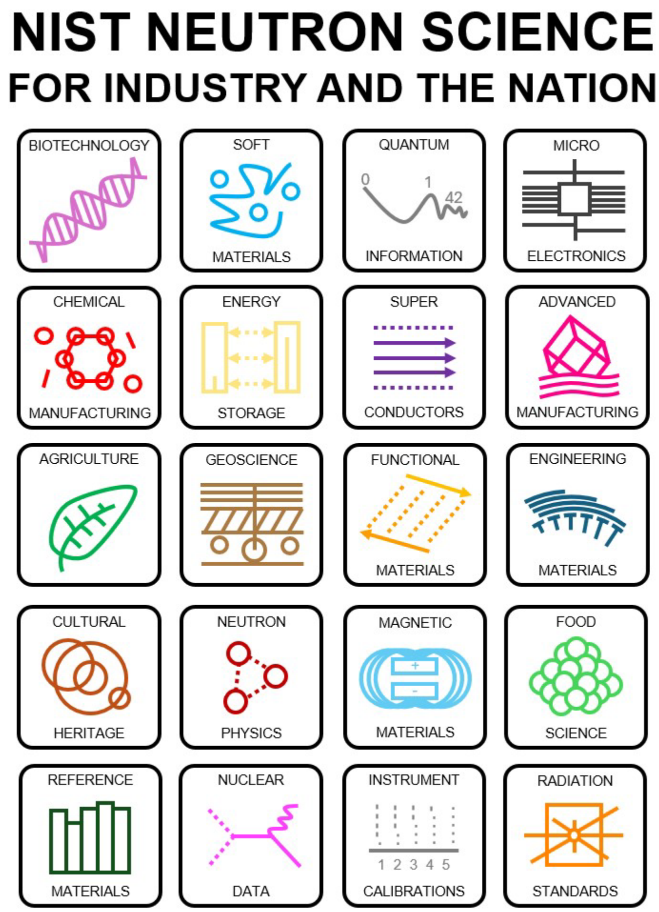

FIGURE 2-2 The breadth of topics addressed by scientific work conducted at NCNR.
SOURCE: NIST 2024a.

EDUCATION PROGRAMS AT NCNR

NCNR hosts education programs through CHRNS for a wide range of participants, including a summer school, fellowships, and internships. The CHRNS Summer School on Neutron Scattering is a 1-week program aimed at graduate students and junior faculty. In July 2023, the school hosted 35 individuals from 17 states (Adams and Kline 2023). The program teaches participants how to do neutron scattering experiments through hands-on experience, from planning to data analysis. The program's focus alternates each summer, one year focusing on small-angle neutron scattering and neutron reflectometry and the next summer on neutron spectroscopy. It has operated continuously for more than 25 years and is the oldest neutron school in the United States.

Neutron science is important to industrial development, advancement of science, and NIST's metrology mission. Education at experimental facilities is required to maintain and grow new generations of neutron scientists and engineers. The Summer Undergraduate Research Fellowship gives students practical experience and mentorship in materials science, biomaterials, chemical and nuclear engineering, and computational science, among others. The CHRNS Outreach and Research Experience is aimed at undergraduate students, including graduated high school seniors and college graduates within a year of graduation. It allows for flexibly timed 2–12-month paid part-time work. The Summer High School Internship Program provides an unpaid 8-week opportunity for high school juniors and seniors to do scientific work directed by NCNR staff. In the summer of 2023, CHRNS hosted 10 students through the Summer Undergraduate Research Fellowship, 10 students through the CHRNS Outreach and Research Experience, and 6 students through the Summer High School Internship Program (Adams and Kline 2023). Other programs are offered to visiting scientists, postdoctoral researchers, kindergarten through grade 12 teachers and students, and the public (NCNR 2024b).

NCNR BUDGET AND STAFF

The NCNR budget for fiscal year (FY) 2025 was $56 million, which supports 184 staff members (federal employees and associates) who enable and support the work of more than 2,500 investigators. NCNR's base budget for FY 2025 represents a 19 percent increase from that in FY 2018 (see Figure 2-3). However, the 27 percent inflation during the same period, as well as additional costs for reactor operations, reactor management programs, an expanded safety program, and compliance costs, have limited increases in productivity that may otherwise be expected with larger budgets (Adams 2025).

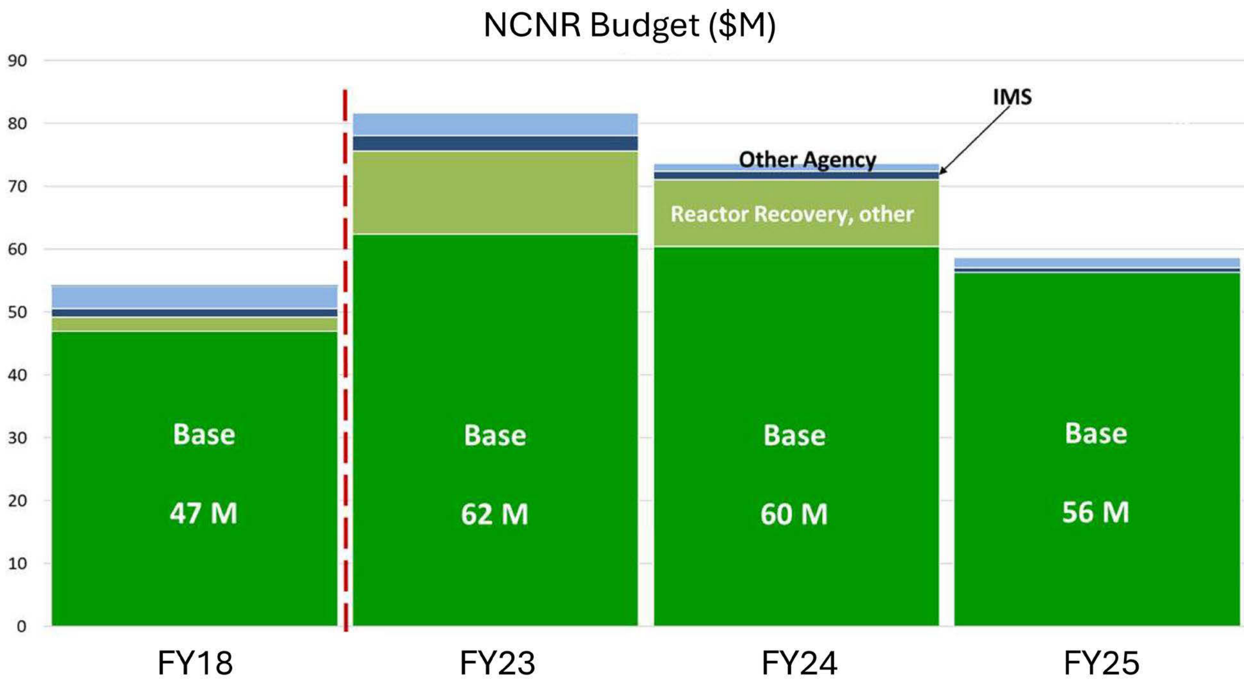

FIGURE 2-3 NCNR budget by year, not adjusted for inflation. IMS stands for the NIST-wide Innovations in Measurement Science program, which competitively awards internal grants among centers and laboratories. The red dotted line indicates a discontinuity in the graph where fiscal year 2018 (year of the last National Academies' review before the shutdown) skips to fiscal year 2023.
SOURCE: Adams 2025.

The NCNR workforce is divided into Reactor Operations and Engineering, Research Facilities and Operations, Neutron Condensed Matter Science, and Center Office staff, the breakdown of which can be seen in Figure 2-4. The Reactor Operations and Engineering group has gained 14 staff members since FY 2018, while the Neutron Condensed Matter Science and Research Facilities and Operations groups combined have 37 fewer staff members in FY 2025 than in FY 2018 (Adams 2025). As of May 2025, NCNR hosted six graduate students and eleven post-doctoral researchers, all within the Neutron Condensed Matter Science group (Jones 2025). A 25 percent reduction in instrument support staff from 2018 to 2025 means that the ratio of instrument staff to instruments has decreased to 4–4.5, significantly lower than at other neutron sources (5.5–6 at the Australian Centre for Neutron Scattering and the National Deuteration Facility, 7 at the Institut Laue–Langevin, and 9–10 at the Spallation Neutron Source; Jones 2025). In order to "right-size" operations, NCNR will not be able to operate 5 of 17 scattering instruments in 2026, which will decrease its capacity to support research in quantum materials, thin-film magnetism and electronics, soft and biomaterials, geology and oil, and advanced materials (Jones 2025). The Research Facilities and Operations group has seen a 20 percent staff reduction since 2018, which is limiting its ability to conduct major instrument repairs (Kirby 2025). The reactor operations team currently does not have enough licensed operators to support operations 24 hours per day, 7 days per week, although a licensing exam is planned for early to mid-2026 (Newton 2025).

The current base budget is insufficient to support the safe operations of the reactor, a neutron instrument-based user facility, and a minimum viable research program. If existing insufficient base funding is continued, NCNR will face significant loss in core capabilities that greatly reduce scientific knowledge generation and support of U.S. industry. As noted in Key Recommendation 6-1, NIST leadership should support the NIST Center for Neutron Research at inflation-adjusted pre-COVID levels immediately, as a minimum to restore core objectives. Even restoration of inflation-adjusted funding with supplemental funding for a full reactor operations staff may not be sufficient to support the needs of U.S. industry.

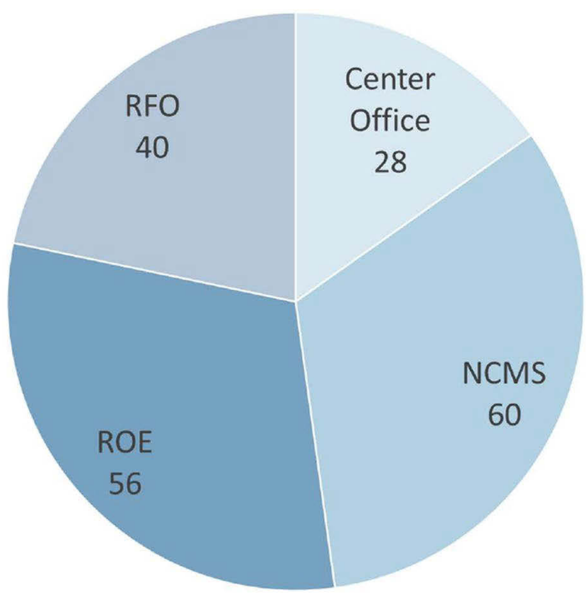

FIGURE 2-4 NCNR workforce overview, showing number of employees by office.
NOTES: NCMS = Neutron Condensed Matter Science; RFO = Research Facilities and Operations; ROE = Reactor Operations and Engineering. Center Office includes administrative staff, health and safety representatives, scientific advisors, associate and deputy directors, and the director.
SOURCE: Adams 2025.

NCNR'S PLACE IN THE NEUTRON RESEARCH COMMUNITY

NCNR supports several aspects of the neutron research community: neutron scattering, fundamental physics research, and industrially relevant research. Neutron scattering has a long history in the United States, starting with the first experiments carried out at Oak Ridge National Laboratory by Nobel Laureate Cliff Shull and others in the 1940s and 1950s. It has since expanded with the construction of multiple research reactors and spallation neutron sources. Today, neutron scattering is the premier technique for materials characterization at multiple length and timescales, providing unique information that cannot be accessed in other ways. NCNR has played a major role in the expansion of the neutron user base by establishing thriving user programs, serving the regional community, and more broadly by drawing users from all over the United States and the world. Before the shutdown, beam time at the neutron instruments was very difficult to come by, with demand for time more than twice the available capacity (Diamond et al. 2025).[1] With the NCNR reactor shut down, the United States is severely short-handed in beam time and neutron instruments, forcing users either to abandon neutron scattering for other techniques or to seek other facilities.

Fundamental wave and particle physics with neutrons is of paramount importance for understanding our universe's early evolution and present-day composition, determining standard couplings and cross sections, and searching for signs of new physics via precision measurements. NCNR has played a pivotal role for decades in each of these domains, contributing best measurements of atomic scattering lengths and cross sections that underpin all of neutron science. Basic services developed and curated at NCNR include calibration for sources and metrology, and advanced methods for neutron polarization and detection. Continuous refinement of these core capabilities has steadily supported both world-leading industrial and user science and enabled cutting-edge, often unique, measurements in fundamental neutron science. The instrumentation and support for fundamental neutron science at NCNR are also unique and world class and were developed over time to address key questions and limitations across neutron physics. Loss or reduction of these capacities would have important negative impacts on pure and applied neutron science globally.

[1] Specifically, per Walsh et al. (2024), "At no point since 2006 has NCNR been able to meet more than 58% of the applicant demand in a single year. In 2020, the percentage of applications awarded time was 41%."

NCNR is a part of the Department of Commerce with its direct mission to advance economic and technical excellence in the United States by providing world-class neutron measurement capabilities to meet the needs of researchers from industry, academia, and government. In 2024, research participants at NCNR came from 16 NIST divisions, 38 U.S. states and Washington, DC, 18 corporations, 19 U.S. government agencies and national laboratories, and 106 academic institutions (Jones 2025). NCNR is uniquely positioned within the broader neutron community to seamlessly engage and partner with industry. This is clearly manifest in cooperative programs like *n*Soft, a consortium that includes multiple partners in the pharmaceutical, consumer products, chemicals, oil and gas, and automotive industries. While industrial participation and activity have declined since the reactor shutdown, NCNR staff has done a commendable job maintaining interest and participation with core participants. NCNR is well positioned to reinvigorate the consortium and broader industry engagement when the reactor and instruments return to full operation.

Neutron sources and scientific instruments have both generative and supportive roles in industrial innovation: fundamental scientific advances generate new knowledge, enable measurements that were not previously possible, and thus drive new commercial developments that would not follow from targeted industrial research alone. Industry also refines the new capabilities derived from fundamental research, feeding them back into the research ecosystem as marketable products, and subsequently profiting from new advances that occur in academic research. Industry leaders rely on a thriving research ecosystem in the United States, in which fundamental science drives commercial innovation and vice-versa. This requirement cuts across disciplinary boundaries, with applications ranging from materials research to drug discovery, sensing applications, and artificial intelligence (AI) hardware. To fulfill its mission as a driver of commerce, NCNR supports industry through science at all levels, through not only industry-specific partnerships and proprietary research, but also basic science advances across the userbase.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 2-1: Neutron science is critical to the competitiveness of the United States. The National Institute of Standards and Technology Center for Neutron Research

(NCNR) plays a pivotal role in neutron science and innovation, running a leading neutron program across strategic areas of national interest such as nuclear physics, quantum science, and materials characterization in partnership with industry. NCNR has an important role in education of the broader neutron science research community through graduate and postdoctoral scholars. Sustained federal funding is required to ensure continuity and growth in scientific capabilities at NCNR to maintain U.S. leadership in neutron science.

Recommendation 2-1: The National Institute of Standards and Technology Center for Neutron Research and government research funding agencies should support graduate and postdoctoral studies in the field of neutron science both to provide for current research needs and to develop a pipeline of future practitioners in industry, government, and academia.

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3
Technical Program at the National Institute of Standards and Technology Center for Neutron Research

The technical program at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) emerges from three pillars: the NCNR staff; the NCNR reactor, instruments, and support facilities; and the user community encompassing industry, academia, and government. Atop this foundation, myriad research programs are built that support NCNR's mission "to address national needs through advances in neutron-based measurement methods and make the capabilities available to academia, industry, and government" (Adams 2025). This chapter examines the technical work of NCNR, including accomplishments, challenges, and opportunities. Details related to the reactor and the instrument suite appear in Chapters 4 and 5, respectively.

TECHNICAL PROGRAM

Research at NCNR continues to be of excellent quality across multiple fields despite not having a fully operating in-house reactor since February 2021. Publication in high-impact journals remains significant (i.e. 20 percent with an impact factor greater than 7 over the past 2 years from staff in the Center for High Resolution Neutron Scattering user facility), resulting from the facility's well-supported scientific research programs led either by NCNR staff or in collaboration with the user community. NCNR staff's high success rate in obtaining beam time at other facilities (around 2,000 experiment-days) during the reactor shutdown indicates the high quality of research being performed. NCNR is actively collaborating with the academic and industrial research communities. For example, collaborations in biotechnology help to understand the structure, dynamics, and mechanisms of interaction in biologically relevant molecules such as antibodies, lipid nanoparticles, and adeno-associated virus and amorphous solid dispersions. Step-change advances in sample environment equipment at NCNR enable acquisition of unique information from neutron scattering. Examples include the integration of an autonomous formulation laboratory and capillary rheology into small-angle neutron scattering instrumentation, and new modeling tools developed internally and in collaboration with other partners at NIST and the University of Maryland's Institute for Bioscience and Biotechnology Research.

Accomplishments

NCNR has notable research achievements in soft matter and biology; hard matter; neutron physics; engineering and imaging; and artificial intelligence (AI), machine learning (ML), and automation. Each of these technology areas has applications of national importance, such as developing materials for pharmaceuticals, automotive, aerospace, and semiconductors. Selected accomplishments during the period since the last National Academies review in 2023 are shared below to illustrate NCNR's particular strengths and role in the neutron science research community.

Soft Matter and Biology

NCNR instruments and scientific staff continue to be world leading in soft matter research, supporting industrial and academic partners. Areas of focus include membrane biophysics, phase behavior, dynamics of self-assembled systems, and pharmaceuticals. NCNR continues to be expert in membrane biophysics. The application of neutron reflectivity to understanding the conformation of protein molecules within lipid bilayers is world class. Deuteration of specific proteins coupled with data modeling has enabled NCNR to interrogate the orientation of multiprotein complexes on lipid bilayers. An exciting development is Reflectometry-driven Optimization and Discovery of Membrane Active Peptides (ROADMAP), which aspires to use automated sample preparation and iterative data analysis to vastly improve throughput (see further description in Chapter 5). The immediate application of ROADMAP is to investigate the properties of membrane-active peptides, but this platform is highly likely to be transformational for other soft matter experiments.

NCNR continues to actively engage with industry through multiple mechanisms, such as cooperative research and development agreements and the NIST neutrons for soft materials consortium (*n*Soft), a consortium including multiple pharmaceutical partners, consumer products companies, and automakers. *n*Soft is also transitioning into a new model with a focus on developing neutron metrology for soft materials manufacturing that will be called the *n*Mat consortium. Through this mechanism, NCNR will continue to work with industry on common challenges across multiple sectors and, using neutrons, bring solutions that will benefit the whole industry. Overall, NCNR's current and proposed engagement mechanisms are aligned with its mission to address national needs through advances in neutron-based measurement methods and make the capabilities available to academia, industry, and government.

As a further example of NCNR's industry engagement on soft matter, researchers at NCNR collaborated with industry and government to characterize the structure of self-amplifying messenger ribonucleic acid (mRNA) in lipid nanoparticles (LNPs). These mRNA LNPs are of key significance to deliver therapies that improve patient outcomes. Self-amplifying mRNA is significantly larger than traditional mRNA to encode the replicon that enables the production of multiple mRNA copies within the cell and ultimately lower doses for the same amount of antigen produced. As a result, the self-amplifying mRNA LNP forms a complex structure that had not previously been characterized. Using neutron scattering and other techniques, researchers characterized the structure and lipid distribution across the core and shell and developed a model to enable analysis of this complex structure, revealing key structural features in the self-amplifying mRNA LNP system that contrasted with previous findings for conventional mRNA LNPs. These results are increasing our understanding of structure and function relationships in these systems, which could benefit the design of mRNA LNPs that enable a broader range of therapeutic applications.

Hard Matter

Neutrons are indispensable probes for advancing our understanding of superconductivity, magnetism, and structural dynamics in quantum materials. This understanding is essential for areas of national importance such as quantum computing, energy security, and the development of faster and more efficient electronic devices (area of spintronics). NCNR leadership in this area has continued over the past years. The discovery of superconductivity that survives to very high magnetic fields was discussed in the last National Academies of Sciences, Engineering, and Medicine review (NASEM 2024). This discovery was made in 2018 by NCNR personnel, and measurements at the National High Field Magnet Laboratory showed that the superconductivity has a reentrant component. More recently, the collaboration involving personnel from Oak Ridge National Laboratory as well as NCNR mapped out the phase diagram in field as a function of direction relative to the crystal axes (Butch 2025). Furthermore, inelastic neutron scattering at the High Flux Isotope Reactor revealed complex magnetic coupled magnetic–electronic excitations. The high field to which the superconductivity survives indicates that the pairing mechanism is very unusual, and inelastic neutron scattering is likely to be important in elucidating it.

NCNR postdoctoral researchers and students have continued to carry out impactful studies at other facilities during the NCNR shutdown. For example, neutron reflectometry measurements were made on strain-mediated magnetoelastic phenomena at the ISIS Neutron and Muon Source in the United Kingdom and the Spallation Neutron Source at Oak Ridge National Laboratory (Grutter et al. 2025). In addition, results from experiments completed prior to the reactor shutdown are still being analyzed and published, such as those on a novel Kagome lattice material (Gaudet 2025). A highlight is the high-impact work arising from the Multi-Axis Crystal Spectrometer (MACS), with three out of the four publications this year in high-impact journals. One such achievement is that of a time-resolved inelastic neutron scattering technique to probe time-dependent nonequilibrium dynamics in a molecular magnet, subjected to microwave pulses (Brown 2025).

Neutron Physics

The Neutron Physics Group has prioritized a small number of scientifically targeted U.S. and world-leading activities built on a foundation of techniques and standards that support academic and industrial user science. Novel detector developments will support not only the traditional use cases of established user groups but also emerging trends such as quantum sensing in neutron physics. Recent highlights include the first demonstration of neutron Airy beams, already known from light optics as a propagation-invariant state with advantageous self-healing and focusing properties that open many potential new applications in fundamental and applied research. It is noteworthy that NIST scientists were able to support this activity, driving a major experimental result, during the unplanned shutdown period.

Advanced metrology, calibration, and standards are deeply integrated in the core mission of NIST. Developments in metrology within neutron physics at NCNR advance the facility’s world-leading role for specific key measurements and open new avenues for user science. The world-leading precision neutron fluence measurement from 2018, based on the alpha-gamma method pioneered at NIST and driven by the (also world-leading) beam-based measurements of the neutron lifetime at NCNR, is now being pushed to unprecedented frontiers with the AlphaGamma 2.0 facility. The AlphaGamma 2.0 target precision of 0.01 percent is not presently achievable by any other method or at any other facility and removes the need for absolute calibration of the alpha source. A major effort is now under way to recalibrate the U.S. national neutron standard NBS-1 using AlphaGamma 2.0. The larger beam coverage and achievable precision within measurement times of a few weeks also make it attractive as a potential new user facility.

The beam-based neutron lifetime experiment BL2 and its planned successor BL3 are uniquely positioned to shed light on the long-standing discrepancy of approximately 10 seconds (i.e., approximately 1 percent), between beam-based and storage-based lifetime measurements using ultracold neutrons. NCNR scientists have gradually and systematically excluded several increasingly subtle proposed explanations for this discrepancy, including key results during the ongoing shutdown that now exclude charge exchange with residual gas molecules (which had been provisionally accepted by many in the field as a definitive explanation). Given the comparative precision and multiplicity of storage-based lifetime experiments, advancing the beam-based measurements is evidently the most productive avenue toward a resolution of this discrepancy—and thus ascertaining whether the answer lies in new physics, or in subtle experimental effects. If it arises from subtle experimental effects, a definitive resolution would open the neutron lifetime as a new “laboratory” for precision tests of the Standard Model of particle physics.

Engineering and Imaging

The engineering diffraction beamlines in NCNR are a cornerstone facility for hard matter and engineering materials research. The Beam Tube (BT)-8 engineering diffractometer provides advanced capabilities to study the structural and mechanical behavior of engineering materials, including metals, alloys, and composites, as well as polymers and complex fluids. The BT-2 neutron imaging beamline provides state-of-the-art imaging capabilities, combining neutron and X-ray tomography to study engineering materials. The dedicated beamline supports a wide range of investigations, including the evaluation of residual stresses induced during manufacturing and processing, in situ measurements of applied stresses under complex loading paths, analysis of crystallographic texture, and phase identification.

The facility has been instrumental in collaborative efforts with academia, national partners, and industry, particularly in the transportation sector, where understanding and optimizing the processing of metals is a key priority. For example, researchers use the facility to study aerospace materials for turbine blades and fatigue-resistant rail steel, both critical for the safety of the public and profitability of large U.S. industries. During the continued outage of the neutron source, the beamline scientists and team conducted neutron stress analysis of wire-feed laser melting of the Inconel superalloy in collaboration with Oak Ridge National Laboratory. The resulting data, including residual stresses induced during manufacturing, are being used to predict the service life of large-scale metal structures. Moreover, in response to the sustained interest from industrial partners in understanding phase stability and mechanical ductility under multiaxial loading, the octostrain device was transferred from NCNR to the Center for Automotive Lightweighting and successfully adapted for integration with an X-ray diffractometer. Additionally, key research activities at the BT-8 diffractometer include contributions to the additive manufacturing (AM) benchmark, which aims to provide vast experimental datasets for validating AM simulations across a broader range of AM technologies and materials systems, which align with the NIST mission.

Artificial Intelligence, Machine Learning, and Automation

Instrument staff has made significant advances in the areas of automation and autonomous instrument operation, leveraging ML approaches. The Autonomous Formulation Laboratory is a unique platform to optimize the measurement of the phase behavior of complex liquid formulations such as paint formulations, sustainable lubricants, or injectable drug systems. Understanding the phase behavior of complex liquid formulations is key to product stability and shelf life. Furthermore, the Autonomous Formulation Laboratory could drastically compress the research and development timeline (and budgets) of relevant industrial sectors by accelerating the ruling out of ineffective formulations. Sectors that would benefit include personal care and detergents, coatings and paints, energy and fuels, and pharmaceuticals.

Reflectometry has time-consuming sample preparation and is frequently flux limited. The AutoRefl and ROADMAP tools allow optimization of measurement strategies, in terms of both sample choice and instrument configuration. These key advances will enhance scientific quality and quantity from the reflectometry instruments, leveraging the large body of expertise in the study of protein–membrane interactions in the reflectometry team.

Challenges and Opportunities

As noted in the previous section, NCNR research covers a very wide range of areas, and the support provided to the user research community is of the highest quality. The biggest challenge is to ensure availability of resources (both financial and human) to continue this excellent work. Because of funding and staffing limitations, NCNR is proposing to stop supporting some instruments provide excellent user support on the remaining instruments. The proposed instrument choice seems sensible but will affect areas of quantum materials, thin-film magnetism, soft matter and biology, advanced materials, and geology, among other things. Ending use and support of instruments also impacts the overall efficiency of the facility on a per-beamline and daily basis, with the fixed costs of reactor operations spread over fewer instruments and resulting in fewer scientific breakthroughs and fewer impacts for industry and government users. The financial and human resources challenge is particularly acute at a time when experimental complexity and demand for high-throughput and multimodal measurements are increasing, all of which require both technical and computational human expertise. Given the initial success of the automation campaigns, this approach can be prioritized and staffed appropriately to maintain leadership. In parallel, there is opportunity to leverage and work much more closely with other facilities in areas such as AI and software development. AI, automation, and multimodal measurement capabilities can also increase the ratio of users and experiments to beamtime, with the potential to maximize efficiency of each beamline.

NCNR has had a strong history of training through various student and postdoctoral programs (see Chapter 2). The young researchers trained in these programs represent one of very few sources that replenish the community of senior researchers in neutron scattering techniques in the United States. The NCNR shutdown, as well as the reduction of scope or delays after resuming operations, presents a significant risk to this pipeline of talent necessary to enable the continued technical leadership of NCNR. Once the base of technical knowledge erodes, it is difficult and expensive, if not unrealistic, to return to a functional level within relevant timelines. This challenge needs to be addressed rapidly when the reactor restarts, and staffing must be at a level that allows for supervision and training of the next generation of neutron scattering experts at the pre-shutdown level. Below are several challenges specific to the different application areas at NCNR.

Soft Matter

NCNR continues to engage with users across multiple industries to support developments in soft materials and biopharmaceutical therapeutics. There is a long-term risk of losing industry engagement after an extended delay. The number of industry participants has declined since the reactor stopped operating, even though participant fees are being waived. Industry participants likely are unable to justify being part of NCNR initiatives without an operating facility and the added uncertainty about the restart time. Another significant challenge is the risk of losing momentum in areas where NCNR provides unique leadership and capabilities for the United States, such as the Autonomous Formulation Laboratory initiative. Insufficient staffing, departures of highly skilled personnel, and financial constraints could severely undermine the substantial progress achieved in advancing these technical capabilities and in fostering vibrant academic and industrial communities around them. The new *n*Mat program represents an opportunity to restart industry engagements. NCNR staff can gather existing and new industry engagements through the new *n*Mat program and start outlining key projects to include as part of the common industry challenges where neutrons can provide insights not achieved by other techniques.

Hard Matter

The long shutdown has clearly compromised the competitiveness of hard condensed matter research and the inelastic scattering instrument suite that was available before the shutdown at NCNR. Staffing losses in magnetism are also leading to challenges for the hard matter research community. However, there are a few remedying factors that could boost the neutron user program restart. There are few inelastic instruments in the United States, so improved instruments at NCNR will help meet the high demand. For example, future developments of the new Quantum Materials Spectrometer would be able to complement the Cold Neutron Chopper Spectrometer at the Spallation Neutron Source, and it is anticipated that users will be seeking to use this machine because of its resolution at very low energies. Moreover, MACS offers unique capabilities nowhere else available in North America, catalyzing further research in magnetism. The return of NCNR will restore regional access to a major neutron source. Following the departure of one of NCNR's leading experts in magnetism, it is very important for the facility to hire an expert to continue to attract research in that area. Last, a modest investment in the powder diffractometer can contribute to the revitalization of crystal chemistry and can facilitate high-throughput experiments with the potential for high research impact.

Neutron Physics

Developing and implementing precision methods in neutron physics requires sustained multiyear efforts, typically exceeding both project funding periods and the duration of PhD or postdoctoral contracts. Such long timescales arise from (1) the statistical limitations of a limited-power facility, and (2) reliance on a large foundation of previous work that underlies increasingly nuanced refinements and/or fundamentally new methods. The first challenge can be mitigated by fully exploiting the beams available at NCNR and other facilities, and by proactive planning for the realization of future facilities that will outperform those currently operating. The second can only be addressed by fostering an environment that is supportive toward both innovative new approaches and detailed examination of present limitations.

Continuing to focus on key activities that cross the boundaries of standards and metrology, basic physics research, and applied and industrial research is likely to maximize the return on investment of time, personnel, and material resources. This ensures the fundamental importance and wide applicability of the obtained results for the global community of neutron researchers as well as for the core audience of U.S. industry, standards, and science. It is critically important, but challenging, to maintain continuity of the necessary knowledge and technical capabilities across successive generations of students and postdoctoral researchers in order to advance and successfully conclude efforts of this type.

As noted above, researchers trained through long-running research programs are one of very few sources that replenish the community of senior researchers in neutron physics. The shutdown of NCNR and lack of a robust program upon restart is a risk to the primacy of U.S. reference standards such as NBS-1, universal reference data such as neutron scattering lengths and cross sections, and globally leading scientific measurements such as neutron interferometry and the beam-based neutron lifetime result. Industries impacted include transportation, energy, advanced manufacturing, aerospace, and communication, with the slow return in industry-critical capabilities such as advanced neutron imaging and detection, and precision calibration methods such as the alpha-gamma technique. NIST's mission of metrology and traceability implemented at NCNR in the neutron scattering domain is unique and particularly demanded by industry developing state-of-the-art materials, systems, and respective characterization techniques. The focus on precision, accuracy and reliability of neutron scattering data makes these methods attractive to industry. The risk to U.S. capabilities in neutron physics can only be mitigated by supporting the NCNR neutron physics community with adequate staff and resources, thus preserving it as an attractive destination for both early career researchers and external users.

Engineering and Imaging

In the face of staffing and resource pressure, sustaining and advancing NCNR's engineering diffraction capabilities could be challenging. The NCNR engineering diffraction team is responsible for instrument maintenance, upgrades, software development, and method commissioning, yet the demands of these activities risk outpacing available support. NCNR has been key in the development of new theoretical models derived from diffraction experiments aimed at improving future stress and strain analyses in engineering materials. This is embodied in the IsoDEC software package, which enables the calculation of diffraction elastic constants, stress, and strain in complex, multiphase, and textured materials. The software also accounts for grain-shape effects and sample-surface effects, where these factors are critical in X-ray and neutron diffraction–based residual stress analysis on engineering metals and alloys. These modeling and software developments address a long-standing challenge in residual stress characterization for industrially relevant alloys and highlight both the importance and vulnerability of the work. Their continued refinement requires stable investment and skilled personnel and presents a strong opportunity for NCNR to lead nationally and internationally in developing, standardizing, and supporting commonality of advanced analysis tools that complement experimental measurements, and to strengthen collaborations with industry and other neutron and materials mechanical testing facilities.

Artificial Intelligence, Machine Learning, and Automation

NCNR's strong work in AI, ML, and automation presents an opportunity for NCNR to take an international leadership position in automation and autonomous experiment control. However, that opportunity is at risk because of the instrument staff–led approach to software development, which limits software sustainability and scalability. Software tools for AI, ML, and automation data processing and analysis are written largely by instrument scientists. Strong engagement between software experts and instrument scientists is commendable as it ensures that the tools are closely coupled to scientific needs. However, the lack of a core team of software experts working on these tools means that sustainability and support depend on the continued commitment and presence of the specific scientists who wrote the tools. At the very least, a stronger central function would help with ensuring commonality of tools and underlying libraries. Automation of tasks allows instrument scientists to be more focused on scientific understanding and less bogged down by process. In addition, these tools can expedite the data reduction process, which can be time consuming. Dependence on the scientist to operate and adapt the software risks being rate limiting. A plan for managing the various software tools being developed and support for the instrument scientists in using software engineering methodologies would encourage maintainability. Options to consider include access to continuous integration tools, use of coding standards and code review, and training in best practices in code management.

SCIENTIFIC AND TECHNICAL EXPERTISE

As described in Chapter 2, the NCNR workforce is comprised of 184 individuals across Reactor Operations and Engineering, Research Facilities and Operations, Neutron Condensed Matter Science, and the Center Office.

Accomplishments

The scientific and technical staff at NCNR are of extremely high caliber, as evidenced by both national and international recognition and from their standing within the scientific community. In the past 3 years, 13 members of staff across a range of career stages have received prestigious awards recognizing their contributions to scientific research and education, some even with multiple awards. These awards include recognition of scientific achievements from bodies such as the Neutron Scattering Society of America or the American Association for the Advancement of Science, and also recognition of highest accolades from the U.S. government such as the Department of Commerce Gold Medal or the Presidential Early Career Award for Scientists and Engineers (Jones 2025). These add to the sustained track record of acknowledgment of NCNR staff by the research community, including a long list of other awards accumulated over the years.

NCNR continues to demonstrate strong and impactful scientific activity, despite the lack of neutrons at NCNR. NCNR staff has been extremely proactive in seeking neutrons (and complementary X-rays) in a wide range of facilities all across the world. The success rate has been extremely high, performing around 2,000 days at more than 5 X-ray sources and 10 neutron sources in the United States, Japan, France, the United Kingdom, Switzerland, Australia, and South Korea in 2024, which is evidence of the high quality of research being proposed and thus accepted. In 2024, 188 papers were published in 99 distinct peer-reviewed journals, plus 2 book chapters and 8 proceedings. The output is around two-thirds of the steady-state output when the reactor is operational (based on an average between 2005 and 2021) (Jones 2025). A large number of publications are in high-impact journals, on average almost a quarter in journals of impact factor greater than 7. Publications lag experimental achievements, and so the full impact of the NCNR shutdown is yet to be felt in these metrics.

Challenges and Opportunities

Challenges

NCNR has been instrumental in training the next generation of neutron users and scientists through internally funded programs and collaborations and investments with various schools, colleges, and universities. However, the prolonged reactor shutdown and limited number of available positions are risking the pipeline of the next generation of high-quality, well-trained instrument scientists. Nonetheless, NCNR's reputation as an exciting, top-quality research facility continues, with many applicants for postdoctoral research and high interest from students. With a lack of positions, NCNR must turn away good candidates, and the uncertainty of intermediate-term funding impacts retention. Because NCNR cannot host as many students and postdoctoral researchers or give them generous access to hands-on neutron scattering, there will inevitably be a generational gap in trained neutron users and future instrument scientists.

Opportunities

One benefit of the shutdown period and need to perform experiments elsewhere has been the exposure of NCNR staff to the capabilities and operating practices of other facilities. These experiences have provided additional knowledge that can be used to improve practices at NCNR. They have also broadened and extended collaborations (e.g., helping to expand the Oak Ridge National Laboratory program on soft matter; supporting the University of Missouri reactor in growing their user base), exposed NCNR staff to different communities, and increased the visibility of NCNR (research program and capability offering) and its staff.

Additionally, during the shutdown period, NCNR staff has been able to work on tasks that are limited during regular reactor cycles, such as science and research for technical developments including instruments, software, and sample environment. Several technical projects and upgrades have been implemented during this time, and many new concepts have been developed for possible implementation in the future.

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

As described in Chapter 2, the budget situation has continued to deteriorate, which is primarily manifested through non-replacement of staff. The previous review (NASEM 2024) noted that NCNR was at a tipping point, and there would need to be a reduction in the capabilities offered by the facility if the budget and staffing continued to decline. This has now come to pass; as noted above and in Chapter 2, some instruments will not be operated upon reactor restart to focus limited resources, leaving important areas of neutron research unsupported because of lack of funds.

Facilities

A tour of the facilities indicated that new instruments (e.g., Chromatic Analysis Neutron Diffractometer or Reflectometer, ν-NSE) are ready to operate when the reactor restarts, and staff members are eager to get the instruments back online when the beam returns. The automation equipment is impressive and likely to have an impact on instrument productivity. Opportunistic work with the guide upgrades is on track. The only area of concern is the wider aging infrastructure at NIST. For example, during the panel meeting, a sinkhole formed near the entrance to NCNR that impacted the entire building's air conditioning. Failure of adequate climate control makes the facility difficult to work in, and also has direct impacts on neutron science. For example, high temperatures lead to inefficient cooling, leading to limits on operation of field coils and air-cooled devices present in many sample environments. Electrical resistance also changes with temperature, leading to drift in thresholds and noisy or biased datasets at the limits of precision, especially for metrology experiments that are key to NIST's mission.

Equipment

The previous National Academies' review (2024) recommended that

> The National Institute of Standards and Technology Center for Neutron Research should develop a plan for access to, and use of, high-performance computing resources to support initiatives in scientific computing, artificial intelligence, and machine learning and to ensure the ability to scale up to meet the needs of scientist-driven initiatives.

NCNR, working with NIST computing, now has access to high-performance computing infrastructure through an agreement with the Texas Advanced Computing Center for access to national frontier compute capability (Frontera and Lonestar-6). Furthermore, NIST has invested in campus-level compute capability with two facilities, Blackbird (100×84 core Central Processing Unit) and Redwing (H200 Graphics Processing Unit cluster). NIST computing has also supported NCNR in upgrading the local high-performance computing cluster to 52×36 cores, allowing local preparative test runs before deployment of code on larger-scale infrastructure. This investment has already shown notable benefits in accelerating the work of the NCNR Computational Neutron Scattering team.

Human Resources

The success of NCNR has been built from the work of its people. There is a highly dedicated, committed staff with a clear passion for the NCNR mission. Management has done a good job maintaining research staff and motivation despite the lack of neutrons, yet continued insufficiency of funds will translate to lack of staffing, especially for the instrument suite. NCNR and the National Science Foundation (NSF) are renewing their collaboration through the Center for High Resolution Neutron Scattering (CHRNS). NCNR could work with NSF to expand the scope of instruments covered by CHRNS during this renewal to provide a potential source of mitigation for the base funding issue for staffing; however, that would depend on the state of the NSF's finances and its funding priorities. Other partnerships could also be explored, such as with NIH which has many overlapping research interests with NCNR in biological and soft materials for pharmaceuticals, for example. NCNR should examine its staffing skill base and prioritize targeted recruitment to make the best use of any potential funding increases to mitigate risks and gaps in capabilities needed for evolving technologies (Recommendation 3-2). The long outage time will have impacted the experience level of research groups, as a cohort of PhD students will have missed out on neutron experiments, and research groups often rely on internal knowledge transfer. There is still likely a lot of pent-up demand for user facility access, so the risk is not that users do not return, but rather that users come back, often with skill gaps, and NCNR will be unable to support them and their additional training needs at the same level as before. A negative consequence of the constrained finances and reactor downtime is the potential generational gap in trained neutron users and succession instrument scientists. This becomes a risk for the facility's general succession planning, especially as the older generation approaches retirement age, and has implications for the neutron scattering research community's overall training and development needs.

RESPONSIVENESS AND IMPACT

Responsiveness to Stakeholder Needs

Relationship with the NCNR Users Group and Stakeholder Engagement

The relationship between NCNR and its Users Group is good, and the community feels well informed of progress and activity. They are satisfied with the level of engagement with and receptiveness of NCNR management. The Users Group is formed from a diverse team that appears to work well and communicate regularly. One concern is the risk of a reduced community following the long downtime, and the possible need to retrain the community. However, NCNR and the NCNR Users Group have co-developed a plan for reengagement based on recommendations for specific actions from the NCNR Users Group. A highlight was the good response from NCNR staff attending major conferences (e.g., the meetings of the Materials Research Society and the American Physical Society) to update the community and call them back to the facility. The NCNR Users Group committee is very incentivized and driven; it is essential to keep that relationship strong.

Another general challenge is the transition to a full user program once the reactor has restarted. For example, the proposal review process may be slowed by the larger number of interested users due to pent up demand from the years of reactor shut down. Although a number of groups have started to prepare for restart, further coordination of work and more holistic oversight of tasks to welcome users back to the facility will speed the return of researchers to perform experiments on functioning instruments.

Support to Early Career Researchers

Information collected from NCNR early-career researchers was a testament of the commitment, mentoring, and "yes we can" attitude of NCNR staff. Early-career researchers felt well supported through this period, and, despite having no in-house neutrons, they have still been productive. One positive consequence has been the opportunity for training in a wider set of experimental and computational techniques, which otherwise may have been limited or biased toward neutron experiments. Another is the opportunity to perform experiments globally, not limited to the NCNR facility. The downside is the uncertainty associated with timescales and funding, which has resulted in less than optimal retention opportunities and a lost cohort of potential NCNR instrument scientists and superusers to eventually train the next generation.

User Support with Experiments Elsewhere

The Small Angle Neutron Scattering (SANS) and Reflectometry teams were very successful in supporting users doing experiments at other laboratories. The teams obtained about 700 experiment-days of beam time (neutrons and X-rays) between them over the outage (to the date of this review) (Butler 2025; Majkrzak 2025). This compares to the approximately 1,600 experiment-days per year of beam time lost because of the shutdown. The 700 experiment-days of external beam time means that these teams supported approximately 9 percent of the pre-outage beam time. The majority of the NCNR staff's work was user collaboration or supporting users with experiments. This excludes work where the NCNR staff was involved remotely or supported with data analysis. Similarly, the Structure and Dynamics team managed to obtain more than 400 experiment-days of beam time at other facilities and supported the ongoing research work of both users and internal programs (Brown 2025). Overall, this is an excellent and commendable level of support provided by NCNR science teams.

Expansion of nSoft to nMAT

As described above, NCNR proposes to expand the *n*Soft consortium to a broader range of neutron techniques and industrial research areas, in a new consortium that will be called *n*MAT (Weigandt 2025). The *n*Soft consortium has been highly successful in building industrial engagement and usage of SANS in some key industries, in particular biomedical companies. The model of precompetitive collaborative research developed by the *n*Soft consortium has worked very well, and this development and expansion to *n*MAT is commended.

Workshop on "Neutrons for the Future"

In response to the Creating Helpful Incentives to Produce Semiconductors and Science Act of 2022, a workshop was held in Rockville, Maryland, in October 2023 to discuss plans for a new neutron source at NIST. More than 200 attendees from the neutron scattering community in the United States and abroad were divided into panels to discuss science drivers and requirements (academic and industrially based), discuss the ability of the current plans for the source to match these requirements, identify support facilities and equipment to help address the scientific priorities, develop a plan to minimize disruption to the user community during the transition, and agree on source specifications. The 3-day workshop was very successful. A report resulting from the workshop showcased (1) the importance of neutrons as a unique and essential tool for helping to solve many of society's big challenges and (2) the importance of facilities like NCNR and its successor to the nation's infrastructure and competitiveness, as well as the global neutron capability (Wilson et al. 2024). Workshop participants agreed that the construction of a new source presents an opportunity for the Department of Commerce and the United States, and that success of such an endeavor critically depends on the highly qualified and expert staff.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 3-1: The prolonged pause of the National Institute of Standards and Technology Center for Neutron Research (NCNR) user program, as a result of the reactor shutdown, is a risk to NCNR's ability to quickly return to its previous capacity as a premiere, world-leading user facility serving thousands of researchers per year.

Recommendation 3-1: The leadership of the National Institute of Standards and Technology Center for Neutron Research should reengage the user community and bring them along on the start-up process of this user facility, including considering options to involve the user community in decisions driven by prioritization—for example, in strategic idling or upgrading of specific instruments.

Conclusion 3-2: Budget compression has prevented the National Institute of Standards and Technology Center for Neutron Research from recruiting and/or staffing core capabilities that evolve with technology advances.

Recommendation 3-2: The National Institute of Standards and Technology Center for Neutron Research (NCNR) leadership should perform an analysis of the skill base that currently exists at NCNR, identifying the risks and possible gaps, and develop a plan for a sustainable future, including prioritization of areas that should be targeted for recruitment should funding become available.

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4
National Institute of Standards and Technology Center for Neutron Research Reactor

This National Academies of Sciences, Engineering, and Medicine review of the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) reactor falls at a critical juncture where the reactor is transitioning from cleanup, through restart, and into operation. The NCNR reactor remains in a state of recovery cleanup following an unplanned shutdown in February 2021. A fuel element was not secured in its grid plate, resulting in the reactor's fuel temperature violating its safety limit and partially melting the fuel. The reactor primary system was contaminated with debris, which has caused a prolonged cleanup effort. During this process, there has been a significant change in the safety culture for reactor operations. The Nuclear Regulatory Commission (NRC) has had frequent oversight and communications with NCNR and granted restart permission in March 2023. Since that time, the reactor has been mostly under maintenance and operating below its normal operating power of 20 MW. The reactor underwent a second cleaning cycle in January 2025, and analysis showed that the debris removed was consistent with the estimated amount present, within error. However, the time for the NRC review of reactor operator qualifications has been long and caused delay in attaining a full staff of qualified operators. The reactor is scheduled for the NRC licensing exam in early to mid-2026 and for full-power scientific operations in 2026.

RESEARCH REACTOR AT NIST

The reactor at NCNR is a 20 MW reactor using 93 percent enriched uranium oxide (U_3O_8) plate-type fuel with deuterium oxide (D_2O) coolant, moderator, and reflector. It has been used since 1967 for various neutron science applications. The NIST research reactor is not operated as a power reactor but rather is licensed by the NRC as a "testing facility" because of its power level (greater than 10 MW). Its main purpose is to produce thermal and cold neutrons for scientific studies (mostly for scattering experiments) and to provide the development, certification, and calibration of standards. Safety of reactor operation is extremely important and required by the NRC license. After the incident in February 2021, NCNR thoroughly assessed its safety procedures and implemented a change in organizational structure and oversight, improvement in the safety culture, and a set of corrective actions. The organizational realignment recognizes that the NIST research reactor has been in service for many decades and needs special attention to deal with the problems of an aging reactor. NIST reactor operation management recognizes that it needs an additional operations shift to permit training and safety improvements while operating the reactor full time. NCNR is implementing an improved training program to attain a full five-shift operational staff. Frequent training and education of the reactor operators, implementing a drill program and possible simulation equipment within this structure, could also support improved safety and effectiveness.

The shift in safety culture is apparent at NCNR since the February 2021 incident and will take considerable time, effort, and resources to fully achieve. Significant advances have been made in communications and issue identification to find solutions. A deep safety culture is one that encourages questioning at all levels in an open environment and seeks to improve, rather than blame. The operations staff members have embraced this culture change and are now working toward continual improvement. Continued focus on improving the safety culture will enable NCNR to reach its goal of full, safe operations in 2026.

Accomplishments

After the incident in 2021, NCNR implemented a Corrective Action Plan. An essential element of that plan was an organizational realignment that included a new Aging Reactor Management Group (11 engineers and technicians), enhancement to the Quality Assurance group with at least three new quality assurance specialists, addition of a fifth operations shift that enables training and operations to occur simultaneously, and an increase in training staff and qualifications requirements. The plan also created a safety culture monitoring panel that is working with staff on continuous improvement in communications, problem identification, and resolution. The safety culture is assessed annually. These additions were allocated an increased budget of $5 million per year for 2022 and 2023.

In addition to the organizational realignment and change in safety culture discussed above, NCNR staff has been preparing for a readiness review to start in late July 2025. At the time of the National Academies' site visit, the preparation for this review appeared to be going well and demonstrated the improved safety culture. Maintenance accomplishments include the second cleaning in January 2025, identification of corrosion issues with the refueling plug and steps toward its resolution, and refurbishment of vent valves. The repair of the refueling plug is on the critical path for the readiness review and start-up.

NCNR staff has also completed several designs and plans for reactor upgrades. First, the cold source upgrade continued to be advanced, and all infrastructure components were acquired, including two cryostats. This upgrade will help maintain neutron flux but will require a license amendment for the use of deuterium-tritium gas and associated accident analysis. Plans were also completed for a conversion to low-enriched uranium fuel to align with the U.S. objective of decreasing the number of high-enriched uranium reactors in the country. The low-enriched uranium conversion and cold source upgrade must proceed together to mitigate the downtime for installations of both. Downtime of non-NCNR facilities is also important to consider when planning NCNR upgrades, to avoid losing critical neutron capacity in the United States.

To increase the availability of neutron beam facilities at NIST, extensive workshops and planning meetings were completed for the design of a new NIST neutron source (NNS) reactor. This design effort could help energize the staff and lead to a long-term solution to the problem of availability of neutron scattering sources in the United States. The new facility design is discussed further below.

Challenges and Opportunities

The challenges and opportunities for the NCNR reactor operations lie in developing and maintaining an attitude that encourages questioning and problem solving, rather than blame, as part of the culture change discussed above. World-class reactor operations ask and answer difficult questions when seeking improvement, even if the resources to meet those answers and address problems are not readily available. The process of questioning and answering helps broaden thinking about the challenges at hand. NCNR is tackling the challenge of culture change head on, and improvements have been noted, but the path ahead is difficult because of shortages in staff and budget. A shortage in the number of qualified reactor operators and a reduced budget have caused operators to look for approaches to operations and safety that minimize cost as opposed to finding solutions that are best. The purchase of an underwater camera was a good addition for operations and safety, but it came too late to help with the incident of February 2021. The camera could also be used for a general inspection program of the fuel, structural components, and tank. Similar opportunities exist with other equipment upgrades and can be considered for new designs, such as the NNS reactor. The budget and staffing challenges are discussed further below.

PLAN FOR REACTOR CLEANUP AND THE RESUMPTION OF SCIENTIFIC OPERATIONS

The second reactor cleanup and evaluation of debris removal demonstrated that the cleanup is on track for the NCNR reactor to return to normal operations in 2026. The improved training program and qualifications for reactor operators and supervisors were needed and are proceeding well but delays in the NRC's response could impact the schedule. NCNR currently has 13 licensed reactor operators, but 15 are needed to maintain five shifts of three operators and/or supervisors per shift. The NCNR Integrated Projects plan describes an approach to achieve the two additional licensed operators before the start-up of scientific operations in 2026. An operator license exam is planned for early to mid-2026, and NIST made a commitment to NRC to have five shifts to facilitate enhanced training with an increased number of training staff. However, this approach provides no leeway should an operator quit or retire abruptly. The plan is reasonable for returning to the pre-2021 level of performance for scientific operations in 2026, but a contingency plan should also be developed and presented to NIST management and key stakeholders so that all involved can evaluate its timeline, merits, and costs (see Recommendation 4-1).

BUDGET, FACILITIES, EQUIPMENT, AND HUMAN RESOURCES

Budget

NCNR has functioned under a tight budget for many years, which has required compromises to be made between scientific and operational investments, including personnel and equipment. Specifically, limited funding for reactor operations and engineering has prevented modernization of operations equipment and, consequently, hindered the culture of continued improvement in all aspects of operations and safety. After the incident of 2021, the budgets were increased temporarily to recover to the state at which NCNR had operated previously. The budget is slated to return to a lower level in 2025. This budget may be insufficient to maintain the commitment of at least 15 operators, the realigned engineering staff to manage and ensure performance of the aging reactor, and the necessary equipment upgrades. NCNR and stakeholders recognize a shared goal of reaching a continually improving and efficient state of safe operations. A budget to match this goal is required, and funding to support resilience in operator staffing is critical.

Facilities

The reactor at NCNR has provided a safe and reliable neutron source for tens of thousands of researchers. However, the aging reactor and current NCNR facilities fall short of accommodating increasing domestic and international scientific demands. Near-term solutions are needed to address the current aging issues to continue operations, such as the aforementioned refueling plug corrosion problem. Issues like the refueling plug corrosion can be found and repaired with a good maintenance program, which requires sufficient financial support but improves reliability to ultimately reduce facility downtime cost.

New high-power multipurpose reactors are being constructed in Europe and China to accommodate the needs for neutron science (European Spallation Source n.d.; Institute of High Energy Physics Chinese Academy of Sciences n.d.), and the United States is falling behind. The National Academies and the American Physical Society have recognized that a new facility is needed in the United States (APS 2018; NASEM 2024), and Congress has asked for a conceptual design of a new reactor and accompanying facilities.[2] NCNR has also recognized the need to plan for a replacement reactor in order to maintain and improve access to neutrons in the United States well into the future. A preconceptual design was completed for the NNS replacement reactor at NIST (Cook et al. 2024; see Figure 4-1). NCNR hosted a workshop in late 2023 to introduce preconceptual design of the NNS and evaluate the need and path forward for neutrons for the future in the United States (see Chapter 3, Wilson et al. 2024). A preconceptual design for a reactor-based neutron source was published by Diamond et al. (2025; see Figure 4-2). A

[2] CHIPS and Science Act. P.L. 117-167, § 10231.

leadership role to increase neutron instrument capabilities and capacity is needed as access to U.S. scattering capabilities is decreasing and the existing facilities are oversubscribed.

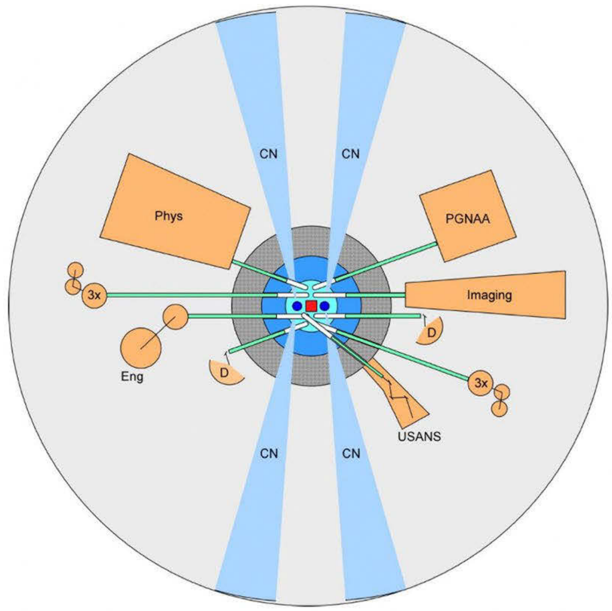

FIGURE 4-1 Schematic showing an example beam hall structure for the NNS, including access to the two cold neutron sources and eight thermal beam tubes for new neutron source at NIST.
NOTE: CN = Cold Neutron source; D = High-Resolution Powder Diffractometer; Eng = White Beam Engineering Diffractometer (with CANDOR-type detector); Phys = High Current Physics Experimental Position; PGNAA = Prompt Gamma Neutron Activation Analysis. USANS = Ultra-Small Angle Neutron Scattering.
SOURCE: Cook et al. 2024.

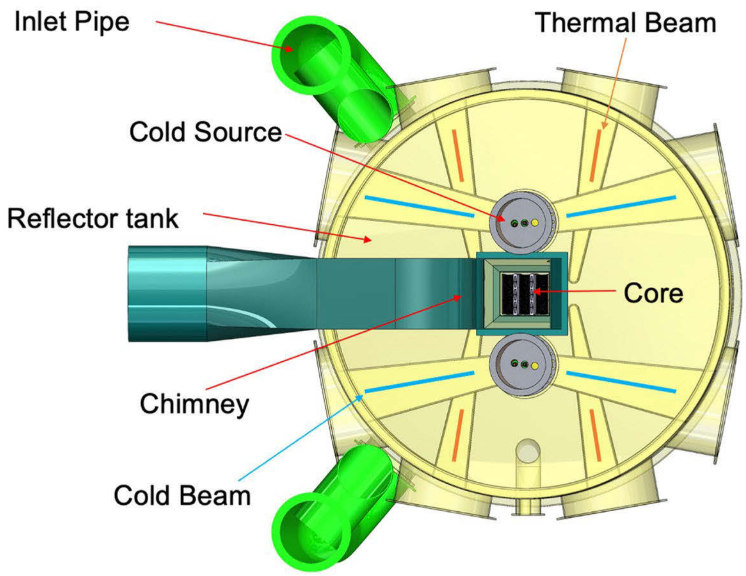

FIGURE 4-2 Schematic design showing proposed reflector tank with reactor core, two cold neutron sources, and neutron beam tubes for a new neutron source at NIST.
SOURCE: Diamond et al. 2025.

Equipment

U.S. neutron capabilities are insufficient, and the new NNS would provide important new capabilities. Currently, the United States operates fewer than 15 percent of the world's neutron instruments, and the majority of these instruments are outdated. Twenty-nine instruments (existing and planned) are expected to be available for fiscal year 2030 at NCNR's current reactor, supporting more than 2,500 researchers per year. With the newly proposed NNS, 12 thermal beamlines and about 35 cold neutron beamlines would be available, offering nearly twice the number of instruments as the current reactor. New capabilities for advances in instrumentation have increased data rates for neutron measurements 1,000- to 10,000-fold. Once built, the NNS is projected to be able to serve 5,000 scientists and engineers, produce 700 publications and more than 100 patents each year, and accelerate innovation by providing neutron-measurement capabilities to more than 100 U.S. companies annually (Wilson et al. 2024). The advanced capabilities and expanded capacity of the NNS would make NIST a premier center for neutron-based research.

Human Resources

NCNR is committed to increased training and qualification of reactor operator staff. Panel members met with a few operators and were encouraged by their dedication to NCNR and the culture being implemented going forward. NCNR is committed to meeting its goal of 15 licensed reactor operators to staff five shifts, and the operators understand that commitment. In general, nuclear reactor operators have great opportunities across the country, but the current job structure within the government can create a challenge to pay and reward the reactor operators at a level that is competitive with the power industry. Therefore, management is challenged to find creative ways to compensate reactor operators to maintain a staff of experienced and qualified licensed operators. NIST leadership and human resources management will need to address this personnel challenge in addition to the budget challenges discussed above. An aggressive outreach and recruitment program targeted at universities with nuclear operations training and Navy nuclear operations training program could help identify candidate operators for NCNR.

Adding to the staff of 15 qualified operators, one or two operators-in-training could provide sufficient contingency if NCNR experiences a loss of qualified operators.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 4-1: The National Institute of Standards and Technology Center for Neutron Research has made significant progress in its safety culture since the February 2021 incident. The panel recognizes culture is a journey that takes years to cement and should be a focus of continuous improvement.

Recommendation 4-1: To ensure full operations, the National Institute of Standards and Technology (NIST) Center for Neutron Research should have sufficient staff for five shifts of reactor operations to facilitate enhanced training. Also, a contingency plan for retirements and departures should be developed and presented to NIST management and key stakeholders so that all involved can evaluate its timeline, merits, and costs.

Conclusion 4-2: There is a critical shortage in access to neutron scattering facilities in the United States and globally. The existing facilities are aging or oversubscribed. New state-of-the-art facilities, such as the planned new research reactor and new instrumentation at the National Institute of Standards and Technology Center for Neutron Research, are desperately needed for the United States to maintain global competitiveness in neutron science and the industries it supports.

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Neutron Instrumentation at the National Institute of Standards and Technology Center for Neutron Research

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) has 29 neutron beam instruments designed for diverse experiments that provide access to different length and timescales. The facility operates several first-class neutron instruments that represent cutting-edge capabilities in the field, including the Multi-Axis Crystal Spectrometer (MACS), the High-Flux Backscattering Spectrometer, Chromatic Analysis Neutron Diffractometer or Reflectometer (CANDOR), Neutron Spin Echo (ν-NSE) spectrometer, ultra-high-resolution Small Angle Neutron Scattering (SANS) instruments with dual 30-meter capabilities, and the Multi-Angle Grazing Incidence K-Vector reflectometer.

The instrumentation suite encompasses capabilities for diffraction, thermal triple-axis spectroscopy, small-angle neutron scattering, neutron spin echo, reflectometry, chemical analysis, and fundamental neutron physics. This array of instruments has demonstrated exceptional productivity throughout its operational history and remains vital for supporting the next generation of scientists and engineers while maintaining competitiveness in a rapidly evolving research landscape that serves both academic and industrial communities. However, the current situation presents significant challenges. The facility's multiyear closure has removed one of only three large scale user facilities in the United States, representing a serious reduction in capacity compared to the growing neutron capabilities in Europe and Asia/Australia, particularly two recent new facilities in China and one under construction in Sweden. When the user program restarts in early 2026, NCNR will not be able to operate five instruments because of resource constraints. Despite these limitations, NCNR has continued making strategic investments during the shutdown to enhance capabilities through upgrades, new instruments, improved software, instrument control systems, and sample environments. The facility has also maintained community engagement by assisting with user experiments, providing sample environments, and continuing the annual neutron summer schools. A critical concern is the reduction in instrument scientists and support personnel over the past 4 years, which must be addressed to operate a successful user program. This staffing challenge compounds the broader impact on the U.S. neutron community, which is severely underserved with the NCNR shutdown.

NEUTRON INSTRUMENTATION

NCNR operates beam instruments across three NIST operating units, comprising a diverse portfolio that includes 17 scattering instruments, 1 test station, 3 nuclear chemistry instruments, 6 neutron physics instruments, and 2 imaging instruments. This suite composition has been strategically developed based on NIST's mission requirements and leverages the unique strengths of the facility's continuous thermal and cold neutron sources. In particular, the instrument suite in fundamental neutron physics has prioritized a small number of scientifically targeted, world-leading activities. These activities drive scientific developments of the highest relevance and are deeply integrated with standards and metrology that are critical to NIST's core mission—for example, world-best calibration of neutron fluence and recalibrating the U.S. national standard neutron source NBS-1.

Accomplishments

NCNR has implemented major instrumentation developments that significantly enhance measurement capabilities and increase data acquisition efficiency. The following highlights represent key accomplishments in neutron instrumentation that demonstrate NCNR's commitment to maintaining world-class facilities while pioneering innovative approaches to materials characterization. These developments span fundamental upgrades to neutron optics and beamlines, the creation of specialized instruments for quantum materials research, and the integration of artificial intelligence (AI) and automation to transform traditional measurement workflows. Together, these advances position NCNR to address critical priorities in quantum information science, advanced materials development, clean energy technologies, and biotechnology.

Quantum Materials Spectrometer

NCNR has held a leading role in triple-axis spectroscopy, and planned improvements to current instruments and development of a new instrument will help it advance quantum materials physics. In the past decade, a variety of new materials have been discovered for which topology plays a major role in their electronic and magnetic behavior. It has been proposed that some of these could make possible new kinds of quantum information processing and detection. Other quantum materials display new kinds of superconductivity or new magnetic states, such as spin liquids. For all such quantum materials, understanding the magnetic structure and dynamics is crucial, and this requires triple-axis neutron spectroscopy. The cold triple-axis instrument proposed on neutron guide (NG)-5, the Quantum Materials Spectrometer (QMS; Harriger 2025), will likely be the only one in the United States when Oak Ridge National Laboratory's High Flux Isotope Reactor shuts down for about 3 years for planned upgrades, so increasing the neutron flux for this existing instrument will be beneficial. The new elliptical focusing NG-5, scheduled for completion in late 2027, and the focusing monochromator are expected to dramatically increase the flux optimized for triple-axis experiments. The new spectrometer will use some components from the decommissioned Spin Polarized Inelastic Neutron Spectrometer (SPINS) instrument, but various improvements coupled with the new NG-5 are expected to improve the data rates for triple-axis measurements by about 10-fold (Kirby 2025).

In addition to the focusing guide and monochromator mentioned above, a number of new components will dramatically improve the performance of the QMS over SPINS. These include an improved V-axis polarizer for spin-polarized experiments and masks to take advantage of the focused monochromator to optimize the trade-off of resolution and intensity. The QMS is essential for NCNR to remain competitive in quantum materials physics.

Neutron Optics Upgrade

NCNR is upgrading neutron guides to improve instrument performance and data acquisition rates. Neutron guides are critical parameters in neutron instrumentation, directly affecting the performance of the beamlines. The cold neutron guides NG-5, NG-6, and NG-7 are aging and utilize outdated ^{58}Ni technology, so they have been slated for upgrades. The NG-6 and NG-7 guide upgrades include supermirrors with increased *m* value, allowing flux gain in the cold neutron guide hall instruments. Beyond the confinement, NG-6 will present a curved shape to decrease background. The NG-5 guide, optimized for the triple-axis spectrometer, presents a bielliptical profile with high *m* values. The installation of the new neutron guides in the confinement areas has been completed, and the installation of the neutron guides in the hall is ongoing (Cook and Adler 2025). The implemented upgrade will increase the performance of the instrument by increasing the flux and reducing background at the sample position.

Autonomous Formulation Laboratory

NCNR has developed advanced capabilities for automated synthesis and measurement of soft material phases using the Autonomous Formulation Laboratory (AFL). The AFL integrates unique sample environments into neutron scattering instrumentation to optimize sample measurement workflows. Traditionally, developing a phase diagram requires multiple sample measurements to explore all possible conditions, a lengthy and labor-intensive process. The AFL leverages AI and automation for efficiency via an autonomous loop that uses active learning from measurements for sample selection. This approach has been demonstrated in multiple systems from injectable formulations, polymer matrixes, and paints.

ROADMAP

NCNR continues to improve its data collection using automation and AI implementation for reflectometry-based measurements of biosurfaces. Reflectometry-driven Optimization and Discovery of Membrane Active Peptides (ROADMAP), the development of autonomous measurements to support neutron reflectometry, includes automated liquid handling and sample preparation; data acquisition, reduction, and analysis; and experimental design and AI-driven measurement campaigns. It is a major technological advance and has the potential to truly transform neutron reflectometry measurements when coupled with the CANDOR instrument, with its 30-fold increase in data collection rate. Proof-of-concept measurements using a quartz microbalance validate the impact of peptides on surface completeness of lipid bilayers. Initial efforts will focus on the activity of membrane-active peptides in lipid bilayers with applications in drug delivery, antimicrobial activity, and vaccine delivery.

BT-2 Beamline

Upgrades in the Beam Tube (BT)-2 beamline, including the replacement of the X-ray camera system, novel sample alignment system, and improved computational infrastructure, will open possibilities for novel science at the beamline, particularly for automotive-scale fuel cell testing with the new test stand with increased hydrogen capabilities. The improved computational infrastructure will allow faster and robust algorithms for hyperspectral tomographic analysis and digital unrolling of X-ray tomography data (Hussey et al. 2025). Employing Wolter optics in the BT-2 upgrade beamline presents a significant opportunity, given the potential combined gains in both flux and resolution.

Octostrain: Multiaxial Loading at BT-8

The BT-8 diffractometer at NCNR is equipped with the octostrain experimental setup, an advanced eight-arm loading device specifically designed to characterize the multiaxial yield behavior of industrial sheet metals under complex deformation modes. Each of the eight arms is independently actuated, allowing for precise control via load cell-based force feedback, grip displacement, or direct strain input. Critically, the integration of a digital image correlation system enables full-field measurement of the in-plane strain tensor within the neutron gauge volume in real time during deformation. This capability allows for the concurrent acquisition of neutron diffraction data for texture and lattice strain, providing a comprehensive view of internal stress development under multiaxial loading. The octostrain setup represents a state-of-the-art platform for investigating anisotropic plasticity, validating yield criteria, and advancing fundamental understanding of deformation mechanisms in advanced high-strength steels and other technologically relevant engineering materials.

Challenges and Opportunities

The suspension of reactor operations at the neutron facility has brought significant challenges to the staff and the user programs. It is unclear what problems may arise with the instrument suite restart. Testing in advance is not always a feasible solution, as a working instrument today does not guarantee trouble-free operation in the future. It will be important for NCNR staff to have a written restart plan for each instrument and program, including anticipated risks, impact, and possible mitigations. Such plans will provide a clear picture of anticipated challenges, prioritization, and possible solutions.

The proposed upgrade plan for instrumentation, including the upgrade of the SANS suite, the neutron-based analytical chemistry instrumentation, and the implementation of extra detector modules in CANDOR, are directly aligned with NIST's mission to promote U.S. innovation and industrial competitiveness through cutting-edge measurement capabilities. The proposed detector, similar to the Continuous Angle Multiple Energy Analysis spectrometer from Paul

Scherrer Institute, would make the QMS state of the art by allowing it to measure a large range of scattered energies simultaneously. This would make inelastic neutron scattering experiments much faster. There is currently insufficient funding to purchase and build all the components proposed for the QMS, but if such resources can be secured, the QMS would be a world-class triple-axis spectrometer.

The research activities at the BT-8 diffractometer regarding the additive manufacturing (AM) benchmark aim to provide vast experimental datasets for validating AM simulations. This presents a great opportunity for AM industry-related partners to contribute to BT-8 instrumentation. Novel sample environments to study samples in situ and operando AM processes could be extremely beneficial for an extended AM bench project. However, the perspective of a new engineering diffractometer based on a time-of-flight approach will significantly increase the steady-state rate capabilities, enabling new opportunities for materials science research.

Compared to the Soft Condensed Matter groups at NCNR, the Engineering Diffraction team operates with fewer staff and limited resources. Despite this limitation, it has effectively advanced industry-relevant research in manufacturing-induced stress analysis through collaborations with Oak Ridge National Laboratory for neutron work and the NIST Center for Automotive Lightweighting for X-ray analysis, adapting the octostrain setup from BT-8. These accomplishments reflect the strength of NCNR’s in-house expertise and strategic partnerships. Continued investment in personnel, postdoctoral researchers, and advanced instrument capabilities is essential to sustain high-impact scientific output and enhance NCNR’s role as a premier user facility.

Leveraging the Center for High Resolution Neutron Scattering (CHRNS) and collaborative agreements with various universities, as well as the proximity to industrial complexes and research academic institutions, puts NCNR at a highly advantageous position to deliver high-quality metrology and research capabilities and advance a competitive research agenda. NIST has a unique mission among government research institutions to support industry. However, many potential industrial users and key stakeholders remain unaware of the capabilities of neutron scattering measurements.

SCIENTIFIC AND TECHNICAL EXPERTISE IN NEUTRON INSTRUMENTATION

NCNR demonstrates world-class expertise in development and utilization of neutron instrumentation. Notably, many of these instruments use innovative techniques developed by NCNR personnel, with methodologies that have been adopted and replicated at neutron facilities worldwide, demonstrating NCNR's leadership in the field.

Accomplishments

During the long, unplanned reactor shutdown, NCNR staff members have opportunistically made needed instrumentation upgrades. NCNR has maintained a long-standing plan to upgrade neutron guides NG-5, NG-6, and NG-7, which are 30 years old and utilize ^{58}Ni technology that is no longer state of the art. As described above, replacing these with modern supermirror guides will deliver significant gains in data acquisition rates. Originally scheduled for 2023, the opportunity arose to integrate this work with the "Clean & Run" project in 2024. This comprehensive integrated project encompassed reactor vessel cleaning, vessel leak mitigation, and guide upgrades, with project management led by Research Facility Operations engineers. The guide replacement work provided the project's schedule backbone because of its well-defined timelines. Detailed advance preparations proved highly effective, achieving approximately 50 percent reduction in worker radiation dose compared to similar work performed in 2011. The project commenced in August 2024, with guide penetrations sealed to allow reactor confinement to be reestablished in February 2025 and all reactor operation prerequisites under the purview of the Research Facilities and Operations group completed by June 2025 (Cook and Adler 2025).

Instrument upgrades conducted during the shutdown have more than doubled the collective data acquisition rate across the facility. Notable improvements include a 30-fold increase for CANDOR, 5-fold for ν-NSE, 8-fold for BT-8, and approximately 2-fold increases for each of the eight instruments on neutron guides NG-6 and NG-7. NG-5 will result in a 10-fold increase for the new cold-neutron triple-axis instrument. These enhancements were achieved through comprehensive instrument control software and electronics upgrades, including the timestamping initiative supported by CHRNS. The Very Small Angle Neutron Scattering (VSANS) system received significant improvements with a high-resolution detector, liquid cells, attenuator, and beam monitor, while a new SANS detector was also installed. Additional performance enhancements resulted from extensive sample environment and software upgrades. These included updated instrument control software and electronics systems, new 12-tesla and 7-tesla dry magnets, and the implementation of the AFL and ROADMAP systems. CHRNS-supported additions encompassed plug-and-play device control, a cryogenic goniometer, high-pressure platform, stopped flow capabilities, and electrochemical cell systems. These combined upgrades have substantially enhanced the facility's experimental capabilities and user research potential, demonstrating NCNR's scientific and technical expertise in neutron instrumentation.

NCNR demonstrates strong capabilities in leveraging state-of-the-art models to enhance data reduction, analysis, and optimization processes. This progress is primarily driven by dedicated instrument scientists. However, with the reactor restart, NCNR faces the challenge of balancing ongoing sustainable software development with the immediate needs of supporting active science programs and the broader user community.

Challenges and Opportunities

The aging of neutron instrumentation presents a significant challenge that must be addressed proactively. A comprehensive maintenance protocol and systematic checking schedule would ensure all instruments are ready for reactor restart and can operate reliably. This preventive approach is essential for maintaining instrument performance and avoiding unexpected downtime that could disrupt user programs at a time when the user community is eager to return to do experiments. Although recent upgrades made during the shutdown have been beneficial, they are not sufficient; instead, continued investment in modern instrumentation is necessary to replace aging systems and maintain technological leadership. The successful replacement of 30-year-old neutron guides with supermirror technology demonstrates the potential for significant performance gains through strategic infrastructure improvements and provides a model for addressing other aging components. The development of robust maintenance protocols for aging instruments and continued modernization efforts would ensure NCNR maintains its position as a world-class neutron research facility and continues advancing the field through innovative instrumentation and methodologies.

Beyond infrastructure challenges, maintaining and developing the specialized expertise required to operate these advanced systems presents both challenges and opportunities. The shutdown period demonstrated NCNR's deep technical expertise in neutron instrumentation through careful planning and successfully managing complex integration of multiple projects. However, instrument scientists now face the challenge of balancing ongoing sustainable software development with the immediate demands of supporting active science programs and user support. This tension between advancement and operations requires strategic workforce planning and resource allocation. The opportunity lies in leveraging NCNR's proven track record to establish formal knowledge transfer mechanisms and training protocols. With the implementation of cutting-edge systems like AFL and ROADMAP requiring new skill sets in AI and automation, NCNR must ensure its staff expertise evolves alongside its instrumentation to maintain its position as a global leader in neutron science methodology development.

BUDGET, FACILITY, EQUIPMENT, AND HUMAN RESOURCES

The development of advanced neutron instruments directly supports NIST's mission to enhance U.S. innovation and industrial competitiveness through state-of-the-art measurement capabilities. Currently, resource constraints limit instrument development to projects requiring minimal capital investment, prompting NCNR to actively pursue additional funding sources for its development initiatives (Kirby 2025). Among these challenges, recent years have seen a reduction in both instrument scientists and support personnel (approximately 25 percent since 2018), directly impacting user program operations (Jones 2025). The combination of funding limitations and staffing shortages has created an unsustainable situation: 4 of NCNR's 17 neutron scattering instruments (BT-4 Filter Analyzer Neutron Spectrometer/triple-axis, BT-5 Ultra Small Angle Neutron Scattering, NG-A Polarized Beam Reflectometer, and NG-B 10 m SANS) will be shut down for the foreseeable future because of insufficient resources to maintain operations. The new NG-5 instrument will not be operational until late 2029 or 2030. Without significant improvement in funding and staffing levels, this situation will lead to reduced efficiency as the fixed costs of the reactor are spread across a smaller instrument portfolio, and threatens to compromise NCNR's ability to deliver world-class neutron measurement capabilities to the U.S. scientific and industrial communities.

Budget

Over the past 4 years, NCNR has established a comprehensive program for instrument replacement, upgrades, and renewal to serve the diverse needs of government, academic, and industrial stakeholders. However, this program requires adequate capital investment and sufficient base funding for essential personnel. Under current budget constraints and staffing limitations, NCNR cannot sustain operations across its complete instrument portfolio. For the United States to remain competitive in neutron-based sciences, expansion of instruments and increased efficiency is required, rather than contraction currently underway in response to insufficient budget. Future instrument and detector developments will need to be carefully selected, measured against other capabilities in the United States, and be designed to be future proof and responsive to the science community's priorities.

Human Resources

The expertise needed for development of cutting-edge neutron instruments is fundamental to NIST's mission of fostering innovation and strengthening U.S. industrial competitiveness through advanced measurement capabilities. Nonetheless, resource limitations have severely constrained development activities to only those projects requiring minimal additional investment. The situation has deteriorated to the point where Research Facilities and Operations can no longer support in-house detector development because of insufficient funding, with all available resources now directed solely toward basic maintenance and operational support. During the extended shutdown, a significant reduction in the workforce has occurred, affecting both scientific and technical personnel. As the facility prepares to resume reactor operations, restaffing these critical positions is essential to restore instrument operations and effectively support user programs. However, the outstanding support that NCNR postdoctoral researchers have received during the outage will be crucial for maintaining scientific expertise and ensuring continuity in research capabilities.

Instrument Access and Responsiveness

NCNR's instrument development activities have historically been responsive to stakeholder needs, as evidenced by world-class instruments like CANDOR, MACS, the High-Flux Backscattering Spectrometer, and others that utilize innovative techniques developed by NCNR personnel and replicated worldwide. Current funding is insufficient to maintain responsiveness to stakeholder needs for instrument development and to reestablish NCNR's capacity for innovative detector and instrumentation development.

NCNR has established effective access mechanisms that serve both academic and industrial communities through two primary modes: mail-in samples and onsite user participation. However, the extended shutdown has disrupted these established pathways and reduced community engagement. Several improvements could be implemented to enhance effectiveness and comprehensiveness upon restart, including (1) the reinstatement of users group engagements to ensure direct communication between instrument teams and user communities, (2) implementation of direct email communication to users to better match instrument capabilities with specific user needs, (3) expansion of outreach mechanisms to reach underserved communities and new user groups, and (4) enhancement of remote access capabilities, building on lessons learned during the shutdown period. The combination of mail-in and onsite participation provides a solid foundation, but these mechanisms can be strengthened with proactive community engagement and improved communication channels to ensure comprehensive access for the broad scientific community upon facility restart.

Instrument Development

NCNR has demonstrated strong responsiveness to stakeholder needs through strategic instrument development and infrastructure modernization initiatives. These activities reflect a clear understanding of user requirements for enhanced performance, improved data rates, and expanded experimental capabilities. The ν-NSE instrument exemplifies successful stakeholder-responsive development, achieving a 5-fold improvement in data rate and extended dynamic range, establishing it as the best neutron spin echo facility in the United States. The replacement of Neutron Depth Profiling with the newly installed NG-A demonstrates the facility’s commitment to evolving its instrument suite to better serve current research priorities. Moreover, the comprehensive neutron guide upgrade program directly addresses long-standing user needs for improved data acquisition rates. The new NG-7 straight supermirror guide will increase data rates by twofold or more across all connected instruments, while the new NG-6 curved guide will provide substantial benefits to cold neutron imaging and test station capabilities, with completion scheduled for early 2027. However, the planned NG-5 modernization, involving SPINS decommissioning and installation of a large guide optimized for triple-axis spectroscopy with 10-fold data rate improvement (planned to be completed by late 2029 or 2030) demonstrates forward-thinking alignment with user needs for enhanced triple-axis capabilities. To strengthen this strategic approach as the facility returns to operation, user community surveys could be employed to identify the most urgent and high-impact instrument improvements, ensuring investments align with emerging scientific priorities across academic and industrial sectors.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 5-1: The National Institute of Standards and Technology Center for Neutron Research has a long history of excellence in providing instrumentation for hard condensed matter physics and remains a world leader in this field. This research area directly aligns with priorities outlined in the National Quantum Initiative.

Recommendation 5-1: To sustain a world-class hard condensed matter program, the National Institute of Standards and Technology Center for Neutron Research (NCNR) should reinstate close collaborations with university partners. NCNR should leverage such relationships to accelerate the development of the Quantum Materials Spectrometer and ensure the instrument is staffed at levels that match its scientific capabilities.

Conclusion 5-2: The demand for high-throughput and multimodal measurement creates high demand for technical and computing expertise.

Recommendation 5-2: The National Institute of Standards and Technology Center for Neutron Research should establish a centralized software team dedicated to the long-term support and maintenance of instrument and data treatment software across the facility.

Recommendation 5-3: The National Institute of Standards and Technology Center for Neutron Research should prioritize automation campaigns on account of their initial success.

Recommendation 5-4: The National Institute of Standards and Technology Center for Neutron Research (NCNR) should establish a comprehensive instrument life-cycle management program that includes preventive maintenance schedules, component replacement planning, and systematic modernization timelines. NCNR

should allocate dedicated funding for both routine maintenance and strategic upgrades to ensure instruments remain at the state of the art in neutron scattering capabilities.

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6
Panel Conclusions and Recommendations

The panel's conclusions and recommendations are described in the preceding chapters, including key conclusions and recommendations in the summary and the conclusions and recommendations specific to each chapter which appear in Chapters 2–5.

KEY CONCLUSIONS AND RECOMMENDATIONS

Key Recommendation 6-1: The National Institute of Standards and Technology (NIST) leadership should support the NIST Center for Neutron Research at inflation-adjusted pre-COVID levels, supplemented by additional budget to support full reactor operations staffing. There is an urgent need to reinstate the financial support for instrumentation, staff, and science programs, in addition to full reactor operations, to fully restart this cornerstone of neutron science and support the U.S. industrial and scientific competitiveness it enables.

Key Recommendation 6-2: The National Institute of Standards and Technology (NIST) leadership should seek congressional approval and funding to design and build a new state-of-the-art research reactor at the NIST Center for Neutron Research consistent with U.S. interest to sustain scientific competitive advantage.

Key Recommendation 6-3: The National Institute of Standards and Technology (NIST) Center for Neutron Research should develop and pursue a strategy that leverages its distinguishing instrument capabilities and science programs. The strategy should align with the NIST mission, national initiatives, and a longer-term vision for the new research reactor.

Key Recommendation 6-4: The National Institute of Standards and Technology Center for Neutron Research should augment its reactor operations and safety procedures to include expectations for continuous improvement.

CHAPTER-SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

Overview of the National Institute of Standards and Technology Center for Neutron Research

Conclusion 2-1: Neutron science is critical to the competitiveness of the United States. The National Institute of Standards and Technology Center for Neutron Research (NCNR) plays a pivotal role in neutron science and innovation, running a leading neutron program across strategic areas of national interest such as nuclear physics, quantum science, and materials characterization in partnership with industry. NCNR has an important role in education of the broader neutron science research community through graduate and postdoctoral scholars. Sustained federal funding is required to ensure continuity and growth in scientific capabilities at NCNR to maintain U.S. leadership in neutron science.

Recommendation 2-1: The National Institute of Standards and Technology Center for Neutron Research and government research funding agencies should support graduate and postdoctoral studies in the field of neutron science both to provide for current research needs and to develop a pipeline of future practitioners in industry, government, and academia.

Technical Program at the National Institute of Standards and Technology Center for Neutron Research

Conclusion 3-1: The prolonged pause of the National Institute of Standards and Technology Center for Neutron Research (NCNR) user program, as a result of the reactor shutdown, is a risk to NCNR's ability to quickly return to its previous capacity as a premiere, world-leading user facility serving thousands of researchers per year.

Recommendation 3-1: The leadership of the National Institute of Standards and Technology Center for Neutron Research should reengage the user community and bring them along on the start-up process of this user facility, including considering options to involve the user community in decisions driven by prioritization—for example, in strategic idling or upgrading of specific instruments.

Conclusion 3-2: Budget compression has prevented the National Institute of Standards and Technology Center for Neutron Research from recruiting and/or staffing core capabilities that evolve with technology advances.

Recommendation 3-2: The National Institute of Standards and Technology Center for Neutron Research (NCNR) leadership should perform an analysis of the skill base that currently exists at NCNR, identifying the risks and possible gaps, and develop a plan for a sustainable future, including prioritization of areas that should be targeted for recruitment should funding become available.

National Institute of Standards and Technology Center for Neutron Research Reactor

Conclusion 4-1: The National Institute of Standards and Technology Center for Neutron Research has made significant progress in its safety culture since the February 2021 incident. The panel recognizes culture is a journey that takes years to cement and should be a focus of continuous improvement.

Recommendation 4-1: To ensure full operations, the National Institute of Standards and Technology (NIST) Center for Neutron Research should have sufficient staff for five shifts of reactor operations to facilitate enhanced training. Also, a contingency plan for retirements and departures should be developed and presented to NIST management and key stakeholders so that all involved can evaluate its timeline, merits, and costs.

Conclusion 4-2: There is a critical shortage in access to neutron scattering facilities in the United States and globally. The existing facilities are aging or oversubscribed. New state-of-the-art facilities, such as the planned new research reactor and new instrumentation at the National Institute of Standards and Technology Center for

Neutron Research, are desperately needed for the United States to maintain global competitiveness in neutron science and the industries it supports.

Neutron Instrumentation at the National Institute of Standards and Technology Neutron Research Center

Conclusion 5-1: The National Institute of Standards and Technology Center for Neutron Research has a long history of excellence in providing instrumentation for hard condensed matter physics and remains a world leader in this field. This research area directly aligns with priorities outlined in the National Quantum Initiative.

Recommendation 5-1: To sustain a world-class hard condensed matter program, National Institute of Standards and Technology Center for Neutron Research (NCNR) should reinstate close collaborations with university partners. NCNR should leverage such relationships to accelerate the development of the Quantum Materials Spectrometer and ensure the instrument is staffed at levels that match its scientific capabilities.

Conclusion 5-2: The demand for high-throughput and multimodal measurement creates high demand for technical and computing expertise.

Recommendation 5-2: The National Institute of Standards and Technology Center for Neutron Research should establish a centralized software team dedicated to the long-term support and maintenance of instrument and data treatment software across the facility.

Recommendation 5-3: The National Institute of Standards and Technology Center for Neutron Research should prioritize automation campaigns on account of their initial success.

Recommendation 5-4: The National Institute of Standards and Technology Center for Neutron Research (NCNR) should establish a comprehensive instrument life-cycle management program that includes preventive maintenance schedules, component replacement planning, and systematic modernization timelines. NCNR

should allocate dedicated funding for both routine maintenance and strategic upgrades to ensure instruments remain at the state of the art in neutron scattering capabilities.

NCNR RESPONSE TO PREVIOUS ASSESSMENT RECOMMENDATIONS

In addition to the above recommendations produced in this report, NCNR shared responses to several recommendations made in previous National Academies of Sciences, Engineering, and Medicine assessments: *An Assessment of the National Institute of Standards and Technology Center for Neutron Research: Fiscal Year 2023* (NASEM 2024) and *An Assessment of the Center for Neutron Research at the National Institute of Standards and Technology: Fiscal Year 2021* (NASEM 2022). The original recommendations and the responses are reproduced below.

2024 National Academies report Recommendation 2-4: To support the hard condensed matter science community, the National Institute of Standards and Technology Center for Neutron Research (NCNR) should

- **Upgrade the BT-1 power diffractometer and BT-4 instruments to make them relevant again.**

NCNR Response: Instrument plan includes plans to upgrade and supplement powder diffraction capabilities to world class. BT-4 three-axis/Filter Analyzer Neutron Spectrometer would require significant investments to return to operation. At current resource levels, instrument development is limited until dedicated funds are secured.

2024 National Academies report Recommendation 2-4: To support the hard condensed matter science community, the National Institute of Standards and Technology Center for Neutron Research (NCNR) should

- **Fully upgrade the Spin Polarized Inelastic Neutron Spectrometer (SPINS), including the backend of the instrument, to provide a fully upgraded instrument; to accomplish this, NCNR should make the SPINS upgrade a central part of its hard condensed matter science portfolio and fund it**

accordingly. NCNR should not rely on funding vehicles like the National Science Foundation Major Research Instrumentation grants to accomplish this.

NCNR Response: NCNR has secured an agreement with McMaster University to partner on the design and building of the Quantum Materials Spectrometer, an instrument that will replace SPINS with a modern cold neutron triple-axis capability.

2024 National Academies report Recommendation 4-3: The National Institute of Standards and Technology Center for Neutron Research (NCNR) should continue to fund and execute an adequate suite of capital improvement projects to better exploit the instrument suite.

NCNR Response: We agree. The development of advanced neutron instruments aligns directly with NIST's mission to promote U.S. innovation and industrial competitiveness through cutting-edge measurement capabilities. However, current resource limitations constrain instrument development to projects requiring minimal additional capital investment. NCNR continues to seek new funding to support its instrument development efforts.

2022 National Academies report Recommendation: To minimize impact to the user community, the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) leadership should make sure that the scheduled downtime for the NCNR cold source upgrade does not coincide with the planned shutdown of the High-Flux Isotope Reactor at Oak Ridge National Laboratory for its high enriched uranium to low enriched uranium conversion and reactor vessel upgrade. NCNR staff should develop a formal plan for user access during the 2023 shutdown as well as a formal plan for user access with the other U.S. neutron facilities.

NCNR Response: The planned installation of the new NCNR cold source was delayed due to reactor recovery efforts. When it does occur, NIST will avoid overlap with the outage for beryllium reflector replacement at the High-Flux Isotope Reactor.

2022 National Academies report Key Recommendation: The Director of the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) should take a leadership role and own this mission with full

support of NIST. The Director of NCNR should commission a study to define what the research community needs for the next 50 years in addition to the economic study already commissioned. In parallel and starting as soon as possible, the Director of NIST and the Director of NCNR should be proactive with the Visiting Committee on Advanced Technology, the User Group Executive Committee, the local community, the U.S. Nuclear Regulatory Commission (NRC), and the appropriate congressional committees to ensure support and to build the case for constructing a new research reactor.

NCNR Response: NCNR held a workshop in October 2023 to discuss plans for a new neutron source at NIST, which resulted in a community-driven report on needs. NCNR also commissioned an economic impact study on investment in U.S. neutron research sources and facilities, which was released in May 2024, and submitted a plan to NIST management about the future of neutrons at NIST.

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Appendix
Biographical Sketches of Panel

AARON P.R. EBERLE (*Chair*) is the ExxonMobil Baytown Technology and Engineering Complex Site Manager. Over the past decade he has held various positions across the company within their technology, business, and corporate functions. Before joining ExxonMobil, he held postdoctoral positions at the National Institute of Standards and Technology Center for Neutron Science and the University of Delaware. His research focused on the rheology of complex systems and colloidal physics connecting macroscopic mechanical behavior to structure with advanced characterization techniques including cold neutron instrumentation. He received a BS and a PhD in chemical engineering from the University of Rochester and Virginia Tech, respectively.

JOHN CHARLES BARBOUR is currently retired as the director of the Center for Radiation and Electrical Sciences at Sandia National Laboratories in Albuquerque, New Mexico. He directed multiple levels of management for high-hazard accelerator and nuclear facilities operations, including the Annular Core Research Reactor Facility, Gamma Irradiation Facility, Auxiliary Hot Cell Facility, Saturn Pulsed Power Accelerator Facility, and High-Energy Radiation Megavolt Electron Source. Furthermore, he had responsibility for the electromagnetic facilities operations, including the Lightning Facility, Electromagnetic Environments Simulator, Reverberation Chamber, and High Voltage Testing Laboratory. He was the responsible director for the Sandia Nuclear Criticality Safety Program. Dr. Barbour set strategic directions for research in radiation effects on devices and circuits, electromagnetic and nuclear environments, and electrical systems modeling. He created and managed a major National Nuclear Security Administration project to develop new methods for system-level qualification in radiation environments through close coupling of experimentation with materials, devices, and circuit modeling. He helped the nation change the way it approaches survivability of its critical assets in the most severe environments. Dr. Barbour is a Fellow of the American Physical Society (APS).

He has been an active volunteer and member of the Materials Research Society (MRS) and served on the MRS Board of Directors. He has organized conferences for and served on the International Committees for the Ion Beam Modification of Materials Conference and the Radiation Effects in Insulators Conference. He is a member of the American Association for the Advancement of Science and the APS. Dr. Barbour received a BS in engineering physics from the Colorado School of Mines (1980) and a PhD in materials science and engineering from Cornell University (1986). He joined Sandia after 1 year in The Netherlands as a visiting scientist at the FOM Institute for Atomic and Molecular Physics (Amsterdam) and Philips Research Laboratories (Eindhoven). He is the author or co-author of more than 150 technical papers and holds several patents.

MARIA MONICA CASTELLANOS is currently an associate director in the Early-Stage Formulation Sciences team at AstraZeneca. She currently supports the biopharmaceutical development of biologics, with focus on drug product development. Dr. Castellanos has more than 14 years of experience in biopharmaceutical research and development, both in academia and industry. Prior to AstraZeneca, Dr. Castellanos was an associate director at GSK, another global biopharmaceutical company, where she led a team of scientists and contributed to the formulation and process development of mRNA lipid nanoparticle vaccine candidates as well as the recently approved RSV vaccine Arexvy™. Dr. Castellanos holds a PhD in materials science and engineering from Pennsylvania State University and was a postdoctoral researcher at the Institute for Bioscience and Biotechnology Research (IBBR). At IBBR, her role focused on supporting the biomanufacturing initiative at the National Institute of Standards and Technology by performing deep structural characterization of the NISTmAb reference material and other antibodies, using a combination of X-ray/neutron scattering and other biophysical techniques. Dr. Castellanos has 14 publications in impactful peer-reviewed journals (and an additional 2 under preparation), 1 patent, and 4 awards. Dr. Castellanos has served as a technical reviewer in the Neutron Science Review Committee for the Spallation Neutron Source High Flux Isotope Reactor at Oak Ridge National Laboratory and as a technical reviewer for the previous National Academies of Sciences, Engineering, and Medicine's assessment of the National Institute of Standards and Technology Center for Neutron Research.

SKYLER DEGENKOLB is a professor of experimental physics at Heidelberg University's Physikalisches Institut, where he started a new research group for low-energy precision measurements in 2021. Previously he was a staff physicist and instrument responsible for the ultracold neutron source SuperSUN at the Institut Langevin. His research focus is on precision tests of the Standard Model and model-independent searches for new phenomena at the intersection of particle physics with nuclear and atomic physics. His expertise includes the design and construction of neutron beamlines and instruments, precision frequency measurements and the phenomenology of permanent electric dipole moments in different systems, and novel approaches to shielding and metrology for background mitigation. His work relies on advancing a wide variety of technical platforms, ranging from superfluid helium cryogenics to laser spectroscopy and low-field nuclear magnetic resonance. He studied physics at the University of Chicago and received his PhD in 2016 from the University of Michigan, Ann Arbor.

VICTORIA GARCIA SAKAI is the division head for neutron spectroscopy at the ISIS Neutron and Muon Facility in the United Kingdom (part of the Science and Technology Facilities Council [STFC] infrastructure portfolio). She has been actively involved with neutron scattering facilities in different capacities for almost 25 years. A chemical engineer from Imperial College London, she moved into the field of neutron scattering during her postdoctoral period at Pennsylvania State University. Garcia Sakai is an internationally recognized expert in quasi-elastic neutron scattering applied to soft matter and biological systems. She has worked extensively on understanding the dynamical behavior of water around different substances from a fundamental point of view and more recently with a view to its role in cancer. She is the editor of the book *Dynamics of Soft Matter* (2012) and has published more than 140 peer-reviewed papers in the field. Garcia Sakai has experience directing, managing, and advising on instrumentation and science user programs. She sits on a number of high-level scientific and instrumentation advisory bodies to neutron facilities around the world, including as the current chair of the European Spallation Source Science Advisory Council. Garcia Sakai worked for 2 years (2021–2023) as STFC's liaison officer for the United Kingdom's synchrotron, Diamond Light Source, and managed for STFC the successful bid for the £500 million Diamond-II upgrade (to a fourth-generation facility), which is currently under way. Garcia Sakai has always had a passion for educating, with more than 10 years of experience training students and postdoctoral researchers in neutron techniques. She was the director of the prestigious Oxford School of Neutron Scattering between 2015 and 2023, and lectures regularly around the world.

ANDREW JACKSON is currently the head of the Large Scale Structures Division at the European Spallation Source (ESS). In this role he leads the development, design, commissioning, and operation of five of the neutron scattering instruments. Dr. Jackson has worked at ESS since 2011, starting as the instrument scientist for Small Angle Neutron Scattering, followed by various leadership and management positions. Prior to working at ESS, he held positions as a guest researcher at the National Institute of Standards and Technology (NIST) Center for Neutron Research, visiting researcher at the Lawrence Berkeley National Laboratory, senior scientist at the University of Delaware, research associate at the University of Maryland, and postdoctoral research fellow at the Australian National University. Dr. Jackson received his MChem and DPhil in chemistry from the University of Oxford and has more than 25 years of experience in the development and application of neutron and X-ray scattering methods, in particular in the areas of soft matter physics, colloid science, and polymer science. He also holds a position as an associate professor in physical chemistry at Lund University and his current research interest is in the structure and behavior of deep eutectic solvents, in particular self-assembly in these nonaqueous hydrogen-bonded solvents. Dr. Jackson has previously served twice on the National Academies of Sciences, Engineering, and Medicine's Panel of Assessment for the NIST Center for Neutron Research.

MARC KASTNER (NAS) is the Donner Professor of Physics (emeritus) at the Massachusetts Institute of Technology (MIT) and an adjunct professor of physics at Stanford University. He was the president of the Science Philanthropy Alliance from 2015 through 2019 and is now a senior external advisor to the Alliance. Prior to leading the Alliance, Dr. Kastner had a long career in research and teaching and a variety of senior positions at MIT. Dr. Kastner joined MIT in 1973 and was named the Donner Professor of Physics in 1989. He became the director of the Center for Materials Science and Engineering in 1993, head of the Department of Physics in 1998, and dean of the School of Science in 2007. He stepped down as dean in 2013. Dr. Kastner's early research focused on the electronic and optical properties of amorphous semiconductors, especially chalcogenide glasses. He and collaborators invented the valence-alternation model that relates the electronic properties of these materials to their chemical bonding. Later, together with Robert Birgeneau, he studied the relationship of the magnetic properties, from neutron scattering, of high-temperature superconductors to their electronic transport and optical properties. In 1990, Dr. Kastner's group fabricated the first semiconductor single-electron transistor and in 1998 they discovered the Kondo effect in these nanostructures; the latter is a state in which electrons inside and outside the transistor are quantum-mechanically entangled. Dr. Kastner chaired the Department of Energy Basic Energy Sciences Advisory Committee (BESAC) from 2018 to 2022, during which time BESAC released its report on "The Scientific Justification of a U.S. Domestic High-Performance Reactor-Based Research Facility." He has served as the chair of the Solid-State Sciences Committee and as the chair of the Board on Physics and Astronomy of the National Academies. He has also served on the Science Advisory Boards of the National Cancer Institute and the Gordon and Betty Moore Foundation. He currently chairs the Science Advisory Board of the Brown Institute for Basic Sciences at Caltech. Dr. Kastner is a member of the National Academy of Sciences, a fellow of the American Academy of Arts and Sciences, a fellow of the American Physical Society (APS), and a fellow of the American Association for the Advancement of Science. In 1995, he received the APS David Adler Lectureship Award and in 2000 he won the APS Oliver E. Buckley Prize. Dr. Kastner received a BS in chemistry, an MS in physics, and a PhD in physics from the University of Chicago and was a postdoctoral fellow at Harvard University.

MEGUMI KAWASAKI is a Jack R. Meredith Faculty Scholar and an associate professor in a materials science program and the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University. Since 2013, she has held a visiting research associate professor position in materials science at Osaka Metropolitan University. Dr. Kawasaki's research focuses on processing bulk nanostructured metals and materials through severe plastic deformation (SPD) techniques. She specializes in characterizing the microstructural evolution of nanostructured materials under extreme environments, employing advanced methods such as X-ray and neutron diffraction, as well as synchrotron high-energy X-rays. Her work has earned international recognition, with successful beamline proposals awarded at prestigious facilities including Spring-8 and J-PARC in Japan, DESY in Germany, and Oak Ridge National

Laboratory and the Advanced Light Source in the United States. An active leader in her field, Dr. Kawasaki has served as an associate editor for the *Journal of Materials Science* since 2020, handling manuscripts on materials and corrosion. She is a member of the International NanoSPD Steering Committee and chairs the International Conference on Superplasticity in Advanced Materials. She previously served on the National Academies of Sciences, Engineering, and Medicine's Committee on the Assessment of the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) in 2024.

DESPINA LOUCA is the Maxine S. and Jesse W. Beams Professor of Physics and the chair of the Physics Department at the University of Virginia. She has been at the university for more than 25 years. Prior to this position, Professor Louca was a postdoctoral research associate at the Los Alamos National Laboratory in New Mexico for 2.5 years. Professor Louca is an expert in neutron scattering and materials physics. She served as the president of the Neutron Scattering Society of America from 2017 to 2021. She was elected a fellow of the society in 2022 and is also a fellow of the American Physical Society (APS). Professor Louca received her AB in physics and biology, her MA in physics from Bryn Mawr College, and her PhD from the University of Pennsylvania in 1997. She has published more than 140 papers and given about 150 invited talks/colloquia and seminars. Her recent professional activities include serving as a member of the China Spallation Neutron Source International Advisory Committee, on the Oak Ridge National Laboratory Heterogeneous Quantum Systems Initiative, on the dean's search committee, College and Graduate School of Arts and Sciences, the McMaster Nuclear Reactor Expert Committee for the Canada Foundation for Innovation, on the Editorial Board of *Physical Review Research*, APS Climate Site Visit, and the Neutron Advisory Board and Physical Sciences Directorate of Oak Ridge National Laboratory.

FLORENCIA MALAMUD is an instrument scientist at the Paul Scherrer Institute (PSI) in Switzerland, where she works on the POLDI time-of-flight engineering diffractometer. Prior to her role at PSI, she was a researcher at CONICET working for the Laboratorio Argentino de Haces de Neutrones and a lecturer at Instituto Balseiro in Argentina. Dr. Malamud earned her PhD in physics at Instituto Balseiro and has since been actively involved in developing and improving neutron-based techniques for industrial and scientific applications. She has collaborated extensively with international research teams to enhance neutron imaging methodologies for diverse materials. Her research focuses on wavelength-resolved neutron transmission techniques, crystallographic texture analysis, and residual stress characterization in engineering materials. She has published more than 30 peer-reviewed papers, developed innovative texture analysis methodologies using neutron diffraction and imaging techniques, and contributed to diverse applications, including additive manufacturing, cultural heritage, and engineering materials.

ANDREW G. STEPHEN is a senior principal scientist in the Cancer Research Technology Program at the Frederick National Laboratory for Cancer Research. He currently directs the RAS Biochemistry and Biophysics Laboratory within the National Cancer Institute RAS Initiative. The goal of the RAS Initiative is to develop therapeutic approaches to target RAS-driven cancers. His group interrogates the biochemical activities of oncogenic mutant KRAS and develops screenable assays to identify small-molecule inhibitors against KRAS. His research interests are directed toward the biophysical details of KRAS activation of signal transduction at the plasma membrane. Toward this end, his group has combined multiple biophysical measurements, including neutron reflectometry, to develop a model of KRAS on the plasma membrane.

KENAN ÜNLÜ received his PhD in nuclear engineering from the University of Michigan. He was a faculty member and the manager of Neutron Beam Projects at The University of Texas at Austin (1990–1998). He joined the Cornell University faculty in 1998 as the director of the Ward Center for Nuclear Sciences. In 2002, he came to Pennsylvania State University (PSU). He is the director of the Radiation Science and Engineering Center (RSEC) and a professor of nuclear engineering at PSU. Dr. Ünlü has extensive experience in the development and use of neutron beam techniques and the utilization of research reactors for scientific research, advancement of scientific knowledge and technological innovation, and teaching. Dr. Ünlü's research and education interests have broadened recently beyond the nuclear science and neutron beam methods to nuclear forensics, nuclear security, and radiochemistry-related projects. With more than 30 years of experience in research reactor administration, Dr. Ünlü has consistently demonstrated exemplary leadership in advancing scientific and technological frontiers. He conducted many research projects at university research reactors with awards of research funds for development and utilization of these reactors while fulfilling all the safety and security requirements for Nuclear Regulatory Commission–licensed research reactor facilities. Dr. Ünlü transformed RSEC into a world-class facility for teaching, research, and service. He initiated and led the development of nuclear security and radiochemistry education and research programs at Penn State. Both programs are crucial for educating the next generation of both national and international technical experts in these fields. He is strongly engaged in research and outreach activities with public and private entities. He has garnered significant national and international recognition and funds. More than 20 industrial and government entities utilize RSEC facilities for radiation services, research, and development for every year. He earned several national and international awards and honors, including the 2020 Radiation Science and Technology award from the American Nuclear Society, Isotopes and Radiation Division. Dr. Ünlü is the 2024 recipient of The President's Award for Excellence in Academic Integration at Penn State. He is currently in the process of installing a small angle neutron scattering (SANS) facility at RSEC. The RSEC will be the only university research reactor facility to have SANS capability in the United States.