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Assessment of the Retrospective and Prospective Economic Impacts of Investments in U.S. Neutron Research Sources and Facilities from 1960 to 2030

Final Report

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This report was prepared by Research Triangle Institute using Federal funds under award 70NANB21H023 from NIST, U.S. Department of Commerce. The statements findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of the NIST or the U.S. Department of Commerce.

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RTI INTERNATIONAL

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Any outstanding errors throughout the report are the responsibility of the research team.

Executive Summary

Background

Neutron research is critical to materials innovation, the physical and life sciences, and physics, and, as such, the competitiveness of American industries. Such is its importance that it cuts across essentially all manufacturing and production industries, from biotechnology to energy technologies to aerospace and defense. Sizable federal investments in research reactors during the 1960s enabled important scientific discoveries, which in turn contributed to the development of new and improved products (Rush, 2015). By 1985, the United States had five federal laboratories with neutron scattering capacity. However, U.S. neutron scattering capacity has been declining since the 1990s. Currently, only two federal facilities with neutron sources support neutron scattering instruments and offer large-scale open-user programs.

Whereas U.S. support for neutron scattering has remained largely flat for the past 15 years, other countries continue to make sizable investments in research infrastructure and talent (APS, 2018). Continued lack of U.S. action could result in loss of research capacity, outdated instrumentation, and fewer individuals trained on and working with neutron scattering. Maintaining and increasing domestic capacity is essential if the United States wishes to remain a world leader in technological advancements and scientific knowledge generation.

Purpose

RTI International received funding from the National Institute of Standards and Technology (NIST) to conduct a study on the retrospective and prospective economic impacts of investments in U.S. neutron scattering research facilities from 1960 through 2030. This report focusses primarily on quantifying the economic returns to investments in the three current U.S. federal neutron scattering facilities with broad open user programs: the High-Flux Isotope Reactor (HFIR) and Spallation Neutron Source (SNS), both located at Oak Ridge National Laboratory (ORNL), and the NIST Center for Neutron Research (NCNR) reactor. This report also provides insights on additional infrastructure and policy needs to help the United States stay globally competitive moving forward.

Methods

Our assessment comprised seven main components:

1. A review of U.S. federal neutron scattering research facility construction, operation, and current capacity to support public research demands.
2. An analysis of the publications, patents, and collaborative research networks stemming from research conducted at the facilities.
3. Surveys (N=247) and interviews (N=50) of facility users addressing their facility use and outcomes, perceived impacts of insufficient access, and additional research needs.

4. An analysis of data on U.S.-based corporations that use the facilities, including their global revenues and employment.
5. Four case studies of U.S. technologies influenced by neutron scattering research, including giant magnetoresistance hard drives, aerospace safety applications, emerging weight loss medications, and electric vehicles.
6. An estimation of the retrospective and prospective economic impact of U.S. neutron scattering facility investment, by conducting a benefit-cost analysis comparing the benefits identified in the case studies to facility construction and operating costs.
7. An overview of policy options to increase U.S. neutron scattering research capacity, drawn from reviews of previous federal and international reports, and supported by interviews with facility users and staff scientists.

A benefit-cost analysis compares investment costs to the monetized social, economic, and environmental benefits attributable to that investment. Benefits and costs accruing over time are each brought to a present value (PV) by adjusting for inflation and social time preferences around consumption. Two values that communicate return on investment are the net present value (NPV), which is calculated as the PV of benefits less the PV of costs, and the benefit-cost ratio (BCR), which is calculated as the PV of benefits divided by the PV of costs.

In this report, we estimate the social, economic, and environmental benefits realized across the four selected case study technologies from 1998 through 2030. We compare these benefits to the construction and operating costs of NCNR, HFIR, and SNS incurred from 1960 through 2030 under various scenarios of benefit attribution to neutron scattering research.

Economic Impact Results

The four case studies of technologies influenced by research conducted at U.S. neutron scattering facilities highlight the substantial benefits to society generated from this research infrastructure. The combined benefits across the four selected case studies fully cover the construction and operating costs of NCNR, HFIR, and SNS if even only 6–11% of the benefits are attributable back to neutron scattering research.

Assuming neutron scattering research accelerated the development of the selected case study technologies by 2 years, the estimated NPV from the neutron scattering research facilities represented by the case studies is $29.4 billion (range: $11.8 billion to $63.6 billion). The estimated BCR is 2.67 (range:1.67 to 4.61), meaning that for every dollar invested in U.S. neutron scattering research facilities, $2.67 in benefits are realized. Similar results are found when considering a scenario where 20% of case study benefits are attributable to neutron scattering research. Both a 20% total attribution rate and a 2-year acceleration effect are reasonable assumptions given expert testimony on the influence of neutron scattering research.

These results are highly conservative as they only rely on benefits from four case studies of technologies influenced by neutron scattering. These represent a small portion of total innovation influenced by U.S. neutron scattering research infrastructure, as we identified at least

22,808 research publications and 1,565 U.S. patents based on research conducted at U.S. federal neutron scattering research facilities from 1960 through 2020. We further identified at least 372 U.S.-based companies that are known to have used at least one of the U.S. federal neutron sources. These include both large-scale entities and small and midsize enterprises (SMEs) across nearly every industry in the United States.

Additional Findings

While facility use has been extensive, we heard from a variety of users that there is a need for increased neutron scattering research capacity in the United States. A survey of 247 facility users identified that 77% of these respondents experienced issues due to insufficient facility access in the five years before facility shutdowns in 2020. Issues included research quality reductions (32%) and lost or underutilized grant funds (25%) totaling $1.1 million per year in aggregate. Of the total survey sample, 19% successfully took research that they were not able to complete in U.S. neutron scattering facilities to an international facility.

Insufficient investment in neutron scattering research infrastructure generates long-term negative effects that are especially difficult to quantify, but could include loss of research capacity, outdated instrumentation, fewer individuals trained on and working with neutron scattering, and therefore reduced innovation and research quality.

Future Considerations

Drawing on experience from other parts of the world, the U.S. neutron scattering ecosystem has the potential to be strengthened through the following actions:

- Forming a unified federal leadership committee or taskforce to develop a decadal plan or roadmap for neutron scattering facilities and national resilience, and
- Maintaining adequate funding for operating and improving existing facilities, strategically invigorating university facilities, and funding construction of new facilities.

Given the decades-long timeline for constructing a new neutron source, longer-term economic modeling would be needed to capture the economic impacts of major changes in U.S. neutron source investments. It could also be useful to fund comparative assessments of competitive and complementary materials assessment technologies, including spallation sources, reactors, synchrotrons, and other emerging X-ray technologies. Such assessments could further inform investment decisions to maximize the available U.S. materials research infrastructure.

1. Introduction

Neutron research is critical to materials innovation, the physical and life sciences, and physics, and, as such, the competitiveness of American industries. Such is its importance that it cuts across essentially all manufacturing and production industries, from biotechnology to energy technologies to aerospace and defense. Sizable federal investments in research reactors during the 1960s enabled important scientific discoveries, which in turn contributed to the development of new and improved products (Rush, 2015). By 1985, the United States had five federal laboratories with neutron scattering capacity. However, U.S. neutron scattering capacity has been declining since the 1990s. Currently, only two federal facilities with neutron sources support neutron scattering instruments and offer large-scale open-user programs.

Whereas U.S. support for neutron scattering has remained largely flat for the past 15 years, other countries continue to make sizable investments in research infrastructure and talent (APS, 2018). Continued lack of U.S. action could result in loss of research capacity, outdated instrumentation, and fewer individuals trained on and working with neutron scattering. Maintaining and increasing domestic capacity is essential if the United States wishes to remain a world leader in technological advancements and scientific knowledge generation.

RTI International received funding from the National Institute of Standards and Technology (NIST) to conduct a study on the retrospective and prospective economic impacts of investments in U.S. neutron scattering research facilities from 1960 through 2030. Our assessment comprised seven main components:

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3. Surveys and interviews of facility users addressing their facility use and outcomes, perceived impacts of insufficient access, and additional research needs.
4. An analysis of data on U.S.-based corporations that use the facilities.
5. Four case studies of U.S. technologies influenced by neutron scattering research.
6. An estimation of the retrospective and prospective economic impact of U.S. neutron scattering facility investment.
7. An overview of policy options to increase U.S. neutron scattering research capacity.

This report describes and quantifies the value of past and current U.S. investments in neutron scattering research infrastructure and provides insights on additional infrastructure and policy needs to help the United States stay globally competitive moving forward.

2. Background

Neutrons can be produced either by nuclear fission in a reactor or by spallation when high-energy protons strike a heavy metal target (Pynn, n.d.). Reactors produce a steady stream of neutrons whereas spallation sources produce high-intensity pulses of neutrons. The reactor-based steady flux of neutrons and the spallation-based pulses of neutrons are interchangeable for some types of research. However, more often they are complementary, with each technique having an advantage in certain areas of research (Basic Energy Sciences Advisory Committee (BESAC), 2020). Other factors that affect the types of research that can be done at a facility include the number and type of neutron instruments, scientific support facilities, the sample environment, and the level of technical support offered by facility scientists (ESFRI, 2016).

2.1 Neutron Research Activities

Current neutron research activities can be divided into three general categories: basic and applied research, commercial applications, and education. We provide descriptions of specific activities within each category in Table 2-1.

2.1.1 Basic and Applied Research

Our economic impact analysis will focus on the value of U.S. neutron sources in supporting basic and applied research activities. We are particularly focused on neutron scattering and imaging for materials characterization, enabling the discovery and production of new materials and the ability to manipulate desirable materials properties to maximize performance. Neutron research has been used in high-impact applications such as visualizing fluid flow in hydrogen fuel cells, mapping stress fields in materials, assessing electronic-lattice interactions in solar cells, examining nanoporosity for environmental studies, and understanding the behavior of living cells (Bureau of Radiological Health, n.d.; International Atomic Energy Agency (IAEA), 2023; Los Alamos National Laboratory, 2015). Not all neutron research has direct commercial applications, but much ultimately leads to commercial translation. Interviews indicated that it typically takes 20 to 30 years to move from the discovery of a new material to its use in a commercial application. Hence, the research of today funds innovations for future generations.

2.1.2 Commercial Applications

Unlike many scientific and training activities that provide little ability to directly defray reactor costs, research reactors can also be used to directly produce commercial goods. The most valuable product is isotopes. Isotopes are forms of an element that have the same number of protons but different numbers of neutrons. Nuclear reactors produce radioactive isotopes (radioisotopes) by bombarding target materials with neutrons so the material absorbs additional neutrons. Radioisotopes are critical for numerous medical, scientific, and industrial purposes. For instance, radioisotopes have powered more than 20 NASA spacecraft (Los Alamos National Laboratory, 2015). Another isotope, californium-252, is used for cancer therapy and detection of pollutants in the environment and explosives in luggage (Bureau of Radiological Health, n.d.).

Isotope production falls outside of the scope of our assessment, but additional details about U.S. isotope production collaborations and oversight are provided in Appendix A.

2.1.3 Education

Research reactors, especially on university campuses, are excellent educational tools on the use of radiation in science and engineering. Reactors enable students to study the principles of reactor physics and safety and the basics of radiation protection. Recently, educational access to research reactors has expanded though online presentation modalities. In this case, students at a university without direct access to reactors can use the facilities at another institution. This approach was pioneered in the United States and is now being used globally.

Table 2-1. Neutron Research Activity Descriptions by Category

Activity	Description (IAEA, 2023)
Basic and Applied Research	
Neutron scattering	Neutron scattering uses a neutron's neutrality to explore a material's deep structure. Although performing some studies using low-power reactors is possible, intermediate- and high-power reactors are most efficient for this application.
Neutron radiography	Neutron radiography, used in conjunction with traditional X-rays, provides detailed descriptions of the inside of an object. Neutron radiography finds applications in various fields, such as archaeology, biology, aeronautics, car industry, and material studies.
Neutron activation analysis	Neutron activation analysis is a qualitative and quantitative analytical technique for determining trace elements in a variety of objects, such as water, air, soil, fish, meteorites, rocks, and even agricultural products and plants. It is a simple and widely used application of research reactors.
Geochronology	These techniques allow geologists to nondestructively date small quantities of minerals.
Materials/fuel testing	High-flux research reactors can reproduce mechanical strains undergone by materials in power reactors. For this reason, research reactors are used to study the aging of older power plants, optimize newer plants, and test fuels and breeder capacities. This research is needed to find materials meeting needs for fusion: resistance against temperatures of several million degrees and high-energy neutron irradiation.
Commercial Applications	
Isotope production	Depending on the available neutron flux, research reactors can produce a variety of radioactive isotopes for use in medicine, industry, research, and other areas.
Transmutation	Research reactors can perform neutron transmutation doping to produce uniform silicon ingots doped with phosphorus for use in the electronics industry. Gemstones can be irradiated with neutrons to improve their properties to increase their monetary value.
Education	
Teaching and training	Every research reactor facility is capable of being used for education and training purposes, involving students in science and engineering. Training of nuclear power plant operators can also be provided by some reactors.

2.2 Relevant Technology Areas

Based on interviews with facility users, subject matter experts, students, and researchers, along with reports such as that issued by the American Physical Society (APS) in 2018 (APS, 2018), we provide an overview of the major technological fields and industries that neutron scattering could affect. We describe both the impact of neutron scattering on the given technological field and the impact of the technological field on the American economy. In total, five major technological areas were identified: soft matter, biological sciences, magnetic materials, infrastructure safety, and fuel cells.

2.2.1 Soft Matter

Soft matter refers to materials that are easily deformed by thermal changes or external forces (Institute of Physics, 2021). Soft matter can be used in a wide variety of industries, including plastics, paints, coatings, cosmetics, and pharmaceuticals (Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy, 2012). For this reason, many researchers around the world are interested in studying the structure of various forms of soft matter and the properties that control those materials' behavior (Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy, 2012). Because soft matter is typically composed of lighter elements (such as hydrogen), neutron scattering has been described as the ideal way to gain a better understanding of the structure of most varieties of soft matter (Volker, n.d.).

As of 2019, the total size of the U.S. plastics industry was about $74 billion (Tiseo, 2021). Overall, North America accounted for roughly 19% of the world's total plastic production, and many of the world's major plastic producers (such as Dow Chemical and the ExxonMobil chemical division) are headquartered in the United States. As of 2020, slightly less than 1 million Americans were employed in the plastics industry, and there is reason to believe the 2020 number of U.S. employees in the plastics industry is lower than it would be in a typical year because of the COVID-19 pandemic (Tiseo, 2021).

Another industry where soft matter plays an important role is the medical device industry. Medical devices are instruments used for the treatment of disease but do not typically include pharmacological, immunological, or metabolic means such as pharmaceutical drugs The United States is the largest medical device producer in the world with a market size of about $156 billion. This market is projected to grow to $208 billion by 2023 (SelectUSA, n.d.-b). The U.S. medical device industry directly employs roughly 93,089 people as of 2021 (IBISWorld, 2021b). However, if indirect employment is taken into account, there are estimated to be roughly 2 million Americans employed in some fashion by the medical device industry (although, as stated previously, some of these jobs may overlap with the plastics industry) (SelectUSA, n.d.-b).

Soft matter also plays a key role in the automobile industry. In addition to plastics, the rubber in car tires and the paint on a car both fall under the category of soft matter (University of North Carolina (UNC), 2021; Wagner, 2020). As we learned in interviews, neutron scattering is increasingly being used to better improve the soft matter components of cars. The U.S. automotive industry (including both manufacturing and sales) generated $1,249 billion (Wagner, 2021). In June 2021, U.S. motor vehicle and parts sellers employed just under 2 million

Americans, while an additional 873,000 Americans were employed in the motor vehicle and parts manufacturing sector. The number of Americans employed in the motor vehicle industry is projected to increase because of an expected rise in demand for automobiles (Wagner, 2021).

Soft matter also plays a role in the construction industry, particularly when it comes to development of more sustainable building materials, better controlling of aging processes, and cement hydration and setting. Neutron scattering could provide a more accurate understanding of the physics behind soft matter construction materials (Del Gado, 2012). The market size of the U.S. construction industry was approximately $1.36 trillion at the end of 2020 and employed over 9 million people in 2019 (De Best, 2021).

2.2.2 Biological Sciences

Neutron scattering is useful in the biological sciences because neutron beams are both highly penetrating and enable researchers to scan cells without damaging them in the process (Qian, 2020). In addition, because many neutron scattering techniques use hydrogen, the adjustment of the proportion of the two different forms of hydrogen (protium and deuterium) in neutron scattering allows for the observation of different components of the cell membrane. Having more knowledge of cell membranes allows researchers to better evaluate the delivery of drugs and antimicrobial compounds to cells (Qian, 2020).

One topical example of the benefits of neutron scattering in the biological sciences is its use in helping researchers understand how the COVID-19 virus infects human cells (Fragneto, 2021). Researchers employed neutron scattering to observe how the COVID-19 virus uses spike proteins to penetrate cell membranes. This knowledge can be used to develop better vaccines and therapeutic treatments for both COVID-19 and future pandemics (Fragneto, 2021).

More broadly, the United States had captured the majority of the worldwide market share in the pharmaceuticals industry as of 2020, at 45.9% (Mikulic, 2021). Sales of pharmaceuticals in the United States generated over $530 billion, although it should be noted that this is in part because of U.S. regulations allowing for higher drug pricing (Mikulic, 2021). As of 2017, the U.S. biopharmaceutical industry employed 811,000 individuals directly and is estimated to have generated an additional 3.2 million U.S. jobs via indirect and induced employment in that year (TEConomy Partners, 2019).[1]

2.2.3 Magnetic Materials

Magnetic materials in the context of neutron scattering research primarily play a role in developing and improving hard drive technology in computers and have a key role in creating high-temperature superconductors for use in potential quantum computing applications.

In terms of hard drive development, neutrons can help reduce the amount of energy required for a hard drive to record bits of data (European Neutron Scattering Association, 2017) because they can be used to construct a system of extremely thin (nanometer or subnanometer width) layers of magnetized and nonmagnetized material in a computer's hard drive as a result of the

[1] These employment figures were derived using proprietary economic models from IMPLAN.

giant magnetoresistance (GMR) or the tunneling magnetoresistance (TMR) effects (IAEA, 2023). This makes neutrons essential for creating hard drives capable of storing gigabytes or even terabytes of data. One interviewee stated that neutrons were essential in the quest for advancing understanding of magnetic structures: “neutrons are highly penetrative, they have spin, they interact with spin of electrons and ions, so you get very direct information of magnetic structure. [The] resolution is exceptional, compared to even the best x-ray techniques.”

Quantum computers are still a developing form of technology. Although conventional computers use optical or electrical signals to form a sequence of ones and zeros to give commands to the computer hardware, quantum computers instead use subatomic particles such as electrons or photons to generate commands (Giles, 2019). The units of information conveyed to the computer hardware by these subatomic particles are known as “qubits,” and because of some of the odd properties associated with subatomic particles in quantum physics, quantum computers would have certain advantages over regular computers (Giles, 2019). Specifically, because of superposition and entanglement, quantum computers could store significantly more information and do far larger calculations than conventional computers (Giles, 2019). The reason neutron scattering is important for quantum computing is that random movements outside of the quantum computer can interfere with it performing any sort of calculation accurately (Sorensen, 2018). Neutron scattering is used to measure the energy levels of the particles in the quantum computer and help suppress this problem (Sorensen, 2018).

It is difficult to overstate the importance of computers to the modern American economy. The U.S. computer manufacturing industry accounted for $10.0 billion as of this writing in 2021 (IBISWorld, 2021a). If related industries such as software are included, the U.S. computer industry overall is estimated to contribute approximately $1.8 trillion to U.S. value-added gross domestic product and provide 11.8 million Americans with jobs (SelectUSA, n.d.-c). This would mean the computer industry constitutes over 10% of the total U.S. economy. Although quantum computers are still a largely hypothetical technology, they could lead to major advances in fields such as materials science and pharmaceuticals, and companies such as IBM and Google are already experimenting with them (Giles, 2019).

2.2.4 Infrastructure Safety

Neutron imaging technology can be used to better portray how and when cracks form in various materials due to strain and fatigue (Reid, 2019). Interviews indicated this function is especially useful when investigating the performance of materials subject to extreme exposure and stress. Specifically, neutron imaging can be used to better evaluate the materials used in airplanes, rockets, and satellites.

Airplanes, rockets, and satellites are collectively designated as part of the aerospace industry (SelectUSA, n.d.-a). As of 2023, North America is the largest market for the aerospace industry in the world, accounting for over 50% of the global industry (TBRC Business Research Pvt Ltd., 2024). The global aerospace industry was valued at $308.7 billion in 2023 (TBRC Business Research Pvt Ltd., 2024). The U.S. aerospace industry directly employs 509,000 workers and indirectly employs 700,000 more workers in related fields (SelectUSA, n.d.-a).

2.2.5 Fuel Cells

Polymer electrolyte fuel cells, also sometimes referred to as polymer electrolyte membrane fuel cells in the literature, are the focus of a significant amount of research and development (R&D) efforts because, when compared with conventional power sources (most notably the internal combustion engine), their operating efficiency can range from 50% to 90%, they do not emit pollutants such as nitrous oxides or particulate matter, and both carbon dioxide and carbon monoxide emissions are reduced to approximately zero (Mench, 2005). Potential consumer applications for these fuel cells include rechargeable batteries, power for houses, and power for cars (Jacobson, 2006). For these fuel cells to function properly, some amount of water vapor must be produced to allow the electricity they generate to flow through the cell (Mench, 2005). However, if an excessive amount of liquid water forms in the cell, the cell will stop working (Mench, 2005). Therefore, to improve fuel cell design, determining in a noninvasive manner how much liquid water exists in a fuel cell is necessary. Neutron imaging is an excellent method for noninvasively visualizing and quantifying the amount of liquid water and its flow formed within a fuel cell (Mench, 2005).

Lithium-ion batteries are another technology that could benefit from neutron imaging techniques. Lithium-ion batteries have a wide variety of applications because they offer improved energy storage capacity, higher operating voltage, a long shelf life, and a lower reduction in their maximum capacity due to incomplete discharges when used previously as compared with conventional batteries (Boisvert, 2019). Unfortunately, lithium-ion batteries also suffer from some technical issues, including problems with their electrical charge and discharge rates. To resolve the latter issue, scientists first need to accurately monitor exactly how lithium ions pass through the various electrodes in a lithium-ion battery, which can vary based on an electrode’s thickness (Boisvert, 2019). While X-ray diffraction and phase imaging can be used for this purpose to an extent, neutron imaging is the most effective method because of lithium’s high absorption coefficient for neutrons (Boisvert, 2019).

Neutron scattering can also help maximize the process of methane separation for fuel cell use. Methane is one of the critical components in many fuel cells, and it must be separated from carbon dioxide before it can be used in a fuel cell. This is accomplished by using membranes that stop the methane but allow the carbon dioxide to pass through. The carbon dioxide can then be captured and reused to help create renewable fuels and chemicals (Leuven, 2017). Neutron scattering can help researchers determine the most effective materials to use in these membranes (Yildirim, 2014).

Hydrogen is another energy source that can be used in fuel cells. However, there are numerous logistical issues with proper storage prohibiting the use of hydrogen in vehicle fuel cells. Neutron scattering can help researchers determine which materials are the most effective for hydrogen storage, thereby making hydrogen fuel cells more effective (Yildirim, 2014).

Any discussion of the impact of fuel cell technology on society must include its environmental benefits. Fuel cell technology has the potential to both reduce nitrous oxide and particulate matter pollution while also reducing carbon monoxide and carbon dioxide emissions to almost zero for the devices they power (Mench, 2005). It is estimated that, replacing 1 MW of power generated by conventional fossil fuels with 1 MW generated by fuel cell technology reduces average nitrous oxide emissions by 11,213 lb and average carbon dioxide emissions by 7.2 million lb (Connecticut Hydrogen-Fuel Cell Coalition, 2016).

There are also direct economic benefits from investing in fuel cell technology. Lithium-ion batteries are expected to have a global market value of $47 billion by 2027 (Boisvert, 2019). Argonne National Laboratory (ANL) estimates that the economic effects of a California state program (the “California Road Map”) could generate double the level of employment in California and increase the total economic output in California by $70 million in 2023 (Mintz, 2014). It should be noted, however, that limitations in the model used by ANL assumed all spending generated by this program occurs in California. On a national level, Bezdek (2019) found that the hydrogen and fuel cell industries could create as many as 1 million U.S. jobs by 2030, many with high salaries (Bezdek, 2019). Bezdek (2019) does caution, however, that estimates of the number of jobs created can vary and that the U.S. educational system may need to be updated to give potential workers the skills required for these jobs.

3. U.S. Neutron Scattering Research Facilities

In the United States, 50 nuclear research reactors are listed in the International Atomic Energy Agency (IAEA) Research Reactor Database. As Table 3-1 depicts, most of these reactors are located at universities or federal facilities. One exception is that the State of Rhode Island operates a single research reactor for teaching and activation analysis. Also, two private companies use research reactors for materials or fuel testing and/or neutron radiography: Aerotest Operations, Inc. GE-Hitachi Nuclear Energy and Dow Chemical Company Michigan Operations (IAEA, 2023).

Table 3-1. Neutron Research Activity Descriptions by Category

Number of	University	Federal	Corporate	State	Total
Reactors	24	23	2	1	50
With power greater than 1 MW	11	9	0	1	21
With power greater than 10 MW	1	6	0	0	7
Spallation sources	1	2	0	0	3
Unique facilities with high-power neutron sources[a]	2	6	0	0	8
Support neutron scattering with broad open-user program[b]	2	2	0	0	4

[a] High-power neutron sources include spallation sources and nuclear reactors with greater than 10 MW of power.
[b] We define an open-user program as one that formally accepts applications from outside researchers on a large scale.
Source: RTI based on information from the IAEA Research Reactor and Neutron Scattering Instrument Databases.

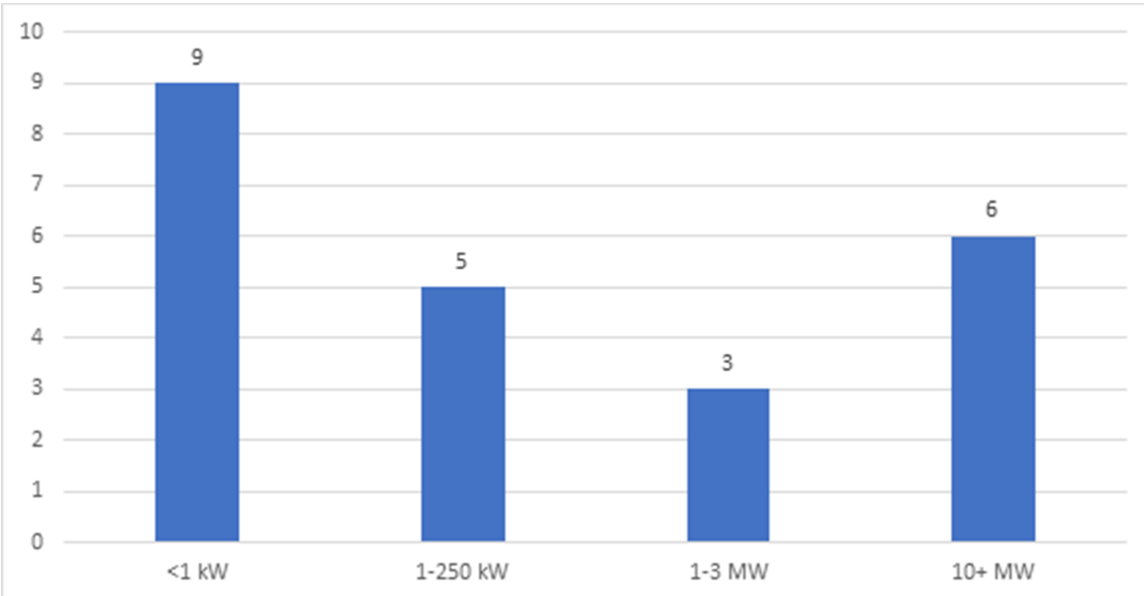
Of the 50 reactors in the IAEA database, only seven have power levels of 10 MW or greater. These high-power reactors are located at one university—the University of Missouri—and five federal facilities—the Nuclear Power Training Unit Charleston, White Sands Test Facility, Idaho National Laboratory, NIST, and Oak Ridge National Laboratory (ORNL). In addition, two high-power spallation sources are in operation in the United States at ORNL and Los Alamos National Laboratory (LANL).

Only two of the six facilities with high-power neutron sources (reactors or spallation sources) support neutron scattering instruments and offer large-scale open-user programs: ORNL and NIST. These two facilities are the main focus of our analysis. However, the subsections below provide a general overview of the current and former U.S. neutron sources within federal facilities and universities.

3.1 Current Federal Facilities

U.S. federal facilities house 23 nuclear reactors. The number of federal reactors by power level is provided in Figure 3-1. Only six of the federal reactors have power levels of 10 MW or greater. There are also two high-power federal spallation sources. The eight high-power neutron sources are located across six federal facilities, only two of which support neutron scattering instruments and offer large-scale open-user programs: ORNL and NIST. Each of these is described below.

Figure 3-1. U.S. Federal Reactors by Power Level



Source: RTI based on information from the U.S. Department of Energy (DOE) and the IAEA.

3.1.1 NIST Center for Neutron Research (NCNR)

The NCNR is operated by the Department of Commerce (DOC) under the auspices of NIST in Gaithersburg, MD. This facility's nuclear reactor, the Neutron Beam Split-Core Reactor (NBSR), is a 20-MW reactor designed to provide large, intense beams for neutron scattering research (Rush, 2015). The reactor became operational in 1967 (Rush & Cappelletti, 2011). The NCNR is considered one of the world's leading neutron research facilities (NIST, 2021).

The NCNR facility serves several purposes: to study a range of NIST interests in materials, chemical analysis, and radiation standards, and to provide neutron measurement capabilities to industry, academia and other U.S. government agencies (Cappelletti et al., 2001). For this reason, NIST scientists created a reactor that would support a large range of neutron scattering activities, neutron trace analysis, neutron standards, and isotope production. NBSR is a modernized version of the ANL CP-5 reactor and the U.K.'s DIDO reactor with a large core and a D2O moderator and reflector (Rush & Cappelletti, 2011). The first four instruments for neutron diffraction structure studies were jointly funded by NIST; the Naval Ordnance Laboratory in White Oak, MD; and the Naval Research Laboratory in Washington, DC. Later, the Army transferred its neutron research group to NCNR and funded two crystal spectrometers to expand complex materials research with inelastic neutron scattering (Cappelletti et al., 2001).

The contribution of NCNR to U.S. scientific research is substantial. Neutron diffraction was used to understand residual stress on materials such as uranium and other metals at NCNR starting in the late 1970s (Cappelletti et al., 2001). During the 1990s, the Center developed an extensive array of cold neutron instruments, making the facility a leading resource for cold neutron scattering research (Rush & Cappelletti, 2011). These efforts resulted in the development of numerous applications in military systems and civilian products (Rush & Cappelletti, 2011). Other neutron research performed at NCNR has contributed to improvements in many common products such as plastics, vaccines, and computers (NIST, 2021).

NCNR has two primary partnerships with industry and academia: the nSoft consortium and the Center for High Resolution Neutron Scattering (CHRNS). nSoft is designed to deliver technology and expertise with neutron-based measurement science to U.S.-based industrial researchers. Member companies collaborate with NIST to develop advanced material measurements and manufacturing processes in areas such as plastics, composites, surfactants, colloidal fluids, and biopharmaceuticals. The Public benefits from more private investment in national facilities, which results in a higher return on investment of federal tax dollars, and from the widespread use of new scientific discoveries (NIST, 2020). CHRNS is a joint NSF and NIST national user facility within NCNR that develops and operates state-of-the-art neutron scattering instrumentation for use by the general scientific community. More than 400 scientists, postdoctoral fellows, and graduate students use the CHRNS instruments each year (NIST, 2019b). NCNR also has partnerships with companies and universities to maintain and conduct research on specific instruments (NIST, 2020). Thirty major instruments are available via a scientific proposal review program or through collaboration with an NCNR scientist. If research data is made available to the public, companies can use the facility for free. Companies also may perform proprietary research at NCNR on a full cost recovery basis (NIST, 2019b).

The NCNR has extensive instrumentation for both thermal and cold neutron beams. The facility has two cold sources that supply neutrons to three-fourths of the beam instruments. There are currently 30 experiment stations: Seven are used for neutron physics and analytical chemistry, and 23 are beam facilities for imaging and neutron scattering research (NIST, 2020). A list of instruments and their uses is provided in Appendix A. Using administrative records, we estimate that 9,381 unique publications have been generated from research conducted at NCNR dating back to the 1968/1969 fiscal year.

On February 3, 2021, the NCNR reactor automatically shut down due to detection of fission products in the confinement building upon normal reactor startup. The Nuclear Regulatory Commission (NRC) cleared NIST to restart operations in March of 2023 (Kramer, 2023), but as of early 2024, the reactor is still not fully operational.

3.1.2 Oak Ridge National Laboratory (ORNL)

The ORNL in Tennessee is operated by DOE and currently contains two of the world's most powerful neutron sources. The Neutron Sciences Directorate manages the sources and the Shull Wollan Center, dedicated to advancing neutron applications in science and training future researchers (ORNL, n.d.-e). The center is named after E. O. Wollan and C.G. Shull who, along with their colleagues, developed neutron diffraction as a tool for studying materials in the mid-1940s, utilizing the Graphite reactor that was built as part of the Manhattan project. Shull was awarded half of the 1994 Nobel prize in physics for this work; Wollan was deceased at the time of this award.

ORNL has developed and run at least 13 nuclear reactors since the 1940s. In 1958, the Oak Ridge Reactor (ORR) was brought online (Rosenthal, 2009). This 30-MW reactor was the first high-flux reactor at ORNL and was based on the Materials Test Reactor conceptualized at ORNL and constructed under the auspices of ANL. ORR was used for neutron scattering research, fundamental investigations of the behavior of metals and ceramics under radiation, and the testing of materials for reactor fuel elements and for fusion devices (Rosenthal, 2009). The ORR operated for 29 years and was decommissioned in 1987 (Office of Scientific and Technical Information, 1992).

Eight years after ORR went critical, the High Flux Isotope Reactor (HFIR) started operating in 1966 to produce “heavy” elements such as plutonium and curium (Rush & Cappelletti, 2011). At this time, HFIR is the most powerful reactor-based source of neutrons in the United States, and it provides a high steady-state neutron flux (ORNL, n.d.-b).

The second neutron source that is currently operating at ORNL is the Spallation Neutron Source (SNS), which began operating in 2006 (Rush & Cappelletti, 2011). SNS was developed at a cost of $1.41 billion, excluding much of the cost of the instrument suite, and was the United States’ flagship endeavor for neutron research in the early 2000s (DOE, 2001). SNS delivers short (microsecond) proton pulses to a target filled with liquid mercury. The mercury “spalls off” free neutrons in response to the proton impact (IAEA, 2023). Those neutrons are then directed toward state-of-the-art instruments that provide a variety of research capabilities (ORNL, n.d.-h).

Together, these neutron sources are used to better understand the structure and dynamics of matter, leading to advancements in materials science, biology, chemistry, and physics. Scientists also use the HFIR facility to manufacture isotopes crucial to medicine, global security, energy, and industry (ORNL, n.d.-b). The HFIR supports 13 beam instruments for neutron scattering and neutron imaging. SNS has 20 research instruments. Lists of HFIR and SNS instruments and their uses are provided in Appendix A.

As scientific user facilities, the SNS and HFIR instruments are available to academic researchers. Beam time is free of charge with the condition that researchers publish their results (ORNL, n.d.-f). Beam time also is available for proprietary research on a full cost recovery basis (ORNL, n.d.-d). Each year, more than 1,000 researchers use SNS or HFIR instruments to perform experiments (ORNL, 2020a).

Both SNS and HFIR are responsible for significant contributions to the United States’ neutron research capacity and provide critical products to the scientific and industrial communities. We estimate that 9,304 unique publications have been generated from research conducted using ORR, SNS, or HFIR dating back to 1968 (see Section 4.1 for estimation details). HFIR is also the Western world’s only supplier of Californium-252, an isotope used for well-logging and industrial scanning, as well as a neutron source for starting up reactors (ORNL, n.d.-c). Basic materials research at HFIR has led to longer-lasting dental implants, more efficient solar cells, and safer batteries (ORNL, n.d.-a). Columbia University researchers used the SNS facility to study small breaks in suspension bridge cable wires and how they affect the overall strength of the cable. SNS's nondestructive study of the wires was used to develop safe, cost-effective cable repair methods. SNS also has been used by NASA and Honeywell to improve the reliability of aircraft components (ORNL, 2020b).

In recent years, several operational events affected the availability of SNS and HFIR. Early in 2019, SNS developed problems with the target mercury loop that prematurely ended the operating cycle. There were additional operational interruptions due to the cryogenic moderator system and premature failure of a mercury target. In November 2018, HFIR was shut down when a defective fuel element was detected. In response, ORNL has prioritized initiatives to strengthen operational stewardship, including an organizational effectiveness assessment; a safety culture assessment; and implementation of asset management (ORNL, 2020a).

In November 1986, tests performed on irradiation surveillance specimens indicated that the HFIR reactor vessel was being embrittled by radiation exposure at a higher-than-predicted rate. Following detailed reviews, HFIR returned to normal operations at a new maximum power level of 85 MW—reduced from 100 MW—in 1990. The lower power level is expected to extend the operating life of HFIR to approximately 2050 assuming six 23-day operating cycles per year (Birgeneau et al., 2020). In October 2020, a federal advisory panel recommended that DOE immediately start preparing for an overhaul of HFIR. The overhaul, which could happen between 2030 and 2035, would permit the reactor to resume operating at 100 MW and allow construction of a new beam guide hall with instruments tailored to upgraded reactor capabilities. The expanded capacity may help alleviate excess user demand at all U.S. neutron scattering facilities. In recent years, user demand has outstripped available time by a factor of about two to three (Thomas, 2020). At the same time, HFIR would possibly be converted to employ low-enriched uranium fuel to meet non-proliferation requirements (Birgeneau et al., 2020).

ORNL is undertaking substantial improvements to SNS, including a proton power upgrade to double its power capability to 2.8 MW, which will be completed in 2024. This upgrade will result in a significant increase in thermal neutron brightness to enable faster experiments and potentially time-resolved neutron spectroscopy experiments for materials research in the thermal energy (shorter wavelength) range (Thomas, 2020). The facility is also planning the construction of a second target station. The second target station will complement existing capabilities by combined use of intense, cold neutrons and instruments that are optimized for exploration of complex materials (ORNL, n.d.-g). Plans call for an initial group of eight additional instruments with more to be added later, eventually utilizing all twenty-two beamlines. The new target station has been intended since the conception of SNS and will deliver substantial performance gains over existing cold neutron instruments (BESAC, 2013).

3.2 Former Federal Facilities

On December 8th in 1953, President Eisenhower gave a speech ushering in the era of Atoms for Peace. Instead of advocating for further development of nuclear weaponry or seeking to maintain a monopoly on this technology, Eisenhower established a plan for using nuclear fission worldwide to support energy generation, commercial applications, and basic research (Hicks, 2014). Soon after, the United States began the Atoms for Peace program to disseminate equipment and information to schools, hospitals, and research institutions. Nuclear research had been slow moving until Congress passed the Atomic Energy Act of 1954, which allowed private industries to develop and build nuclear reactors for electricity generation and use (Wank, 2010). The Act required civilian use of nuclear materials and nuclear facilities to be licensed and empowered the U.S. Atomic Energy Commission and its successor, the NRC, to establish and enforce safety and health standards for nuclear activity (Gaertner, 2016; Wank, 2010).

Once the regulatory framework was in place for nuclear reactors, two primary purposes emerged: power generation and basic and applied research. Unlike commercial nuclear reactors used primarily for energy production, research reactors are used to determine reactor dynamics, measure nuclear properties, and observe the effects of radiation on organic and synthetic materials (Wank, 2010). The power output of research reactors varied from less than 1 kW, the amount of power needed to operate a toaster, to approximately 10 MW (Paik, 2011; Wank, 2010). In contrast, nuclear reactors designed for power production could have power output in excess of 3,000 MW (DOE, 1981). Research reactors were built and operated by universities, private companies, and various branches of the federal government.

Federal publications from DOE clarified that neutron research was performed at two federal facilities that no longer undertake this type of research. Brookhaven National Laboratory (BNL) performed neutron research using the High Flux Beam Reactor (HFBR) until the reactor was closed in 1997 (BNL, n.d.-b). ANL also performed neutron scattering with the Intense Pulsed Neutron Source (IPNS) until 2008 (Westfall, 2007). Finally, LANL houses the Los Alamos Neutron Science Center (LANSCE) containing five research divisions. One of these divisions, the Lujan Center, used to support an open-user program for neutron scattering research that was ended in 2014.

3.2.1 Los Alamos Neutron Science Center (LANSCE)

LANSCE was established by DOE and is now operated by the National Nuclear Security Administration (NNSA), a semi-independent entity of DOE. The Center's neutron research began in 1972 and expanded in 1977 with construction of a pulsed spallation neutron source to supply moderated and unmoderated neutrons to time-of-flight experiments in the Weapons Neutron Research facility (LANSCE, n.d.-b). LANSCE contains a linear accelerator (LINAC) used for proton radiography and to produce the wide energy spectrum of spallation neutrons needed to interrogate various materials (LANSCE, n.d.-c). This was the nation's most powerful accelerator until 2006 when the SNS at ORNL became operational (Sinnis et al., n.d.).

LANSCE houses five distinct divisions. One division, the Lujan Center, is dedicated to neutron scattering and was operated jointly by DOE's Basic Energy Sciences (BES) division and NNSA for more than 20 years (Neutronsources.org, 2012). This facility was once the largest DOE neutron scattering user facility in the country (BES, 2009). In 2000, a report by BESAC found that although Lujan had the potential to be a world-class user facility, its management structure was dysfunctional and beam reliability was low (Taylor, 2020). BES began an open-user program at Lujan in 2000/2001 but halted their operational support of the Lujan Center in 2014/2015, ending the associated open-user program. We estimate that 1,615 unique publications originating from Lujan BES research were generated between 2003 and 2011.

The Lujan Center still operates a national nuclear science facility with five instruments and runs for approximately 3,000 hours per year (LANSCE, n.d.-d). Former and current Lujan neutron research instruments are provided in Appendix A. Although Lujan facilities can be used by outside researchers, this research must adhere to the NNSA's mission "to maintain and enhance the safety, security, and effectiveness of the U.S. nuclear weapons stockpile; work to reduce the global danger from weapons of mass destruction; provide the U.S. Navy with safe and militarily effective nuclear propulsion; and respond to nuclear and radiological emergencies in the United States and abroad" (NNSA, 2021). As such, LANSCE's research priorities center on hydrodynamics, nuclear weapons science, and materials science. The facility works to expand understanding of nuclear weapon performance, reliability, and safety. These scientists also test new materials and new material models for stockpile stewardship (LANSCE, n.d.-a). Given the narrow scope of the NNSA mission, we do not consider this to be an open-user program for broad neutron scattering research.

3.2.2 Brookhaven National Laboratory (BNL)

The BNL, a DOE laboratory located in Upton, NY, was founded in 1947 and contained the Brookhaven Graphite Research Reactor (BGRR), the first peacetime nuclear reactor built in the United States after World War II (BNL, n.d.-a). By 1955, it was apparent that BGRR would not be able to produce high enough neutron fluxes to support the desired research. To fill this need, BNL constructed the HFBR at a cost of $12 million ($79 million in 2019 dollars[2]) (Shapiro, n.d.-b). HFBR, which achieved criticality in 1965, was initially powered at 40 MW. After 17 years, the power increased to 60 MW.

HFBR was different than most reactors because the neutron flux reached its maximum outside the reactor core, rather than inside. This expanded the range of experiment designs compared to other reactor configurations. In addition, the beam tubes that extracted neutrons for experiments were located tangentially to the core, decreasing the fast neutron background without affecting the intensity of the extracted neutron beams. These two features were replicated in nearly all subsequent research reactors (Shapiro, n.d.-b).

HFBR was primarily used for experiments in nuclear and solid-state physics, biology, material science, and chemistry (BNL, 1974). In 1994, HFBR was upgraded with a new powder neutron diffractometer built as part of a collaboration with Georgia Institute of Technology and commercial partners. At the time, this diffractometer produced the highest resolution diffraction patterns in the world (BNL, 1974). Appendix A includes information about the instruments at HFBR. In 1995, more than 250 researchers from 73 institutions and companies used the

[2] Calculated using GDP index from measuringworth.com.

neutron source. We estimate that 1,120 unique publications were generated from research conducted at HFBR over the course of its operation.

Scientific accomplishments involving HFBR include the discovery of the structure for ribosomes and myelin, the covering for nerve cells. Scientists used HFBR to determine the structure of the 23 amino acids that make up protein in all cells. Testing magnets near their critical temperatures at the HFBR helped scientists formulate and test Nobel Prize–winning theories of cooperative ordering in large collections of atoms. This knowledge helped explain a similar phenomenon observed with superconductivity at temperatures above 90 degrees kelvin (BNL, n.d.-a). Brookhaven staff also tested sample irradiations for other users (BNL, 1995). HFBR was a national user facility and open to the worldwide scientific community for high quality fundamental research (Shapiro, n.d.-b).

In 1989, HFBR was shut down to analyze a possible accident resulting in loss of coolant. It was restarted at half power in 1991. However, HFBR was shut down again in 1997 due to a leak in the spent-fuel canal that contaminated nearby groundwater with tritium. The investigation revealed a small leak in the pool where spent reactor fuel was stored in the basement of the HFBR building. BNL determined that tritiated water had been leaking from the spent-fuel pool for at least 10 years. By 1999, DOE made the decision to permanently close HFBR, citing an ongoing environmental impact assessment, budgetary limitations, and the availability of other neutron research facilities as reasons (BNL, n.d.-b). The agency's decision may have been influenced by the surrounding community demanding the reactor be closed despite no apparent danger to nearby residents (Goodwin, 2000).

3.2.3 Argonne National Laboratory (ANL)

ANL is in Lemont, IL, and was established in 1946 as the country's first national laboratory. Its primary purpose was to develop nuclear reactors for energy generation (ANL, n.d.). The laboratory made numerous scientific advances such as producing the first ultrasound images of the human body and the discovery of elements einsteinium and fermium. In 1963, the GeV Zero Gradient Synchrotron (ZGS), a proton accelerator, opened at a construction cost of $50 million. This facility advanced high-energy physics research until 1979 when ANL constructed IPNS (Simpson et al., 2006).

IPNS was an advancement in neutron scattering capabilities for the United States because it was one of the first facilities in the world to use spallation, which produces more neutrons per unit of power than fission. Spallation also produces less heat per neutron than fission and can create short bursts of high-flux neutrons (Westfall, 2007). The builders for IPNS sought to create a machine that produces more useful neutrons so that neutron scattering researchers would have the benefit of better resolution and the ability to use smaller samples (Westfall, 2007).

Construction on IPNS started in 1979. More than $40 million in resources such as the accelerator system, the building, roads, electrical power, instrument components, and cooling towers were salvaged from the ZGS and CP-5 reactors (Westfall, 2007). The facility opened in 1981 and achieved success in the scientific community for work done on high-temperature superconductivity in 1987 (Westfall, 2007). At its peak, IPNS had 11 instruments supporting the user program but while all were considered useful research tools, none were world-class due to the low power of the source (DOE, 2001).

IPNS was a crucial resource and, at times, one of the only functioning federal neutron scattering facilities in the nation due to technical problems at LANSCE and safety reviews that occurred at the BNL and ORNL reactors in the wake of Three Mile Island and Chernobyl (Westfall, 2007). However, once the SNS facility opened in 2006, DOE made the decision to close IPNS in 2008 (Westfall, 2007). We estimate that 1,388 unique publications were generated from research using IPNS throughout its operation.

3.3 University Research Reactors

Below we review U.S. university research reactors or other neutron sources that either currently have the capacity to conduct neutron scattering research or have plans for conducting neutron scattering in the future. Section 9 provides a more detailed overview of the history of university research reactors in the United States.

3.3.1 North Carolina State University Nuclear Reactor Program (NRP)

The North Carolina State University (NCSU) Nuclear Reactor Program (NRP) has a 1-MW PULSTAR research reactor equipped with four instruments: a neutron powder diffractometer, a neutron imaging facility, a state-of-the-art intense positron source, and an ultracold neutron source. The reactor is routinely used by engineering, science, medical, and agriculture program faculty and students from both within and outside the NCSU campus to perform irradiations and testing. In addition, the PULSTAR is used to examine unirradiated and irradiated materials such as graphitic materials, semiconductor materials, metals, magnetic materials, and soft matter. The PULSTAR reactor is a member of DOE's Nuclear Science User Facilities (NSUF) and is a partner in the NSF Research Triangle Nanotechnology Network. Any student enrolled at NCSU can take part in training with the PULSTAR reactor to become a nuclear reactor operator licensed by the NRC.

Reactor management has focused on cultivating long-term research collaborations with federal entities, such as the DOE national laboratories, the Naval Nuclear Laboratory, and the Nuclear Criticality Safety programs of the NNSA, as well as various private companies. NCSU faculty and NRP staff provide the needed expertise to support utilization of the reactor, including the military's needs for neutron imaging and irradiation testing. In some cases, military technical staff visit the NRP PULSTAR facilities to participate in tests and bring tools and expertise. Contract research and external grants defray approximately 75% of the annual operating expenses for the reactor.

NCSU has benefited from Nuclear Energy University Program's (NEUP) grants for research reactors and infrastructure improvements (see NEUP for more information). Since 2010, these grants have allowed the NRP to install equipment in support of the power upgrade of the PULSTAR reactor, establish a hot cell capability, and install new reactor control console instrumentation and monitoring equipment. These improvements have allowed NCSU to contribute to large national experiments, such as the ultracold neutron effort at ORNL, and have positioned the reactor to serve an important role in the development of small modular reactors and other advanced nuclear reactor concepts. New facilities for testing nuclear fuel, and to perform irradiations in molten salt environments, are being established.

Dr. Ayman Hawari, distinguished professor of nuclear engineering and director of the NRP, is optimistic about the reactor's future. "The PULSTAR's impact, as a state-of-the-art research reactor, will be more evident as we move into the 21st century." Moreover, NCSU is currently considering building an advanced research reactor, with a thermal power of 10–20 MW, to expand its science and engineering applications portfolio.[3]

3.3.2 Massachusetts Institute of Technology Reactor (MITR-II)

In 2000, the Massachusetts Institute of Technology (MIT) Reactor, MITR-II, along with the reactors at Cornell University and the University of Michigan, were in danger of closing. Although a Task Force recommended funding, DOE declined to support these university research reactors (Rogers, 2002). By 2003, the reactors at both the University of Michigan and Cornell University were closed. Despite the conditions of the time, MIT managed to sustain reactor operations.

According to Dr. Gordon Kohse, the Managing Director for Operations for MITR-II, MIT made a series of decisions to focus on research activities that supported the needs of DOE, to increase reactor use among MIT faculty, and to undertake a limited amount of commercial activity. MIT developed a strong nuclear materials and in-core research program, contributing to advances in nuclear fuel and materials to support light-water and next-generation nuclear power reactors. Because of its relatively high-power density, capability to control chemistry and thermal conditions to reflect prototypic conditions, easy-access geometric configuration, and space for up to three independent in-core irradiation tests, MITR-II is well-suited for carrying out such nuclear materials studies (MIT Nuclear Reactor Laboratory 2024). These DOE-sponsored research projects are the major sources of financial support for the reactor, together with DOE fuel cycle support.

Another strategic move was the decision to appoint three codirectors for the MIT Nuclear Reactor Laboratory (NRL) in 2019. This joint leadership structure increased collaboration between reactor users and university departments. The codirectors seek to expand external collaborations and work with MIT faculty from wide-ranging disciplines to support research and education objectives (MIT Office of the Vice President for Research, 2019).

This renewed financial stability has allowed the NRL to continue a limited amount of neutron scattering experimentation and research to better develop focusing optics used in imaging and small angle neutron scattering (MIT, 2007).

MIT's neutron scattering activities use a neutron optics test station beamline with polychromatic neutron beam (MIT Nuclear Reactor Laboratory, 2024). This beamline has been used occasionally for neutron-focusing optics testing, neutron imaging, and building demonstrations of novel neutron scattering techniques. MIT hopes to expand its neutron scattering capacity by

[3] Hawari, A. (2023, May 25) Personal communication with RTI.

adding a Small Angle Neutron Scattering (SANS) instrument in the next 3–5 years, and X-ray imaging for simultaneous neutron/X-ray radiography and tomography. These instruments would serve the research needs of MIT faculty and students, and the local biotechnology and batteries communities. Although MITR-II is not powerful enough to rival national user facilities, Kohse envisions a facility with enough functionality to make it useful for people who do not need to push technical boundaries. It will also be a laboratory where people can test-run experiments before going to federal facilities with greater time constraints.

MIT's strategic actions to identify the types of research best suited to its reactor, to have a cross-disciplinary leadership team, and to engage in commercial work, along with continued support from MIT's administration, have created a financially strong program. This strong foundation has supported neutron scattering instrument development with plans to expand neutron scattering instrumentation in the future. By investing in neutron scattering instruments that can be used by the university faculty and local industry, the NRL is poised to attract new users while continuing to support its existing user base.

3.3.3 University of Missouri Research Reactor (MURR)

The University of Missouri Research Reactor (MURR) is the most powerful university research reactor in the United States, located at a research institution with a growing neutron scattering program. Four neutron scattering scientists at MURR are working to use its neutron resources to the best possible advantage.[4] When asked about the facility, MURR representatives provided the following information:

> *MURR is a unique facility that operates at 10 megawatts, 24 hours per day, 6.5 days per week, and 52 weeks per year. This operating schedule makes MURR indispensable for medical isotope production and neutron-based research programs. MURR is the sole U.S. supplier of four short-lived medical radioisotopes critical to patient diagnosis and the treatment of heart disease and cancer, and regularly supplies dozens of other isotopes to researchers across the country and around the world. Over 1,600,000 medical doses for cancer and cardiac patients are made at the reactor every year and shipped nationwide.*
>
> *In addition to medical isotope production, MURR is renowned for many of its research programs including leading programs in radiopharmaceutical development, materials science, plant imaging, and trace element epidemiology, as well as the Archaeometry Lab, which has been continuously supported by the NSF for over 35 years. MURR currently operates four neutron scattering instruments: a triple-axis spectrometer, a neutron reflectometer, and two diffractometers. The former two provide unique capabilities on a university campus. One of the diffractometers was recently upgraded with support through the NSF IGERT program that also boosted graduate training in neutron scattering techniques, an area that has been a long-held strength of MU and MURR. Although MURR does not run a user program, its researchers regularly*

[4] Heitmann, T. (2023, January 17), Personal Communication with RTI.

collaborate with partnering research groups on and off the MU campus as a means to make facilities more broadly available.

In order to handle the increasing activities, MURR is preparing to build a 48,000 square foot addition with groundbreaking scheduled for later this year (2023). This additional space will include laboratories for research and engineering, additional offices, student workspace, and more. In addition, discussions have started regarding the construction of a new reactor. An earmark in the National Institute of Standards and Technology FY 2023 budget provides $20 million for preliminary work and planning of a next generation reactor at MURR. A new reactor not only improves the national landscape for commercial medical isotope production, but also may provide future opportunities to develop the neutron scattering instruments and faculty to support high-impact research in materials, nuclear, and biological sciences.

3.3.4 Breazeale Research Reactor

One of the first university research reactors in the county, the Breazeale research reactor at Penn State, has long been a training ground for international and domestic commercial reactor operators. In recent years, it has embarked on an ambitious plan to improve the facility and instrumentation to support advanced nuclear reactor research.

In 2022, the Breazeale reactor received a donation of a SANS instrument, from the Energy Research Institute Helmholtz-Zentrum Berlin in Germany. This instrument lets researchers measure how neutrons scatter when they interact with a variety of materials. If installed and calibrated, Penn State will be the only university research reactor with a SANS facility in the United States (Schaffhauser, 2022).

In late 2022, Penn State announced that it would lead the Post-Industrial Midwest and Appalachia Nuclear Alliance to facilitate nuclear research, infrastructure, education, and workforce development for advance reactors in their region (WennersHerron, 2022). The focus of the alliance is to promote innovation in microreactor technology to assist with the decarbonization of industry. Penn State hopes to use the partnership to form a nuclear battery research and development center using Westinghouse Electric’s eVinci microreactor (ANS Nuclear café, 2022).

3.3.5 McClellan Nuclear Research Center

One of the newest university research reactors in the United States is the University of California’s McClellan Nuclear Research Center (MNRC). Built in 1990 for the U.S. Air Force, it was transferred to the University of California, Davis (UC Davis) in 2000 (Kitaura, 2016). This facility specializes in using neutron imaging for nondestructive testing and was built to detect low-level corrosion and hidden defects in aircraft structures (McClellan Nuclear Research Center, 2024).

Testing flight components for NASA missions is one important use of the facility. The center performed neutron imaging of the pyrotechnic devices known as “frangible rings”—responsible for stage separation of a rocket—to ensure they worked correctly for the Artemis I space mission. Currently, the center is testing components for Artemis III, which will return humans to the surface of the moon (Gautam, 2022).

3.3.6 Low Energy Neutron Source (LENS)

The NSF approved a major research instrument grant for the United States' first compact accelerator-driven neutron source (CANS) in 2003, envisioned as a low-cost, regional neutron facility that would be well-suited for developing novel instrumentation, educating new neutron scientists, and conducting materials research and feasibility studies for future experiments at user facilities (NSF, 2003). The result is the Low Energy Neutron Source (LENS) at Indiana University's Center for Exploration of Energy and Matter. LENS is a pulsed neutron source, not a nuclear reactor, that became fully active in 2005.The facility includes three instruments: a SANS instrument, a spin echo scattering angle measurement instrument, and a moderator imaging station. A second target station is designed for testing radiation effects with fast and thermal neutrons. LENS operates at 4 kW, making it a medium-power CANS facility, as opposed to high-flux, high-power facilities operating at more than 10 kW and small facilities that produce less than 1 kW of power (League of European Neutron Sources Ad-hoc Working Group CANS, 2020).

LENS received additional grants from NIST to support cooperative research activities, including the development of neutron scattering instrumentation, new scientific techniques and applications, and outreach, fostering instruction and training in neutron scattering research across institutions, as well as funding from both the NSF and DOE for developing neutron-spin-manipulation devices and experimental neutronics research. However, the project faced challenges, including the closure of the co-located Indiana University Cyclotron Facility (in 2014) and the Midwest Proton Radiotherapy Institute (in 2015), reducing access to knowledgeable technical staff. Ultimately, LENS leadership concluded that the facility was a strong resource for training graduate students, developing instrumentation, and preparing experiments, but there was no sustainable way to fund the source. LENS has been inactive since 2020, yet it was a bold initiative to support neutron-reliant science through creation of a smaller-scale facility. Dr. David Baxter, Chair of the Physics Department at Indiana University Bloomington, summarized the lasting impact of the LENS facility this way: "LENS demonstrated that interesting science and innovation programs can be developed at CANS facilities of modest power, and it has served as an example that has since led to the development of similar facilities across the globe with a wide range of missions."

Although LENS remains a singular facility in America, CANS have been constructed in Japan, China, and Europe. In recent years, the League of Advanced European Neutron Sources identified CANS to replace smaller, aging reactor sources of neutrons and serve as the base in a hierarchy of sources to maintain a thriving user community. A work group noted that CANS offer capabilities that are challenging to accommodate at high-performance sources, may serve as important links with existing institutes, and can create widespread knowledge about how to use accelerator-based neutron sources among local researchers (League of Advanced European Neutron Sources Ad-hoc Working Group CANS, 2020).

3.3.7 Molten Salt Research Reactor (MSRR)

The Nuclear Energy eXperimental Testing Research Alliance (NEXTRA), centered at Abilene Christian University (ACU), is pursuing development of the Molten Salt Research Reactor (MSRR). Although ACU does not have an existing research reactor, the consortium includes the University of Texas at Austin, Texas A&M University, and the Georgia Institute of Technology, all of which had or have research reactors.

NEXTRA submitted a construction permit application to the NRC in August 2022 to build the MSRR to conduct nuclear energy R&D. It is the first permit application for a new university research reactor in more than 30 years (Thomas, 2022).

4. U.S. Federal Neutron Scattering Facility Research Outcomes

Neutron scattering research conducted at NCNR, ORNL, Lujan, HFBR, and IPNS has produced significant research output in the form of publications and patents. The quantity, visibility, and quality of publications and patents resulting from neutron research at the five facilities were analyzed based on various citation-based bibliometric indicators well as source-based indicators. Additionally, we performed a thematic analysis to identify the domains in which the patents originated and to provide an indication of where they are likely being applied. Lastly, we extracted network data from publication and patent records to conduct network analyses identifying key contributors and the extent of collaboration occurring within the research space.

4.1 Research Publications

NCNR, ORNL, and Lujan each provided RTI full or partial publication archives. We created a processing workflow using Python to associate the publication records with publications in the Dimensions database. This workflow is described in detail in Appendix B. All facilities except NCNR—that is, ORNL, Lujan, BNL, and ANL—went through a second supplemental step to find likely additional publications to fill gaps in available administrative records.

1. First, a corpus of associated concepts (from the concept field available through Dimensions) was assembled for a first pass. These concepts were related but not limited to neutron scattering and spectroscopy techniques and associated keywords.
2. Next, the Dimensions database was queried for keywords related to specific instruments and neutron sources by facility, bounded by the operating years for each facility. The number of publications found is shown in the last section of Table 4-1.

Table 4-1 indicates the number of publications extracted from available administrative records for NCNR, ORNL, and Lujan along with the number and percentage of records matched in Dimensions. A record could go unmatched in Dimensions either because our search methods were unable to successfully account for all possible differences in record format (e.g., author name or title inconsistencies) or because a record has not yet been digitized and incorporated into Dimensions. Because digitized records are less prevalent for years preceding online publications, record matches were lowest for earlier years.

Table 4-1 also indicates the number of publications identified through supplemental searches in Dimensions for years in which no archival publication records were available. This process was not necessary for NCNR because full archival publications records were available for that facility. We used the percentage of publications from NCNR administrative records in each decade that were matched in Dimensions to inflate the number of records identified through supplemental Dimensions searches for other facilities. This decreases the known undercounting from relying exclusively on Dimensions searches for identifying publications but also only provides a rough estimate of total publications as the record match ratio is not guaranteed to be the same across facilities.

Table 4-1. Publications Extracted from Administrative Data and Identified in Dimensions

Facility (Years Covered)	1960s	1970s	1980s	1990s	2000s	2010s	2020s	**Total**
Publications Extracted from Administrative Records								
NCNR (1969–2021)	32	615	1,298	2,833	3,427	3,020	271	11,496
ORNL (1968–2021)	—	—	—	—	380	6,120	690	7,190
Lujan (2003–2011)	—	—	—	—	546	254	—	800
Rate of Unique Publications in Administrative Records								
NCNR (1969–2021)	100%	71%	73%	68%	82%	99%	100%	85%
ORNL (1968–2021)	—	—	—	—	100%	99%	100%	100%
Lujan (2003–2011)	—	—	—	—	88%	99%	—	94%
Publications Identified in Dimensions								
NCNR (1969–2021)	13	291	612	1,373	1,984	2,498	222	6,993
ORNL (1968–2021)	—	—	—	—	254	4,280	546	5,119
Lujan (2003–2011)	—	—	—	—	302	217	—	270
Rate of Successful Identification in Dimensions (C/A)								
NCNR (1969–2021)	41%	47%	47%	48%	58%	83%	82%	58%
ORNL (1968–2021)	—	—	—	—	67%	70%	79%	72%
Lujan (2003–2011)	—	—	—	—	55%	85%	—	70%
Count of Publications Found in Dimensions via Supplemental Search Methods								
NCNR (1969–2021)	—	—	—	—	—	—	—	—
ORNL (1968–2021)	37	120	208	360	843	—	—	1,605
Lujan (2003–2011)	—	—	—	—	552	—	—	712
BNL (1968–1996)	34	250	339	181	—	—	—	804
ANL (1981–2008)	—	—	179	354	463	—	—	996
*Estimated Total Count of Publications (A*B + E/D)*								
NCNR (1969–2021)	32	434	945	1,923	2,795	2,982	271	9,381
ORNL (1962–2021)	51	166	288	498	1,545	6,066	690	9,304
Lujan (2003–2011)	—	—	—	—	1,363	252	—	1,615
BNL (1966–1996)	47	348	472	252	—	—	—	1,120
ANL (1981–2008)	—	—	249	493	645	—	—	1,388

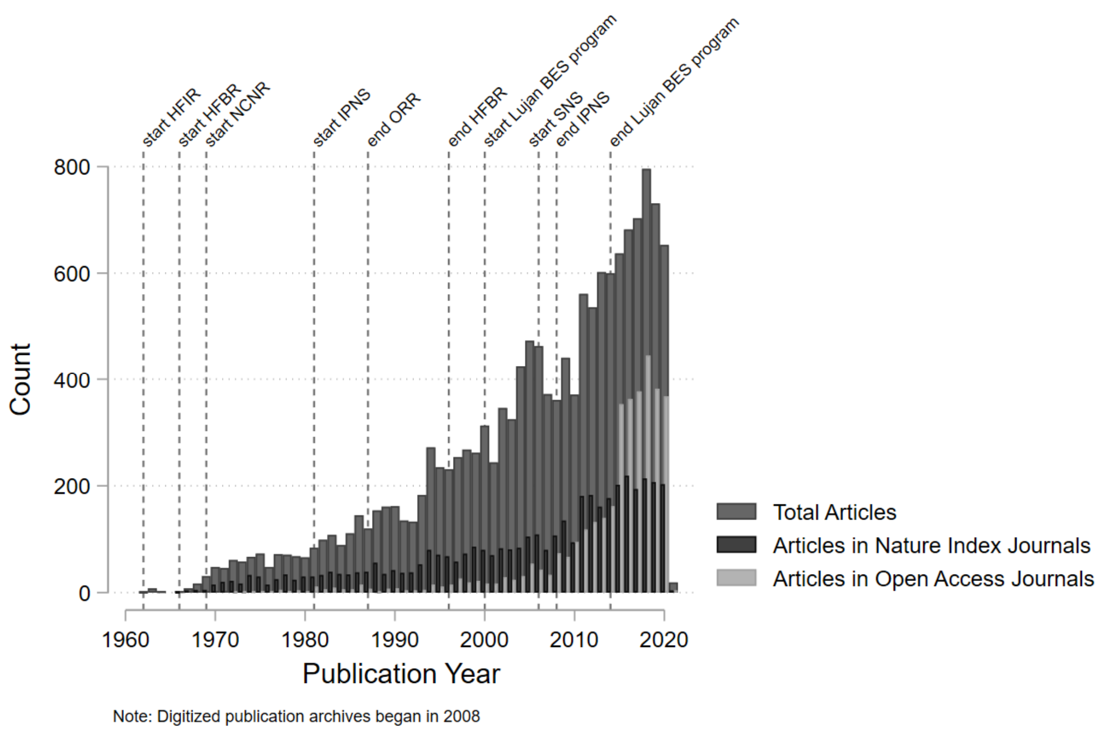
4.1.2 Journal Types

Our bibliometric analysis focuses on journal articles, which comprise about 93% of total publications, to apply journal- and citation-based metrics to better understand trends in quantity, visibility, and scientific significance over time. The number of articles published each year across the five facilities has increased over time. The trend in Figure 4-1 depicts a roughly linear increase until the 2000s, at which point the rate of production increased more dramatically until

2018. This trend is partly a function of the increased number of journals. Also, access to digitized records from 2007 onward improved our ability to identify and retrieve relevant publication records from Dimensions. Nonetheless, the trend reveals a strong increase in scientific production over time.

In addition to the quantity of articles, a substantial share of articles coming from these facilities each year continues to be published in top journals. The list of journals indexed by Nature, which recognizes only top journals (as determined by a panel of expert editors), is arguably a reliable indicator of quality that is more robust than Journal Impact Factors, which can fluctuate wildly over time and are influenced by differences in citation patterns across disciplines. Notably, the share of articles in Nature index journals has remained relatively stable over time even as the total number of articles has increased, indicating that publishing quality has not been sacrificed at the expense of publishing quantity.

Figure 4-1. Total Articles, Articles in Nature Index Journals, and Articles in Open-Access Journals, by Publication Year

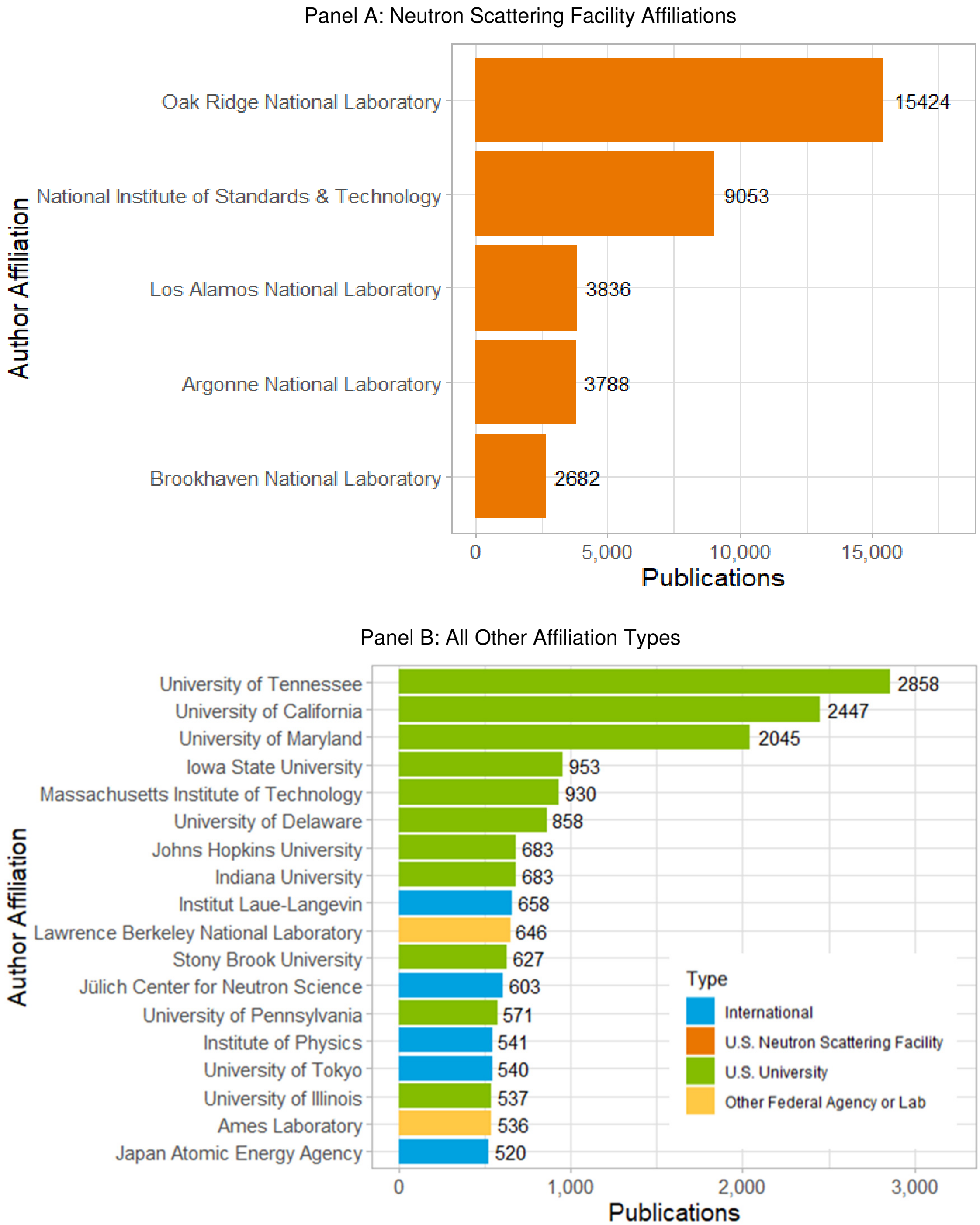


In addition to an increasing number of articles each year, an increasing share of those articles is more visible and accessible. The number of articles appearing in open-access journals exploded in the 2010s, although the share of articles published in open-access journals has been on an exponential trend since the 1980s.

4.1.3 Authors

Author affiliations across publications and years identify key contributors in neutron scattering research as well as facility user groups. Figure 4-2 shows the top institutional affiliations by number of publications, indicating the prevalence of research activity at those institutions.

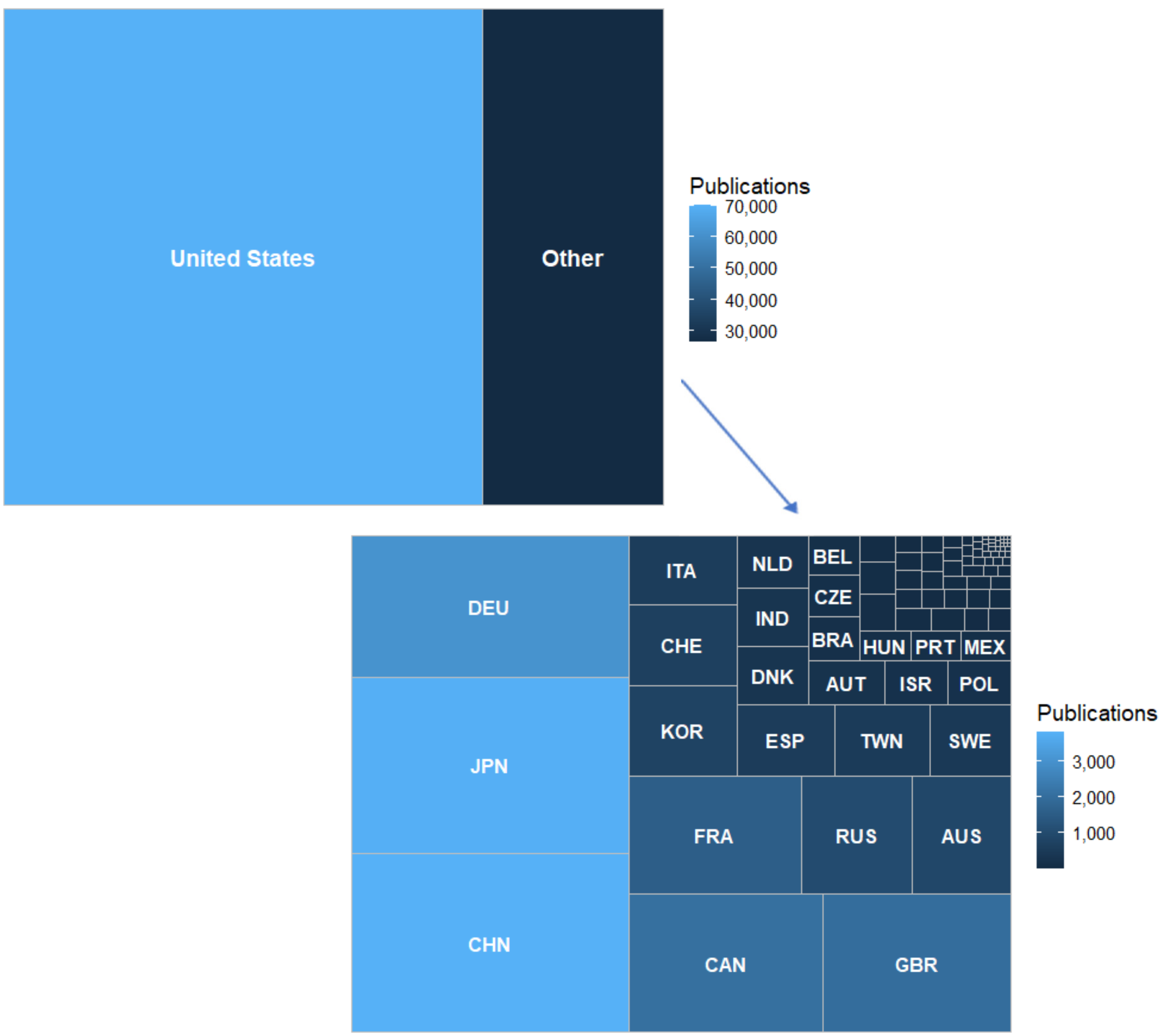
Figure 4-2. Publications by Author Affiliation



Most of the publications in our dataset come from authors who are directly affiliated with one of the U.S. neutron scattering facilities. The second most common author affiliation type in our corpus is U.S. universities, with the University of Tennessee, University of California, and University of Maryland systems each having over 2,000 publications. There are fewer publications from other U.S. federal agencies or labs and international facilities.

Figure 4-3 provides a breakdown of publications by author affiliation country. Publications stemming from research conducted at U.S. neutron scattering facilities are overwhelmingly written by U.S. authors, accounting for over 70,000 publications. Other countries comprise less than one-third of total publications. Non-U.S. institutional affiliations identify the countries that work in conjunction with U.S. neutron scattering facilities. The countries contributing to the most U.S. neutron scattering publications are China, Japan, and Germany, each with over 3,000 publications, followed by Canada, the U.K., and France, each with around 2,000 publications.

Figure 4-3. Publications by Author Affiliation Country



See Table B.1 for ISO Alpha-3 code key.

4.1.4 Funders

The origin of funding for publications is important for identifying the main organizations invested in neutron scattering research. Funding for neutron research is concentrated in a few key players, as shown in Figure 4-4. Article funders are grouped into four categories: U.S. neutron scattering facilities, other U.S. federal agencies or labs, nonprofits, and international entities. U.S. federal agencies and neutron scattering facilities are the dominant funder types. The U.S. Department of Energy (DOE) is the largest sponsor of journal articles, funding 8,416 publications, followed by NSF with 3,655 publications, and ORNL with 2,511 publications.

Figure 4-4. Publications by Funder

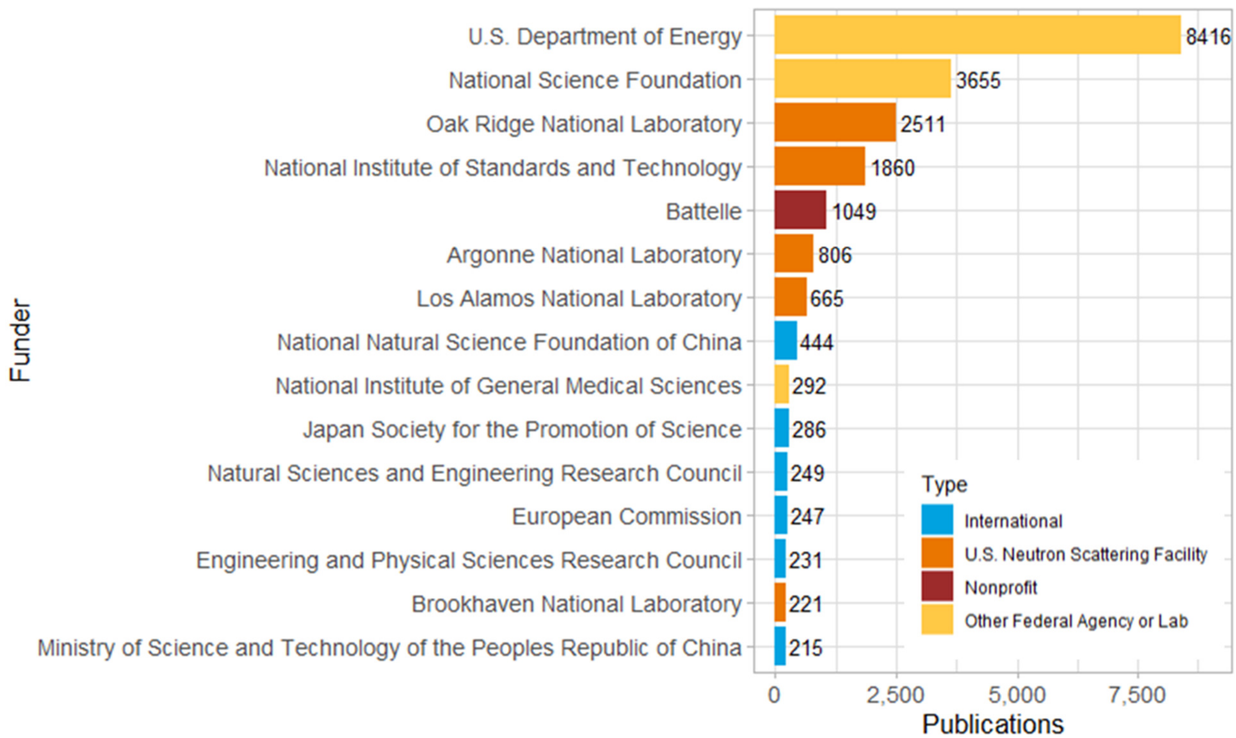
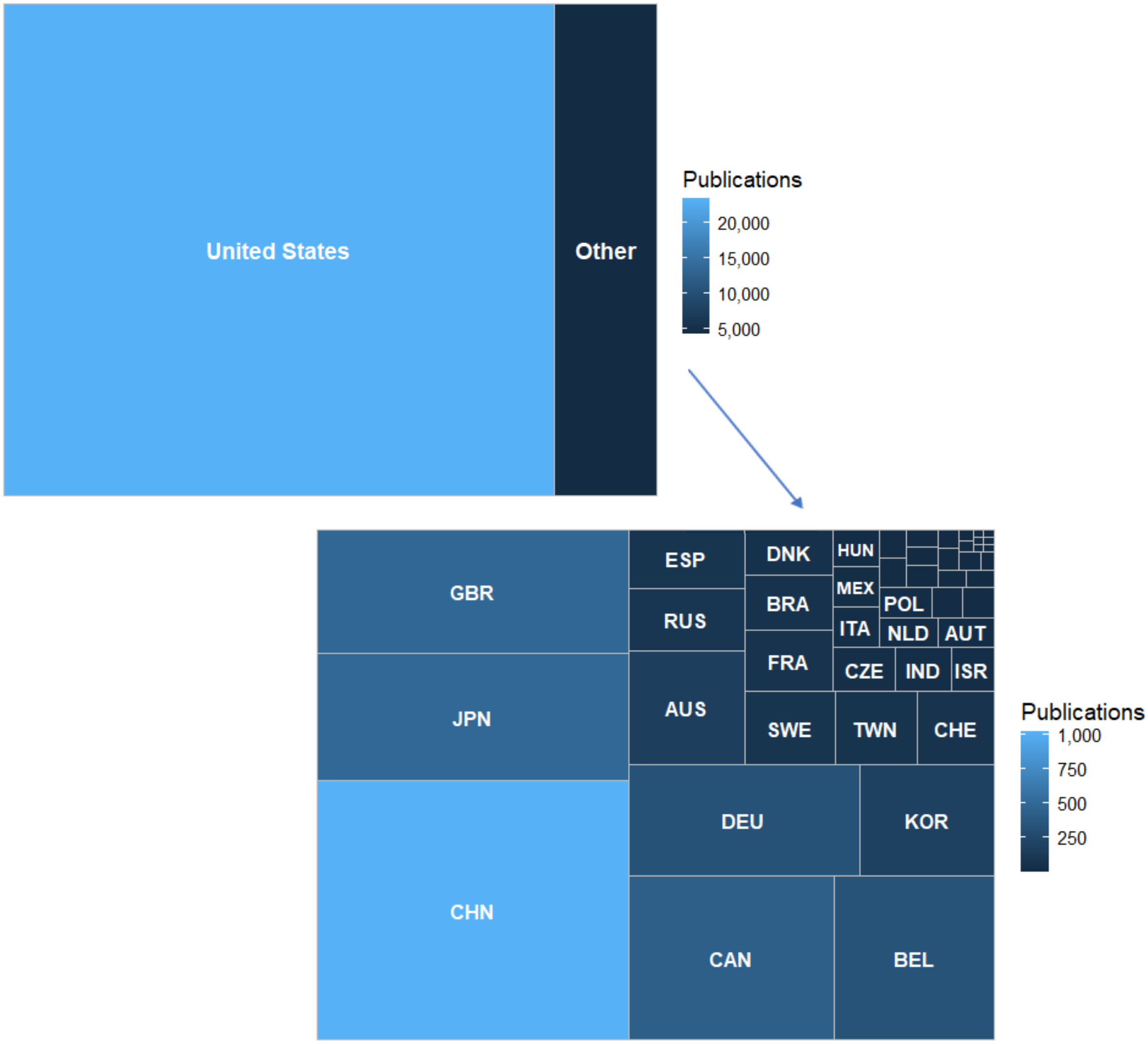


Figure 4-5 provides a closer look into the geographic distribution of article funders. Approximately 85% of article funding comes from U.S. institutions, accounting for 23,500 publications. China, Japan, and the U.K. are the largest international funders, with 1,000, 500, and 490 publications respectively. The remaining 9% of article funding highlights the extent of international collaboration sponsoring U.S. neutron scattering research, spanning six continents and 43 countries.

Figure 4-5. Publications by Funder Country



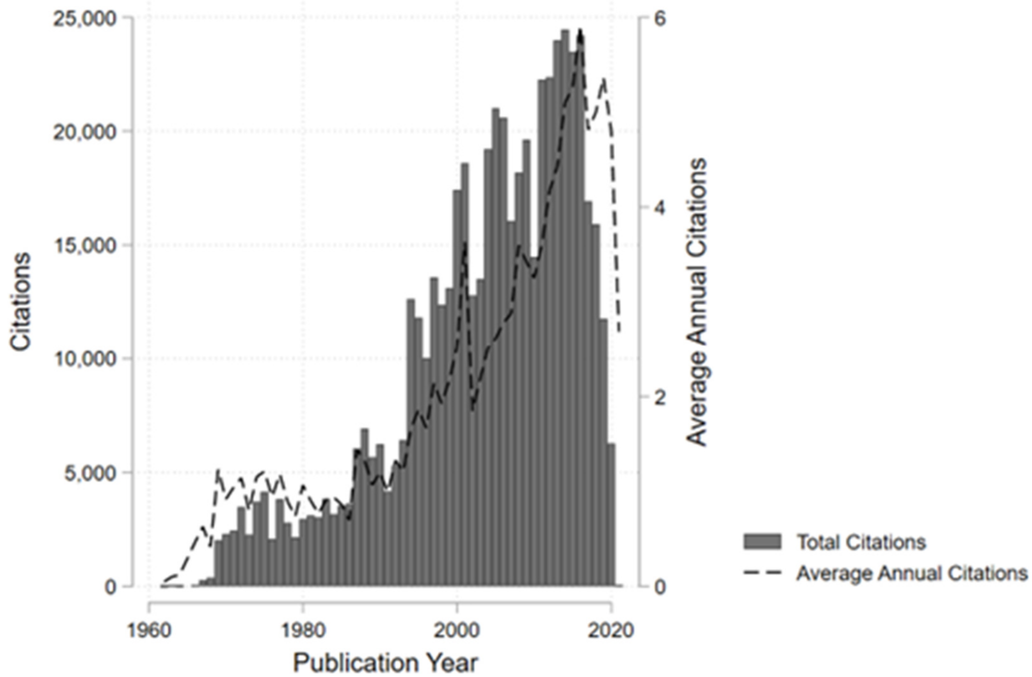
See Table B.1 for ISO Alpha-3 code key.

4.1.5 Citations

Forward citations provide a good indicator of the visibility and influence of a scientific article. Citations by later articles indicate increased awareness among future authors of the work and perceived relevance to future work (Waltman, 2016). Total citations have steadily grown with the total number of articles up to about 2013, at which point the total citation count per year begins leveling off and declining (Figure 4-6). This pattern is expected for more recent years because of the lag between a publication being read by a researcher and incorporated into a new research project and having that new research flow through the publication process. The accumulation of forward citations is thus a lagging indicator of visibility.

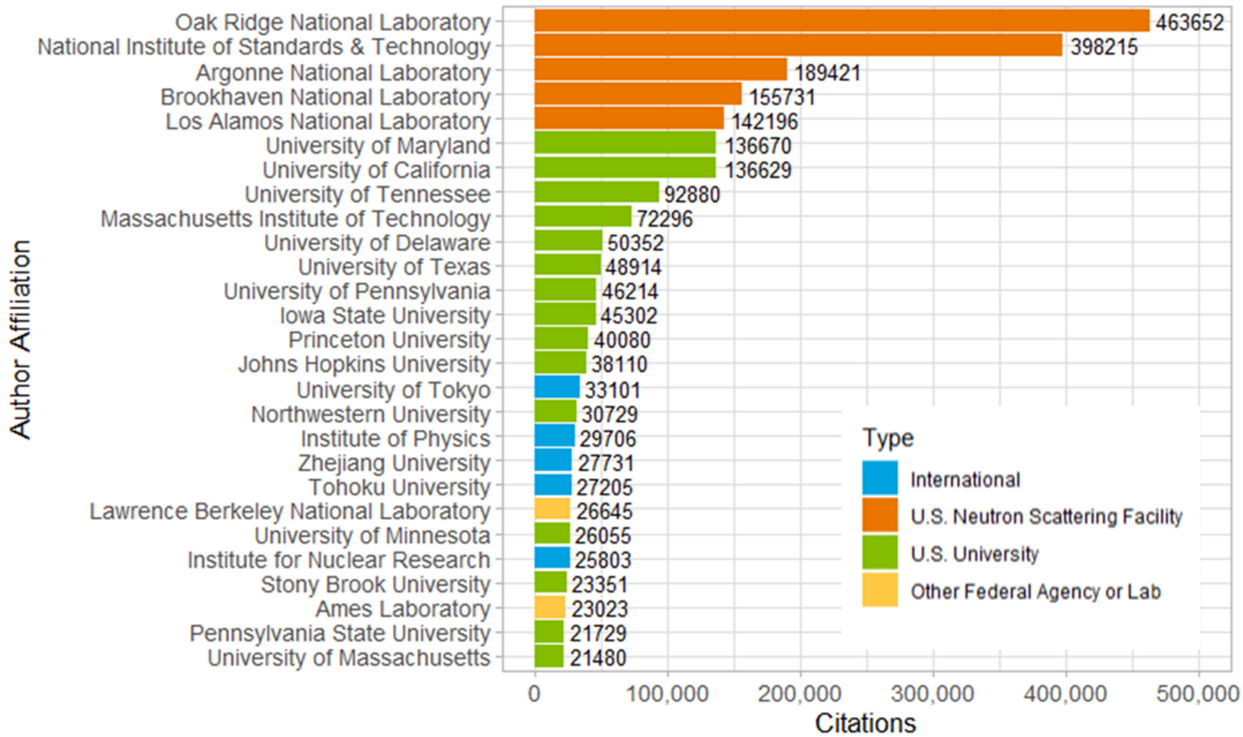
To adjust for time lags, we calculated the annual citation count for each article, which somewhat levels the comparison between older and more recent articles. Then we averaged the annual citation count of articles published in each year. The average annual citations for articles have grown over time, as depicted in Figure 4-6. The notable spike in 2001 is largely the result of a single extremely highly cited article. Part of the strong increasing trend in average annual citations could be driven by the increase each year in the number of journals and total number of published articles. Nonetheless, average annual citations have approximately tripled since 2000, which is indicative of an increase in the visibility of research performed at these neutron scattering facilities.

Figure 4-6. Total Citations and Average Annual Citations of Articles, by Publication Year



To provide a closer look into the distribution of forward citations, we repeated our analysis for author affiliations on the number of citations. While the concentration of total citations follows a similar distribution to that of total publications, Figure 4-7 highlights key differences that speak to the visibility of publications by author affiliation. First, the gap between ORNL and NIST (NCNR) is smaller for number of citations than number of publications, suggesting greater visibility of NIST-affiliated authors' publications. While the University of Tennessee system was the top publisher of non-facility affiliations, the University of Maryland and University of California systems surpass them in number of citations. This indicates a higher level of visibility and relevance of University of Maryland and University of California authors' publications to the body of neutron scattering research despite a lower publication output overall. The prominence of NIST and University of Maryland as top-cited affiliations can be linked to frequent collaboration between their authors, which will be explored further in the network analysis.

Figure 4-7. Citations by Author Affiliation



Note: Author affiliations within larger organizations were aggregated to avoid double counting. For this reason, NCNR was grouped into the NIST affiliation, as shown above.

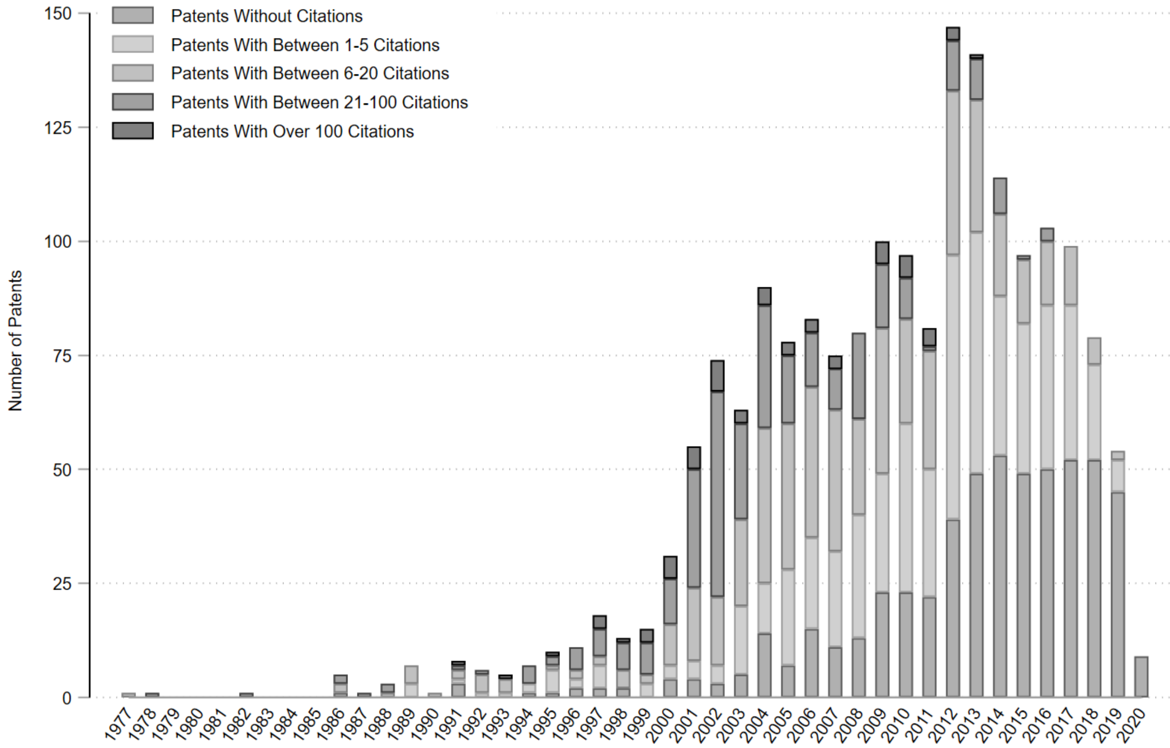
4.2 Patents

None of the U.S. neutron scattering research facilities maintain records of patents published based on research conducted at the facilities. Instead, RTI searched the Dimensions database for patents that cited the publications identified for each facility. In addition, when facility user lists were provided, we searched for relevant patents filed by these users. Using the described search methods, RTI identified 1,565 patents granted in the United States between 1968 and 2020 that cite research conducted at U.S. neutron scattering facilities.

4.2.1 Patent Counts

Figure 4-8 shows the number of patents granted per year that cite neutron research conducted at U.S. facilities. The number of granted patents citing neutron scattering research per year steadily increased up to 2012 before expectedly declining after that point. This decline is not a marker of a decrease in research productivity or industry relevance, but rather a natural pattern due to the lag time between research being conducted, published, and incorporated into a patent filing that is then granted. Research conducted in recent years is not likely to appear in patent filings for some time. Still, the overall pattern is one of strong growth in the influence of research conducted at U.S. neutron scattering facilities on the development of U.S. patents.

Figure 4-8. Number of Patents Granted per Year Based on Research Conducted at U.S. Neutron Scattering Facilities, by the Number of Forward Patent Citations



4.2.2 Assignees

Like authorship data for publications, assignee data for patents is useful for determining the key contributors in neutron scattering research output. The number of patents granted to an assignee indicates their level of research and innovation activity. Figure 4-9 shows the number of patents granted to top original assignees, categorized by assignee type. The most prolific patent assignee by far is Micron Technology Inc. who is active in the semiconductor application area of neutron scattering, with 220 patents. The most common assignee types are companies and U.S. universities, with the University of Illinois and University of California systems as the top academic assignees. Unlike with publications, the U.S. neutron scattering facilities are not strongly active in filing patents based on research conducted at the facilities.

Figure 4-9. Patents by Original Assignee

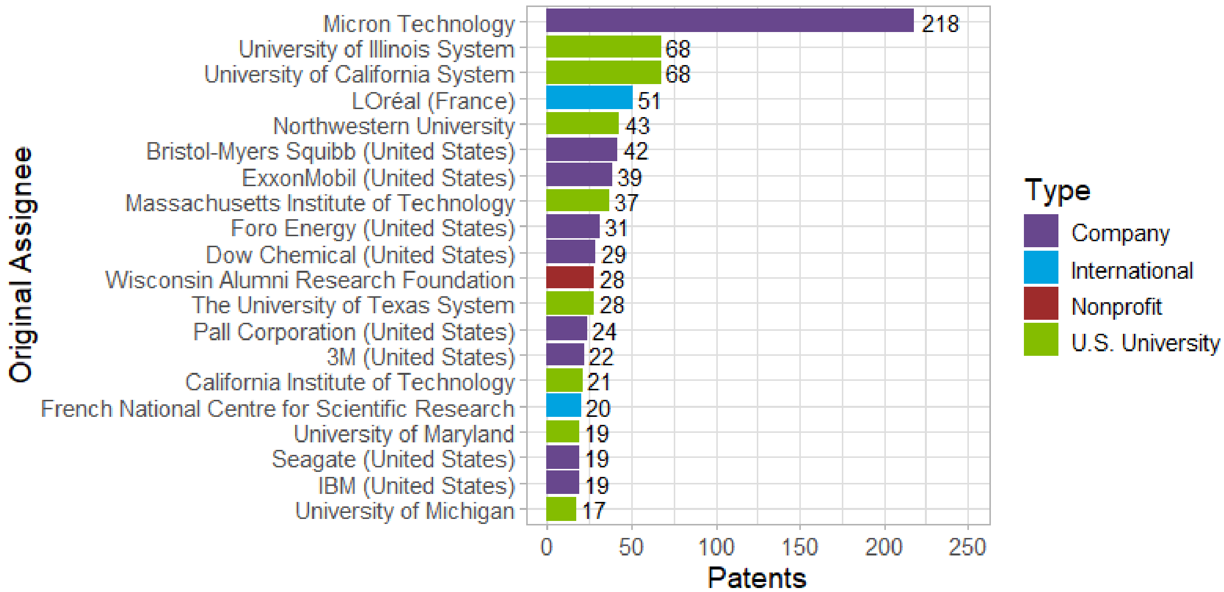
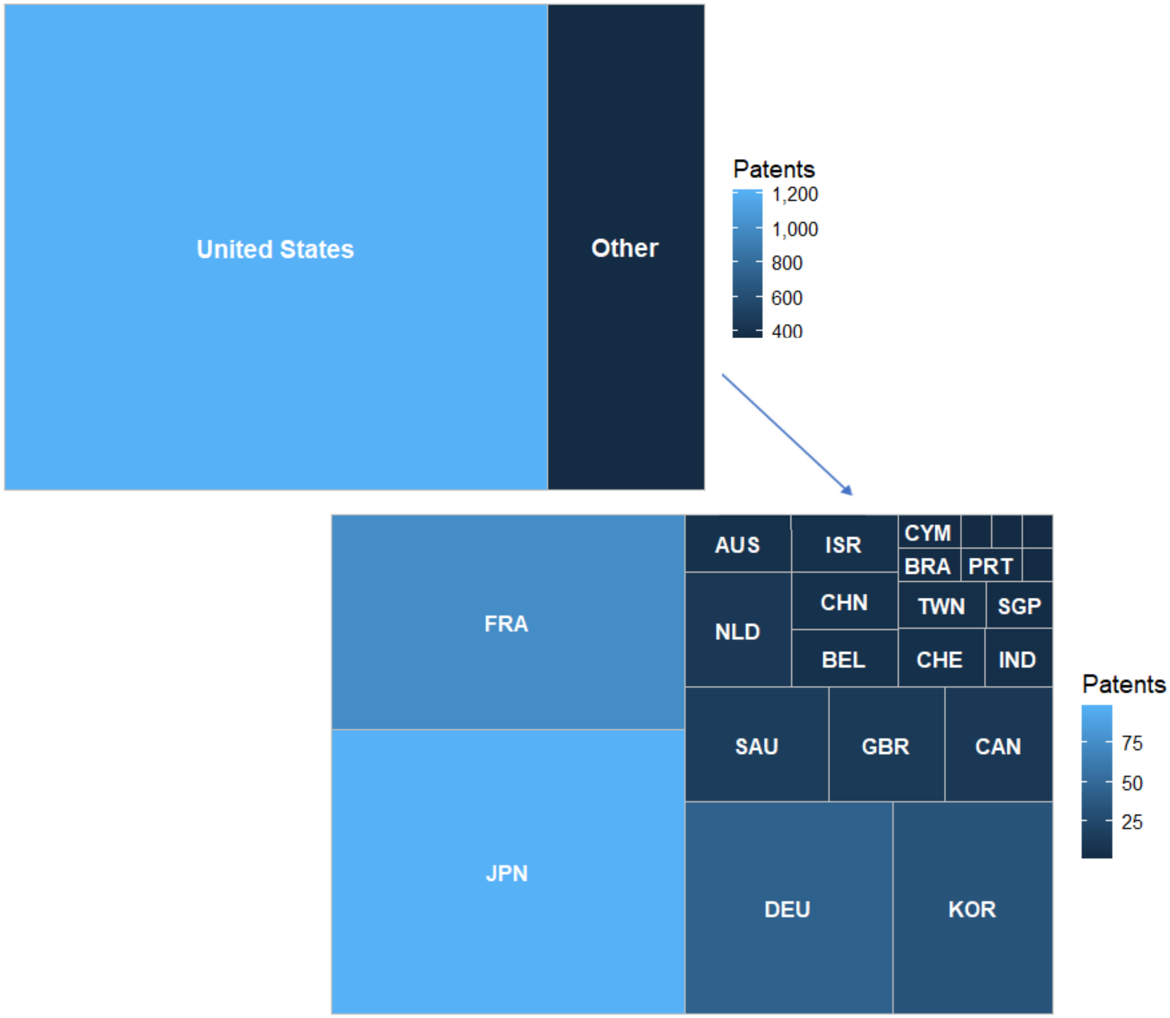


Figure 4-10 shows the geographic distribution of original assignees of patents. Approximately 75% of patent assignees are U.S.-based, accounting for 1,355 patents. While there is a greater percentage of international owners for patents (25%) compared to publications (15%), the total number of non-U.S. countries represented in patenting (N=28) is lower than the number represented in publications (N=89). This suggests that international patenting is more highly concentrated within a smaller number of countries. The most common international affiliation among original assignees is France with 123 patents, followed by Japan (73), Germany (46), and South Korea (34).

Figure 4-10. Patents by Original Assignee Country

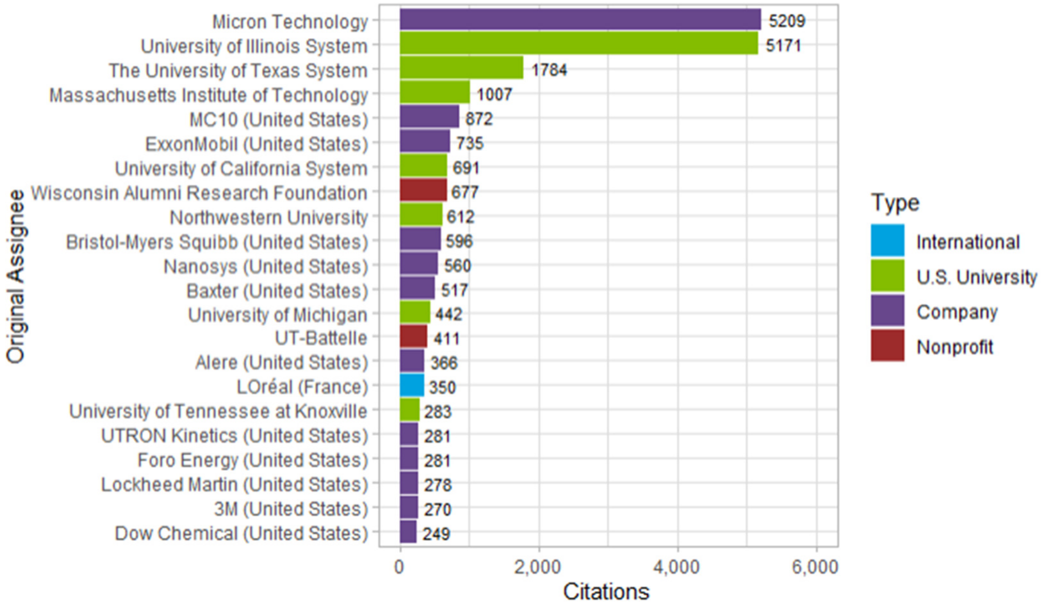


See Table B.1 for ISO Alpha-3 code key.

4.2.3 Citations

One potential marker for patent quality or impact is the number of forward citations it receives, or times that patent is cited in other patents. The number of forward citations can reflect the relative influence of their technologies on future patents. Previously, we examined the number of patents granted to original assignees in Figure 4-9, which portrays Micron Technology as the dominant producer of patent outputs for neutron scattering research. However, looking at the number of patent citations in Figure 4-11, patents by Micron Technology and the University of Illinois system each have around 5,200 citations. This suggests that University of Illinois's patents were highly influential and impactful for future innovation activity. Another influential assignee on this list is the University of Texas system, which has the third most forward citations despite a comparatively lower quantity of patents produced. While many assignees remain key players in both number of patents and number of citations, highly cited assignees with fewer total patents can indicate the strength of the impact of their technologies.

Figure 4-11. Patent Citations by Original Assignee



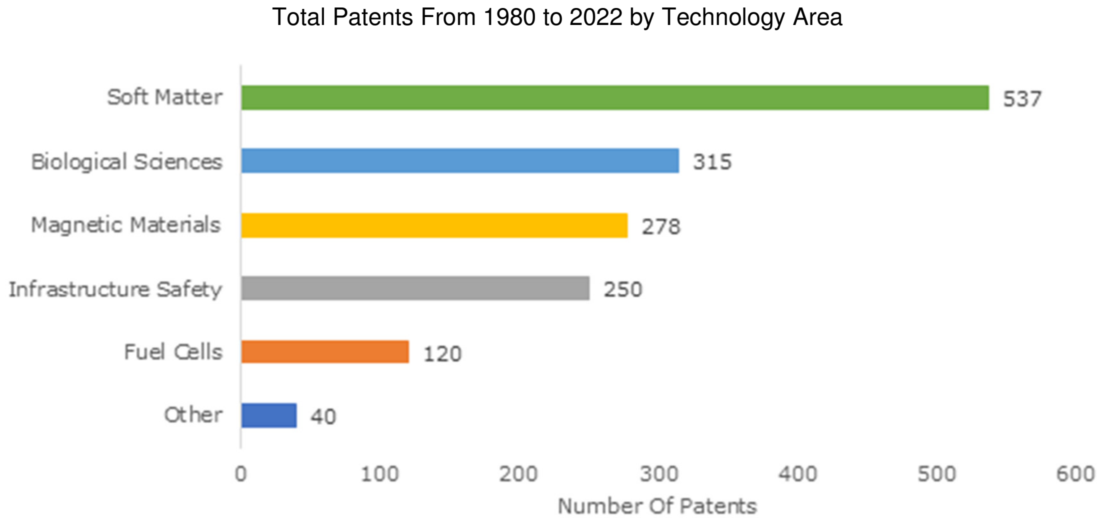
4.2.4 Technology Areas

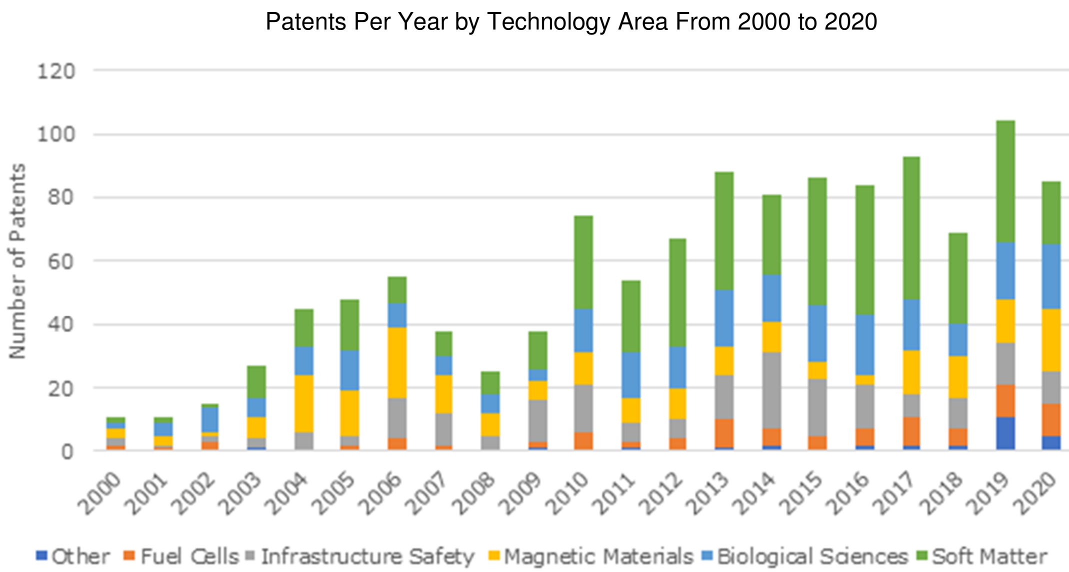
Of the 1,565 patents we identified based on research conducted at U.S. federal neutron scattering facilities, we were able to categorize 1,540 into five key technology areas: soft matter, biological sciences, magnetic materials, infrastructure safety, and fuel cells. For a subsample of patents in our corpus, the abstract of each patent was checked for keywords related to one of the technology areas. Relevant keywords for each technology area were identified through interviews, reports such as those issued by the APS (2018), and additional research into the five technology areas. Once appropriate keywords were identified, we trained an algorithm to search the abstract text of the remaining patens in our corpus. The 25 patents that were not able to be categorized did not have abstract text available in the Dimensions database. An additional 40 patents were classified as ‘other’ due to a lack of identifiable keywords in their abstracts.

Figure 4-12 shows the number of patents granted based on research conducted at the federal neutron scattering facilities between 1968 and 2022, broken out by technology area. We also summarize annual trends in patent output by technology from 2000 through 2020.[5] Soft matter accounts for most patents granted overall, followed by biological sciences, magnetic materials, and infrastructure safety. Despite accounting for fewer patents overall, the area of fuel cells has accounted for an increasing proportion of patents over time. The number of patents granted in magnetic materials decreased through 2016 but has grown since then along with an increased industry focus on supporting quantum computing development. However, much of the recent developments in magnetic materials research are still in early stages and are not likely to show up in patent records for some time.

[5] The summary period is reduced to 2000 through 2020 because of the reduced quality of the publication data available from earlier years and the reduced publications in 2021 and 2022 resulting from interruptions in facility access caused by the COVID-19 pandemic.

Figure 4-12. Patents Based on Research Conducted at Neutron Scattering Research Facilities by Technology Area Overall and Over Time





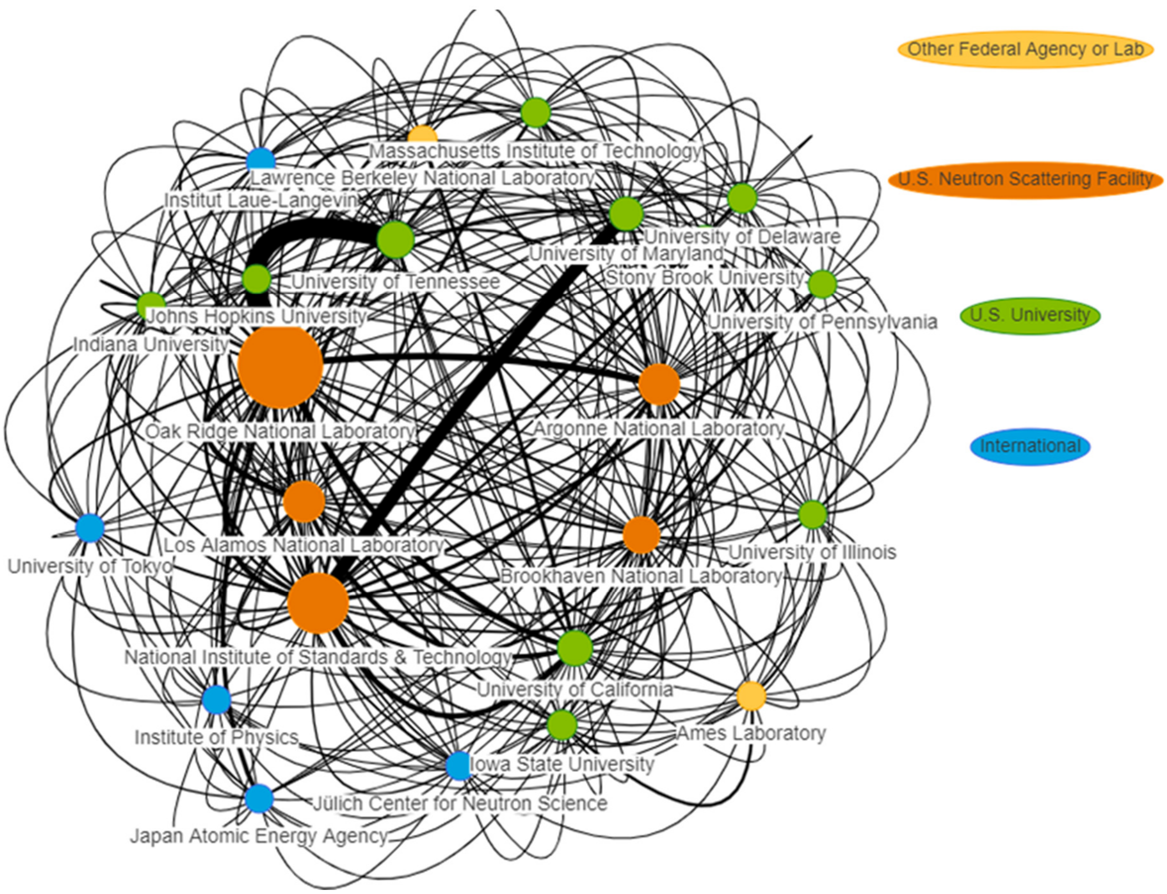
4.3 Network Analysis of Neutron Scattering Research Outcomes

The publications and patent records from U.S. neutron scattering facilities contained rich network data providing insight into research collaborations between authors and assignees. We applied network analysis methods to publications and patent data focusing on three distinct types of collaborative relationships: co-authorship, co-funding, and co-assignee. Each network is characterized by individuals, or “nodes,” and partnerships, or “edges.” The networks are weighted; the size of the circles (nodes) and the thickness of the lines (edges) connecting them represents the quantity of research output. The networks presented highlight the key contributors and collaborators facilitating the production of neutron scattering research publications and patents.

4.3.1 Research Publications

This section describes the findings of network analyses applied to author affiliations and article funders for publications related to U.S. neutron scattering research facilities. Figure 4-13 displays a weighted network of co-authored publications by author affiliation, where each node represents an affiliation, and each edge represents a co-authorship pairing. The weight of the node represents the number of publications written by authors affiliated with the individual institution, and the weight of the edge represents the number of publications co-authored by the pairing. The network is colored by affiliation type: U.S. neutron scattering facility, other U.S. federal agency or lab, U.S. university, and international.

Figure 4-13. Co-Author Affiliation Publications Network



The co-author affiliation publications network is highly saturated, with highly interconnected nodes. This reflects low centralization, as each node in the network has around the same number of linkages as other nodes. The weights of nodes and edges in the network emphasize key contributors and collaborators in neutron scattering research publications. The strongest partnership is between ORNL and the University of Tennessee, producing 688 co-authored publications. The weight of this edge reflects both the dominance of both entities in the user space as well as their physical proximity to each other, facilitating greater collaboration. Physical proximity can also explain the frequency of collaboration between NIST and University of

Maryland, with 419 co-authored publications. The University of California system demonstrates more diverse collaborations, having edges of similar weights with multiple neutron scattering facilities including ORNL, NIST, and LANL.

Another key finding evident in Figure 4-13 is related to the types of institutional collaborations. U.S. neutron scattering facilities in general appear to interact primarily with other facilities and U.S. universities, with occasional international collaboration. Likewise, U.S. universities most frequently collaborate with other U.S. universities and facilities. This demonstrates that U.S. neutron scattering facilities and U.S. universities are highly interconnected. This is largely driven by the inclusion of facility scientists in the publications of outside users. When external scientists do an experiment at a facility, they are assigned a facility scientist to assist them. Outside users often include these facility staff as coauthors on their resulting publications.

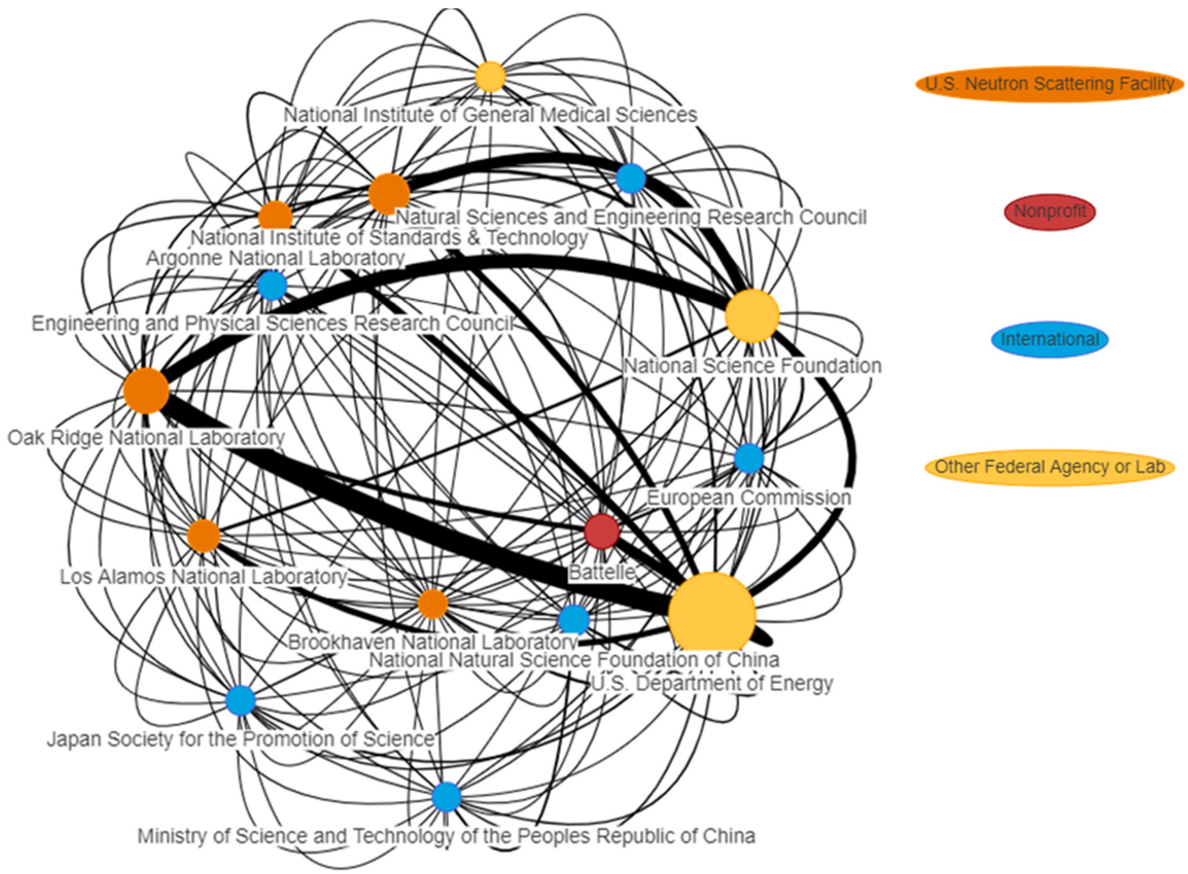
International affiliations appear on the periphery of the network, linking mostly with other international entities, indicating that international institutions are less strongly linked to U.S. authors. The strongest U.S.-international partnership is between ORNL and the Japan Atomic Energy Agency, with 110 co-authored publications. Overall, the co-author affiliation publications network displays a high degree of collaboration regardless of affiliation type.

Figure 4-14 provides a visual representation of article funding partnerships with a weighted network of publication co-funders. Each node represents an individual funder, and each edge is a co-funding relationship, where the weight of the node represents the number of publications funded by that entity and the weight of the edge represents the number of publications co-funded by the pairing. The network is colored by type of funder: U.S. neutron scattering facility, other U.S. federal agency or lab, nonprofit, and international.

Like Figure 4-13, the publication co-funding network is a highly saturated network with low centralization, with each node having around the same number of linkages with other nodes. This demonstrates that funders of research articles developed at U.S. neutron scattering facilities are highly interconnected by the same awardee base. The weights of edges in the network highlight frequent co-funding relationships, reflecting the dependence of the user base on multiple institutions. For example, the top funder—the DOE—most often funds research that is also funded by ORNL, with 1,482 co-funded publications. The DOE also frequently funds research that is also funded by Battelle and ANL, with 639 and 449 co-funded publications respectively. NSF, the second most prevalent funder, is most strongly linked to ORNL (945 publications), NIST (719 publications), and the DOE (480 publications) through co-funding relationships. This shows that the neutron scattering researchers often rely on multiple funding sources, creating a strongly interconnected web of neutron scattering research funding.

Unlike the author affiliation network where nodes tended to segregate by type, the funder network graph shows greater collaboration across types. Most notably, international funders have many linkages with U.S. neutron scattering facilities and U.S. federal agencies or labs, which are the dominant funder types. Key international funders – including the National Natural Science Foundation of China, European Commission, and the Japan Society for the Promotion of Science – have co-funding relationships with the DOE, NSF, and ORNL. This indicates a greater degree of connectedness between U.S. and international funders than between U.S. and international authors. As such, international funders play a key role in the funding of research conducted at U.S. neutron scattering facilities.

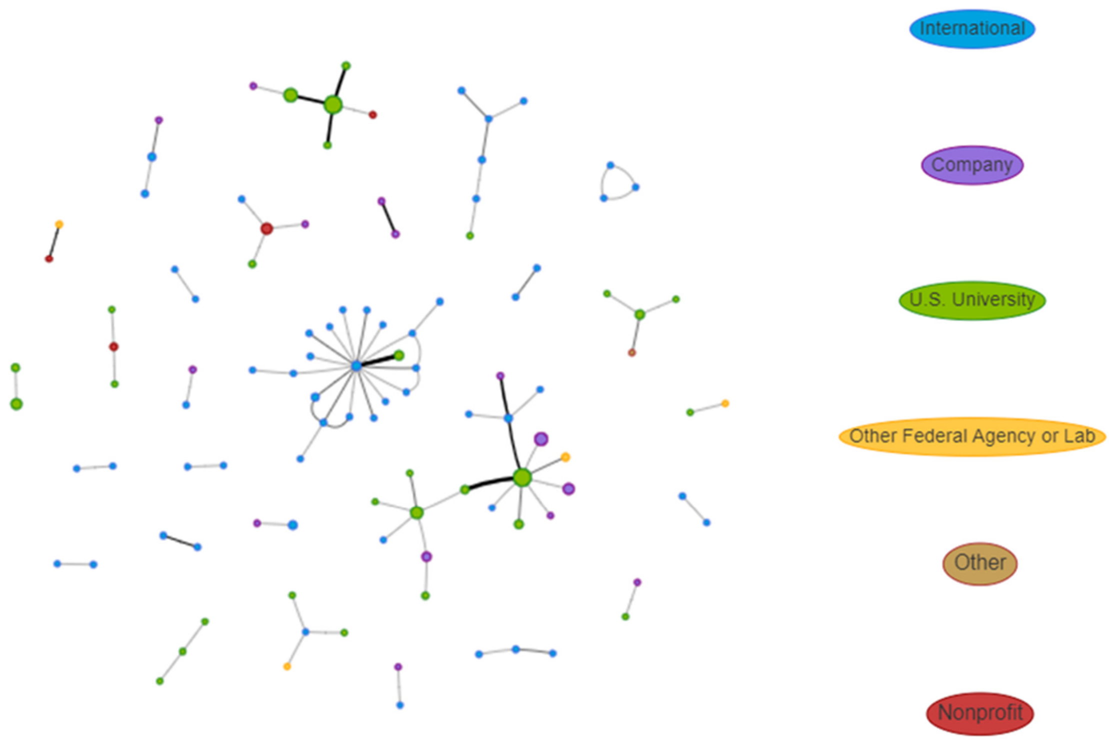
Figure 4-14. Co-Funder Publications Network



4.3.2 Patents

This section provides the findings of the network analyses applied to patent records stemming from research at U.S. neutron scattering facilities. We developed network visualizations for original assignee patent networks, highlighting key players and patent collaboration. Each figure below represents a weighted network of patents colored by original assignee type: international, U.S. company, U.S. University, other federal agency or lab, other, and nonprofit. Figure 4-15 displays a network graph by original assignees, where each node represents the original assignee, and each edge represents a co-assignee pair. The weight of node represents the number of patents assigned to the original assignee and, the weight of the edge represents the number of patents assigned to the pair of assignees.

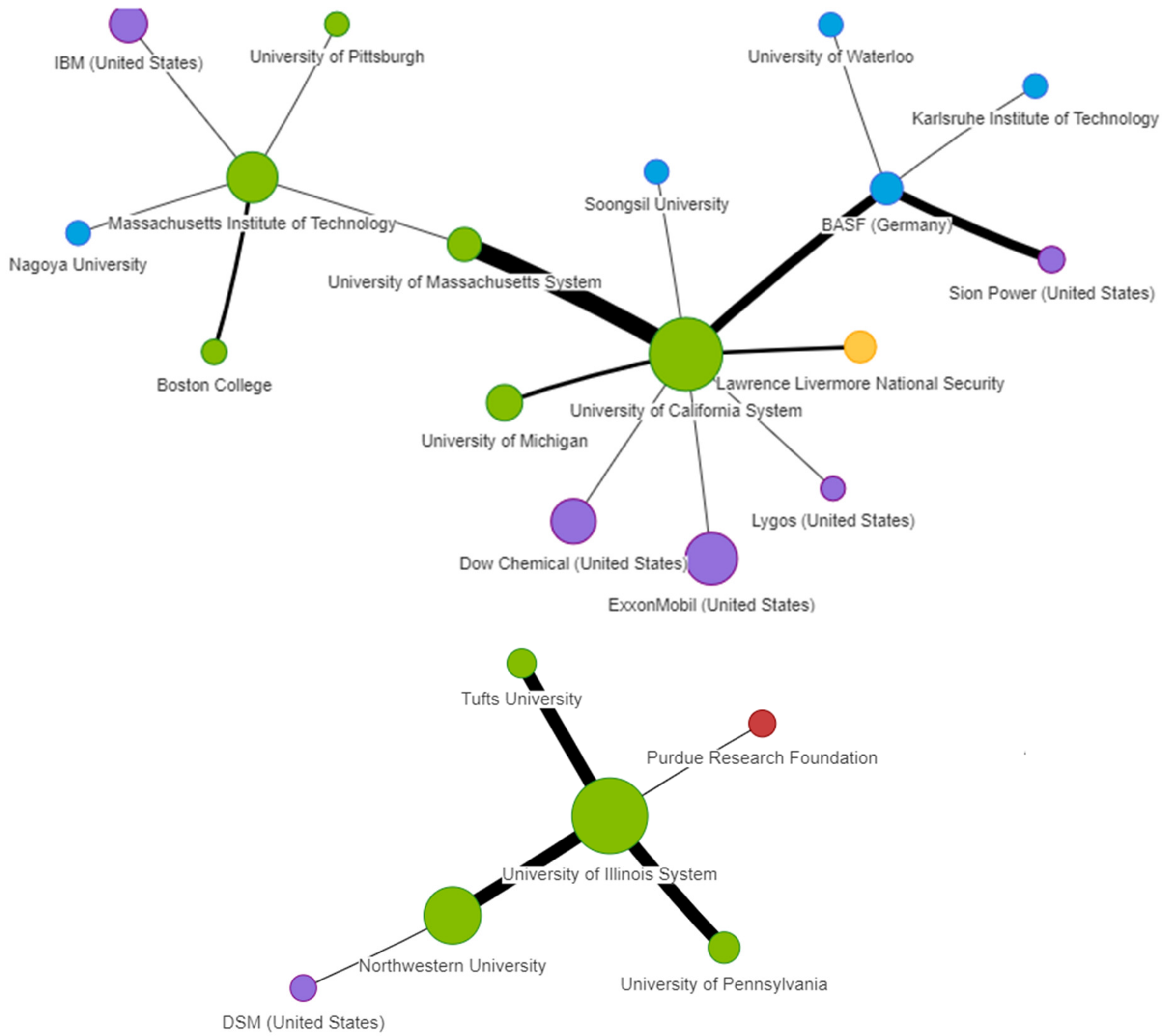
Figure 4-15. Original Co-Assignee Patent Network



There are key differences evident between patent and publication networks. In Figure 4-15, we find a high degree of centralization with edges clustered around various key nodes. This indicates there are lower levels of cross-collaboration between assignees across the corpus of neutron scattering patents, as well as the existence of central, or dominant, key original assignees. Another observation is that the patent network consists of thinner edges and fewer linkages compared to the publications network, indicating less frequent collaboration between assignee pairs and fewer co-assignee partnerships overall. Interestingly, the most prevalent assignee type in the network is international, indicating that international assignees collaborate in patenting more often than U.S. assignees.

Figure 4-16 displays a zoomed-in excerpt of Figure 4-15 highlighting collaborative patent assignees. The shape of these clusters resembles star networks, in which the U.S. universities are central nodes exhibiting many direct links to other nodes and serving as the “shortest path” between other nodes (Zhang & Luo, 2017). These nodes include the University of California System, Massachusetts Institute of Technology, and the University of Illinois System, which are top assignees in both number of patents and forward citations. In these networks, central universities appear to collaborate with different original assignee types, such as companies, international assignees, other federal agencies or labs, and nonprofits. This demonstrates cross-industry patent collaboration among neutron scattering facilities.

Figure 4-16. Network Clusters of Top Patent Assignees



4.4 Key Takeaways

Our analysis of journal articles produced from neutron scattering research at U.S. facilities indicates a strong increasing trend in the quantity of scientific output, accompanied by a consistent share of that output that is high quality and highly visible. The impact of recent articles will not be observable for many more years given the time needed to accrue citations and influence. Moreover, additional time is required to combine knowledge and create new commercial applications, which can also lag a foundational article's publication date by years or decades (Ke, 2015). The number of patents stemming from neutron scattering research also reflects this trend, strongly increasing since 2000 and peaking in 2012, followed by a slight decline. Patent output is a lagging indicator of research outcomes since recent research requires time to become patented technologies.

Overall, the user space of neutron scattering research is characterized by a diverse base of contributors featuring influential key contributors, which has produced significant research output. The United States is the most prominent country producing research output from U.S. neutron scattering facilities, accounting for a disproportionate share of publications and citations by both author affiliation and funder, as well as patents and forward citations by original and current assignees. The key international contributors in authorship of research articles are China, Japan, and Germany, and the top countries in publication funding are China, Japan, and the U.K. The most prominent international patent assignees are France and Japan. The most common author affiliation types are U.S. neutron scattering facilities and U.S. universities, with a notable number of highly published and highly cited universities. The top funder of U.S. neutron scattering research publications is the DOE, followed by NSF. The most prolific assignee of patents is Micron Technology, while University of Illinois ranks closely in the number of patent forward citations.

Our network analyses of publication data by author affiliation and article funder showed a high degree of collaboration between top institutions. Publication networks were highly interconnected. The strongest author affiliation partnership is between ORNL and University of Tennessee, followed by NIST and University of Maryland, suggesting that physical proximity is an indicator of collaboration. For funders, the DOE and ORNL were the strongest co-funding pair. In this highly saturated network, there is no central node that facilitates collaboration. Rather, each institution has multiple links to other nodes, demonstrating a high degree of closeness between authors of research publications.

Network analysis of patent data told a different story, in which patent assignees collaborated with fewer partners and less often. The original assignee patent network was disjointed rather than interconnected, with a few key clusters around central nodes serving as the primary producers of co-assigned patents. These central nodes facilitate collaboration within the network. They include University of California, Massachusetts Institute of Technology, University of Illinois, and the French Centre for Scientific Research.

Both patent and publication networks showed collaboration between different types of institutions, particularly with regards to international collaboration. In fact, international entities show a high degree of participation in co-producing research publications, representing a large share of nodes within all three networks. Future analysis could examine the drivers behind cross-institutional collaboration, as well as the impact of collaboration on the quality and visibility of research output.

5. Costs of Insufficient Access to U.S. Federal Neutron Scattering Facilities

RTI surveyed current users of the neutron scattering research facilities at NIST and ORNL to gain their perspectives on their access to neutron scattering research infrastructure. Questions asked about users' access to U.S. neutron scattering facilities, research outputs, and issues relating to insufficient access.

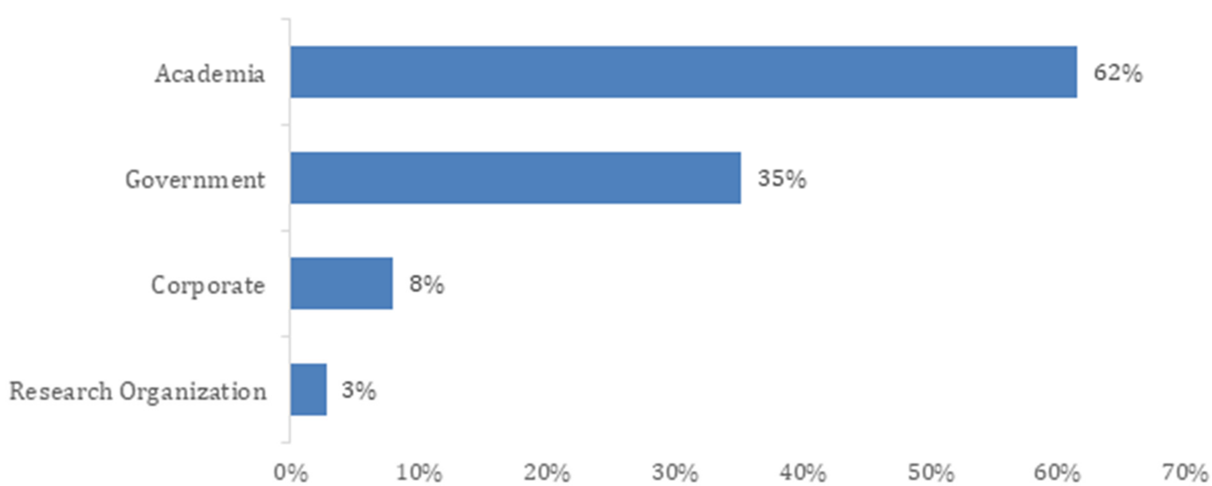
U.S. neutron scattering facility users were identified from the NCNR and ORNL user lists. RTI constructed the survey using Alchemer software; a copy of the instrument is available in Appendix C. Facility leadership emailed the survey link directly to their users in an initial survey invitation and in two email reminders.

The survey ran from June through August 2022 and elicited 355 total responses. Of these, RTI removed 45 partial responses, and another 35 responses from individuals who reported not using any facility in the last five years. RTI removed 28 additional respondents from individuals who reported being current graduate students or post docs. These actions resulted in a final analysis sample of 247 respondents.

5.1 Respondent Background

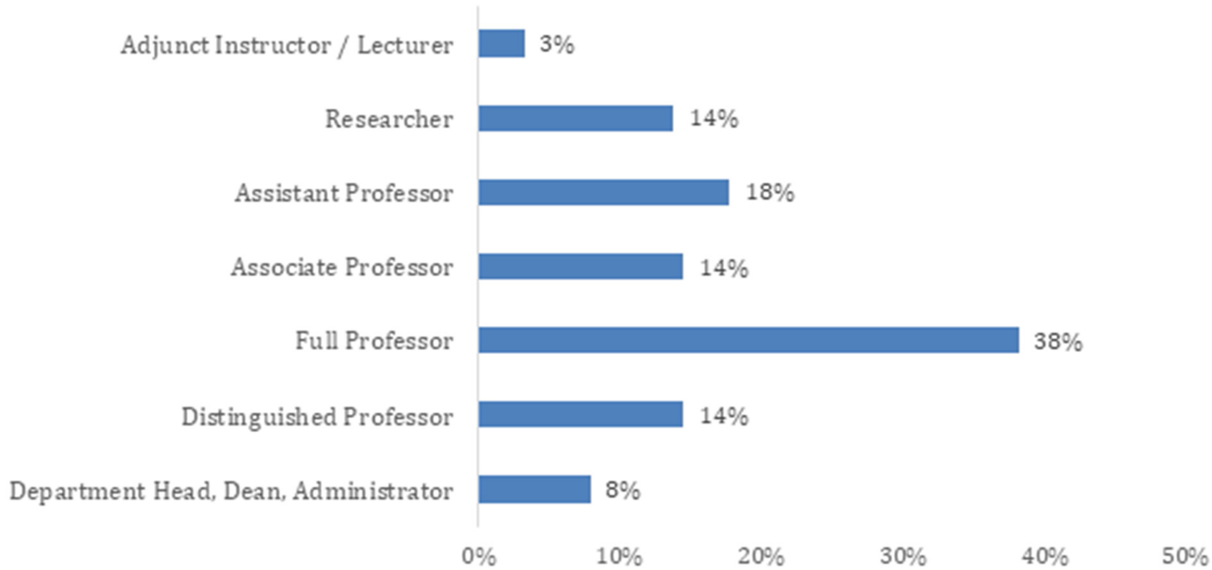
On average, respondents reported earning their terminal degree in 2001 (range: 1964–2021), indicating an average of 21 years of professional experience. Most respondents (N=247) were affiliated with academic institutions (62%) or government institutions (35%). Few were affiliated with corporate (8%) or independent research (3%) institutions (see Figure 5-1). Respondents could indicate more than one affiliation.

Figure 5-1 User Survey Participant Professional Affiliation(s) (N=247)



Among respondents affiliated with academic institutions, 38% reported being full professors. Senior-level professors (department heads, distinguished professors) were less prevalent than junior-level professors (assistant professors and associate professions). About 14% of academic respondents were researchers or research professors (see Figure 5-2). Respondents could select more than one academic title.

Figure 5-2 Academic User Title(s) (N=152)



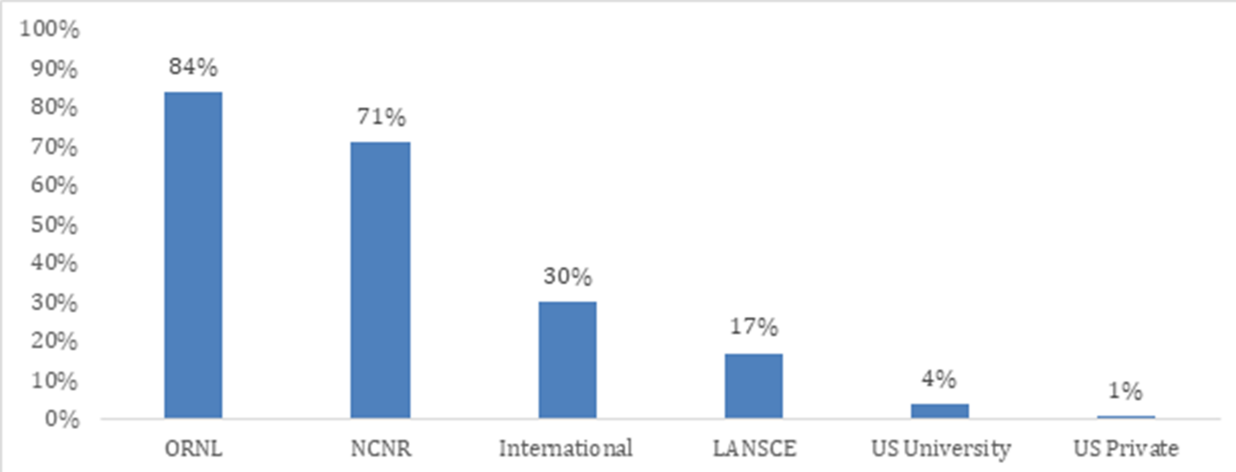
5.2 Facility Use

RTI asked respondents which facilities they have used in the last five years (see Figure 5-3). Because respondents were drawn from the NCNR and ORNL user lists, it is not surprising that most had used one or both facilities. Responses also suggest extensive overlap in facility use, with cross tabulations indicating that 56% of the sample used both NCNR and ORNL in the last five years. While 30% of respondents reported using an international facility in the last five years, all but one of these users reported also using a U.S. facility during that same period.

While LANSCE does still accept applications from public users, their user program has been greatly reduced in recent years to only about 10 to 15 users per year. Some respondents who indicated using LANSCE may not have paid close attention to the five-year timespan covered in the survey question.

Although the capacity of U.S. university neutron scattering research facilities is far lower than that of the federal facilities, it is possible that the low portion of respondents reporting using these facilities is because we sampled the federal facility user base. The small portion of respondents using private facilities likely reflects the very limited number of these facilities.

Figure 5-3. Percent of Survey Participants Using Each Facility in the Past 5 Years (N=247)

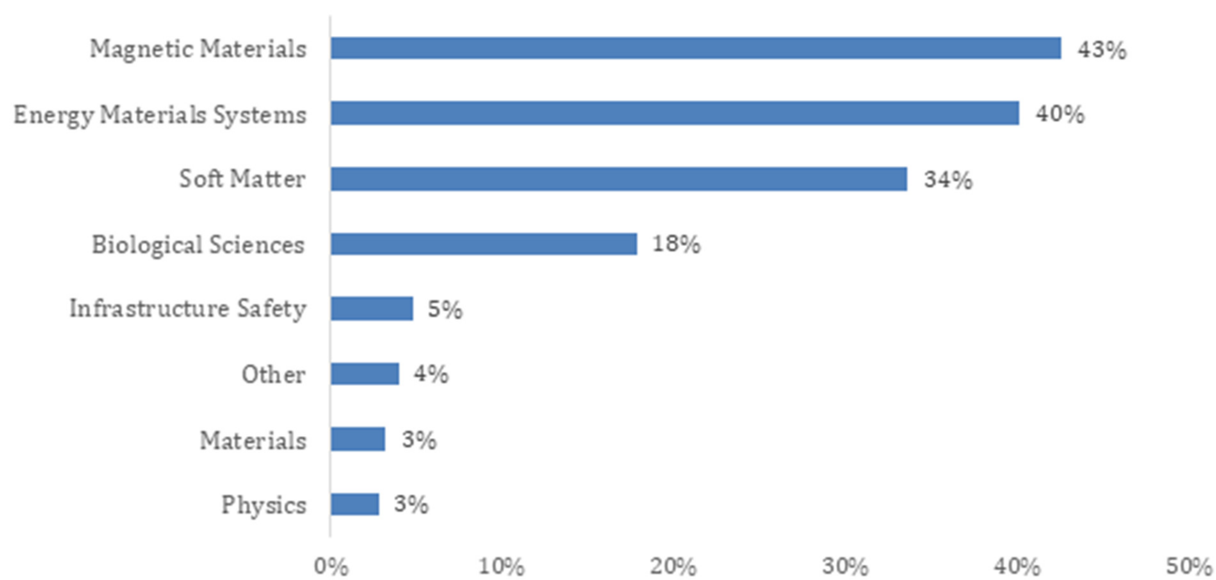


Respondents reported completing an average of 13 applications during the past five years (range: 1-50; 95% CI:11-16). This indicates an average of about two to three applications per year with the most active researchers writing as many as ten applications per year.

5.3 Research Output

RTI asked respondents to select which technology area(s) best represent their research. The most common technology areas selected were magnetic materials (43%), energy materials systems (40%), and soft matter (34%) (Figure 5-4). Most write-in responses were in the areas of physics and other materials.

Figure 5-4. Percent of Participants Conducting Research in Each Technology Area (N=247)



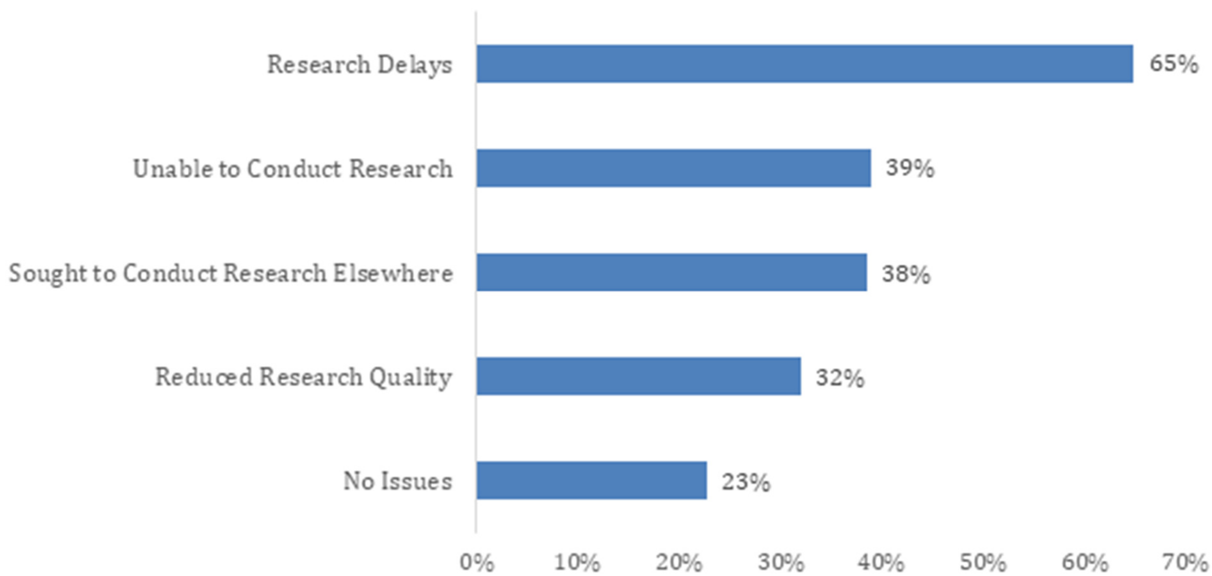
Respondents spend an average of about four months preparing their experiments for beam time at a neutron scattering facility (range: 0–36 months; 95% CI: 3–5 months) and allocate an average of about $15,000 in grant funds to each beam-time allotment (range: $0–$500,000; 95% CI: $9,000–$20,000). After using a facility, respondents take an average of 13 months to submit their research for publication (range: 1–48 months; 95% CI: 12–15 months).

Patents are a less frequent outcome of neutron scattering facility use than publications. Only 25 respondents reported filing patents based on the research they do at the facilities, with a total of 55 patents filed among them in the last five years. Respondents take an average of about 14 months to file a patent after facility use (range: 2–36 months; 95% CI: 10–18 months). Corporate respondents are twice as likely to file patents as academic or government respondents. Patents are filed by 20% of corporate respondents versus 10% of academic or government respondents (difference significant at 10% level).

5.4 Facility Access Issues

Most respondents (77%) experienced issues due to insufficient beam-time access in the past five years (see Figure 5-5). The most common issue was experiencing research delays (65%) followed by being unable to conduct the desired research all together (39%) or needing to seek another facility to use (38%). About a third of respondents (32%) reported reductions in the quality of their research due to insufficient access. Respondents could indicate experiencing more than one issue.

Figure 5-5. Percent of Participants Reporting Insufficient Facility Access Issues (N=247)



On average, respondents who experienced research delays or being unable to carry out their intended research lost or wasted about 13 months of research time (range: 1–36 months; 95% CI: 11–16 months).

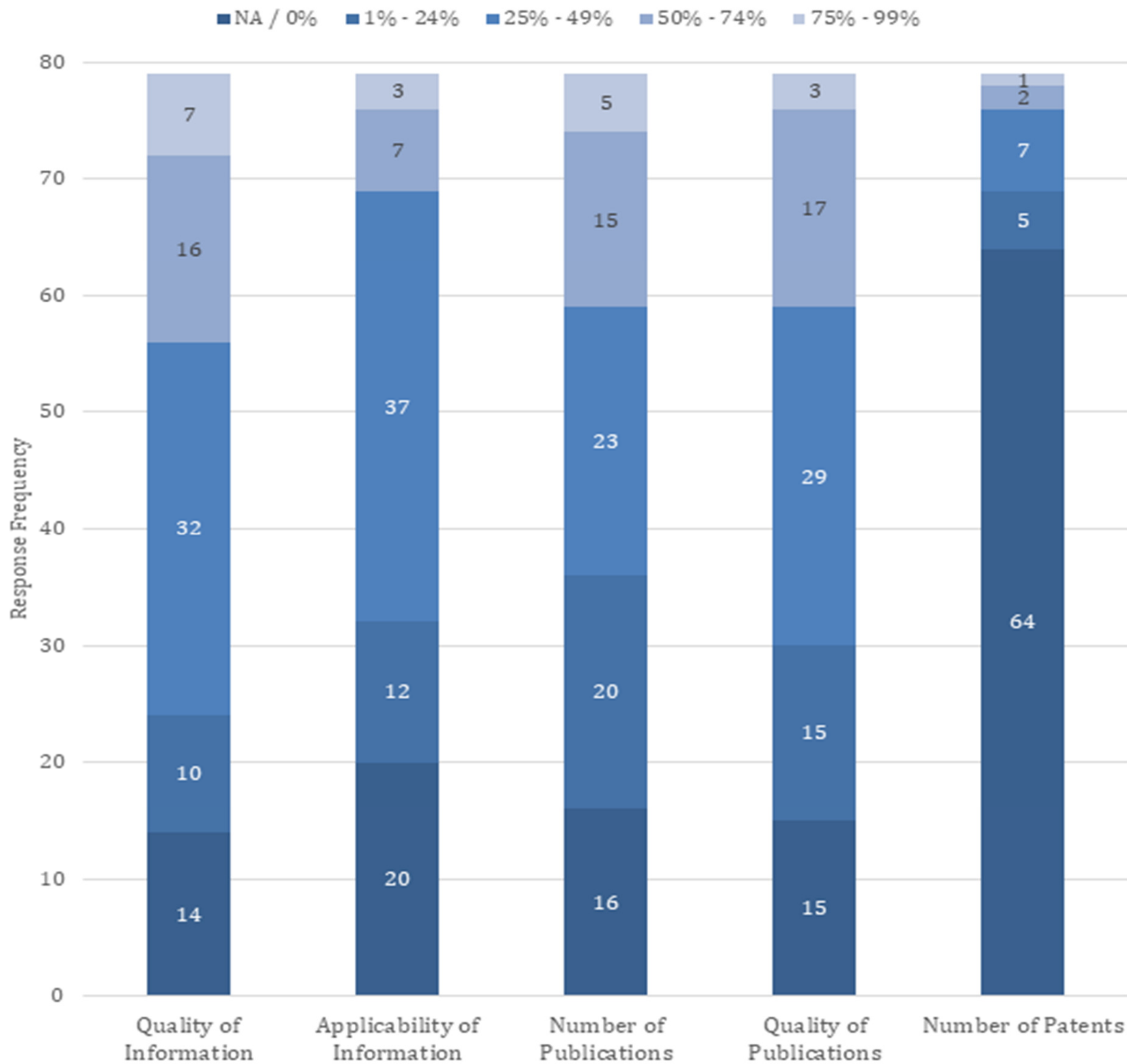
Individuals who reported losing funds due to research delays or being unable to conduct the desired research reported losing or spending about $75,000 on average (range: $0–$500,000; 95% CI: $46,000–$104,000). In aggregate, $5,760,500 in funds were reported lost or spent due to research being delayed or being unable to conduct the desired research. Follow-up interviews clarified that these funds have often been spent on graduate student or post-doc salaries, which typically entail yearly to multiyear contracts. Interviewees also noted that some granting agencies, like the DOE, offer limited flexibility for reallocating research grant funds.

On average, those who were unable to carry out their desired research expected that they would have produced three publications from the work they were unable to accomplish (range: 0–15; 95% CI: 2–4). Also, among those who were unable to carry out their desired research, 14 respondents expected to have filed 1.5 patents each (range: 1–3) on average.

Among those who reported seeking access at another facility, about 81% were able to gain access to another facility, with most applying to an international facility or to a federal facility other than the one where they first applied. Of the total survey sample, 19% successfully took their research overseas.

On average, those who reported experiencing quality reductions reported a 44% reduction in the depth of information revealed from the research, a 39% reduction in the quality of publications resulting from the research, a 37% reduction in the number of publications resulting from the research, and a 34% reduction in the applicability of information revealed from the research (see Figure 5-6). Few respondents reported impacts to the number of patents filed, likely because few researchers reported filing patents based on their research at all.

Figure 5-6. Percent Reduction in Each Research Element Among Participants Reporting Insufficient Facility Access Issues (N=79)



5.5 Open-Ended Responses

The survey ended with an open-ended question asking respondents to provide any additional thoughts they had regarding their experiences with neutron scattering facilities. There were 97 individuals who responded to this open-ended question for a 39% response rate out of the 247 total observations.

The most common topic mentioned by survey participants in open-ended responses pertains to the importance of neutron scattering research for U.S. scientific and technological advancement. This sentiment was expressed in 56% of open-ended responses. Another common sentiment was that the demand for U.S. neutron scattering facilities greatly outpaces access, with 49% of responses discussing issues around this topic. Users also noted that the inability to secure facility access will push new researchers and students away from the tools, resulting in a dwindling user base and decreased research innovation moving forward. Similarly, 25% of open-ended responses expressed concerns about the status of U.S. neutron scattering research internationally as other countries invest more in maintaining and increasing neutron scattering research facilities.

Requests for improved research support and training at U.S. neutron scattering facilities or for increased transparency and impartiality in the beam-time application process were mentioned in 31% of open-ended responses. Finally, 6% of open-ended responses simply expressed appreciation for the staff and resources available at U.S. neutron scattering facilities.

5.6 Key Takeaways

The survey of users at NCNR and the ORNL neutron scattering research facilities revealed important aspects of U.S. neutron scattering research capacity and the constraints of insufficient facility access. Survey results reveal that most researchers who use U.S. neutron scattering facilities rely on multiple facilities to meet their needs. This level of use is accomplished by completing multiple beam-time applications per year.

Survey respondents report allocating substantial time and funds to each beam-time allocation and typically expect to produce two to four publications or one to three patents after each use. Importantly, respondents report that it takes a little over a year from the time of facility use to generate publications or patent filings. This highlights the gap between when basic research is conducted and research impacts are realized, especially since it takes additional time for published or patented research to be incorporated into an applied innovation.

Most survey respondents (77%) reported experiencing issues due to insufficient access to U.S. neutron scattering facilities. The most commonly reported outcome of insufficient access was lost time due to research delays or the inability to complete research. About a third of respondents also reported experiencing research quality reductions including decreases in the depth of information gained or the quality of resulting publications. In addition, 25% of respondents lost or underutilized an aggregate of $5.7 million in grant funds due to delayed or abandoned research. Finally, nearly a fifth of survey respondents succeeded in taking research that they were unable to complete at a U.S. neutron scattering facility to a facility located in another country.

Together these results highlight the importance of maintaining sufficient neutron scattering research infrastructure to support U.S. research and innovation.

6. U.S. Industry Reliance on Federal Neutron Scattering Facilities

Neutron scattering is a premier technique for materials characterization for basic and applied research applications. As a neutral subatomic particle, neutrons can pass through atomic spacings and interact with the nuclei of samples, allowing for deep penetration into materials samples (Hosseni et al., 2021). Common advantages over similar techniques such as X-rays, nuclear magnetic resonance (NMR) spectroscopy, or light scattering include that neutrons have an angle-independent form-factor and sensitivity to magnetic order and light elements (Hosseni et al., 2021). The lack of charge and weak interaction with materials also makes it ideal for use with complex sample environments and allows neutrons to be a nondestructive probe for biological materials (Hosseni et al., 2021). These qualities provide value propositions that make neutron scattering a necessary technique for some types of materials analysis.

In addition to general properties of neutron scattering, there are a diverse set of neutron scattering instruments used for a wide breadth of basic and applied research applications. Common techniques for industrial applications include neutron diffraction, radiography, in situ neutron scattering, small angle neutron scattering, and neutron scattering under diverse pressure and temperature conditions. Applications of some of these techniques include:

- Neutron diffraction characterizes materials statically on the atomic level, which is useful for materials characterization, such as for pharmaceutical compounding, machinery, automotive, or aerospace applications (Albertini et al., 1999; Bull, 2020).
- Small angle neutron scattering is a subcategory of neutron diffraction for the measurement of large (1 nm–1 µm) objects. This can be useful for analysis of complex fluids, porous media and biological assemblies, and is relevant in epidemiology, food science, and the manufacturing of vehicle engines (Balagurov et al., 2014; Bull, 2017; Hosseni et al., 2021; Lopez-Rubio & Gilbert, 2009; OER, 1993).
- Neutron spectrometry, unlike diffraction methods, is a form of inelastic neutron scattering. This involves neutron interaction with samples that results in a change in energy for the neutron, which is then observed by detectors. This has been useful in the testing of materials for battery and fuel cell materials, especially in the case of hydrogen fuel cells, where neutrons are uniquely powerful for detecting hydrogen atoms (Ramirez-Cuesta et al., 2009).
- Neutron radiography is a similar technique to neutron scattering, utilizing beams of neutrons to image samples. Radiography looks at scales much larger than other neutron techniques (10–100 µm) and can view objects and take time series over second to hour lengths. This is of particular interest for many industrial applications, especially for manufacturing, since machines can be viewed while in operation, nondestructively (Anderson et al., 2010; Hosseni et al., 2021).

Despite the numerous applications of neutron scattering and potentially high-value propositions, neutron scattering is not widely used in industry (Boudou & Johnson, 2022). This is due to multiple factors including that neutron research infrastructure is expensive to produce and maintain privately, public facilities are oversubscribed in the United States, and neutron scattering is difficult to learn and interpret.

Below, we provide an overview of the available facilities for neutron scattering use and the channels for industry access to neutron scattering equipment. We then characterize the current industry neutron scattering userbase utilizing a sample of U.S. neutron scattering user companies collected by RTI. Finally, we present the results of survey and interview efforts, which have provided key insights into the barriers that have prevented growth of the industrial scattering userbase, and relay recommendations from interviewees for the furtherance of industry use of neutron facilities.

6.1 Mechanisms for Industry Use of Public Facilities

Neutron scattering is not a widely available technique due in part to the prohibitive cost of building and maintaining a neutron source. The current cost of a modern research reactor or spallation source is on the scale of billions of dollars. The European Spallation Source (ESS) is being constructed at an estimated cost of $3 billion (Physics World, 2023) and the newest source in the United States, SNS, cost $1.6 billion to develop in 2006 (BES, 2022). The cost of staff, operation, and maintenance of SNS is also considerable at around $200 million per year, with the cost of running an instrument for a day estimated to cost thousands to tens of thousands of dollars (NRC Panel on Neutron Scattering, 2016).

Although smaller neutron sources may be considerably less expensive, few corporations have invested in reactors for materials and fuel testing and neutron radiography, and none have used private reactors for neutron scattering purposes. Because it is not practical for an individual firm to invest in producing and maintaining its own neutron source, it makes sense that ownership of neutron scattering facilities has been left to federal governments.[6]

6.1.1 Rationale for Public Usage

In the United States, there is no singular objective behind the support of neutron facilities. Rather, the support of user facilities neutron infrastructure is split between NIST and DOE, who differ in the rationale for supporting these facilities and their affordance of user programs.

National Institute of Standards and Technology

NIST’s stated mission is to promote U.S. industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life (NIST, 2016). NIST discusses neutron science within the context of their mission in the most recent edition of their 3-year plan, stating that “the NIST Center for Neutron Research (NCNR) is the only U.S. facility with a focus on enhancing industrial competitiveness” and that

[6] There are few university facilities that are capable of neutron scattering. As the discipline of neutron scattering and the technology used to engage in it have advanced, university reactors have largely been left behind, due to being outclassed by modern high-tech reactors in terms of flux.

“neutrons can provide information that simply cannot be obtained using more conventional methods available in the researchers’ own laboratories” (NIST, 2016).

From these statements, NIST makes clear that the user program is justified by the provision of an advanced measurement technique usable for the advancement of scientific progress in material science and for the resultant impacts of material science outputs for industrial applications. NCNR’s operation has clear alignment with these policy objectives. To ensure a robust and diverse userbase, NIST has performed outreach and training activities including neutron summer school and internship experiences. NIST has also made available many types of neutron access, including proprietary time and consortium access, which ensure that industry has access and contributes to NIST’s economic impact goals.

Oak Ridge National Laboratory

ORNL is one of DOE’s 17 national laboratories. DOE’s objective in running these national laboratories is to “…tackle America’s energy innovation, environmental, and nuclear challenges to help ensure peace and economic well-being for generations to come” (DOE, 2020). Referencing these objectives, the user facilities are stated to be “…essential to the mission of the Department, as well as to the more than 30,000 researchers at universities and in industry who make use of their capabilities each year. Upgrades of existing facilities and the construction of new unique facilities, such as the Electron-Ion Collider, are underway to keep our Nation’s network of scientific facilities at the international forefront” (DOE, 2020).

This mention of keeping American science at the forefront appears to be an end in itself for DOE in operating the national laboratories. As stated in the 2020 national laboratories report, “An important reason for establishing the National Laboratory system was to provide a home for large-scale, costly scientific facilities that universities could not afford but were critical for sustaining America’s effort in science” (DOE, 2020). This sentiment matches the issue of investment in neutron scattering infrastructure.

6.1.2 Types of Access

In the furtherance of these objectives, NCNR and ORNL provide multiple methods of access to neutron scattering instruments. The methods of access include the NCNR and ORNL user programs, discretionary time, paid usage, and through consortium time.

User Programs

NCNR, HFIR, and SNS are all available to researchers via user programs, in which users reply to requests for proposals and are allotted time to use their requested instruments. Oversubscription of these user programs is a known issue, with two to three times the applicants applying as the amount of time that is available. This oversubscription does have some benefits in terms of allowing for the selection of only high quality proposals; however, there are numerous drawbacks of oversubscription, which are discussed at length in the accompanying RTI neutron scattering policy memorandum.

Like all users through the proposal system, industry users do not pay for time but are given free time on the condition of publishing results. This has a natural public benefit of advancing public knowledge of science. Beyond scientific knowledge gained from experimentation, advances made in developing sample environments, measurement methods, instrumentation, and data analysis techniques benefit the whole user community.

Paid Time

Rather than going through the typical user program channel, external entities can choose to pay the neutron facilities for use of neutron scattering equipment to keep results proprietary. There is a federal mandate of full cost recovery for paid usage of both NCNR and ORNL per the DOC DAO 217-19 and the DOE Order 522.1A, respectively. It costs about $6,000 for 24 hours of beam-time on the NCNR High-Resolution Powder Diffractometer.[7] Proprietary use fees defray public costs and proprietary use can lead to the development or improvement of market products for public use.

Consortium Time

Occasionally, partnerships form for the creation or sponsorship of instruments at neutron scattering facilities. As a result of these partnerships, some time is set aside on a regular basis for usage by consortium members. One such consortium exists surrounding NCNR's NG7 SANS instrument, which was sponsored and developed jointly by the NCNR, the ExxonMobil Research and Engineering Co., and the University of Minnesota. For each 38-day cycle of scattering operation, ExxonMobil receives 4 days of beam time and University of Minnesota receives 2 days of beam time, compared to the 10 days allocated to proposal work and 22 days allocated to proprietary and collaborative research (NIST, 2018). Unlike standard paid time, private consortium members are required to publish their findings.

The nSoft consortium operates the 10-meter SANS instrument at NCNR and is available to the general industry userbase. The nSoft consortium consists of companies who pay a flat $25,000 annual membership fee. RTI interviewed 6 nSoft members, who noted multiple advantages of membership. First, nSoft has dedicated instruments. Accordingly, relative to proprietary usage, which may have to use the same instruments available to user program participants, nSoft members have an advantage of exclusive access to that SANS instrument. Additionally, nSoft has a goal to increase the scientific capacity and depth of member institutions and offers training and guidance to members through access to subject matter experts in related fields.

All three U.S. federal neutron sources have some instruments available for public use and others that are only available for private use through discretionary time or consortium use. Although some instruments provide duplicative capacity, others are specialized for various scientific applications that are not available through the general user application channel.

[7] Estimate provided by NCNR staff.

Discretionary Time

The operators of neutron machinery, instrument scientists, are PhD-level scientists. An incentive for instrument scientists to work in federal labs is that they are allotted discretionary time to utilize the neutron scattering instruments for their own scientific inquiries. The neutron scattering community is small and general users get to know instrument scientists, allowing for cross-pollination of ideas and the forming of collaborations between external users and instrument scientists. Discretionary time can be used for whatever an instrument scientist desires to work on, and, for collaborating external users, it can often serve as an additional channel for accessing beam time.

Discretionary time serves as an incentive to retain and attract talent rather than a channel in service of desired research to meet policy objectives. From interviews with stakeholders, there is a widespread impression that instrument scientists are spread thin and overworked, and do not receive compensation at the level of private-sector employees. Accordingly, the ability to give discretionary time to instrument scientists serves as a great recruitment tool as, for people interested in the discipline, there is no superior way to get access to beam time.

6.2 Contributions of Industry Users of Neutron Scattering Facilities to the U.S. Economy

Industry users often work on direct refinement of products, such as neutron diffraction of metals for manufacturing stress testing or radiography of engines during operation. Accordingly, as demonstrated in RTI's case studies detailing the benefits of neutron scattering for hard drives, electric vehicles, aerospace, and pharmaceuticals, industry usage of facilities provides clear value cases for consumers that utilize the improved and new products that are generated.

6.2.1 Data and Methods for Identifying Industry Users of Neutron Scattering Facilities

NCNR provided RTI with historical data of user affiliations. In addition to these direct user records, RTI collected data on users from publicly available sources to create a dataset of known industry users of U.S. federal neutron sources (NIST, 2019a; ORNL, 2022). The only companies included were companies with public records of having used neutron scattering equipment at national user facilities including NCNR, ORNL, BNL, ANL, and LANL. Records of use were found both via online searches for individual accounts of industry usage[8] and via a search of the Dimensions database[9] for publications authored by industry users with confirmation of laboratory use. To reflect the domestic benefits of American neutron facilities, only companies headquartered in the United States were included in our sample, based on headquarters location. A total of 372 companies met these sample criteria.

[8] Individual records of usage were found both via records of use on the NIST and ORNL websites, and references in academic literature. Over 200 sources were used to verify commercial use of facilities.

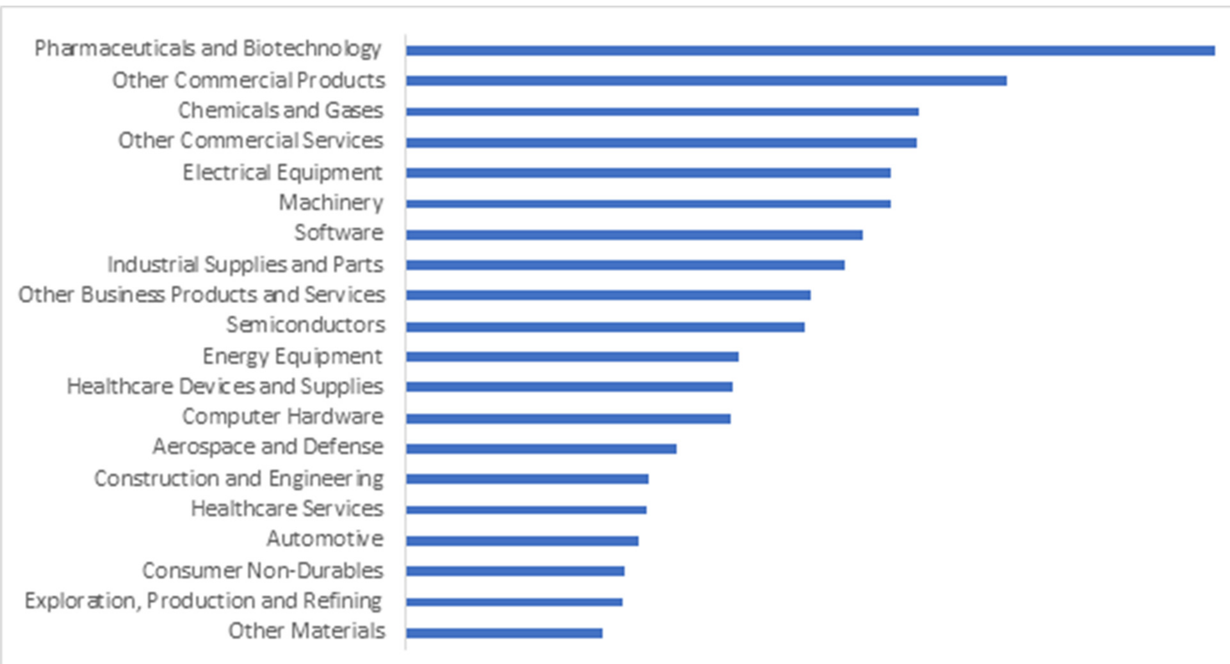
[9] Dimensions is a worldwide database of publications, grants, patents, clinical trials, and policy documents, which contains bibliometric and altimetric information regarding publications and related materials.

Identified companies were searched for through Pitchbook[10] to obtain industry classification, employment, and revenue data for each identified company. There are 44 Pitchbook defined industries in our sample, and the full business count, revenue and employment statistics for each industry are available in Appendix D. Pitchbook annual revenue and employment counts are international figures, reflecting company-wide totals regardless of where employees are stationed or where revenue accrues. Of the user companies identified, global employment figures were available for 265 of them and global revenues were available for 158.

6.2.2 Industry Usership of Neutron Scattering Facilities

RTI created a simple combined metric of the count of businesses and business usership ratio for each industry to determine the 20 industries with the most frequent industry use. Figure 6-1 shows these industries in rank order.

Figure 6-1. Top 20 Industries that Most Frequently Use Neutron Scattering Facilities



Source: RTI calculated using Pitchbook data and public records of industry users of neutron scattering facilities at NCNR, ORNL, BNL, ANL and LANL. See Section 6.2.1 for more details.

The pharmaceutical and biotechnology industry is the largest user industry in our sample, and users include well-known companies such as Pfizer, Bristol-Meyers Squibb, Amgen, and Eli Lilly. Common uses of neutron scattering for the pharmaceutical industry includes reflectometry to see how drugs interact with targets under real-use conditions, since neutrons are not damaging to biological specimens. Also, neutrons are a uniquely good detector of hydrogen,

[10] Pitchbook is a financial data and software company that provides comprehensive private and public market data, including revenue information, employee count, and headquarters locations.

and differences in hydrogen bonds are impactful on molecular structure, which can affect drug performance (Bull, 2020).

Other biomedical industry companies use neutron diffraction and SANS for the nondestructive investigation of biological materials such as cancer cells, invasive disease cells, or biological therapeutics and SANS for the development of microsized drug delivery tools (Martins et al., 2022; Petrenko et al., 2012; Wang et al., 2022). Neutron reflectometry also can be useful for testing the dynamic interaction of biological therapeutics with targets, and quasielastic neutron scattering can observe the dynamics of biological therapeutics in solution (Wang et al., 2022).

Among the remaining top using industries, there are a wide range of applications of neutron scattering. The other commercial products, other commercial services, and business products and services industries are catch-all industries with varied examples of neutron scattering use. These industries include the glass manufacturer Corning, and the corporate conglomerates 3M and General Electric. The consumer non-durables industry is also a diverse industry that includes consumer products companies, such as Procter & Gamble and Colgate-Palmolive, and food and beverage companies such as Coca-Cola and Hershey. Examples of use in these industries have included investigations of tannin production in wine, the mechanisms of starch varieties with positive health impacts, the interaction of food substances with human digestive processes, and the improvement of foam behavior in shampoo (Lopez-Rubio & Gilbert, 2009; Koizumi et al., 2023).

Other industries take advantage of neutrons' ability to probe materials for chemical, electrical, and mechanical properties. Both electrical and chemical properties of materials can be gauged using neutron diffraction, as atomic-level analyses on structure of materials can reveal useful chemical or electrical properties. Additionally, SANS can be useful for electrical and chemical purposes, as polymer membranes that control the flows of gases and electricity can be characterized using SANS (Chan et al., 2020). Additionally, neutrons can characterize magnetic fields at depth or at low temperatures, which has helped with the development of small and powerful semiconductors and other electrical components for hard drives and cell phones (CINS, 2016). Companies using neutron scattering for these purposes include Dow Chemical and PPG Industries in the chemicals and gases industry, Coherent Corp. and Raychem in the electrical equipment industry, and Intel and Texas Instruments in the semiconductor industry.

Industries focused on the advantages of neutron scattering of mechanical properties utilize neutron diffraction for atomic-level materials characterization, and neutron radiography. Neutron diffraction can show important characteristics for mechanical applications, such as the detection of stresses in welds for vehicle part manufacturing. Radiography is of use for mechanical industries such as the machinery and industrial supplies and parts industries, as rather than just observing a small segment of material, whole industrial products can be inspected for stresses, such as airplane turbine blades or car engines (Heller and Brenizer, 2009). Companies that use neutron scattering for such mechanical property applications include Caterpillar and John Deere in the machinery industry and Precision Castparts and Nanophase Technologies in the industrial supplies and parts industry.

Like other mechanically focused industries, the aerospace industry benefits from neutron diffraction for the analysis of materials for airplane construction and the use of radiography to nondestructively investigate machinery in working conditions. Alloys for spacecraft parts have been examined for stress profiles using neutron scattering, including major structural materials for the European Space Agency's Spacelab, major structural materials and fuel takes on NASA's Space Shuttle orbiter (Albertini et al., 1999), and welds on the skin-clip T-joints (particularly high stress areas) of common commercial aircraft (Bayraktar et al., 2008).

Energy equipment includes oil and natural gas companies such as Schlumberger and the energy refining industry includes companies like ExxonMobil. These companies use neutron scattering to characterize and understand how the chemical composition of products affects their behavior, such as for the creation of more efficient fuels through fuel additives. ExxonMobil has been especially active in the neutron scattering community and has partnered with NIST on developing the 30-m SANS instrument (Cappelletti, 2008).

Besides the oil and natural gas components of energy industries, there are also green energy companies such as TPI Composites and Plug Power that create wind turbines and hydrogen power systems. Wind turbines benefit from the stress detection abilities of neutron scattering. Fuel cells have also been a thriving area of research in the neutron scattering community, with companies in the automotive sector such as General Motors (ORNL, 2012) and Toyota (ORNL, 2017) investing in and researching fuel cells. Neutrons benefit this area of research due to their sensitivity to light elements and ability to distinguish between elements and isotopes. Research has included characterization of materials for fuel cell development, including atomic-level crystal structures and interatomic interactions within lithium-ion batteries (Balagurov, 2014), and testing of key electrochemical and sorption properties of fuel cells for hydrogen storage and energy conversion from hydrogen (Horderer et al., 2020; Ramirez-Cuesta et al., 2009). Additionally, in situ techniques have been used for the investigation of lithium batteries and have yielded helpful information regarding the structural processes and degradation of common battery electrodes under use conditions (Balagurov, 2014). These studies have resulted in the development of longer-lasting, more reliable, and more powerful fuel cells for vehicle usage.

6.2.3 Employment and Revenues Among Industry Users of Neutron Scattering Facilities

In aggregate, neutron scattering user companies with available data generate more than $3.1 trillion in annual global revenue and employ 4.5 million people worldwide. Table 6-1 presents a breakdown of revenue and employment among the top using industries sorted by average revenue. Table 6-2 and Table 6-3 highlight the companies with the highest revenue and employment figures among the top using industries. Together, these tables show the global economic contributions of U.S.-based companies that rely on neutron scattering.

Table 6-1. Global Revenue and Employment of U.S. Sectors with Most Frequent Neutron Scattering Use

Sector	Top Using Industries	Average Revenue ($m)	Average Employment
Energy	Exploration, Production and Refining; Energy Equipment	$71,274	13,226
Consumer Products and Services	Automotive; Consumer Non-Durables	$54,116	57,174
Health Care	Pharmaceuticals and Biotechnology; Health Care Devices and Supplies; Health Care Services	$15,492	21,196
Business Products and Services	Aerospace and Defense; Machinery; Other Business Products and Services; Construction and Engineering; Other Commercial Products; Industrial Supplies and Parts; Electrical Equipment; Other Commercial Services	$13,514	18,989
Information Technology	Semiconductors; Computer Hardware; Software	$8,587	10,048
Materials and Resources	Chemicals and Gases; Other Materials	$7,995	6,172

Source: RTI calculated using public records of industry users of neutron scattering facilities at NCNR, ORNL, BNL, ANL and LANL as well as Pitchbook data on industry users.

The energy sector and consumer products and services sector, which is dominated by the automotive industry, have by far the highest average revenues. The average revenues among the companies that use neutron scattering facilities in these sectors is more than $71 billion and $54 billion, respectively. The top five revenue companies in the entire industry user sample are from these sectors as well and include ExxonMobil, Chevron, Phillips 66, Ford, and General Motors (see Table 6-2).

Table 6-2. Top Revenue Companies within High Usership Industries

Company	Industry	Global Revenue ($m)	Description
ExxonMobil	Energy Production and Refining	$394,585	An integrated oil and gas company that explores for, produces, and refines oil around the world.
Chevron	Energy Production and Refining	$232,245	An integrated energy company with exploration, production, and refining operations worldwide.
Phillips 66	Energy Production and Refining	$168,207	An independent refiner with 12 refineries that have a total crude throughput capacity of 1.9 million barrels per day.
Ford	Automotive	$165,055	Manufactures automobiles under its Ford and Lincoln brands.
General Motors	Automotive	$160,740	The leading automotive company in U.S. market share.

Source: Pitchbook.

Employment figures indicate the number of livelihoods supported by industries that utilize neutron scattering. The consumer products and services sector has by far the highest average employment among top using industries. Both the automotive and consumer non-durables industries have high employment levels within this sector. Other individual industries with high average employment levels include aerospace, machinery, and other business products and services. Four of the companies with the highest employment levels are from the aerospace and automotive industries (see Table 6-3). The fifth company, General Electric, is from business products and services. General Electric accounts for 56% of the employment of the business products and services industry, and without General Electric, the remaining 14 companies in the industry would only rank 11th in terms of total industry employment.

Table 6-3. Top Employment Companies within Sample of High Usership Industries

Company	Industry	Employment	Description
Raytheon	Aerospace	182,000	A diversified aerospace company with roughly equal exposure as a supplier to commercial aerospace manufactures and to the defense market.
Ford	Automotive	173,000	Manufactures automobiles under its Ford and Lincoln brands.
General Electric	Business Products and Services	172, 000	A global leader in air travel and in the energy transition, known for aerospace engines, gas and steam turbines, and onshore and offshore wind turbines.
General Motors	Automotive	167,000	The leading automotive company in U.S. market share.
Boeing	Aerospace	156,000	A major aerospace and defense firm. It operates in four segments: commercial airplanes; defense, space, and security; Global services; and Boeing capital.

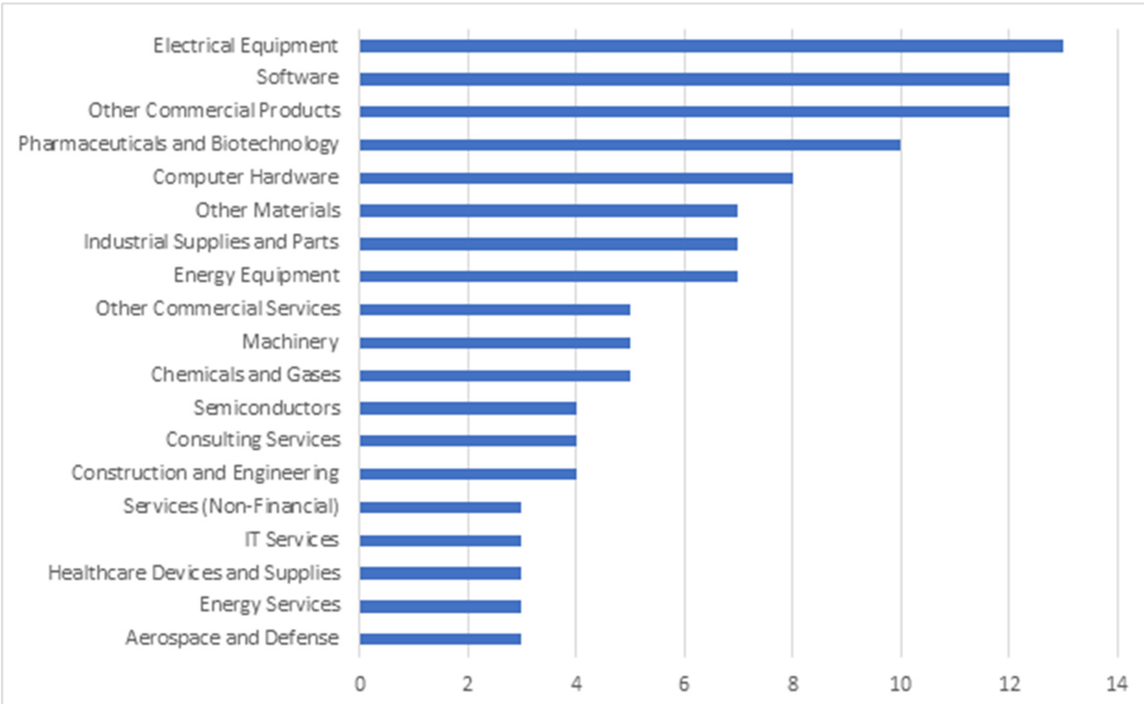
Source: Pitchbook.

6.2.4 Early-Stage and Small and Midsize Enterprise Use of Neutron Scattering Facilities

Large corporations are not the only users of U.S. neutron scattering facilities. Neutron scattering facilities provide access to smaller, early-stage companies focused on commercializing new technologies. Among the user companies with employment information available in Pitchbook, 45% employed 250 or fewer employees, qualifying as small and midsize enterprises (SMEs). This includes 47 early-stage companies that were formed in the past 15 years. There are an additional 19 early-stage companies in the user dataset that either do not have employment information available or that currently employ between 250 and 700 employees.

There are a few notable industries where early-stage and SME reliance on neutron scattering facilities is higher than is the case for all companies (see Figure 6-2). These include electrical equipment, computer hardware, industrial supplies and parts, and other materials. The other commercial products and pharmaceuticals and biotechnology industries have many users among both large, established companies and early-stage companies and SMEs. Most of the other industries with high early-stage and SME neutron scattering use overlap largely with the top using industries based on all companies.

Figure 6-2. Number of Early-Stage Companies or SMEs in Each Industry That Use Neutron Scattering Facilities



Many of the U.S.-based early-stage companies and SMEs that use neutron scattering facilities are pre-revenue and rely on investment funds from private equity sources, angel investors, innovation accelerators, and venture capitalists to fund commercialization activities. The early-stage and SME user companies in our sample raised an aggregate of over $4.6 billion in this type of funding from 2000 through 2023. Companies also raised over $800 million in grant funding over this time. Of these companies, 26 have had initial public offerings or were acquired by another company. An additional 23 began generating revenues independently.

6.3 Barriers to Entry and Recommendations

High quality science is achievable at neutron sources only with a robust user community. However, there are several barriers that have limited the widespread participation of industry in neutron scattering. Below we describe barriers commonly mentioned by industry users during interviews that RTI conducted with members of the neutron scattering community along with recommendations to rectify these issues. As acknowledged by interviewees and U.S. neutron scattering facility staff, the Japan Proton Accelerator Research Complex (J-PARC) has done an excellent job of attracting, supporting, and retaining industrial use of its facility. Throughout, we suggest aspects of J-PARC practices and supporting policies that could be replicated to increase industry use of U.S. neutron scattering facilities.

6.3.1 Awareness

Neutron scattering is a technique that few even within the physics community become aware of without direct academic exposure. Of the 52 neutron scattering users interviewed by RTI, 20 offered information regarding when they were first introduced to neutron scattering. Of these, 16 respondents stated that the first time they were exposed to neutron scattering was in post-secondary education, with 10 stating that their first exposure was in graduate school. Only 4 of these 20 respondents were exposed to neutron scattering after their graduate or post-graduate education. This picture appears slightly different for industry users. From our sample of industry users, only four interviewees mentioned their first exposure to neutron scattering including one respondent who was introduced in graduate school and three who were introduced after their education. Thus, currently, the academic pipeline for neutron scattering is extremely important for gaining future users of neutron scattering and the recruitment of industry to utilize neutron scattering may require more potential industry user outreach.

One drawback of the academic pipeline is that it does little to expand the breadth of the neutron scattering userbase. With most users discovering the technique through their professors or colleagues, this channel does little to tap into the wide applicability of neutron scattering for industrial uses and keeps neutron scattering confined within existing use cases.

Both ORNL and NCNR have initiatives to advance neutron scattering education and to perform outreach to potential users. These consist of internships and experiential learning programs for students and teachers, graduate courses, financial assistance for visiting scientists, and neutron scattering schools. The ORNL school is focused on graduate students and fulfills the role of providing hands-on experience to boost the academic neutron scattering pipeline. The NCNR CHRNS Summer School is more open to participants of all ages and work experience and provides instruction on the theory and practice of neutron scattering techniques for new users.

Despite these efforts, industry interviewees expressed a desire for DOE and NIST to increase their user outreach activities. J-PARC in Japan does a good job of actively seeking industry users and consortium arrangements, which is an approach that is well-suited for the objectives of NCNR. J-PARC's industry outreach activities are supported by the Comprehensive Research Organization for Science and Society (CROSS), an institution focused on promoting public access of J-PARC beam lines that includes an industrial collaboration promotion division (CROSS, 2023). Efforts to promote industry usage of J-PARC include the CROSS new user promotion effort that makes all of the seven beamlines operated by CROSS available to new users and J-PARC's wide-reaching collaboration for J-PARC's neutron school, including support from the Japan Atomic Energy Agency, the High Energy Accelerator Research Organization (KEK), the Institute for Solid State Physics at the University of Tokyo, and the Industrial Users Society for Neutron Application (CROSS, 2018; J-PARC, 2016). In the past, NCNR has organized consortiums for the development of instruments with specific capabilities, such as the NG7 SANS instrument collaboration with ExxonMobil and University of Minnesota, and further efforts in this direction align well with their objective of enhancing industrial competitiveness.

6.3.2 Accessibility

Neutron reactors or spallation sources are multimillion-dollar investments, even for small, low-power set-ups. Accordingly, a natural barrier for participating in neutron scattering is the need to travel to neutron sources. Both NIST and ORNL are located on the east coast of the United States and neither offer support for travel to the facilities nor lodging. In contrast, European facilities offer travel and lodging compensation and are more spatially dispersed than U.S. facilities. While facility dispersion is not an immediately actionable problem, travel support to reduce bias towards local users may help grow the neutron scattering community.

Beyond physical barriers, access through open user programs is complicated by oversubscription. Users interviewed by RTI mentioned that oversubscription can dissuade first-time applicants from neutron scattering research entirely and restrict the breadth of proposals that receive beam time. In response to oversubscription, most industry users proposed the construction of a new neutron source. Other responses to oversubscription among interviewed industry users included the following:

- Increasing the geographic diversity of neutron sources,
- A general increase in science spending,
- Larger maintenance and improvement budgets, and
- The creation of a hub including X-ray, light scattering, NMR, and neutron scattering to provide complementary techniques in one locale.

Consortium time also offers an important pathway for industrial access. The SANS instrument at NCNR that is set aside for nSoft consortium members has improved accessibility for industry users at that facility. J-PARC has taken a similar approach by setting aside an instrument, iMATERIA, primarily for industry use (J-PARC, 2015a).

6.3.3 Usability

The second major barrier pertains to the difficulty in obtaining useful results from neutron scattering experiments. Data reduction and interpretation requirements are high for neutron scattering, to the degree that some users reported taking multiple years before data are in a publishable form. One user mentioned having such a backlog of data, that they sat out multiple years of proposal submissions due to the time required to interpret past data. Complicating this need further, NCNR and ORNL's data processing systems have been developed without compatibility in mind, thus requiring users to learn the intricacies of each facility system when switching between facilities.

Other difficulties arise from the challenge of learning how to use neutron scattering instruments, with many interviewees mentioning that it is common to not get usable data from their first attempt at using an instrument. Even some high-frequency users at neutron scattering facilities tout a 1:2 ratio of publication-quality results per facility visit, due to the difficulty of successfully using instruments to answer the questions they wish to answer. These issues are reflected in the consensus among industry users who mentioned a desire for industry-focused trainings for neutron scattering use. Other common suggestions included the following:

- Increasing facility focus on the automation of neutron instrumentation,
- Improving data processing support, and
- Increasing staffing to ease burdens and provide more support.

J-PARC supports usability by assigning seven staff to the iMATERIA beamline team, all of whom are part of CROSS. This ensures that industry users have ample support and guidance when using the instrument. This is especially helpful because industry users are less likely to have the background knowledge of academic users needed to use neutron scattering instruments more independently.

6.3.4 Policy Alignment

Proprietary time is key to enabling industrial utilization of the unique R&D capabilities of neutron scattering, which then improves consumer products and provides benefits to the American public. However, keeping results proprietary also opens the possibility of companies performing duplicative work to stay competitive in their marketplace, which is arguably an inefficient use of already limited beam time. One interviewee mentioned that Japanese car companies have effectively mitigated the issue of duplicative work through the development of consortiums for their proprietary neutron scattering work, such as a collaboration between car brands Nissan, Toyota, Honda, and Sumitomo (J-PARC, 2015b). It is unclear whether similar agreements have been or could be made among companies in the United States.

Another common refrain among interviewees is that NCNR and ORNL do not sufficiently coordinate in their support of the neutron community. Although NIST and DOE have disparate objectives that do not result in full alignment, they both aim to support a robust neutron user community and have the potential to work more effectively together to meet common objectives. Multiple reasons were offered for needing increased coordination, including:

- Difficulties in dealing with separate application processes, resulting in duplicative work for both applicants and facility staff,
- Better coordination of resources, ensuring all beam time is used effectively, and
- A need for duplicative instruments at both facilities due to planned maintenance downtimes and the possibility of unplanned outages.

Finally, a recommendation provided in the 2015 National Research Council review of NCNR, suggested maintaining robust metrics of success on nSoft finances, participating companies, and patents, publications and new products that result from nSoft usage (NASEM, 2015). Information regarding proprietary usage of NCNR by industry users outside of nSoft would also be necessary to provide a complete picture of industry usage.

Developing metrics of industrial neutron scattering success is one step toward ensuring that NCNR is meeting its industrial competitiveness mission. The technology transfer pathway from basic neutron scattering research to product commercialization is long, and tracking industry outcomes is difficult at best. Industrial usage is often more directly illustrative of successful technology transfer. Clear connections from the research completed by NCNR industrial users to realized commercial impacts would demonstrate NCNR meeting its mission.

7. Economic Impact Case Studies of Technologies Influenced by Neutron Scattering Research

The breadth of value generated by neutron scattering research coupled with the opaque nature of the U.S. R&D process make it difficult to estimate the monetized benefits that U.S. neutron scattering research facilities deliver. As a conservative method of identifying tangible research impacts, we completed four case studies of key U.S. technologies known to have been influenced by neutron scattering research.

First, we look at computer performance applications, focusing on the rapid understanding of giant magnetoresistance gained through polarized neutron reflectometry that quickly led to advances in hard drive technology. Second, we look at aerospace technologies that increase the safety of aircraft travel, focusing on two applications: the use of small angle neutron scattering to develop a fuel additive with reduced flammability, and the use of neutron diffraction for identifying residual stresses in aircraft components to improve aircraft structural integrity. Next, we estimate the impact of adopting new weight loss drugs for which development was influenced by small angle neutron scattering, by modeling resulting changes in obesity levels. Finally, we look at the influence of multiple neutron scattering techniques on improving electric vehicle performance.

These case studies rely on multiple assessment methods as appropriate to each application. We draw on existing literature and expert elicitation to identify the realized or potential impacts of each technology. Quantitative assessment methods include market analysis, counterfactual analysis, and health outcome modeling. Where direct market information is not available, we apply benefits transfers to estimate the economic values associated with various outcomes.

7.1 Computer Performance

Hard drives are a significant component of the computer storage industry and, through it, the American economy. Three of the seven largest storage device companies are headquartered in the United States (Hoover's Inc., 2023). Computer original equipment manufacturers such as IBM and Hewlett Packard Enterprises also have divisions focused on data storage and thus play a role in the industry (Hoover's Inc., 2023). In addition to personal computers, laptops, and other electronic device markets, some of the main industry sectors that use computer storage devices include autonomous vehicles, surveillance and security, health care, telecommunications, media and entertainment, and geosciences and energy (Seagate Technology, 2023; Doshi, 2023).[11]

Advances in the computer storage industry have benefited data-driven industries by making storge less expensive, smaller, and more reliable. Neutron scattering techniques have made significant contributions to the development of computer storage devices by giving researchers greater insight into the magnetic materials essential to their creation. In this report, we discuss the effect that neutron scattering has had on the hard drive industry (and its resulting impact on

[11] One of the major computer storage device manufacturers, Seagate Technology, is technically headquartered in Ireland for tax purposes but effectively still run from its American location (Pittman 2010; Hoover's Inc. 2023).

the American economy), and the role neutron scattering is playing in the development of quantum computing technology.

7.1.1 History of Hard Drive Development

Hard drives are devices that allow computers to store vast quantities of information (Griffith, 2022). Whereas other devices performing similar functions have been created, the reliability, speed, and capacity of hard drives have led to them holding a dominant position in the digital storage industry for decades (Griffith, 2022). Although in recent years hard drives have faced some competition from solid state drives, they are nevertheless a major technology in digital storage and (depending on the metric used) are forecasted to hold their dominant position going forward (Mellor, 2002).

Modern hard disk drives function by storing information as binary, magnetic bits on thin layers of magnetic film, which are arranged into a perpendicular structure (Venkataramana, 2011). By developing a greater understanding of the properties of these thin layers of magnetic film, computer scientists were able to store more information into smaller areas on hard drives (Venkataramana, 2011).

IBM developed and shipped the first hard drive in 1956 (see Figure 7-1). The drive was five feet high by six feet wide, weighed over a ton, and stored 3.75 megabytes (MB) of data (Computer History Museum, 2023a). By 1980, Shugart Associates, which would eventually become Seagate Technology, released a 5.25-inch hard disk drive that could store up to 5 MB of data (Computer History Museum, 2023b). A 2.5-inch hard drive with 20 MB of data was introduced in 1988, with 200 MB of storage fitting in the same dimensions by 1992. By 1999, a 1-inch microdrive could hold 170 MB of data, although 3.5-inch and 2.5-inch hard drives have remained standard for computing purposes (Computer History Museum, 2023b).

Figure 7-1. Photos of Hard Drives throughout U.S. History

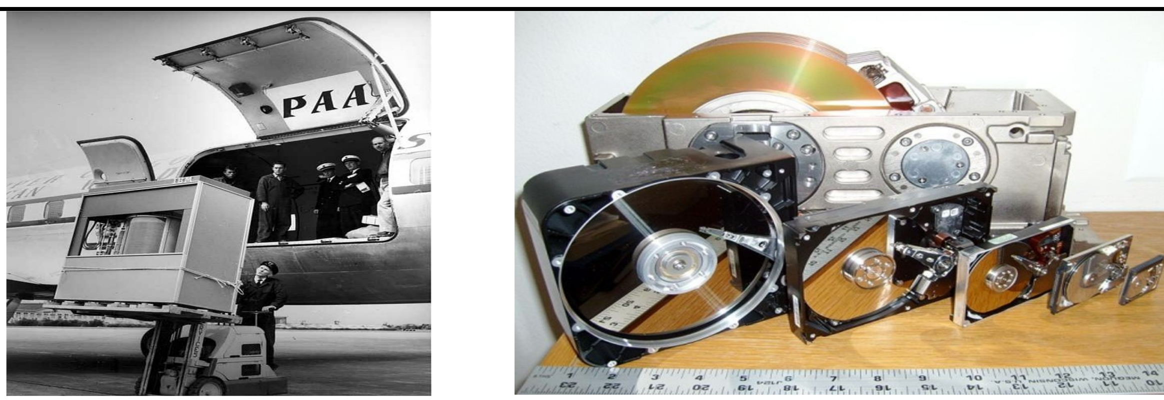


Photo of one of IBM's first hard drives being loaded onto a plane for shipment

Photo of 5.25-inch hard disk drive (leftmost front) and other small hard drives

Source: Computer History Museum (2023a-b)

While keeping the same basic technological design, hard drives have rapidly improved the storage capacity of computers from 1 gigabyte (GB) of data in 1999 to 1.5 terabytes (TB) by 2008 (Yeo, 2009). These increases in storage capacity and size reductions allowed hard drives to be integrated into modern personal computers as they are today (Venkataramana, 2011). This trend has not shown signs of slowing. As of 2022, a variety of hard drives allowing computers to have a storage capacity of more than 20 TB are on the market, with Seagate Technology releasing a hard drive with over 30 TB of storage capacity in 2024 (Horizon Editorial, 2022; Seagate Technology LLC, 2024).

7.1.2 Role of Neutron Scattering in Hard Drive Innovation

Neutron scattering has been instrumental in furthering scientific understanding of the magnetic properties of hard drive materials at the nanoscale. Indeed, Fitzsimmons et al. (2004) argue that neutron scattering was “seminal” to promoting the understanding of ferromagnetism, the basic principle on which hard drives operate (p. 138). Due to their neutral charge, neutrons can get close to the nuclei of atoms and thus penetrate deeply into materials in a nondestructive manner (Venkataramana, 2011). In addition, neutrons possess an inherent magnetic moment, which allows them to interact with the unpaired electrons in magnetic atoms and thereby provide information about the internal magnetic fields of a given material (Venkataramana, 2011). For these reasons, neutrons are ideal for use in studying the properties of magnetic materials on a nanoscale level (Neutron Sciences Directorate, 2018).

Research on giant magnetoresistance (GMR) serves to illustrate how neutron scattering techniques promoted the development of hard drive technology. GMR occurs when a system of extremely small (nanometer or subnanometer in width) alternating magnetic and nonmagnetic conductive layers undergoes a major change in electrical resistance after being exposed to an external magnetic field (Pessoa Barradas, 2017). GMR enabled hard drives to detect the presence of even extremely small magnetic fields, allowing them to store and access significantly more information (Pessoa Barradas, 2017).

The high-density magnetic recording of modern hard drives would not have been possible without the discovery of the GMR effect (Pessoa Barradas, 2017). Crucially, using GMR for this purpose depends on a thorough understanding of the characteristics of each nanolayer in a hard drive (Pessoa Barradas, 2017). Polarized neutron reflectometry, a specific type of neutron scattering, is uniquely suited for acquiring this understanding and is described as the “technique of choice” for this matter (Pessoa Barradas, 2017).

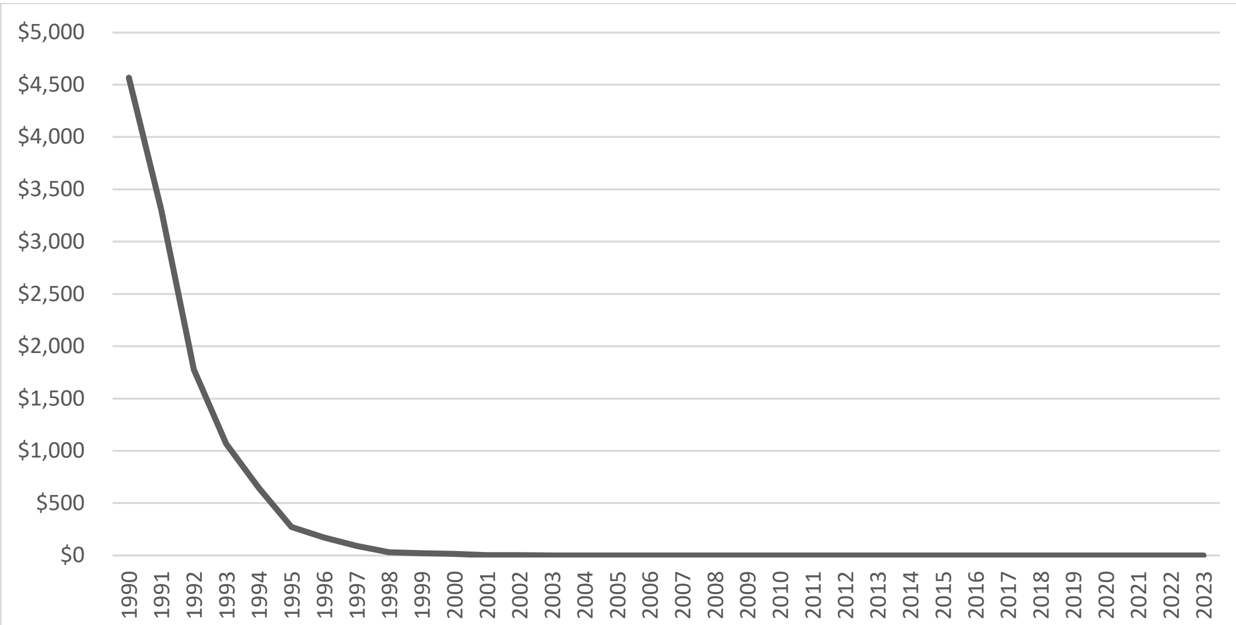
U.S. neutron scattering facilities continue to enable research on hard drives and magnetic materials. IBM, which has used U.S. neutron scattering facilities, has 150 patents related specifically to the GMR effect. Also, of 14,607 academic publications derived from U.S. neutron scattering facilities since 2003, about 23% are related to hard drives or magnetic materials based on a regular expression search of their titles and abstracts.[12] These publications, in turn, generated 128,787 additional citations, for an average of approximately 39 citations per paper.

[12] Calculated by RTI using the Dimensions database and methods described in Walsh et al. (n.d.).

7.1.3 Welfare Effects of Hard Drive Price Decreases

As more data have been able to fit onto smaller and smaller hard drives, prices per GB have declined. Because common storage capacity was substantially below a GB in the decades before 1990, the implied hard drive data storage cost per GB was tens of thousands to hundreds of thousands of dollars. As shown in Figure 7-2, the average cost of hard drive data storage has fallen dramatically since then, from more than $4,500 per GB in 1990 to $0.015 per GB in 2023 (McCallum, 2023).

Figure 7-2. Average Hard Drive Price per GB from 1990 through 2023



Source: McCallum (2023)

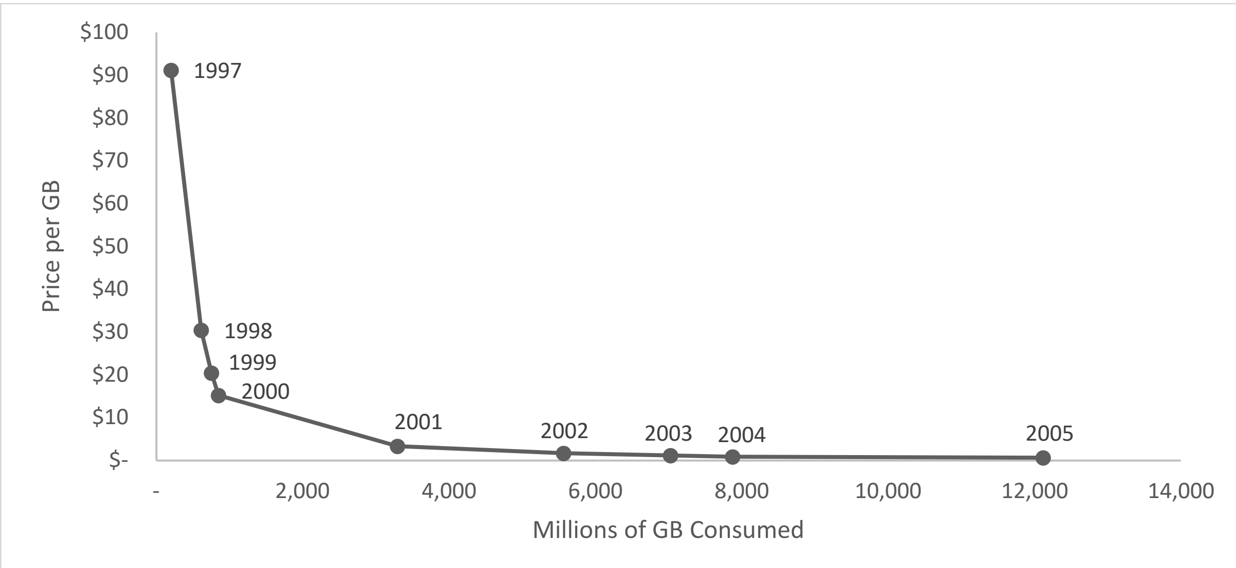
GMR presented a step-wise change in hard drive development and arguably drove the majority of price decreases from 1997, when the first GMR hard drive was sold by IBM, to at least 2005, the year before the first cloud storage and solid state drive options entered the market (Computer History Museum, 2023c-2023e). These technologies were the first computer storage devices that had the potential to compete with hard drives on a meaningful scale, and the entry of competitive technologies would have been likely to push hard drive prices down beyond the efficiency savings driven by GMR. The drastic decreases in hard drive price were met with increases in U.S. consumption.[13]

To estimate the consumer surplus associated with less expensive hard drives, RTI used the annual price and consumption levels from 1997 through 2005 to compile the long-run demand

[13] Consumption data were calculated using metrics on annual shipments of computer storage devices from U.S. manufacturers (U.S. Census Bureau, 2023a) plus computer storage device imports minus exports (U.S. Census Bureau, 2023b) as well as the percentage of the global computer storage device industry that is held by hard drives (U.S. Census Bureau, 2023c).

curve for hard drives in the United States (see Figure 7-3). The price and consumption changes over this time benefited hard drive consumers as measured by annual increases in consumer surplus. Consumer surplus is the additional value consumers receive above and beyond the value reflected in the purchase price of the product. It can be measured as the area under the demand curve above the equilibrium price and quantity. The annual change in consumer surplus can then be aggregated to determine the value received by consumers from decreases in hard drive prices (see Table 7-1).

Figure 7-3. Long-Run Hard Drive Demand from 1997 through 2005



Consumption(m) = [Manufacturing Shipments($m) + Imports($m) – Exports($m)] / Price($)
Sources: Manufacturing (U.S. Census Bureau, 2023a), Imports (U.S. Census Bureau, 2023b), Exports (U.S. Census Bureau, 2023c), Prices (McCallum, 2023)

We compound[14] past figures to their present value by applying a discount rate of 2%, as recommended by the Office of Management and Budget (OMB) (2023) guidance. The compounded aggregate change in consumer surplus from 1998 through 2005 was more than $114 billion, or roughly $14 billion per year on average. Compounded total consumption during this same period was valued at more than $159 billion, implying that 71% of consumption value went to consumers.

The compounded aggregate increase in hard drive consumer surplus from 1998 through 2005 provides a conservative estimate of the value derived from technological advancements informed by neutron scattering research for two reasons. Primarily, this assessment only captures a narrow period and type of technological progress. Neutron scattering research has arguably informed many stages of hard drive development, from the technology's origins

[14] This practice is more commonly referred to as discounting in benefit-cost analysis. Compounding is the practice of applying a discount rate to past figures to pull them forward to present values while discounting is the practice of applying the same discount rate to future values to pull them back to present values.

(Fitzsimmons et al., 2004) to its continued downsizing and increased storage capacity (Neutron Sciences Directorate, 2018). As discussed below, neutron scattering research is even informing the feasibility of the next generation of quantum computer storage devices. The financial values are also conservative because it is unclear if the historic prices are inflated, and we treat them as if they are. Inflation adjustments would further increase the estimates.

Table 7-1. Hard Drive Price per GB, Millions of GB Consumed, and Annual Change in Consumer Surplus from 1997 through 2005

Year	Price per GB [a]	Quantity (Millions of GB) [a]	Change in Consumer Surplus (2021$m) [c]	
			Real	Compounded
1997	$ 89.03	207	---	---
1998	$ 29.70	631	$ 24,848	$ 39,182
1999	$ 19.92	772	$ 6,858	$ 10,602
2000	$ 14.78	873	$ 4,232	$ 6,414
2001	$ 3.20	3,376	$ 24,611	$ 36,571
2002	$ 1.64	5,701	$ 7,069	$ 10,298
2003	$ 1.11	7,198	$ 3,395	$ 4,848
2004	$ 0.80	8,065	$ 2,432	$ 3,406
2005	$ 0.60	12,410	$ 1,984	$ 2,724
Total Value	---	---	**$ 75,429**	**$ 114,046**

[a] Source: McCallum (2023)
[b] Consumption(m) = [Manufacturing Shipments($m) + Imports($m) – Exports($m)] / Price($). Sources: U.S. Census Bureau (2023a-2023c)
[c] Calculated annually as follows: $(1/2)*(P_1-P_2)*(Q_1+Q_2)$

7.1.4 Neutron Scattering and Quantum Computing

Quantum computing is a new, developing branch of computer science that seeks to utilize quantum mechanics to create computers capable of solving problems too complex for even classical supercomputers to handle (IBM, n.d.). While classical computers use bits to perform operations, quantum computers use qubits (IBM, n.d.). Unlike bits, qubits can place the information they hold into a state of superposition, which represents a state of all possible configurations of the qubit (IBM, n.d.). Thus, while a classical bit is either a 1 or a 0, a qubit can reflect the entire spectrum of possibilities between (and including) 1 and 0 simultaneously (Collins, 2022). In addition, whereas classical bits operate independently of each other (i.e., one bit being a 1 has no effect on whether a different bit is 1 or 0), changes to one qubit can directly cause changes to another qubit if they become entangled at the quantum level (IBM, n.d.; Collins, 2022). Quantum algorithms can take advantage of these two properties of qubits by using the relationships between them to solve complex problems more efficiently than classical computers (IBM, n.d.; Collins, 2022).

Although quantum computing as a technology is still developing, its potential is enormous—it is estimated that quantum computers could operate 158 million times faster than the most advanced traditional supercomputer in existence (as of 2022) and perform in four minutes a task that would take a traditional supercomputer 10,000 years (Smith, 2022). This potential has led to a global competition between some of the largest companies in the world to better exploit the power of quantum computers, with IBM, ExxonMobil, and Mercedes-Benz being among them (Smith, 2022; IBM, n.d.). Governments around the world are also investing more in researching quantum computing, a trend that may be related to quantum computing's applicability to the fields of cryptography and cybersecurity (Smith, 2022; Walker, 2022).

For quantum computers to have practical applications, it is necessary for the information they create to be stored long enough for calculations to be based on it (Niels Bohr Institute, 2018). This is problematic because this quantum information often exists for less than a microsecond due to quantum mechanical disturbances known as "tunnelling" (Niels Bohr Institute, 2018). Researchers have theorized that changing the forms of the magnetic molecules involved in quantum computing may help reduce tunnelling, but the energy measurements necessary to study this phenomenon can only be gathered via neutron scattering (Niels Bohr Institute, 2018). Indeed, Chiesa et al. (2019) describe inelastic neutron scattering as the "technique of choice" for probing the magnetic molecules involved in quantum computing and argue that developments in neutron scattering will form a synergistic relationship with developments in quantum hardware.

Neutron scattering is contributing to academic research on quantum computing. Out of the 14,607 academic publications relating to research done at U.S. neutron scattering facilities, 511 dealt with quantum computing based on regular expression searches of their titles and abstracts. The specific search terms used were capitalized and lowercase versions of the words "quantum" and "qubit." These 511 publications generated a total of 18,402 additional citations, for an average of approximately 36 citations per publication.

7.1.5 Conclusion

This case study illustrates the far-reaching and significant positive effects that neutron scattering research has had on the U.S. economy and the potential for it to continue aiding America in developing even more sophisticated computer technology. Today's hard drive technology would have been impossible to develop without the insights into magnetic materials provided by neutron scattering. By focusing on the application of the GMR effect to hard drive downsizing and increased storage capacity, RTI estimates sizable economic benefits to American consumers. We conservatively estimate increases in consumer surplus of more than $75 billion from the introduction of GMR hard drives in 1997 through the introduction of potential competing storage technologies in 2005. These monetized impacts dwarf the total value of hard drive improvements informed by neutron scattering throughout the history of the technology's development. Neutron scattering is further poised to provide similar benefits for quantum computing and is thus essential for America's technological progress and growth in the computer science industry.

7.2 Aerospace Safety

The aerospace industry encompasses airplanes, rockets, and satellites, serving as a vital sector in modern technology and transportation (SelectUSA, n.d.-a). Neutron scattering is a valuable tool for enabling technological advancements within the industry. Advancements include improved fuel efficiency and safety along with improvements in the aerospace manufacturing process, resulting in enhanced structural integrity, reduced weight, and heightened aerodynamic capabilities of spacecraft and aircraft. Neutron scattering also informs research on mitigating the effects of space radiation on human bodies and electrical components.

This section highlights the successes of neutron scattering research applied to the aerospace industry. Economic impacts are estimated for the cases of developing safer aviation fuel and for manufacturing aircraft components with improved structural integrity. Other areas of research are highlighted to show the breadth of potential impacts in the aerospace industry.

7.2.1 U.S. Aerospace Industry

The value of the aerospace industry was estimated at $308.7 billion on a global scale (TBRC Business Research Pvt Ltd., 2024. With over 50% of the global market share, North America is the leader in the global aerospace industry (TBRC Business Research Pvt Ltd., 2024). The United States also plays a significant role in aerospace exports, contributing $151 billion in sales per year (SelectUSA, n.d.-a). The aerospace industry directly employs over 500,000 individuals in the United States, while creating indirect employment opportunities for an additional 700,000 workers across related fields (SelectUSA, n.d.-a).

Over the last decade, the need for advancements in airplanes, rockets, and satellites has motivated significant surges in private aerospace development. Private companies within the newfound space economy have emerged as key players, challenging the traditional authority of government space agencies in space launches and exploration initiatives. The aerospace industry has experienced a growing capital injection as enthusiasm for innovation within the field has grown. The pioneering aerospace industry continues to push the boundaries of present-day space travel and satellite deployment.

The private-sector boom within the aerospace industry has resulted in an accelerated pace of technological advancements. The focus of private industry on developing reusable rockets and cost-effective satellite launches has increased the need for innovations in lightweight materials, efficient fuels, and cutting-edge propulsion systems. These developments aim to improve upon the performance and cost within the space sector to pursue ambitious missions on both the moon and Mars.

In parallel, the aerospace industry continues to see significant progress within the aviation sector. As airplanes become more standardized, key design areas need further advancements. There is an ongoing demand to create more-lightweight aviation components to reduce fuel consumption, enhance fuel efficiency, and improve overall aircraft performance. Moreover, passenger comfort, emission reductions, and safety procedures exist at the forefront of potential improvement on the aviation front.

7.2.2 Safer Aviation Fuel

Neutron scattering can play a vital role in enhancing the safety of fuel used in airplanes. Scientists can identify potential hazards within fuel using neutron scattering, mitigating against hazards. By understanding the behavior of additives, contaminants, and degradation products, scientists can provide risk assessments for the performance and stability of aviation fuels.

When an aircraft crashes, its fuel tanks can rupture, resulting in the fuel spraying out as a fine, floating mist. This mist is highly flammable and can result in fuel explosions or fire (Fluid Efficiency, n.d.). Often, the resulting fire or explosion can be more dangerous than the initial crash due to both the flames and the release of carbon monoxide and other dangerous gases into the air (Rossier, 2023). A grim example of this occurred in 1977 in the Canary Islands when two Boeing 747s collided with each other on a runway. Although the collision itself would have been survivable, the resulting fuel explosion caused 538 casualties (Extance, 2015).

To reduce the likelihood and severity of fuel explosions, Fluid Efficiency, a spin-out company from the California Institute of Technology, developed a fuel additive that causes aircraft fuel to form larger droplets instead of a fine mist when it sprays. Larger droplets release energy more slowly, either preventing spilled aircraft fuel from igniting altogether or resulting in a shorter, cooler fire if it does (Fluid Efficiency, n.d.; Extance, 2015). The fuel additive consists of long, durable polymers that can repair themselves if they break, thus ensuring that they will not break down when pumped into airplanes (Extance, 2015). The additive has already been approved for use by the Environmental Protection Agency (EPA) in diesel and gasoline fuels in the United States (Fluid Efficiency, n.d.).

Based on interviews with NCNR personnel, neutron scattering substantially accelerated the development of Fluid Efficiency's fuel additive by providing insights into the nano-scale behavior of the fuel additive under flow that could not be obtained using any other technique. The three cofounders of Fluid Efficiency partnered with the NCNR to use neutron scattering to prove that a precursor to their finalized fuel additive had self-repairing polymers (Fluid Efficiency, n.d.; Dimeo and Kline, 2016). Thus, neutron scattering has helped reduce the threat posed by fuel explosions and enabled the formation of a new small business in the process.

To gain a more quantitative understanding of the hazards fuel explosions pose, we pulled data on aircraft fuel explosions in the United States from 2008 to 2022 from the National Transportation Safety Board's (NTSB) Case Analysis and Reporting Online (CAROL) database (NTSB, n.d.).[15] We identified 34 aircraft incidents that included a post-impact explosion, 32 of which resulted in at least one casualty. Of the aircraft involved in these incidents, 26 were destroyed completely, while the remainder suffered substantial damage. A total of 71 casualties resulted from these incidents. For comparison, data on accidents involving an aircraft crash in general in the United States from 2008 to 2022 were drawn from the NTSB's (2023) census of U.S. civil aviation accidents. About 27% of general aircraft crashes resulted in at least one fatality and about 13% resulted in the complete destruction of the aircraft.

[15] We applied three rules to a query of the CAROL database: "Aircraft category" was set to "Airplane," "Country" was set to "United States," and "Event category" was set to "Explosion (post-impact)."

We use these estimates to produce a counterfactual scenario in which no post-impact explosions occur in the 34 incidents that did result in a post-impact explosion by applying the risk levels of the 8,522 crashes without post-impact explosions to those 34 incidents. Incidents in the counterfactual scenario are more than three times less likely to result in either any casualties or the complete destruction of the aircraft than incidents that did result in a post-impact explosion. Some of the incidents with a post-impact explosion then shift to less dangerous outcomes, serious injury, and substantial damage as opposed to death and total destruction. Because of this, incidents resulting in substantial damage to the aircraft or serious injury to at least one individual are more likely in the counterfactual scenario. The actual and counterfactual scenarios are presented in Table 7-2.

Table 7-2. Aircraft Crashes with and without Post-Impact Explosions

	Sample of U.S. Aircraft Crashes without Post-Impact Explosions[a]	All U.S. Aircraft Incidents with Post-Impact Explosions[b]	Counterfactual Scenario without Post-Impact Explosions[c]
Total Incidents	8,522	34	34
Incidents Resulting in Complete Destruction of Aircraft	1,108 (13%)	26 (76%)	4.4 (13%)
Incidents Resulting in Substantial Damage to Aircraft	7,438 (87%)	8 (23%)	29.7 (87%)
Incidents Resulting in at Least One Casualty	2,301 (27%)	32 (94%)	9.2 (27%)
Average Casualties per Incident	1.7	2.2	1.7
Incidents Resulting in at Least One Serious Injury	1,125 (13%)	3 (9%)	4.5 (13%)
Average Serious Injuries per Incident	1.7	1	1.7

[a] NTSB (2023)
[b] NTSB (n.d.)
[c] Calculation Methods: Proportions from the data on crashes without post-impact explosions were multiplied by the number of incidents which did result in a post-impact explosion (34) to produce the counterfactual results.

Using guidance from the Federal Aviation Administration (FAA) (2022), it is possible to estimate the total cost of post-crash fuel explosions in terms of lives lost and damage to aircraft. As of 2016, the FAA (2022) has determined that the Value of a Statistical Life (VSL) is $10.7 million, with a lower bound of $6.0 million and an upper bound of $14.9 million.[16,17] For quantifying the losses associated with serious injuries, the FAA (2022) multiplies the VSL by 0.253.

[16] For ease of comparison, we converted all values assigned by the FAA (2022) into 2021 dollars using GDP deflators from the U.S. Bureau of Economic Analysis (2022).
[17] It is important to note that the term “VSL” can be misleading—it does not mean that the FAA is assigning a dollar value of $10.7 million to each human being, but that $10.7 million is the additional cost that, in aggregate, individuals are willing to bear to decrease the expected number of fatalities by one (FAA 2022).

For damage to aircraft, the FAA (2022) estimates that the average market value of a passenger aircraft is $18.6 million. This is therefore assumed to be the average cost of any aircraft that is "completely destroyed" (FAA, 2022). The average cost of repairing an aircraft that has experienced "substantial damage" is estimated to be $3.8 million (FAA, 2022).

We use the cost estimates from the FAA (2022) and the information on plane crashes from the NTSB (2023) to estimate the total cost of post-crash fuel explosions, excluding the costs of the crashes themselves. These results are presented in Table 7-3. Using the NTSB (2023) projections, we estimate that eliminating post-impact explosions would have prevented about 55 casualties and would have prevented the destruction of about 22 planes from 2008 through 2022. Applying these estimated incidents to the FAA's (2022) VSL and plane damage estimates, we estimate that the average annual cost of post-crash fuel explosions in the United States from 2008 through 2022 was about $60 million per year (range: $43–$75 million).

Table 7-3. Total Estimated Costs Avoided by Eliminating Post-Crash Fuel Explosions in the United States from 2008 through 2022

	Estimated Change in Incidents by Eliminating Post-Impact Explosions[a]	Average Estimated Cost Per Incident[b] (2021$m)	Estimated Cost Avoided (2021$m)
Casualties	-55.4	$10.7 ($6.0 – $14.9)	$592.8 ($332.4 – $825.5)
Serious Injuries	+4.7	$2.7 ($1.5 – $3.8)	-$12.7 (-$7.1 – -$17.9)
Planes Completely Destroyed	-21.7	$18.6	$401.76
Planes Substantially Damaged	+21.7	$3.8	-$82.46
Average Annual Cost Avoided			**$60.0** **($43.0 – $75.1)**

[a] Calculation methods: Values were calculated by subtracting the estimates for the counterfactual scenario in Table 7-2 from the actual values of these metrics based on the 34 incidents which resulted in a post-impact explosion.
[b] FAA (2022)

7.2.3 Improved Aircraft Components

By utilizing neutron beams to probe the atomic and molecular structures of materials, crucial insight can be gained into both the material properties and behaviors of a variety of materials under diverse conditions. This insight aids the design and development of high-performance materials, allowing aerospace vehicles to endure harsher environments.

During manufacturing, aircraft components such as wing parts can experience residual stress when parts cool at different rates (League of European Neutron Sources Initiative, 2023). Residual stress can lead to tiny cracks forming in aircraft components, which are typically invisible to manufacturers but can damage the structural integrity of aircraft over time (LENS Initiative, 2023). Residual stress can have serious consequences. An aircraft crash in the Netherlands caused by the disintegration of the plane's sole engine was ultimately determined to be the result of residual stress in a single pin in one of the engine's levers, a component that only cost a few dollars (Kolkman et al., 1996). Also, the economic pressure the aerospace industry is feeling to increase fuel efficiency is causing aircraft manufacturers to focus on improving component longevity while working with lighter materials, which necessitates accurately measuring residual stresses in aircraft components (Klawonn et al., 2018). For these reasons, aircraft operators are starting to employ new technologies to detect faults at early stages and predict failures more accurately before they occur (Meissner et al., 2021).

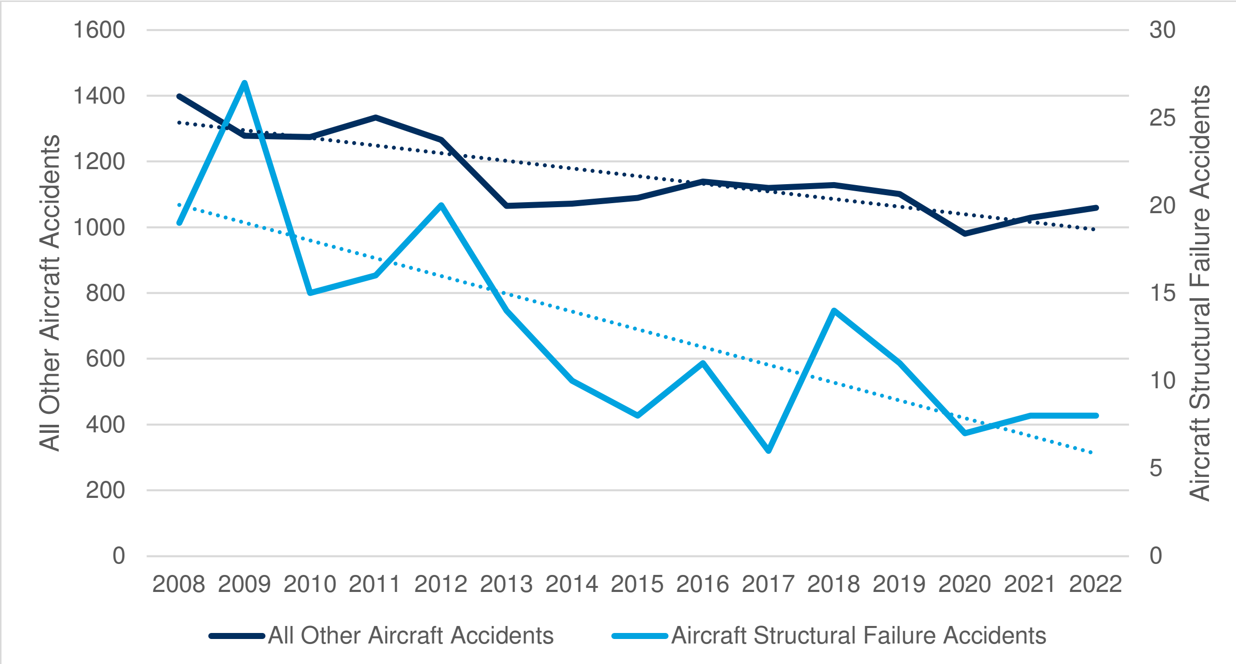
Fortunately, neutron scattering offers a way to help reduce structural failures caused by residual stress in airplanes. Neutron scattering can reveal the cracks in aircraft components caused by residual stress, allowing aircraft manufacturers to experiment with different materials and designs to lessen residual stress and reduce crack growth (LENS Initiative, 2023; Canadian Neutron Beam Centre, 2017). Neutron scattering is uniquely suited to this type of analysis because neutrons can deeply penetrate materials and components and probe them in a nondestructive fashion (LENS Initiative, 2023). While neutron scattering techniques are more commonly used to correct residual stress issues when designing aircraft components, they have also been used to evaluate residual stresses in spacecraft components for NASA at LANL (Rathod et al., 2004).

Businesses have taken notice of how useful neutron scattering can be for reducing residual stresses and cracking in aircraft components. Both Airbus and Rolls-Royce have employed neutron scattering to help create better, longer-lasting aircraft parts (LENS Initiative, 2023; Canadian Neutron Beam Centre, 2017). Also, Bouwer et al. (2022) found that reducing capital costs by increasing the lifespan of aircraft was a key reason why some airlines were able to maintain high profits while the industry overall was experiencing poor performance.

To gain a better understanding of the quantitative impact of reducing structural failures in aircraft, we again drew U.S. data from 2008 to 2022 from the NTSB's CAROL database (NTSB, n.d.). In this case, the three parameters that the query adhered to were that "Aircraft category" was set to "airplane," "Country" was set to "United States," and "Event category" was set to "Aircraft structural failure." For comparison, we ran a query where "Aircraft category" was set to "airplane," "Country" was set to "United States," and "Event category" was set to "accidents."

These queries returned a total of 17,334 airplane accidents, of which 194 were due at least in part to structural failures. Since 2008, accidents due to aircraft structural failures have been decreasing at a higher rate than all other aircraft accidents (see Figure 7-4). The same holds true for the associated numbers of fatalities, serious injuries, severe aircraft damage, and complete aircraft destructions.

Figure 7-4. Number of Accidents Due to Aircraft Structural Failures and All Other Causes from 2008 through 2022, Including Lines of the Best Fit for the Trends in These Incidents



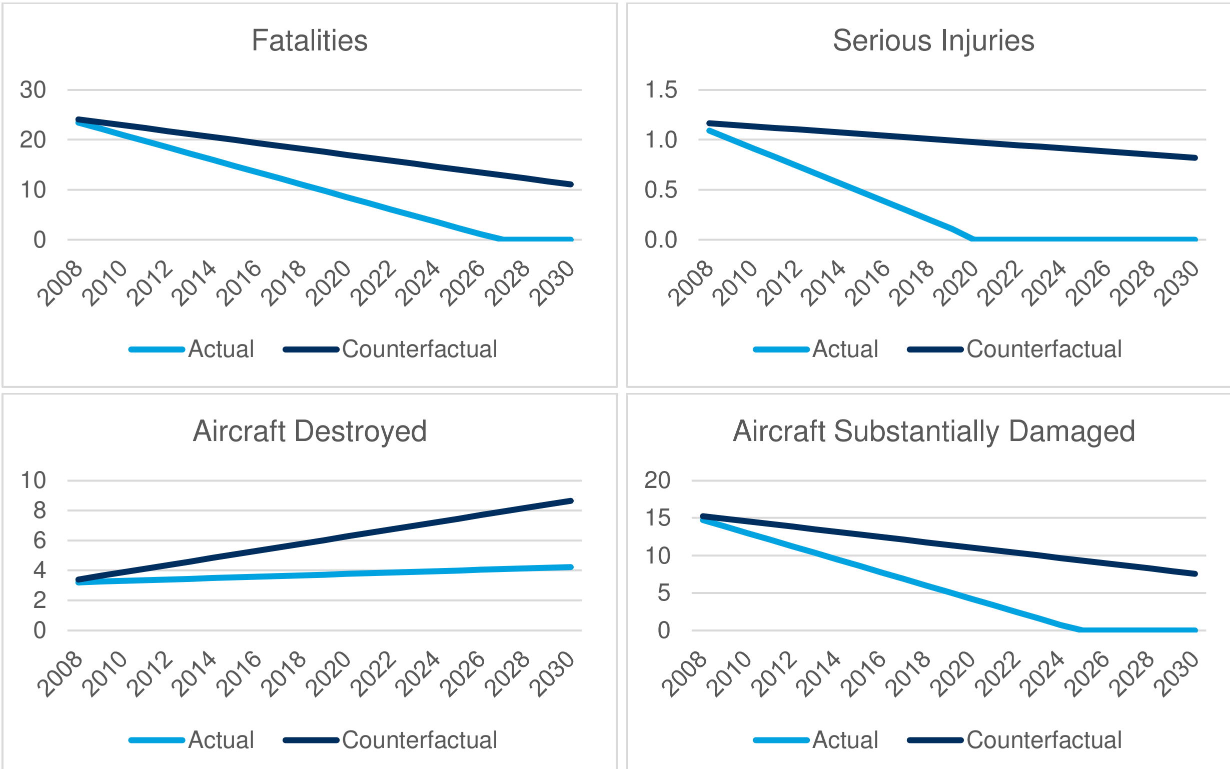
Source: NTSB, n.d.

We estimate the decrease in aircraft structural failure accidents and associated outcomes by comparing the actual lines of best fit for each outcome of aircraft structural failure accidents to the counterfactual trendlines generated by applying the relative decrease in all other aircraft accidents (see Figure 7-5). We project these trends forward to 2030 to estimate the future reduction of incidents.

We monetize the impacts of decreased aircraft structural failures by employing the FAA's (2022) guidelines regarding damage inflicted on aircraft and human beings (see Table 7-4). We also consider the cost of investigating an aircraft accident and removing any wreckage. While the previous section focused on technology reducing the harm after an accident occurred, here we examine the reduction in accidents occurring at all (FAA, 2022). Averaged across all categories of investigation, the FAA (2022) estimates that it would take a combined public and private cost of $947,780 to investigate and clean up after an accident.

We use the values from the FAA (2022) to estimate the value of reduced aircraft structural failures in the United States from 2008 through 2030 (see Table 7-4). We convert estimates from past and future years to present values by applying the U.S. standard discount rate of 2% (OMB, 2023). We estimate the discounted aggregate costs avoided to be $3.4 billion with a range of $2.6 billion to $4.2 billion. This is equivalent to $149.9 million per year on average with a range of $115.1 million to $181.5 million.

Figure 7-5. Actual and Counterfactual Trends in the Number of Fatalities, Serious Injuries, Aircrafts Destroyed, and Aircrafts Substantially Damaged Due to Aircraft Structural Failures from 2008 through 2030



Source: RTI calculations based on data on aircraft structural failures and all other aircraft accidents from NTSB (n.d.)

Table 7-4. Value of Reduced Aircraft Structural Failure Incidents in the United States from 2008 through 2030

	Averted Aircraft Structural Failure Incidents[a]	Average Estimated Cost Per Incident[b] (2021$m)	Estimated Cost Avoided (2021$m)
Incidents Requiring Investigation	175	$0.9	$166.3
Casualties	171	$10.7 ($6.0 – $14.9)	$1,828.8 ($1,028.7 – $2,552.6)
Serious Injuries	16	$2.7 ($1.5 – $3.8)	$42.1 ($23.7 – $58.8)
Planes Completely Destroyed	53	$18.6	$987.6
Planes Substantially Damaged	131	$3.8	$499.0
Discounted Aggregate Costs Avoided from 2008 through 2030 (2021$m):			**$3,448.7 ($2,646.7 – $4,174.3)**

[a] NTSB (n.d.)
[b] FAA (2022) and author calculation of average accident investigation cost across all types of accidents.

7.2.4 Other Aerospace Manufacturing Applications

Within the aerospace industry, water cutting has revolutionized the manufacturing process, creating lighter and stronger aircrafts with heightened aerodynamic capabilities. The water cutting technique has also facilitated the production of intricate cooling channels and geometries in aerospace components, allowing for greater advancements within vehicle design. With the help of neutron scattering research conducted at the NIST Center for Neutron Research (NCNR), OMAX's water cutting process has emerged as a highly successful technique (Niels Bohr Library & Archives, 2020).

Neutron scattering has revolutionized water cutting practices by passing neutrons through the pressure-head to identify weaknesses that would typically go unnoticed. The precision of neutron scattering allows for the identification of microscopic fractures within the pressure-head, which makes water cutting a more effective and exact practice. This will continue to contribute to the advancement of aerospace technology for the next-generation aircrafts.

Similarly, researchers at Honeywell Aerospace and NASA collaborated to explore the potential of friction welding within the aerospace field. Robert Carter and Daira Legzdina utilized the VULCAN instrument at the Spallation Neutron Source at ORNL to examine high-temperature nickel alloy samples with linear friction welds (ORNL, 2016). Neutron scattering allows examination of the properties and performance of these welds in extreme conditions, offering valuable insights for aerospace applications. By leveraging friction welding techniques, the aerospace industry can benefit from enhanced structural integrity, reduced weight, improved fuel efficiency, and increased overall safety in aircraft design and manufacturing. These advancements contribute to the continuous evolution of aerospace technologies and drive the industry towards greater efficiency and reliability.

7.2.5 Protecting Against Space Radiation

The future of space travel holds immense potential with the growth of commercial space travel. Commercial space travel is projected to become more accessible by 2030, with an estimated 10,000 individuals having undergone suborbital flights (Cision, 2022). Space tourism is predicted to bring more than $3 billion in revenue annually into the aerospace economy (Kamin, 2022). Both SpaceX's and Blue Origin's new reusable rocket initiatives will significantly reduce the cost of launching payloads up to 50%, increasing sustainability within the field (Chang, 2017). The future is filled with thrilling possibilities for space travel as the industry pushes the boundaries of human exploration and technological innovation.

However, space radiation presents a hurdle for expanded space travel. Space radiation tends to be more dangerous than radiation people on Earth are exposed to because it is often ionizing, meaning that the electrons have been stripped from the atoms comprising it (Dunbar, 2019). This quality allows space radiation to penetrate most materials far more easily than non-ionizing radiation (Dunbar, 2019). Exposure to space radiation can result in radiation sickness and an increased likelihood of developing cancer, neurological disorders, or various degenerative diseases (Dunbar, 2019). Space radiation can also cause errors to occur in the advanced electronic devices necessary for space travel, and even affect avionics in high altitude commercial aircraft (Andreani et al., 2018; National Aeronautics and Space Administration, 1999). While space travel on a commercial or industrial level is still too novel to fully quantify the negative effects of space radiation, scientists have identified exposure to space radiation as an important issue that needs further study to ensure that individuals in space for long periods can be safe (Kamin, 2022; Australia Nuclear Science and Technology Organisation, 2011).

Fortunately, neutron scattering can assist in researching space radiation and methods to counter its negative effects by replicating the effects of space radiation and the space environment in a laboratory setting (Tulk, 2021). For instance, Andreani et al. (2018) used neutron scattering to test the effects of space radiation on certain electronic components in spacecraft. Similarly, a professor at Suffolk University used neutron scattering to help test out various types of shielding to guard astronauts against space radiation (Suffolk University, 2017). Indeed, Kolos et al. (2022) argue that creating effective shielding from space radiation for the crews of spaceships requires an accurate characterization of the outer space environment and more specifically knowledge of the properties associated with neutrons produced as a secondary result of space radiation's collision with any proposed shielding. This call is echoed by LENS (2020), which states that space radiation is one of the primary obstacles to space exploration and that neutron beams can be used to test both physical and biomedical countermeasures to it.

7.2.6 Conclusion

Neutron scattering holds significant potential for the aerospace industry, offering substantial advantages in terms of safety enhancement and economic growth. While it is impossible to eliminate all accidents and predict every circumstance, manufacturers can use neutron scattering research results to make the aerospace industry safer and more lucrative. As the United States and other nations continue to lead in space travel and exploration, the benefits of neutron scattering research for the aerospace sector are poised to expand further. By leveraging neutron scattering techniques to advance material science, improve fuel systems, optimize energy storage, and enhance radiation shielding, the aerospace industry can make significant advancements, safeguarding human lives and generating economic prosperity. With ongoing research and development, neutron scattering will continue to play a pivotal role in shaping the future of the aerospace industry and space exploration.

7.3 BioPharma

In this case study analysis, we sought to quantify the potential impacts of new, highly efficacious weight loss drugs on the prevalence of obesity in the United States over the next 6 years. In 2018, more than 42% of U.S. adults were obese, defined as having a body mass index (BMI) of 30 or higher (Fryar et al., 2020).[18] Obesity is associated with a wide range of health problems, including diabetes, heart disease, stroke, and depression.[19] Health care-related costs attributable to obesity in the United States exceed $173 billion annually, and labor productivity losses have been estimated at $3 billion per year (Trogdon et al., 2008; Hammond & Levine, 2010). Efforts to encourage weight loss among people with obesity have largely focused on behavioral changes (e.g., changes in diet and activity levels) and, to a lesser extent, on weight loss drugs and bariatric surgery. Weight loss drugs have historically shown modest promise, producing weight loss of approximately 1.5% to 6% among obese individuals after approximately one year (LeBlanc et al., 2018). New drugs, such as semaglutide and tirzepatide formulations, may have larger effects on weight loss, with clinical trials suggesting weight reductions of approximately 15% over 68 weeks of use (Jastreboff et al., 2022). Use of these drugs could result in dramatic reductions in obesity in the United States.

Based on current clinical trial results, we estimate that those who use these new weight loss drugs could move into non-obesity within 1 to 9 years of use depending on their initial BMI when starting the medications and the efficacy of the medications over time. We found medical cost savings from the reduction in obesity levels among medication users, net of drug costs, of $44.5 billion by 2030 (range: $6.2 billion to $105.6 billion) in 2021 dollars.

7.3.1 Background

Neutron scattering techniques can play a valuable role in studying the structure and dynamics of biological molecules at the atomic and molecular level. SANS techniques can detect and quantify peptide and protein aggregation and can assess how peptides change in the presence of stabilizers. This information helps evaluate the effectiveness of stabilizers in preventing peptide or protein aggregation and in better understanding stability mechanisms to optimize drug formulation. Additionally, SANS is used to study the behavior of drug molecules within various delivery systems, such as micelles, and can provide insights into the drug's location, orientation, and dynamics within these systems.[20] The obtained information helps optimize drug delivery systems for improved stability, controlled release, and enhanced therapeutic efficacy. Such information has been instrumental in the design and formulation of new classes of drugs for weight loss among people with diabetes and obesity.

Semaglutide (brand name formulations include Ozempic and Wegovy) is a long-acting glucagon-like peptide-1 (GLP-1) receptor agonist. GLP-1 is a naturally occurring peptide hormone that helps regulate blood sugar levels by stimulating insulin secretion and suppressing

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[18] BMI is a measure of weight relative to height that is typically used to assign individuals to weight categories (Silverman & Lipscombe, 2022).
[19] See NHLBI (2013), NIH (1998), Bhaskaran et al. (2014), Morrison et al. (2015), Halfon, Larson, & Slusser (2013), Beck (2016), Kasen et al. (2008), and Luppino et al. (2010).
[20] See Nugrahadi et al. (2023), Ford et al. (2023), and Gilbert et al. (2021).

glucagon release. Semaglutide has a half-life of around one week, which means it can be administered once weekly as a subcutaneous injection. Tirzepatide (brand name formulation is Mounjaro) was also approved in November 2023 for treatment of Type 2 diabetes and obesity (FDA Office of Medical Affairs, 2023). Tirzepatide is a fusion of three peptide sequences derived from different proteins: GLP-1, glucose-dependent insulinotropic polypeptide (GIP), and the Fc region of an IgG1 antibody. This fusion provides tirzepatide with a unique mechanism of action that targets multiple pathways involved in glucose regulation and appetite control.

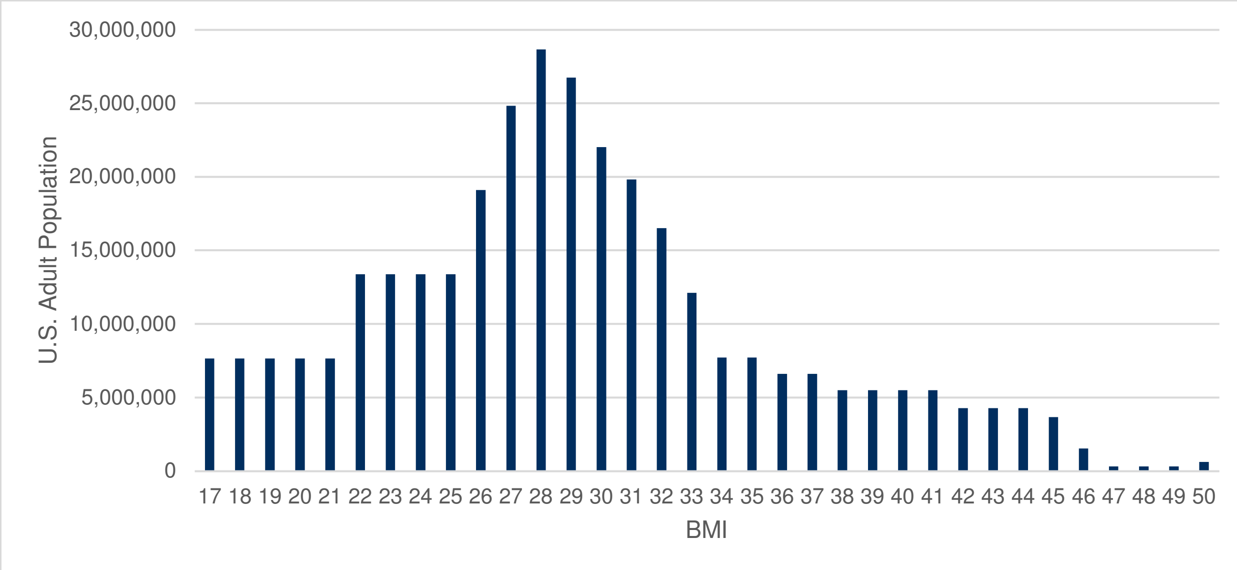
Both semaglutide and tirzepatide formulations may prove to be transformative in addressing the worldwide epidemic of obesity. The Semaglutide Treatment Effect in People with obesity (STEP) clinical trial showed that 68 weeks of weekly subcutaneous administration of semaglutide 2.4 mg was associated with approximately 15% weight loss among obese and overweight individuals (Bergmann et al., 2023). Tirzepatide has also shown promising results in recent clinical trials, with participants losing an average of 15% of their bodyweight after 72 weekly 5 mg doses (Jastreboff et al., 2022). Weight loss results are higher for individuals who are obese but do not have Type 2 diabetes.

7.3.2 Approach

To explore the potential impact of recently approved GLP-1 weight loss drugs, we compared medication costs to reductions in obesity-related medical costs through 2030 under plausible assumptions about the effectiveness of the medications and the percentage of people with obesity who will be prescribed the medications and tolerate them for long-term use.

We began by generating a baseline distribution of BMI for the U.S. adult population ranging from below 17 to above 50 (see Figure 7-6). We did so by applying published estimates of the percentage of people with normal weight, below normal weight, obesity, and morbid obesity to the estimated size of the U.S. adult population (National Institute of Diabetes and Digestive and Kidney Diseases, 2021).

Figure 7-6. Estimated Baseline Distribution of BMI Levels among U.S. Adults



Source: RTI calculations using data from the National Institute of Diabetes and Digestive and Kidney Diseases (2021)

Next, we calculated the potential impact of newer weight loss drugs on the yearly BMI distribution among those who take the drugs through 2030. As shown in Figure 7-7, our impact analysis assumed the use of these weight loss drugs increased the probability that someone who started out as morbidly obese would move into the obese subpopulation and that someone who started out as obese would move into the normal weight subpopulation.

Figure 7-7. Approach for Analyzing the Potential Impact of Weight Loss Drugs on the Distribution of the U.S. Population's BMI by Weight Classes.

We based estimates on the percentage of those with a BMI of 30 or higher who take the GLP-1 drugs on the current level of access and the fact that demand currently outpaces access (McPhillips, 2023). The base case analysis assumed that 10% of those with a BMI of 30 or higher will use one of the weight loss medications. The most conservative scenario assumed that 3.3% of those with a BMI of 30 or greater will use the medication based on the estimated population that had access to the drugs in 2023, while the most optimistic scenario assumed that 20% use on of the medications.

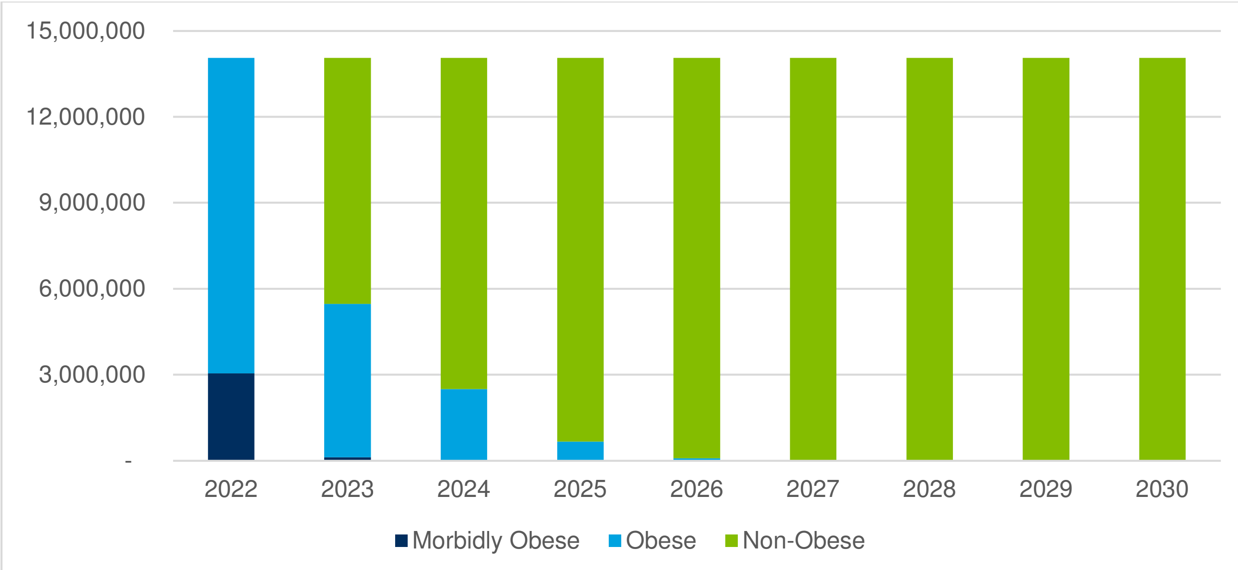
We based estimates on the efficacy of the GLP-1 medications on the various clinical trial results that have been made available to date (Jastreboff et al., 2022; Bergmann et al., 2023; Little et al., 2024). Because the drugs have not been tested in the long-term, we assume that efficacy decreases over time by a varied percent in each scenario. The base case analysis assumed that use of weight loss medications results in a 15% reduction in weight over the first year, with the rate of loss decreasing by 20% each year. The conservative scenario assumed that use of weight loss medications results in a 10% reduction in weight over the first year, with the rate of loss decreasing by 15% each year. The optimistic scenario assumed that those using the weight loss drugs experience a 20% reduction in weight over the first year, with the rate of weight loss decreasing by 25% each year.

We estimated the potential cost savings that might arise from the reduction in obesity estimated in the various scenarios. The estimated annual medical costs attributable to obesity are $2,505 in 2018 dollars, which we adjusted to $2,769 in 2021 dollars (Cawley et al., 2021). We assumed an average annual cost of the weight loss drugs of $2,769 in 2021 U.S. dollars based on the recently published cost of $2,544 in 2018 Canadian dollars (CADTH, 2019). We calculated the aggregate, cumulative medication costs and medical cost savings through 2030 by applying the discounted annual per-person cost estimates. We assumed a 2% annual discount rate, following OMB (2023) guidance. For medication costs, we applied the discounted, annual per-person medication costs to the estimated number of people using the medications in each scenario. For medical cost savings, we applied the discounted, annual per-person medical costs attributable to obesity to the number of people who became non-obese after each year of medication use. Net cumulative costs in each year were calculated as aggregate cumulative medication costs minus aggregate cumulative medical costs averted.

7.3.3 Findings

Under the base case scenario, we assumed that about 14.1 million people use the newer GLP-1 medications starting in 2023. Results indicate that all these individuals would become non-obese within 5 years of medication use (see Figure 7-8). This is important because, under our modeling assumptions, the quantified benefits of weight loss medication use only outweigh medication costs once an individual taking the medication moves into non-obesity.

Figure 7-8. Base Case Projected Distributions of BMI Levels among U.S. Adults Taking GLP-1 Medications Starting in 2023 (N=14.1 Million)

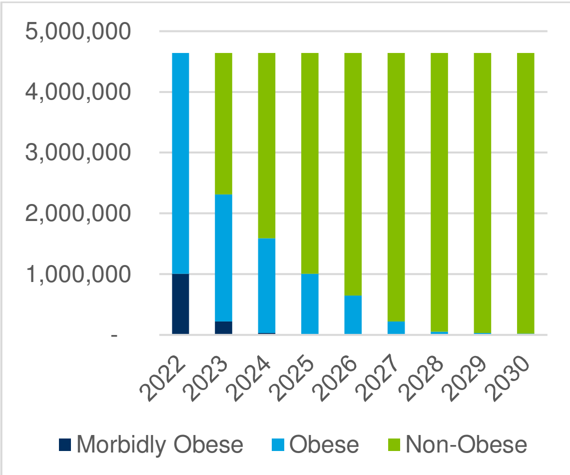


Source: RTI calculations assuming 10% of those with a BMI of 30 or higher use one of the GLP-1 medications and that use of the medications results in a 15% reduction in weight over the first year, with the rate of loss decreasing by 20% each year.

The key differences between the base case and alternate scenarios are the number of individuals assumed to use the GLP-1 medications and the time it takes for individuals to move into non-obesity (see Figure 7-9). Under the conservative scenario, we assumed that about 4.6 million people use the medications starting in 2023 and results indicate that about 20,000 individuals would remain obese after 8 years of use. Under the optimistic scenario, we assumed that about 28.1 million people use medications starting in 2023 and results indicate that all these individuals would become non-obese within 4 years of use.

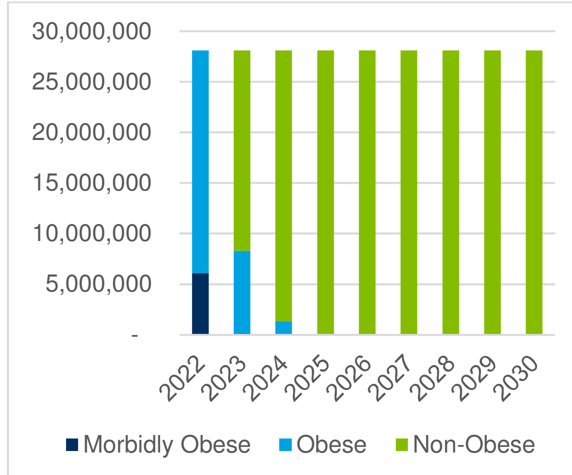
Figure 7-9. Projected Distributions of BMI Levels among U.S. Adults Taking GLP-1 Medications Starting in 2023 under Conservative and Optimistic Scenarios

Conservative Scenario (N=4.6 million)



Source: RTI calculations assuming 3.3% of those with a BMI of 30 or higher use one of the GLP-1 medications and that use of the medications results in a 10% reduction in weight over the first year, with the rate of loss decreasing by 15% each year.

Optimistic Scenario (N=28.1 million)



Source: RTI calculations assuming 20% of those with a BMI of 30 or higher use one of the GLP-1 medications and that use of the medications results in a 20% reduction in weight over the first year, with the rate of loss decreasing by 25% each year.

Table 7-5 summarizes the results of our analysis across the three adoption and outcome scenarios. In every scenario, the discounted cumulative reduction in obesity-related medical costs outweighs the discounted cumulative costs of the medications by 2028. By 2030, the cumulative discounted difference in costs is $42.5 billion, with an estimated range of $6.2 billion to $105.6 billion.

Table 7-5. Difference between the Cumulative Discounted Medication Costs and the Cumulative Discounted Reduced Obesity-Relate Medical Costs from 2022 through 2030 (2021$m)

Adoption and Outcome Scenarios	Discounted Cumulative Medication Costs	Discounted Cumulative Reduced Obesity-Related Medical Costs	Difference
Base Case	$ 219,081.89	$ 261,580.25	$ 42,498.36
Conservative	$ 72,297.02	$ 78,495.19	$ 6,198.16
Optimistic	$ 438,163.78	$ 543,720.02	$ 105,556.24

Results calculated by applying estimated annual medical costs attributable to obesity of $2,769 (Cawley et al., 2021), an average annual cost of the weight loss drugs of $2,128 (CADTH, 2019), and a 2% annual discount rate (OMB, 2023) to the adoption and outcome scenarios depicted in Figure 7-8 and Figure 7-9.

7.3.4 Discussion

Our assessment estimates the results of a single cohort of patients taking GLP-1 medications under various scenarios of adoption and weight loss outcomes. However, it is likely that uptake of these medications would increase over time as more data on their efficacy is gathered and published. Increased uptake of the weight loss medications over time would not linearly increase the net benefits of their use, as each new cohort will experience some years of taking the medications before becoming non-obese, during which time medication costs will outweigh reductions in obesity-related medical costs. These results also assume that GLP-1 medication use among each cohort remains constant over time, as current clinical trial results indicate that long-term use of the medications is needed to maintain weight loss. The impacts of varied use over time would also impact results in non-linear ways. Also, outside of the clinical trials our outcome assumptions are based on, users may be less likely to follow the prescribed drug protocol and may thus experience smaller weight loss effects than those observed in clinical trial settings. Confidence in the assessment of GLP-1 benefits will improve as more information is known about the long-term outcomes of medication use outside clinical trial settings.

Perhaps most importantly, we assumed in our analyses that medication costs will be $2,128 per year in U.S. 2021 dollars, consistent with costs from a Canadian payer perspective. However, drug prices for Wegovy are currently closer to $14,000 per year in the United States. At such a high cost, the obesity-related medical cost savings of $2,769 are insufficient to offset medication costs (Atlas et al., 2022). Yet, because it is unclear whether U.S. drug prices may come closer to those paid by national health systems in Canada and the U.K., especially over an extended time horizon, we assumed a cost of $2,128 per year for the full analytic horizon (Scott, 2023).

It should also be noted that we assumed users of the weight loss drugs would be equally distributed across the full distribution of people with obesity; 10% of people with each BMI level of 30 or higher were assumed to initiate and continue use of the weight loss drugs. It is not yet known whether use of the drugs would be evenly spread across people with obesity or concentrated more heavily among people with mild or morbid obesity. We also do not account for differential uptake by race or ethnicity, although current prescription data suggests that white patients have disproportionately higher access to GLP-1 medications (McPhillips, 2023). However, equitable reductions in obesity could improve health equity, as obesity prevalence immediately preceding the COVID-19 pandemic was 49.9% among Black adults, 45.6% among Hispanic adults, and 41.4% among non-Hispanic white adults (Stierman et al., 2021).

7.3.5 Conclusion

SANS is a powerful tool that has been instrumental in the design and formulation of recent weight loss drugs. These drugs offer tremendous promise for achieving and maintaining weight loss for people with obesity, as they lead to meaningful weight loss in most people who use them (Frias et al., 2021). Widespread use of these medications may reduce the high prevalence of obesity in the United States and in countries around the world where rates of obesity have been on the rise. Because obesity can lead to severe and costly health conditions such as diabetes, heart disease, and stroke, medications that lead to substantial weight loss have the potential to improve population health and reduce medical spending in the United States and in other countries where obesity is a major contributor to growth in health care utilization and spending.

7.4 Electric Vehicles

In this case study, we examine the potential impact that neutron scattering and imaging technologies may have on the U.S. automotive industry, particularly the electric vehicle (EV) segment of the industry. We run a prospective analysis of the estimated value of the U.S. battery electric vehicle (BEV) industry over the coming years and make assumptions regarding the share of this value attributed to neutron technologies. Our quantitative analysis will only consider the BEV segment of the industry since this is the fastest growing industry segment and because the goal of most governments and car manufacturers is to transition to fully electric cars in the future.

EVs are powered by electric motors using electricity stored in large battery packs to propel the car as opposed to gasoline or diesel-powered combustion engines in an internal combustion engine vehicle (ICEV). The share of electricity as a fuel source in propelling the vehicle varies by type of EV. Hybrid electric vehicles (HEVs) rely the least on the electric motor, using it only on low speeds, whereas BEVs rely exclusively on electricity as a fuel source. Plug-in hybrid electric vehicles (PHEVs) lie between the two extremes and vary depending on the size of their battery pack, their weight, and brand, among other factors.[21] We will use the term EV to indicate any car that incorporates a battery-operated motor regardless of whether the car also has an internal combustion engine or not, thus including BEVs, HEVs, and PHEVs.

7.4.1 U.S. Electric Vehicle Production and Adoption

Even though the first EV built in the United States was in the 1800s, the popularity of EVs rose and fell several times throughout the 20th century. Two milestones ocurring at the beginning of the 21st century generated substantial public interest in EVs. One was Toyota's introduction of the first mass-produced hybrid car, the Prius, in 1997 and subsequent worldwide release in 2000. With rising gasoline prices and environmental awareness, the Prius grew in popularity and continues to be one of the best-selling hybrids in production. The second event was in 2008 when Tesla Motors, a Silicon Valley startup company, produced the first fully electric car, the Roadster, which can travel more than 250 miles on a single charge (DOE, 2023).[22]

Tesla's success with the Roadster prompted other car companies to introduce their own EVs or PHEVs. In late 2010, General Motors (GM) introduced the Chevy Volt, which was the first commercially available PHEV and Nissan released the Leaf, a fully electric car. Since then, other legacy car manufacturers as well as new EV startups have joined the growing EV industry.

The United States is a major player in global EV production. As already mentioned, Tesla produced the first commercially available BEV in the 21st century while GM produced the first PHEV. Both Tesla and GM are U.S. car manufacturers and Tesla continues to be one of the largest producers of BEVs in the global market (Counterpoint, 2023). Additionally, several BEV-

[21] The difference between the two types of hybrids are that PHEVs can be charged by an external electricity source, whereas the HEV mostly relies on regenerative braking to charge the battery and does not plug in to an external electricity source (AFDC, 2023).

[22] The Roadster, a luxury sports car, was Tesla Motor's first fully electric car. It was built with a lithium-ion battery, which took between 24 and 48 hours to charge fully on a standard home electric outlet. Given that its price was over $100 thousand, it was not affordable to most consumers. Tesla Motors later changed their name to Tesla in 2017.

producing U.S. startup companies have been established such as Rivian, Lucid, Bollinger, Canoo, Fisker, and Aptera.

7.4.2 Benefits of U.S. Vehicle Electrification

Enhanced U.S. Energy Security

The transportation sector accounts for almost a third of all U.S. energy consumption (30%) and more than two-thirds of U.S. petroleum needs (70%). Wider adoption of EVs of all forms raises energy security in the United States through two main routes. The first is that they require less nonrenewable fuels (fossil fuels) and so lower U.S. dependence on petroleum imports and usage of national petroleum reserves.[23] The second way by which EVs increase energy security is that they create a more diversified fleet that relies on multiple types of fuel. Electricity in the United States is generated using both renewable (wind, solar, hydropower) and nonrenewable (coal, natural gas, nuclear) energy, and this increases national energy security (AFDC, 2023).

Reduced Greenhouse Gas Emissions

The transportation sector is one of the largest contributors of greenhouse gas (GHG) emissions in the United States, accounting for the largest share of emissions (29%) out of all sectors in 2021. Within the transportation sector, passenger cars and light-duty trucks[24] were the largest segment contributing to transportation-related GHG emissions, accounting for 58% of the sector's emissions. Moreover, transportation GHG emissions have increased in quantity during the period of 1990 through 2021 more than any other sector. The main reason for this is the increased demand for travel (EPA, 2023).

The ultimate impact of higher electrification on global GHG emissions is not conclusive since the life cycle emissions of EVs depend on the energy sources that are used for both producing the batteries as well as those used to charge the vehicles, in addition to the impacts of battery disposal. Different studies have produced different results with respect to the overall environmental and human health impacts of wider EV adoption (Brennan and Barder, 2016; CRS, 2020; AFDC, 2023). However, multiple studies have found that the expanded use of BEVs is expected to reduce GHG emissions and global warming potential (GWP) compared to the use of ICEVs (Brennan and Barder, 2016).

The reduced GHG emissions from the use of EVs is especially important in the United States given the new, more ambitious GHG emissions standards and regulations proposed by the EPA in April 2023 for light-duty and medium-duty vehicles released in 2027 or later (EPA, 2023).

Potential Consumer Cost Savings

Even though the prices of EVs are typically higher than ICEVs, sometimes significantly so, the cumulative cost of ownership can be higher or lower depending on different factors. Energy

[23] A main caveat is that this finding is restricted to the United States, and not globally. If we consider the global implications of wider EV adoption, we would need to consider the use of fossil fuels in the extraction of materials needed to produce EV batteries. These mines are mostly located in other countries besides the United States and results are inconclusive as to the environmental benefits of wider EV adoption in that regard.

[24] Light-duty trucks include sport utility vehicles (SUVs) and minivans (EPA, 2023).

costs of EVs are generally lower than ICEVs, with BEVs having the lowest energy costs since they do not use gasoline or diesel at all, followed by PHEVs and HEVs.[25] Maintenance costs of BEVs, especially, are much lower than ICEVs due to the fewer moving parts involved. Additionally, there is a federal tax credit, which some EVs qualify for, and which vary from $2,500 to $7,500, depending on different factors.[26] There are also often state-level and utility-level incentives for purchasing an EV that can all be used to offset the initial higher purchase price of the vehicle. As battery technology improves and the EV production capacity of car manufacturers expands, the purchase prices of EVs are expected to come closer to those of ICEVs (AFDC, 2023).

7.4.3 The Role of Neutron Scattering Research in Improving EV Performance

Neutron scattering research has led to multiple advances in the U.S. auto industry. Attribution of a particular advancement to a specific source is obfuscated by the corporate nature of the industry, which prevents car manufacturers from disclosing proprietary information related to their business. Therefore, not enough information or data are available to definitively attribute value added in the auto industry to contributions from neutron scattering research. Consequently, we will describe the general ways in which neutron research has been used to benefit the U.S. EV industry rather than focusing on a specific advancement.

Reduction of Vehicle Component Weights

One of the main vehicle specifications that consumers consider and one where car manufacturers compete against each other is fuel efficiency. This is especially true as fuel prices continue to rise. Therefore, the more fuel efficient a vehicle is, all other things held constant, the more in demand it is. One of the main considerations guiding fuel efficiency is vehicle weight; the heavier a car is, the less fuel efficient it is because it requires more fuel to travel the same distance compared to a lighter vehicle, all other things being equal.

Car manufacturers continue to research different materials and metal alloys that can be used to reduce vehicle weights. Neutron diffraction can be used to better understand the materials and provides improvements in measurement methods. It can inform how these alloys and materials would respond under different conditions. Different materials have been tested such as aluminum, magnesium, and carbon fiber. The latter, for example, has been used in some high-end cars to replace specific components of the vehicles and make the car lighter overall, leading to higher fuel efficiency.[27]

Overall, the weight of vehicles over the years has not changed significantly even though the weights of some of their components, including their frames, have been reduced. These weight savings have allowed car manufacturers to incorporate other safety and convenience features in

[25] To compare the cumulative cost of ownership of different vehicles, including a breakdown of the different cost components, see the Vehicle Cost Calculator at https://afdc.energy.gov/calc/.
[26] There are other consumer-related qualifications that need to be met for a person to qualify for the federal tax credit.
[27] Based on an interview with Thomas Gnaupel-Herold and Adam Creuziger on May 11, 2023.

the cars in addition to fuel-saving technologies, such as regenerative braking, without increasing overall vehicle weights.[24]

For EVs and especially for BEVs, their heaviest component is the battery. Therefore, one of the main advancements that would enable the increase in fuel efficiency (and therefore travel range) would be a reduction in battery weight and/or increase in its energy density.

Improved Battery Technology

ICEVs contain lead-acid batteries, which are used to activate the engine (WorkTruck, 2023). Most EV batteries, on the other hand, are lithium-ion batteries (LIB), which have higher energy capacity, are more energy dense, and have longer lifespans as well as higher cycle lives (Skill Lync, 2022).[28] However, LIBs still require improvements in their energy density, safety, and cycle life to maximize performance and reliability (Bak et al., 2018).

Batteries are complex systems with multiple components that need to work complementarily together to efficiently and safely produce power. Therefore, research into methods of improving their safety and performance should not be done solely on individual components, but on the entire battery structure as it is in operation.[29] Improvements in LIBs can only be done by developing a thorough understanding of their mechanisms for power storage, degradation of performance, and reactions at the electrolyte/electrode interfaces (Bak et al., 2018). Abitonze et al. (2022) synthesize the findings of various studies demonstrating the superiority of neutron-based techniques in providing a more thorough characterization and real-time monitoring of battery performance compared to other techniques such as X-ray diffraction.

Some of the main barriers to wider adoption of EVs lie in their charging requirements and the current status of charging technology.[30] These barriers lie in the charge times, concerns over battery safety, and availability of charging infrastructure. Another major barrier to wider adoption is range anxiety since the vast majority of EVs do not achieve the same range as an ICE vehicle. We will discuss each of these barriers in more detail below and describe how neutron scattering can help overcome them.

For LIBs to be reversibly charged and discharged and for longevity of battery life, they require the formation of a solid electrolyte interphase (SEI), which is generated during the first few charging cycles of the battery (Heiskanen et al., 2019). This layer is necessary for performance, operation, and safety. [28] Even though rare, LIB fires tend to be extremely dangerous and can reignite hours, or even days after being put out (FDNY, 2023). Anecdotally, some consumers do not want to park an EV in their garages for fear of a battery fire (Jones, 2023). Therefore, making EV batteries safer would promote wider adoption among consumers.

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[28] Even though both lead acid and LIBs contain a cathode, anode, and electrolyte, their materials are different. Despite the fact that LIBs are initially more expensive to produce and install, their longer lifespans make them more cost effective in the long run (Skill Lync, 2022).

[29] Based on an interview with Joseph Dura and Jamie Weaver on May 12, 2023.

[30] There are three levels of charging speeds: Level 1 (L1) is 110 V at alternating current (AC), Level 2 (L2) is at 240 V, and Level 3 (L3) is at 500 V direct current (DC) (CRS, 2020). L1 is widely available using a regular outlet at home. L2 chargers can be installed in homes to charge EVs in a few hours or overnight. L3 chargers are not available for installation in residences due to their high voltage.

EV battery fires are most often caused by the breakdown of the SEI layer, which is poorly understood (Heiskanen et al., 2019). Recent study outcomes suggest that improved performance of the SEI layer could be achieved with more stable SEI components. Heiskanen et al. (2019) also argue that a better understanding of the nano structure of the SEI layer is crucial for achieving better stability and outcomes. At NIST, research was initiated in collaboration with GM in 2011 using neutron scattering to better understand the SEI layer with the goal of improving stability and performance and raising battery safety.

In addition to battery safety, LIBs still need improvement to increase charging speeds and EV ranges. The long charge times of EVs put them at a disadvantage compared to ICE vehicles. Another issue is the relatively shorter range of EVs compared to ICE cars. Even though some EVs have a range of over 300 miles on a single charge (for example, Tesla, Lucid, GM Hummer), these vehicles are relatively expensive and may not be affordable for the average consumer. More affordable EVs have shorter ranges and therefore, many consumers are reluctant to use an EV as their daily vehicle for fear of not having enough range to do so.

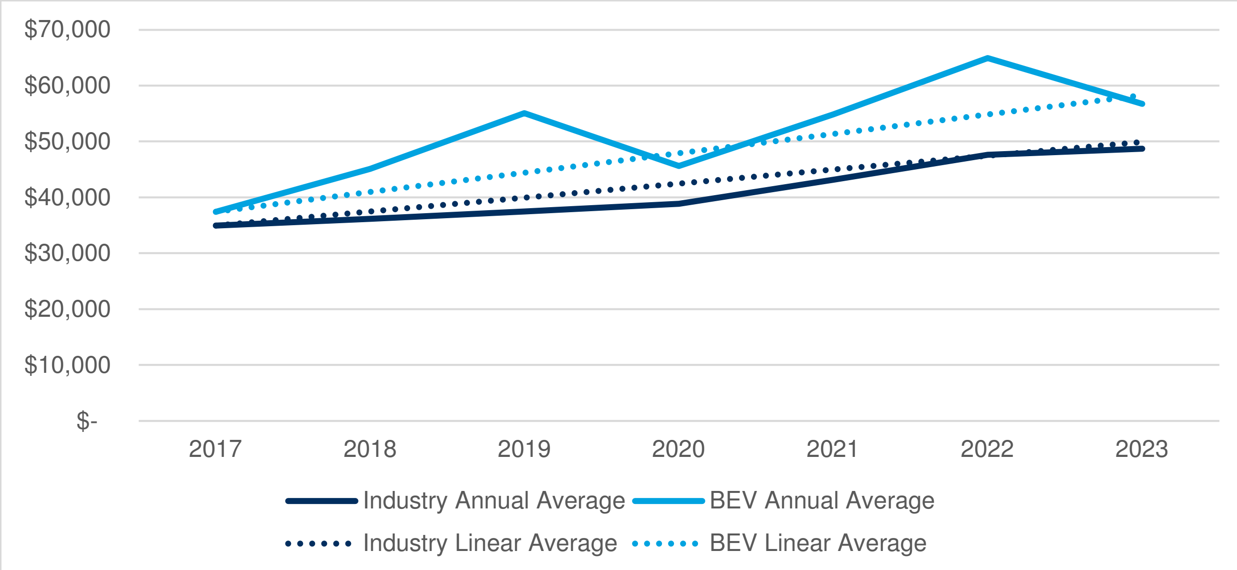
One of the potential solutions to these issues is the use of solid-state lithium batteries (SSLB) instead of LIBs. These batteries offer advantages compared to traditional LIBs in that they are safer, more energy dense, and more stable at high temperatures (Abitonze et al., 2022). However, the electrochemical performance of SSLBs needs to be improved before they are ready to use in EVs. This cannot be accomplished without the use of advanced characterization methods to identify current shortcomings with the operation of SSLBs. As mentioned above, neutron-based techniques are more capable of distinguishing different elements and materials compared to other techniques (Abitonze et al., 2022).

7.4.4 Quantified Benefits of Increased U.S. EV Adoption

One way to monetize the benefits of EV adoption in the United States is to assess consumer willingness to pay for EVs compared to ICEVs. Kelley Blue Book (2023) data provide the annual prices of BEVs versus all vehicles from 2017 through 2023.[31] As shown in Figure 7-10, the average annual BEV price has been consistently higher than the average industry price, indicating that consumers are willing to pay a premium to own an EV. Because the BEV market is small and emerging, average BEV prices have fluctuated more extensively over this time. We therefore calculate the linear average of both BEVs and the full industry to provide a steadier price comparison over time. The linear average estimates indicate that BEVs cost $2,503.08 more than the industry average in 2017 and $8,350.44 more than the industry average in 2023.

[31] Data suggest that the price of PHEVs was similar to the industry average (Irwin, 2023).

Figure 7-10. Annual and Linear Average BEV and Industry Prices from 2017 through 2023



Source: RTI calculations and Kelley Blue Book (2023).

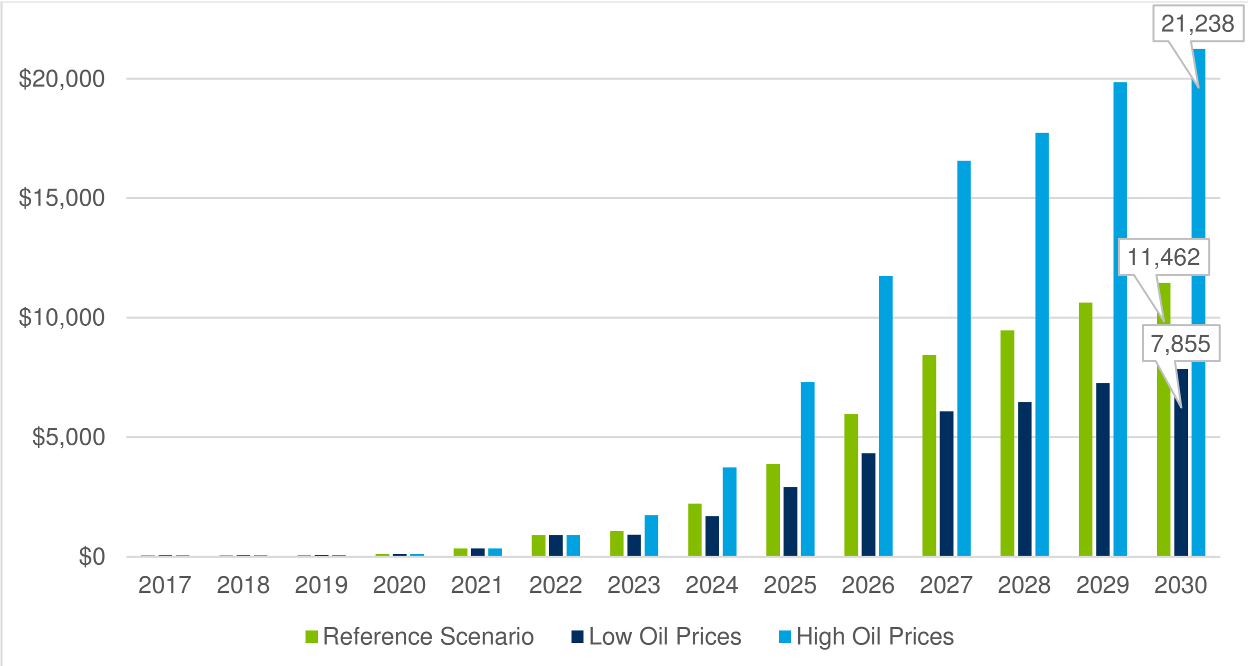
Average BEV prices compared to the industry average provide a conservative estimate of consumers' average willingness to pay for EVs over ICEVs. Estimates are conservative because the industry average prices include the BEV prices, which are higher than average. This means the actual difference between average BEV prices and average ICEV prices is higher than these estimates suggest. We make another conservative assumption by presuming that the 2023 difference in average prices is maintained through 2030 even though average BEV prices have been increasing at a higher rate than the industry average.

We applied the estimated average of U.S. consumer willingness to pay for BEVs to estimates on the number of BEVs manufactured by U.S. automotive companies who are known to conduct research at U.S. neutron scattering facilities. The U.S. Energy Information Administration (EIA) (2023) *Annual Energy Outlook* provides future projections of all U.S. electric light-duty vehicle sales under current conditions and under scenarios of low and high oil prices. We augmented these industry-level projections with manufacturer-specific data records to estimate future EV production by U.S. manufacturers using neutron scattering facilities.[32]

Figure 7-11 shows the annual estimates from 2017 through 2030 of aggregate U.S. consumer willingness to pay for EVs produced by U.S. manufacturers who conduct research at neutron scattering facilities. We provide projections from 2023 onward under the base case scenario and under assumptions of lower or higher oil prices. Projections indicate an aggregate annual willingness to pay of $11.5 billion in 2030 (range: $7.9 billion to $21.2 billion).

[32] U.S. Chevrolet Bolt sales are from GM Authority (2023). Data on U.S. EV sales by manufacturer from 2020 through 2023 are from Cox Automotive (2023). As of this writing, Tesla is not a known user of U.S. neutron scattering facilities. We assume that Tesla will use the facilities in the future so that future Tesla sales are increasingly included in the projections from 2024 onwards.

Figure 7-11. Annual U.S. Consumer Willingness to Pay for U.S. Manufactured BEVs from 2017 through 2030 (2021$m)



Source: RTI calculations using data from the U.S. Energy Information Administration (2023), GM Authority (2023), and Cox Automotive (2023).

We apply the U.S. standard discount rate of 2% to the resulting time series of U.S. consumer willingness to pay for BEVs from U.S. manufacturers that use neutron scattering research. We thus generate a discounted aggregate willingness to pay for U.S. BEVs from 2017 through 2030 of $48.1 billion, with a range of $34.5 billion to $89.0 billion (see Table 7-5).

Table 7-5. Discounted Aggregate U.S. Consumer Willingness to Pay for U.S. BEVs from 2017 through 2030 (2021$m)

Adoption Scenarios	Aggregate Quantity of U.S. BEVs Sold (million vehicles)	Discounted Aggregate Consumer Willingness to Pay for U.S. BEVs (2021$m)
Base Case	6.62	$48,091.10
Conservative	4.75	$34,457.94
Optimistic	12.22	$88,987.19

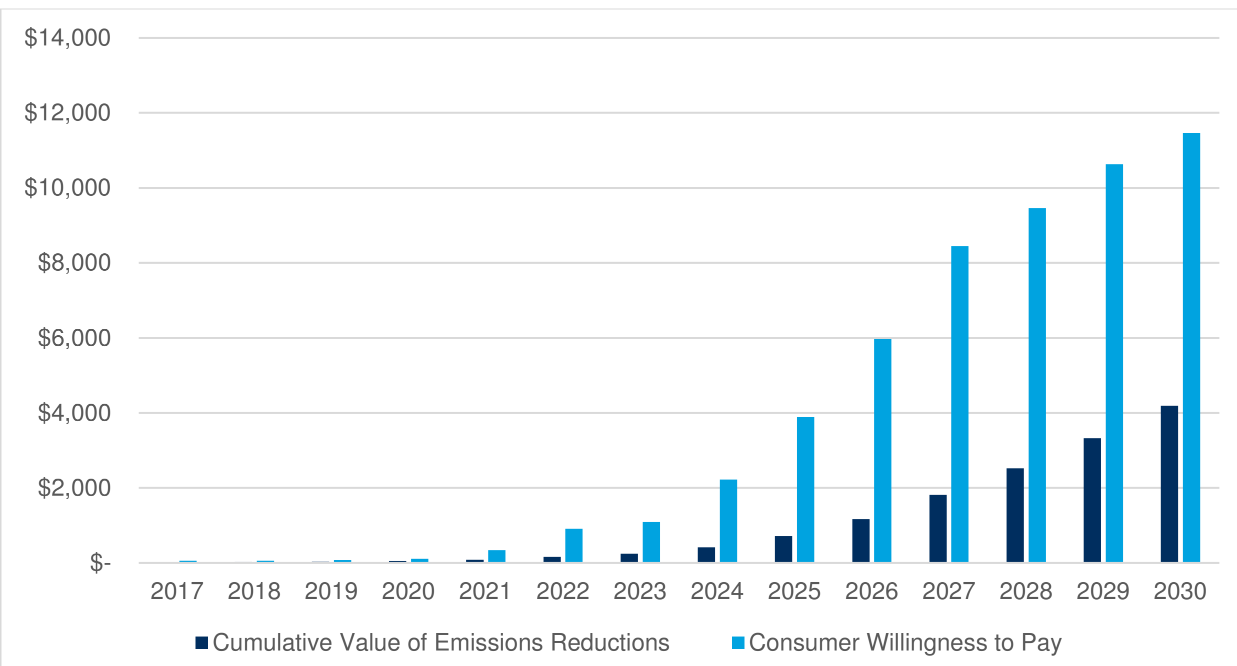
Results calculated by applying estimated annual sales of BEVs to the annual difference between average industry and BEV prices (Kelley Blue Book, 2023).

7.4.5 Discussion

Our estimates of the value of BEVs over ICEVs in the United States are conservative for several reasons. First, we estimate willingness to pay as the additional average price of BEVs beyond the industry average vehicle price. However, market prices provide lower bounds of willingness to pay; we know consumers are willing to pay at least the market rate, but many consumers may be willing to pay a price above the market rate. We further understate the willingness to pay for BEVs by comparing BEV prices to industry average prices, which include BEV prices. Average ICEV prices are certainly lower than the industry average when removing the higher average BEV prices. Finally, we conservatively assume that the average price difference between BEVs and ICEVs will remain constant from 2023 onward, when current price trends indicate a widening gap in prices between the two vehicle types.

It is important to note that we do not include additional estimates of the value of reducing GHG emissions by increasing BEV adoption. This is because we assume that consumer willingness to pay for BEVs includes consumers' perceived value of reducing greenhouse gases. Figure 7-12 shows the annual U.S. consumer willingness to pay for BEVs alongside the annual estimated value of GHG emissions from cumulatively increased BEV adoption. As can be seen, the willingness to pay estimates outweigh the estimated GHG emissions, indicating that either consumers value GHG emissions beyond the standard U.S. estimates for the value of emissions, or that consumers value BEVs for more than their ability to reduce GHG emissions.

Figure 7-12. Annual U.S. Consumer Willingness to Pay for U.S. Manufactured BEVs from 2017 through 2030 (2021$m)



7.4.6 Conclusion

Neutron research has led to multiple advances in the U.S. auto industry, including increases in the availability and quality of EVs. Benefits to EV use include increased U.S. energy security, reductions in greenhouse gas emissions, and potential consumer cost savings. Our impact estimates confirm that U.S. consumers place a high value on EV adoption. Additional improvements in vehicle component materials and battery performance would further increase consumer benefits from EV adoption. Ongoing neutron scattering research on alternative fuel cell options has the potential to elicit even greater efficiency and quality improvements.

8. Estimated Economic Impacts of U.S. Federal Neutron Scattering Facilities

Neutron research facilities require extensive, long-term investments. It is important to understand the value of the benefits that U.S. taxpayers experience in return for these investments. Towards this aim, we estimated the social return on U.S. investment in neutron scattering research facilities by completing a benefit-cost analysis.

A benefit-cost analysis compares investment costs to the monetized social, economic, and environmental benefits attributable to that investment. Benefits and costs accruing over time are each brought to a present value (PV) by adjusting for inflation and social consumption time preferences. Two values that communicate social return on investment are the net present value (NPV), which is calculated as the PV of benefits less the PV of costs, and the benefit-cost ratio (BCR), which is calculated as the PV of benefits divided by the PV of costs.

First, we compiled the total cost history of the U.S. federal neutron scattering facilities that currently offer broad open-user programs—NCNR at NIST and HFIR and SNS at ORNL—including their construction, instrumentation, and operation from 1960 through 2021. We projected cost trends forward to 2030, assuming that the current level of funding is sustained through that time. Next, we aggregated the benefits of the technologies identified as having been influenced by neutron scattering that are presented in the case studies in Section 7. Case study benefits were estimated from 1998 through 2030. We then compared the aggregate time series of technology benefits attributable to neutron scattering research to the aggregate times series of neutron scattering facility costs. Our benefit-cost analysis methods and results are provided in detail below.

8.1 Aggregate Facility Investment Costs

We collected data on the costs associated with U.S. federal neutron scattering facility construction, instrumentation, and operations and maintenance. ORNL facility costs since 1987 were gathered from public accounting records (BES, 2023) while NCNR costs since 1997 were provided by facility staff. Initial construction and instrumentation costs for older facilities were gathered from historical documents (Price & Rush, 1994; Rush & Cappelletti, 2011). Early facility operating costs for years without available data were modelled based on the compound annual growth rate displayed by available cost figures. Table 8-1 provides a summary of aggregate costs for the NCNR, HFIR, and SNS facilities, as these are the only current federal U.S. neutron scattering research facilities with broad public access. Costs are provided in both nominal terms, as these will more directly coincide with historical knowledge about facility costs, and their 2021 equivalents after adjusting for inflation.

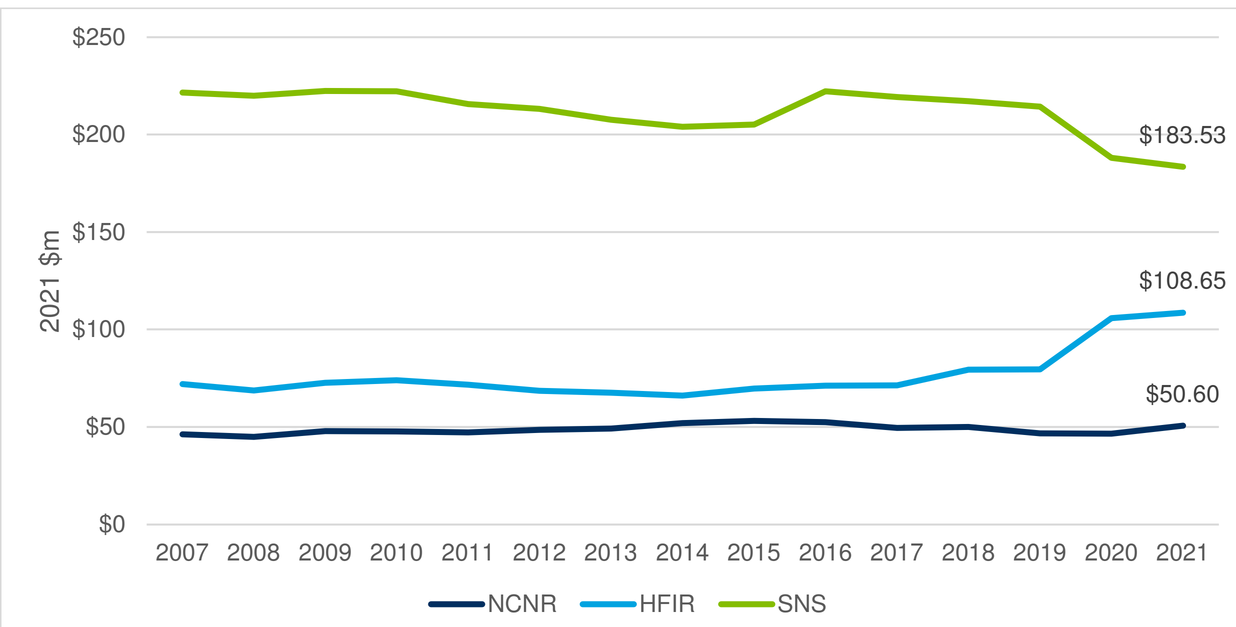
Table 8-1. Aggregate Costs of NCNR, HFIR, and SNS from 1960–2021

	Nominal Values (1960-2021$m)			Real Values (2021$m)		
	NCNR	HFIR	SNS	NCNR	HFIR	SNS
Initial construction cost	$ 8.70	$ 15.00	$ 1,231.00	$ 61.97	$ 113.12	$ 1,854.98
Operation and maintenance (appropriation)	$ 943.66	$ 1,741.21	$ 2,993.82	$ 1,726.07	$ 3,598.91	$ 5,127.79
Instruments	$ 106.60	$ 23.91	$ 140.87	$ 179.45	$ 36.83	$ 177.51
Construction projects (Other)	$ 143.19	$ 17.14	$ 258.00	$ 221.58	$ 41.01	$ 742.76
Total	**$ 1,202.15**	**$ 1,797.27**	**$ 4,623.69**	**$ 2,189.07**	**$ 3,789.87**	**$ 7,903.03**

Source: RTI based on data from facilities and external sources.
Actual and modelled annual values were aggregated. Nominal values were kept at the levels realized in each respective year (from 1960 through 2021) while real values were inflated to 2021 dollars using the government consumption expenditures and gross investment index produced by the St. Louis Federal Reserve.

As seen in Figure 8-1, ORNL has been narrowing the gap in annual appropriation funding between its facilities since 2016 by passing funds from SNS to HFIR. However, total annual appropriations across the ORNL facilities have remained largely flat for the past 15 years, as have the appropriations for NCNR.

Figure 8-1. Annual Appropriation Funding for NCNR, HFIR, and SNS 2007-2021 (2021$m)



Source: RTI based on data from facilities and external sources.

We project facility costs forward to 2030 using patterns in current funding levels. We conservatively assume that facility appropriations remain constant moving forward.[33] We also assumed that instrumentation and additional construction investments for each facility would hold with their average levels over the previous 5 years. Applying a discount rate of 2% as recommended in OMB (2023) guidance, we find a cumulative PV of costs of $17.6 billion in 2021 dollars across the NCNR, HFIR, and SNS facilities from 1960 through 2030.

Our future facility cost assumptions purposefully do not account for any major increases in appropriations or investments that may be planned for the near future. Any such increases in spending would not generate increased or improved facility access for several years and therefore would not be associated with follow-on benefits for at least a decade. A long-run assessment looking forward 20 to 30 years would be needed to accurately estimate the economic impacts of major increases in U.S. neutron scattering facility investments.

8.2 Aggregate Case Study Impacts

The case studies presented in Section 7 provide assessments of four key technologies identified as having been influenced by neutron scattering research. These technologies are associated with social, economic, and environmental benefits, which we estimated annually from 1998 through 2021 and projected forward through 2030 (see Table 8-2). We compiled an aggregate time series of benefits realized across the analyzed technologies. We apply the U.S. standard 2% discount rate to generate an aggregate PV of benefits of $207.7 billion with a range of $157.5 billion to $311.2 billion in 2021 dollars.

Table 8-2. Estimated PV Benefits Identified through Case Studies of Selected Technologies Influenced by Neutron Scattering Research

Technology Application	Reference Report Section	Benefits Year Range	PV Benefits (2021$m) at Each Impact Level		
			Reference	Low	High
GMR Hard Drive Development	7.1.3	1998 – 2005	$ 114,046.34	$ 114,046.34	$ 114,046.34
Safer Aviation Fuel	7.2.2	2023 – 2030	$ 430.62	$ 308.63	$ 539.55
Improved Aircraft Components	7.2.3	2008 – 2030	$ 3,448.70	$ 2,646.69	$ 4,174.34
GLP-1 Weight Loss Medications	7.3.3	2023 – 2030	$ 47,882.15	$ 31,507.25	$ 62,246.79
Improved EV Performance	7.4.4	2017 – 2030	$ 42,498.36	$ 6,198.16	$ 105,556.24
Total		1998 – 2005 2008 – 2030	**$ 207,681.83**	**$ 157,536.23**	**$ 311,233.93**

Individual case study methods and results are detailed throughout Section 7.
Benefits are all normalized to 2021$m through inflation and discounting.

[33] Total cost estimates across all three facilities are not impacted by continued changes in the allocation of ORNL funding across its HFIR and SNS facilities.

8.3 Minimum Attribution of Benefits to Neutron Scattering Research

The aggregate case study impacts provide estimates of the total benefits from the analyzed technologies influenced by neutron scattering research. However, only a portion of these benefits are attributable to that neutron scattering research. Among other potential influences, neutron scattering research can enable the discovery of new technologies, improve product quality, and accelerate the R&D process to bring new technologies to market faster. The varied nature and range of the influences of neutron scattering research on technology development make it impossible to determine the exact level of benefits attributable back to the neutron scattering facilities where fundamental and applied research occurred. However, we identified that at a rate of 8% attribution to neutron scattering research (range: 6-11%), the cumulative PV benefits associated with the four technologies evaluated in the Section 7 case studies fully cover the entire history of costs for NCNR, HFIR, and SNS (PV of costs). The implied minimum range of attribution levels to neutron scattering research is highly reasonable when compared to typical examples of licensing and royalty agreements like the 25% rule (Goldscheider, 2011).

8.4 Return on Investment

We estimate the social return on investment in U.S. neutron scattering facilities from 1960 through 2030 under two different scenarios of research impact. For both scenarios, we use the estimated range of cumulative PV benefits across the four technologies influenced by neutron scattering that were analyzed in Section 7. We compare the PV benefits to the cumulative PV costs across the three U.S. federal neutron scattering research facilities that currently offer broad public access: NCNR, HFIR, and SNS.

In one scenario, we assume that neutron scattering research accelerated the R&D of the influenced technologies by 2 years, comparing the time series of realized benefits to a counterfactual stream of benefits occurring 2 years later. In the second scenario, we assume that 20% of the cumulative PV benefits across the case studies were attributable to the neutron scattering research that influenced the technologies.

Table 8-3 summarizes the return-on-investment analyses across the various scenarios of technology benefits and neutron scattering research impact. The two-year acceleration scenario suggests a BCR of 2.67 (range: 1.67 to 4.61), meaning that for every dollar invested in U.S. neutron scattering research facilities, $2.67 in benefits are realized. The estimated NPV is $29.4 billion (range: $11.8 billion to $63.6 billion). The results of the 20% benefit attribution scenario fall within the same range as the 2-year acceleration results.

Table 8-3. Estimated Return on Investment in NCNR, HFIR, and SNS Facilities from 1960–2030 Under Various Scenarios of Impact

	Impact Level		
	Reference	Low	High
PV Facility Costs from 1960-2030 (2021$m): $17,613.88			
2-Year Acceleration of Realized Cumulative Case Study Benefits from Neutron Scattering from 1998-2030			
PV Benefits (2021$m)	$47,024.13	$29,380.88	$81,210.82
BCR (PV Benefits / PV Costs)	2.67	1.67	4.61
NPV (PV Benefits – PV Costs)	$29,410.25	$11,767.01	$63,596.95
20% Total Attribution of Cumulative Case Study Benefits to Neutron Scattering from 1998-2030			
PV Benefits (2021$m)	$41,536.37	$31,507.25	$62,246.79
BCR (PV Benefits / PV Costs)	2.36	1.79	3.53
NPV (PV Benefits – PV Costs)	$23,922.49	$13,893.37	$44,632.91

Table compares the discounted cumulative benefits of the four technologies influenced by neutron scattering research from 1998–2030 that were analyzed in Section 7 to the discounted cumulative costs of the NCNR, HFIR, and SNS facilities from 1960–2030 presented in Table 8-1.
Benefits and costs are all normalized to 2021$m through inflation and discounting.

8.5 Discussion

All results indicate strong returns to the U.S. investment in federal neutron scattering research facilities. The estimated returns are certainly conservative since they rely only on the benefits attributable to four case studies of U.S. technologies known to have been influenced by neutron scattering research. Remembering that RTI identified at least 1,565 patents granted in the United States between 1968 and 2020 that cite research conducted at U.S. neutron scattering facilities, these four technologies represent only a small fraction of those that are likely to have been influenced by neutron scattering research.

In addition, by focusing on cases of research that have been applied industrially in the United States, our impact estimates underestimate the total value of basic neutron scattering research in the country. Additional benefits from neutron scattering research that are more difficult to quantify include knowledge generation, skills development, and research infrastructure improvements. These benefits are positively cyclical and thus increase in value over time. Basic research also contributes to future applied work in ways that are difficult to predict. The hard drive case study is a perfect example of this, where basic research identified the GMR effect, which then went on to revolutionize computer storage device technology.

For these reasons, our analysis monetizes only a very small portion of the total benefits of investing in U.S. neutron scattering research facilities. Still, even these highly conservative estimates indicate that returns are strongly positive.

9. Policy Options to Increase U.S. Neutron Research Capacity

U.S. neutron scattering capacity has declined overall since the 1990s. Many factors and conditions led to this erosion in capacity, including a lack of sustained policy interest and funding to support existing facilities and a reluctance to plan and fund facilities that will be needed in the future (Rush, 2015). The unexpected closure of the NCNR reactor in February 2021 crippled the researchers and industrial users who rely on access to neutron scattering facilities (Physics Today, 2021). Future planned outages to upgrade HFIR and NCNR may have similar impacts on the research community and reinforce the need for operational redundancy. Facility outages and limited technical and staff resources hinder researchers by decreasing productivity, reducing opportunities for new workers and students in the field, and making neutron scattering inaccessible to many scientists. It will take decades to shore up existing infrastructure and construct future facilities, narrowing the opportunity to reverse this decline.

Meanwhile, the factors that led to the decline of U.S. university research reactor capacity illuminate pathways for national leaders to improve coordination, funding resources, and utilization of these facilities. Small reactor facilities in Europe, some of which (Vienna, Delft) are based at universities, are credited with fostering innovation, making neutron scattering more accessible to scientists, and supporting a large and vibrant user community (ESFRI, 2016). The potential exists for U.S. facilities to do the same with appropriate public and private support.

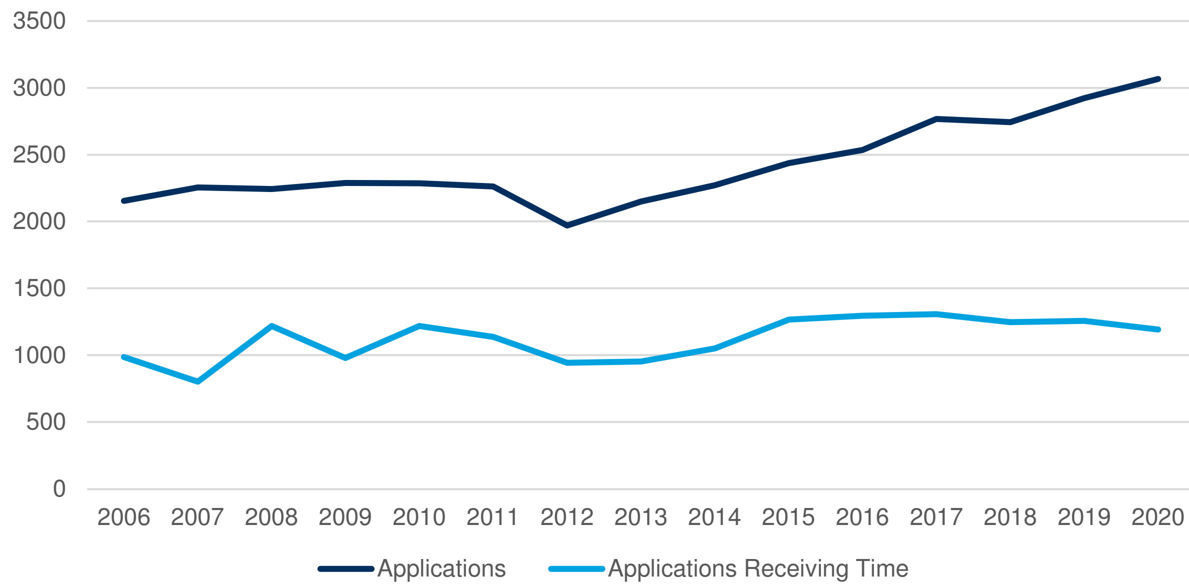
Here, we document the decline in federal and university research infrastructure, examine how insufficient facility investment impacts the research community, and propose policy options that have the ptoential to reverse this trend. We present examples of how other countries and regions of the world have addressed similar challenges threatening their neutron scattering infrastructures. We draw on survey and interview data to identify the impacts of capacity constraints on the neutron scattering user community. Additional survey and interview sample descriptions and results are summarized in Section 5. Based on this information, we offer policy options to sustain and grow the U.S. neutron scattering ecosystem.

9.1 Federal Neutron Scattering Capacity

Sizable federal investments in research reactors during the 1960s enabled researchers to make important scientific discoveries which in turn contributed to the development of new and improved products (Rush, 2015). By 1985, the United States had five federal laboratories with neutron scattering capacity: HFBR at BNL, IPNS at ANL, NCNR at NIST, HFIR at ORNL, and LANSCE at LANL. Yet by 1999, the number of federal laboratory reactor sources declined from three to two due to the closure of HFBR at BNL. The number of spallation sources for neutron scattering increased from two to three with the opening of the SNS at ORNL in 2006. However, this increase was diminished when the DOE closed the IPNS facility in 2007 and eliminated support for the broad open-user program at the Lujan Center in 2015 (Rush, 2015). These actions resulted in a net loss of one spallation source, leaving the nation with a single national lab providing broad public access to these capabilities.

Reductions in capacity translate into less total availability for individuals who wish to use federal facilities. As depicted in Figure 9-1, the gap between the number of applications for research time at NCNR and requests granted has increased in recent years. 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%. In 2021, a consensus report for the National Academies of Science asserted that the amount of beam-time requested was triple the available beam capacity at NCNR, HFIR, and SNS (NAS, 2021). Additional demand has been placed on U.S. facilities in the wake of the 2018 closure of the Canadian Neutron Beam Centre (CNBC) at Chalk River, the single national Canadian neutron scattering facility. The Canadian Foundation for Innovation (CFI) funds agreements with ORNL and NIST providing beamline access to Canadian researchers (Peters, 2021).

Figure 9-1. NCNR Applications for Beam Time Versus Number Receiving Time, 2006-2020



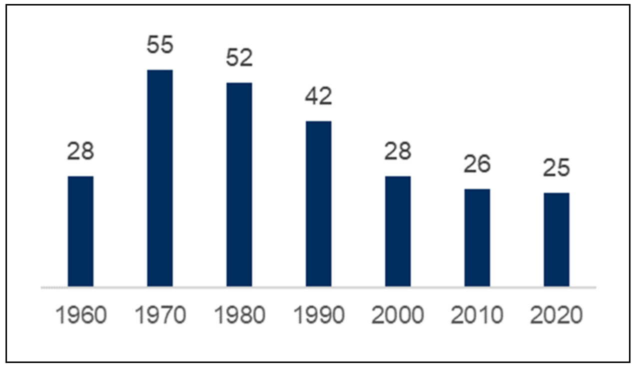
Source: RTI based on data from the NIST Center for Neutron Research.

9.2 University Research Reactor Capacity

Federal funding from the U.S. Atomic Energy Commission spurred a wave of university research reactor construction in the 1950s and 1960s (Rogers, 2002). As a result, the United States was able to engage in broader, nuclear-related scientific innovation, provide a skilled workforce for nuclear power plants, and provide capacity for the training of students and scientists. The first civilian nuclear reactor in the world was the Raleigh Research Reactor on the campus of NCSU, which went critical in 1953. By the 1970s, around 55 campus research reactors were producing an abundance of neutrons, allowing faculty to experiment with neutron scattering, develop instrumentation, and use excess capacity for collaboration across institutions (National Research Council, 1988) (see Figure 9-2).

Institutions with reactors also engaged in collaboration with national laboratories, and staff moved back and forth between institutions (National Research Council, 1988; Rush, 2015). The 1994 Nobel Prize winners Bertram Brockhouse and Clifford Shull, who pioneered the development of neutron spectroscopy and diffraction, spent large portions of their careers both at university research reactors and national laboratories (Mason and Rogers, 2002). Many of the research techniques now used at national laboratories were pioneered at university facilities, and a large portion of neutron scattering experts were trained at university research reactors (Harling, 1990).

Figure 9-2. Number of University Research Reactors in the United States by Decade, 1960-2020



Source: RTI based on information from the U.S. Atomic Energy Commission and DOE

These conditions sparked advances in neutron scattering and in our understanding of organic and inorganic materials. These advances then led to innovations in a panoply of commercial products, including automobiles, computers, medicine, and batteries. Detailed assessments of technological innovations and specific products influenced by neutron scattering research can be found in the case studies presented in Section 7.

9.2.1 Concerns about Loss of University Research Reactors

As far back as 1988, the United States grappled with the loss of university research reactors. Factors that contributed to the decline include outdated reactors that could not meet emerging research needs because of lower-power output, a lack of consistent federal and local financial support, a lack of growth in the nuclear power industry, and, in some cases, prolonged hearings and litigation during licensing (National Research Council, 1988). Universities also grappled with negative public perceptions of nuclear reactors in the wake of the accident at Three Mile Island in 1979 (Calder & Nusitchaiyakan, 2015). These factors created a cycle in which reduced support led to less student and faculty interest, further reducing reactor usage and support.

Of these concerns, the most pressing was the lack of consistent funding to continue operations. In 1988, the only constant source of federal support was DOE fuel assistance and faculty travel for use of off-campus reactors under the reactor sharing program. Grants from other federal agencies, such as NSF and the National Institutes of Health, stipulated that these funds could not be used to defray operating costs (Rogers, 2002). In some instances, the need to be financially self-sufficient drove universities to prioritize money-making experiments, isotope production, and fee-based users, at the expense of university-based researchers, who often used campus facilities for free (National Research Council, 1988). In a similar vein, funding for reactor upgrades and equipment had to be cobbled together from a variety of sources, including the universities themselves, private companies, and federal agencies.

A 1988 study by the Committee on University Research Reactors of the National Research Council asserted that university research reactor capacity was unable to meet national interests, particularly for high-technology research. A lack of peripheral research equipment and limited access to national facilities with better equipment contributed to this situation. The Committee argued that U.S. university research reactor facilities should be upgraded and provided with modern equipment. At the same time, it concluded that not all existing university research reactors were essential to fulfilling teaching, research, and industrial development missions because of the ability to access national laboratories (National Research Council, 1988).

To address these findings, the Committee offered a series of recommendations that:

1. Directed the federal government, along with the universities, to develop and implement a national research reactor strategy with university and national laboratory centers of excellence in specific areas of neutron science;
2. Permitted the closure of some university facilities as others were upgraded;
3. Encouraged development of a national reactor network to enhance utilization; and
4. Ensured that university research reactor closures would not go so far as to damage national educational and research capabilities.

Other recommendations would have placed a single federal agency in charge of administering programs in support of the national research reactor program, complete with a standing advisory structure, and would have provided up to $20 million each year to universities for operational support and facility upgrades. None of these recommendations were implemented, and a second call for funding, issued by the then Secretary of Energy Hazel O'Leary in 1994, similarly went unheeded (Rogers, 2002).

In 2001, researchers again sounded an alarm about the decline in university research reactors. At that time, 28 facilities existed, of which 3 facilities were on the verge of closure. DOE formed a Task Force on University Research Reactors to examine the condition of specific campus research reactors and make recommendations as to near-term actions that should be taken by the federal government and a long-term strategy to ensure the continued operation of university reactor facilities (Long et al., 2001). The Task Force recommended offering a one-time grant of $250,000 to the three facilities most in danger of closure. DOE elected not to provide one-time grants to struggling university facilities. By 2004, two of the three struggling university research reactors were closed (Brand, 2001; Giebel & Smith, 2017).

9.2.2 Contemporary Federal Support for University Research Reactors

The DOE Task Force on University Research Reactors also recommended supporting five regional reactors operating at a power level of 500 kW or higher and three University Training and Education reactor facilities operating at lower-power levels. Up to $20 million of federal funds would be made available annually for the entire group (Rogers, 2002). Motivated by Task Force findings, in 2002, DOE initiated the Innovations in Nuclear Infrastructure and Education (INIE) program to provide annual financial support to regional university research reactor consortia. The program encouraged the development of strategic consortia among universities, DOE national laboratories, and industry, and the leveraging of resources made available by the partners (U.S. Committee on Science, 2003). In 2002, DOE provided $5.5 million in funding for four consortia (Gutteridge, 2002). By 2006, the program had distributed $9.41 million to six consortia consisting of both higher-power research reactors and lower-power training reactors (American Physics Society [APS] Panel on Public Affairs, 2008). DOE support for university research reactors also consisted of fuel provision and removal, graduate student scholarships, and competitive funding for basic and applied research projects.

A working group of the APS asserted that the INIE program increased student enrollments in nuclear science and engineering, stimulated hiring of new tenure-track faculty, improved the physical infrastructure and instrumentation at university research reactors, and played an important role in keeping them from possible decommissioning (APS Panel on Public Affairs, 2008). A Program Assessment Rating Tool completed for INIE during the 2007 budget cycle determined that target enrollment levels for the program had been met and that the number of universities offering nuclear-related programs had increased. As a result, the 2007 DOE budget proposed termination of this program (DOE, 2007). U.S. Congress rejected DOE's proposal and opted to provide $16.5 million in 2007—far less than the $27 million the program received in previous years (APS Panel on Public Affairs, 2008). In 2008, U.S. Congress again rejected ending the program and allocated $17.9 million in the 2008 budget: $2.9 million remained at DOE for university reactor fuel services, and the rest ($15 million) was transferred to the NRC to support the other programs. At the time, the sentiment in the research community was that these funds would not be sufficient to maintain the needed support, particularly for the INIE program (APS Panel on Public Affairs, 2008).

In 2009, university research reactor support programs were consolidated in the NEUP, a section of DOE's Office of Nuclear Energy, to better integrate university research with the office's technical programs (Office of Nuclear Energy, 2024). For the last 14 years, funding for university research reactor facility improvements and university-led research has been allocated by NEUP. NEUP funds two types of grants: R&D and infrastructure. R&D grants are awarded competitively to support work primarily in two areas: fuel cycle and reactor concepts. DOE has provided more than $581 million for 810 research projects. Infrastructure grants include general scientific infrastructure support and research reactor maintenance but do not fund instrumentation (DOE, 2022). University research reactors may receive up to $250,000 (this may require a cost match) for general scientific infrastructure and up to $1.5 million for reactor upgrades. To date, DOE has funded 286 infrastructure grants at 69 institutions at a value of more than $64 million, an average of about $4.6 million per year (DOE, 2022).

These federal infrastructure programs, along with the DOE-funded research, university support, and commercial activities, have prevented the additional loss of university research reactors. The last closure of a university research reactor was at the University of Arizona in 2010 (Offerle, 2010). However, just a handful of university reactors have the capacity and staff to perform neutron scattering. This low level of university-based neutron scattering resources limits the number of scientists and students with access to and training on these techniques, reduces the size of the user community, and fails to ease capacity constraints when federal facilities temporarily close for repairs or improvements. Furthermore, the lack of university-based neutron scattering programs reduces opportunities to perform experiments that require large amounts of beam time and proof-of-concept work.

9.2.3 Perspectives from the Neutron Scattering Research Community

RTI International interviewed more than 50 users of national neutron scattering research facilities to elicit opinions about the national supply of neutrons, user access to federal facilities, and the role of university research reactors within the national neutron scattering landscape. The responses were clustered thematically and summarized by topic, resulting in the following collective observations:

1. **University research reactors maintain the pipeline of students with the technical ability and interest to staff national laboratories and enter careers in nuclear sciences**. University reactors support national laboratories and industry by training doctorate researchers who understand the theory and applications of neutron scattering. These students serve as the pipeline for future instrument scientists at national laboratories and provide the neutron scattering user base for industry and academia. By providing opportunities for hands-on learning, university research reactors expose science and engineering students to neutron scattering and other reactor-based research methods. Any reduction in university facilities increases barriers to entry in the field and reduces the user community.

2. U**niversity reactors are lower-powered and often have less advanced equipment than national facilities. Nevertheless, they still serve as important public resources.** University reactors can be used as staging grounds for experiments before they are attempted at a national laboratory, reducing possible errors and research delays. Even experienced scientists require weeks to prepare an experiment, so preparatory testing avoids wasted effort. The most powerful university reactors can also fulfill important research niches and provide “work horse” instruments such as SANS instruments, to serve campus and local industry needs. For example, MNRC at UC Davis undertook neutron imaging of the pyrotechnic devices responsible for stage separation of a rocket for NASA’s Artemis I mission. Wesley Frey, Director of the MNRC, noted that, “The UC Davis reactor is literally the only place on earth where NASA can image these critical pieces due to the very limited number of neutron-based imaging facilities and the size of these pieces” (Gautam 2022).

Analysis of the neutron sources and neutron scattering community in Europe indicates that the diverse mixture of small and large multinational facilities enhances the scientific capabilities available to researchers. A 2020 Brightness review noted that small facilities, with fewer than 50 distinct users per year, specialize in a few scattering techniques, such as SANS, powder liquid diffraction, and imaging, and have strong non-scattering programs that are useful to industrial users. “Small facilities’ scientific expertise in a specific area of science makes them an invaluable focus point for a specific community. … this demonstrates the importance of small- and medium-scale research facilities in terms of unleashing the scientific potential and productivity of the European neutron scattering community” (Brightness, 2020).

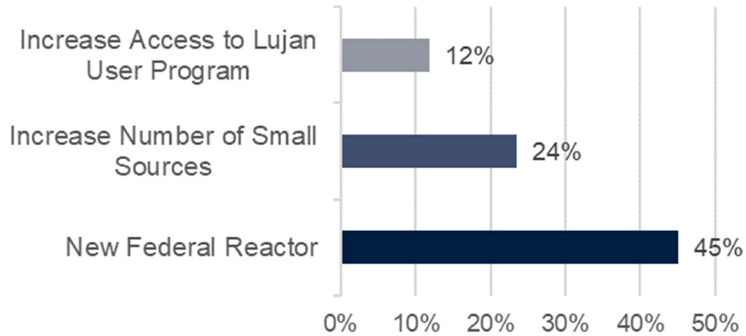
3. **When national user facilities are unavailable, university research reactors can provide the nation with neutron sources for industrial and scientific uses.** This point is particularly salient as the NCNR reactor was closed in February 2021 and remained closed for more than 2 years (Cho, 2023). During this period, HFIR at ORNL was also unavailable during planned closures between cycles (i.e., December 2022 through April 2023), leaving the United States without an operating reactor-based user program (ORNL, 2023). This left only SNS at ORNL operational, greatly reducing the national capacity for producing neutrons for research purposes. Future outages are also planned for both HFIR and NCNR to complete important facility upgrades. Some interviewees indicated that DOE has put “all its eggs in one basket” by funding a single nuclear source for neutron scattering, whereas there was greater capacity in the past when Brookhaven was operating and there were more university facilities.

4. **University neutron research faculty serve as educators to other university faculty, thereby increasing knowledge and demand for neutron scattering capacity.** Several interviewees indicated that part of their role is to serve as ambassadors for neutron scattering to their fellow faculty in the university environment and reduce barriers to wider use of these techniques. Researchers indicated a large barrier to more neutron scattering work is that a lot of scientists do not realize how it can contribute to their work. By maintaining campus facilities, current users can raise awareness about neutron scattering methods and how they can be applied in a variety of academic disciplines.

5. **University reactors serve as the testing environment for new instrument designs. The neutron scattering instruments used in national laboratories are often conceived, prototyped, and tested at university facilities.** For instance, in 2019, the University of Delaware, along with the University of Maryland, was awarded an NSF Mid-Scale Science Infrastructure award to develop a world-class neutron spin echo spectrometer housed at CHRNS (Bryant, 2019). This instrument will boost U.S. research in engineering, soft matter, and biological sciences. The role of academia in instrument design was echoed in a 2021 BESAC report: “…development of mid- and small-scale instrumentation by individual or small groups of scientists is another cornerstone of fundamental energy science…the design and building of new instruments to address specific fundamental science questions in individual laboratories has historically led to both scientific breakthroughs and ultimately new tools used for applications that benefit society” (BESAC Subcommittee on International Benchmarking, 2021).

We asked researchers an open-ended question about ways to increase U.S. neutron scattering capacity. Nearly half of respondents stated that the nation needed a new reactor as a federal user facility (see Figure 9-3). About 25% supported the idea that small sources, such as university research reactor programs, should be expanded to increase training, research, and innovation from neutron scattering. About 12% of respondents believe the Lujan open-user program should be reinvigorated and expanded to a broader range of research to increase national capacity.

Figure 9-3. Open-Ended Recommendations from Neutron Facility Users (N=51) to Increase Neutron Scattering Capacity



Source: RTI, based on interviews with neutron scattering facility users
Note: respondents could provide more than one recommendation.

9.2.4 New Forces Emerge

Renewed interest in nuclear power and advanced nuclear reactors is spurring the federal government and universities to reinvest in university research reactors. The federal government and private industry are reexamining options in nuclear power generation as a non-carbon–emitting energy source. For the first time in nearly 30 years, two new power reactors are being constructed in the United States, underwritten by more than $12 billion in loan guarantees by DOE (Holt, 2021). In March 2021, the Biden Administration's American Jobs Plan included an Energy Efficiency and Clean Electricity Standard that would require increasing percentages of power generation from non-carbon–emitting sources, such as nuclear plants (Holt, 2021).

DOE is also investing in advanced nuclear reactors to meet national needs for non-carbon-emitting power sources. Advanced reactors use new and existing materials and technologies to reduce cost and/or improve security, waste management, and versatility. Advanced reactors may be water-cooled reactors (e.g., small modular light-water reactors, supercritical water-cooled reactors), lead- or salt-cooled reactors, or fusion reactors. Some advanced reactor concepts are relatively new, whereas others have been under development for many years (Holt et al., 2023). Microreactors and small modular reactors provide more flexibility in size and power capacity than existing power generators, which may help power providers avoid some operating costs associated with light-water reactors (Office of Nuclear Energy, 2024).

This renewed interest in nuclear power presents clear opportunities for existing and possibly new university research reactors. There will be a need to test reactor prototypes, train new workers and provide training to the existing workforce, and engage in operations research and innovation (Huff, 2021). In recognition of this need, federal funding for university research reactors may sizably increase for the first time since INIE funding ended in 2006. Public Law 117-167 directs DOE, pending appropriations, to support consortia that increase access to research and training reactor facilities. The law also directs DOE to fund reactor renovations, with a focus on projects that support advanced nuclear technologies or convert reactors to using low-enriched uranium fuel (U.S. Congress, 2022).

Recent legislation further directs DOE to support the construction of up to four new university-based reactors, explicitly citing advanced reactor concepts and medical isotope production as priorities. The CHIPS and Science Act set a funding target of $45 million in FY 2023, increasing to $140 million in FY 2027, for new university research reactor construction. The final spending legislation for FY 2023 provided none of the requested funds. However, an earmark in the NIST FY 2023 budget provides $20 million for work on a “next-generation” reactor at the University of Missouri, which hosts a major reactor facility that started operations in 1966 and primarily produces medical isotopes (see University of Missouri Research Reactor). This funding improves the national landscape for commercial medical isotope production and may contribute to broader neutron-reliant research capabilities.

9.3 Factors that contribute to Neutron Scattering Capacity in Other Countries and Regions

By reviewing federal and international reports that examine scientific competitiveness, we identified factors that sustain and grow neutron scattering sciences throughout the globe. Although the circumstances of each country or region are different, these themes summarize international approaches to planning, funding, and sustaining neutron research infrastructure.

9.3.1 Planning and successful construction of scientific infrastructure

One leading factor that had buoyed neutron-reliant research capacity in other counties has been the ability of countries and regions to plan and build needed scientific infrastructure. While the United States has been hesitant to invest in neutron scattering infrastructure, the number of neutron scattering facilities outside of North America is increasing. New spallation and nuclear facilities have recently opened, or are being planned and constructed, in Sweden (ESS), France (Jules Horowitz), United Kingdom (ISIS II), China (Chinese Spallation Neutron Source), and Korea (Kijang Research Reactor).[34]

To prepare for some facilities reaching the end of their useful life, countries have refurbished facilities such as Institut Laue–Langevin (ILL), to extend operations and have planning underway for the next round of neutron scattering facilities. For example, ISIS was opened in 1985 and had an anticipated useful life of 20 years, which was extended to 40 years through substantial refurbishment (Technopolis, 2016). The United Kingdom already has planning underway for ISIS II, which should be ready for construction after 2030 to maintain the UK’s supply of neutrons (UK Science and Technology Facilities Council, 2020). Planning for the Jules Horowitz reactor started in 2006 and it will open at some point after 2030 (ESFRI, 2016). Given the long planning and construction timelines for these facilities, having a national roadmap for science infrastructure and the political will to fund these efforts is essential. To facilitate the joint establishment and operation of pan-European research infrastructures like ESS, the European Union formed the European Research Infrastructure Consortium (ERIC) framework in 2009. ERIC was created to reduce fragmentation of the research and innovation ecosystem, avoid

[34] A review of international neutron sources may be found at https://www.iaea.org/resources/databases/research-reactor-database-rrdb

duplication of effort, and coordinate the development and use of research infrastructure (European Commission, Directorate-General for Research and Innovation, 2020).

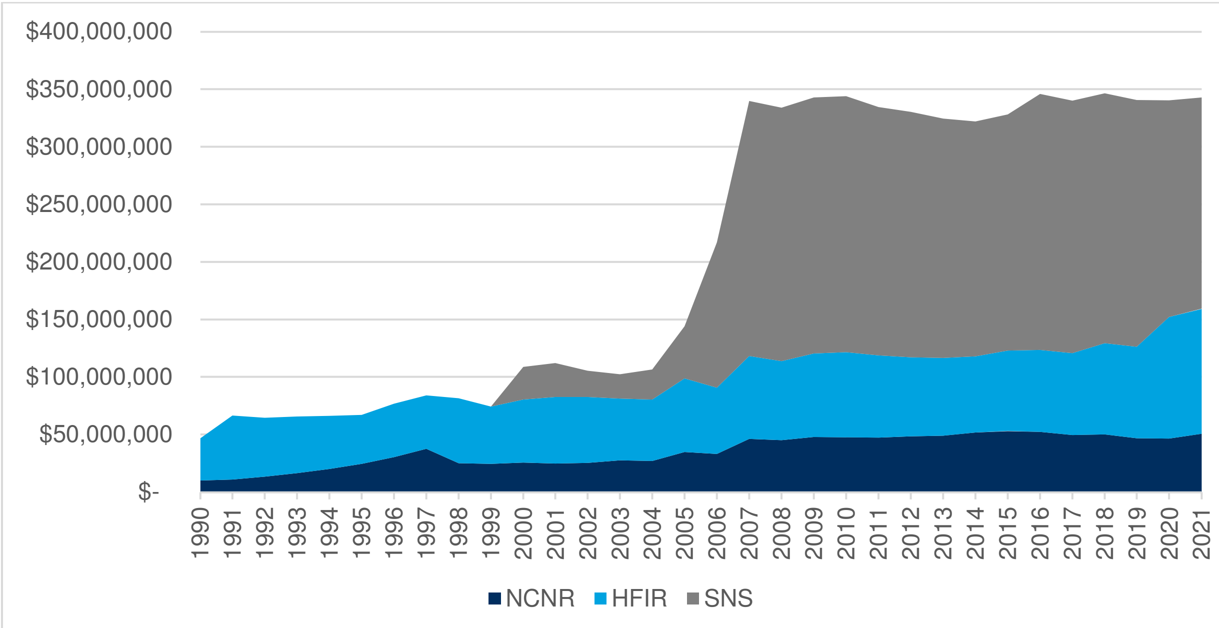
Countries that fail to engage in long-range planning for neutron sources may disadvantage their research interests. For example, Canada has been without a national neutron source since 2018, when the CNBC at Chalk River closed. At the time, it was the longest running research reactor in the world, at 70 years of age (Banks, 2018). Instead of constructing a new national facility, the government supported the Canadian Neutron Initiative, led by the scientific community, to establish a new, pan-Canadian, university-led framework for stewardship of Canada's capability for research with neutron beams, and thereby enable a national program for research using neutron beams (Neutron Canada, 2023). In recent years, McMaster University received $35M in investments to develop a national neutron beam user laboratory at the university reactor. Two beamlines are to open as user facilities soon, with three more to be completed over the next several years (Neutron Canada, 2023). This years-long gap in a domestic supply of neutrons has led some Canadian researchers to move to the United States and other countries to conduct research (RTI, 2023).

9.3.2 Sufficient Construction and Operating Funds

A general observation provided during user interviews was that the overall level of funding for facility construction and operations was below required amounts. For example, one individual noted that when ORNL ran out of construction funding for the first SNS target station, it had to take funds from the instrument budget to make up the shortfall, resulting in less-than-optimal neutron scattering instrumentation. In contrast, when the ESS exceeded original budget estimates by more than 550 million euro, the 13-member countries agreed to cover the additional costs to build the facility as originally intended (ESS Council, 2022).

Sufficient operational funding is another critical component to successful research facilities. As depicted in Figure 9-4, the inflation-adjusted operating budgets for NCNR, HFIR, and SNS have been relatively flat since 2007. A 2021 consensus report from the National Academies of Sciences found that for NCNR, the long-term impact of flat budgets has been a reduction of scientific staff by nearly 20% because the organization chose to reduce scientific staff to maintain staff required for reactor operation and safety. Current NCNR staffing is low by international standards, at fewer than five staff members per instrument, compared to seven at ILL in France (NAS, 2021).

Figure 9-4. Annual Appropriation Funding for NCNR, HFIR, and SNS, 1990–2021 (2021$)



Source: RTI based on data from facilities and external sources.
Notes: These figures are presented in 2021 dollars and are adjusted using the government consumption expenditures and gross investment index produced by the St. Louis Federal Reserve.

9.3.3 A High Level of National and International Coordination

Individual countries such as France (Ministry of Higher Education and Research) and Germany (Federal Ministry of Education and Research) have a single federal entity that coordinates planning, funding, and management of major research facilities. At a regional level, the European Strategy Forum on Research Infrastructures (ESFRI), has a central role in policy making for research infrastructures in Europe. It is composed of national delegates nominated by research ministers of EU countries. ESFRI's mandate contains several aims:

- Establish a European roadmap for research infrastructures for the next 10-20 years, stimulate the implementation of these facilities, and update the roadmap as needed;
- Support a coherent and strategy-led approach to policy making on research infrastructures in Europe;
- Facilitate multilateral initiatives leading to a better use and development of research infrastructures; and
- Ensure the follow-up of implementation of already ongoing ESFRI projects after a comprehensive assessment, as well as the prioritization of the infrastructure projects listed in the ESFRI roadmap (European Commission, 2017).

In contrast, in the United States, infrastructure planning is distributed among a number of agencies (DOE, DOC, NNSA) and there is no central body that provides coordination between facilities. The National Strategic Overview for Research and Development Infrastructure presented by the National Science and Technology Council (2021) further illuminates the strategic vision for greater coordination between federal agencies, private industry, and international bodies. Interviewees posited that facility leadership may feel that they must compete for funding, lowering their incentive to coordinate. For researchers, this lack of coordination means they must make separate applications to several facilities to get beam time rather than submitting a single application to a coordinating body who will allocate time at the most appropriate facility. Lack of systematic coordination also may lead to some facilities being underutilized, the potential for more than one facility being closed at the same time, and a lack of system redundancy when unexpected closures occur.

This lack of interagency coordination for neutron-reliant research also contrasts with other federally supported science fields such as nanotechnology. The National Nanotechnology Initiative (NNI) is a U.S. government R&D initiative that was established through legislation. More than thirty federal departments, independent agencies, and commissions collaborate to advance the ability to understand and control matter at the nanoscale, thereby spurring advancements in technology and industry. The NNI promotes shared infrastructure and interagency coordination of nanotechnology research, and leverages resources to avoid duplication. The organization works with members to establish goals, priorities, and strategies that complement agency-specific missions and activities (NNI, n.d.). Another example of interagency coordination can be found in the National Quantum Initiative[35] which is a whole-of-government approach to coordination of research and development in quantum sciences to advance economic and national security of the nation (U.S. Congress, 2018).

9.3.4 A Network of Diverse Neutron Scattering Facilities

Europe's approach to research and development infrastructure involves a portfolio of different sized neutron scattering sources, which gives it more flexibility and options for the user community (ESFRI, 2016; LENS, 2020). For the EU, smaller neutron sources "act as a nursery for new instrumental ideas … and train the next generation of neutron instrument scientists. Important also is the fact that having a distribution of sources helps to diminish the air of mystery surrounding the use of neutrons" (ESFRI, 2016). In particular, the scientific expertise in a specific area of science makes smaller-sized facilities an invaluable focus point for research communities (ESFRI, 2016). In 2020, Brightness, an EU-funded project in support of ESS within the European Commission's Horizon 2020 Research and Innovation program, classified European neutron scattering facilities into three categories based on the number of users:

- **Category A**: Large-scale facilities: Neutron sources in this category have a large user base comprised of 450–1600 unique users. These facilities have between 20-37 instruments deployable over 8-10 different experimental methods.
- **Category B**: Medium-scale facilities: Neutron sources in this category have a medium-sized user base comprised of 50–350 unique users. The facilities have between 8-15 instruments deployable over 7-9 different experimental methods.

[35] https://www.quantum.gov/

- **Category C**: Small-scale facilities: Neutron sources in this category have a small user base comprised of up to 50 unique users. The facilities have between 1-9 instruments deployable over 1-5 different experimental methods (Brightness, 2020).

Table 9-1 depicts the number of facilities by number of users in Europe with those in the United States. Europe has more overall capacity than the United States across all sizes of facilities. Although the United States has three flagship institutions, it has no medium-sized facilities, and the four smaller-scale facilities are academic reactors with lower staffing and funding levels than the federal reactors.

Table 9-1. Comparison of Facilities for Europe and the United States, 2020

Facility Type	Europe	United States
Category A	4	3
Category B	2	0
Category C	6	4
Total	**12**	**7**

Note: There are 11 university research reactors with power 1MW or greater. Only four have instruments for neutron scattering whereas the others engage in neutron activation analysis, irradiation, and radiography.

The limited number of facilities in the United States creates a significant barrier to increasing the size and output of the neutron scattering community. Since access to instruments is highly controlled, there are few opportunities to train large numbers of scientists on techniques. One interviewee noted that very few biologists in the United States use neutron scattering methods compared to researchers in Europe. Another echoed this opinion stating that, "the biggest barrier for biological researchers at the moment is to find and work with somebody who guides them through the (neutron scattering) process, we need more people that actually work with the biological research community." Another person cautioned that after 3 years of diminished user facility capacity due to COVID-19 and the NCNR shutdown, the user community will further decline as a significant cohort of PhD students engaged in science were unable to access these facilities and therefore lack practical training in neutron scattering.

9.4 Possible Public Policy Responses

Changes to existing public policy may help replicate the robust neutron scattering ecosystems in Europe and Asia. Decisive and coordinated federal action may help alleviate current and future neutron shortages while creating more support for smaller facilities and users. Available policy options, detailed below, include the following:

- Form a unified federal leadership committee or taskforce to develop a decadal plan or roadmap for neutron scattering facilities and national resilience, and
- Maintain adequate funding for operating and improving existing facilities, strategically invigorating university facilities, and funding construction of new facilities.

At the same time, this is a critical juncture for federal policy as it relates to university research reactors. It is key to consider how these facilities benefit U.S. scientific, defense, and innovation communities apart from benefits related to the nuclear power industry.

9.4.1 Establish a Federal Coordination Mechanism

A national committee or taskforce could provide leadership and coordination to ensure that the United States maintains adequate access to neutron scattering facilities. This effort could be led by the White House' Office of Science and Technology Policy, the National Science and Technology Council, or a similar body. The committee or task force could be charged with identifying and implementing measures to facilitate better coordination between national facilities run by the DOE and the DOC and facilitate long-term planning with participation from the user community and other federal agencies such as the Department of Defense and the National Institutes of Health. Such a group could focus energy and resources on issues that threaten the future of neutron scattering facilities in the United States.[36] Recent experiences in the United States and abroad suggest some early tasks for this group:

Develop a resilience plan: This plan would address known and unanticipated future nuclear and spallation source closures during the next decade. The temporary shutdown of NCNR in the United States and the closure of CNBC at Chalk River in Canada indicate that the nation needs contingency plans to deal with such disruptions. A Resilience Plan would ensure that scientists and students can continue their research when specific facilities close for planned maintenance or experience an unexpected closure. This plan could consider expanding agreements with other countries or facilities like the Lujan facility, which currently has a limited open-user program, and assess current and potential university reactor facilities for use by individuals who have traditionally used federal facilities.

Create a Neutron Scattering Decadal Plan or National Roadmap: The U.S. neutron scattering community could engage the National Academies of Sciences to undertake a facilitated process to determine which national- and university-level infrastructure and support resources are most needed during the next decade to maximize the federal government's return on investment in neutron sources and instrumentation. This process would be akin to the current decadal process used by the Astronomy and Astrophysics community to plan for future investments and activities (NASEM, 2023). Similarly, a National Roadmap[37] effort would bring together stakeholders and demonstrate the resources and investments required to meet demand for facility capacity over the next 10 to 20 years.

Collaborative evaluation of existing instrumentation and joint decision-making about future investments for national instrumentation could provide the foundation to better advocate for

[36] One model is the Asia-Oceania Neutron Scattering Association (AONSA), founded in 2010. AONSA's objectives are to: (i) to identify the needs of the neutron scattering community in Asia and Oceania. (ii) to promote optimized use of present neutron sources in the region. (iii) to stimulate and promote neutron scattering activities and training in the region, and in particular to support the opportunities for young scientists. (iv) to support long-term planning of future neutron sources (AONSA, n.d.).

[37] Examples of roadmaps include the Swiss Academies' Neutron Science Roadmap for Research Infrastructures 2025–2028 (Swiss Academies, 2021) and the forthcoming Canadian Neutron Long-Range Plan 2025–2035 (Neutrons Canada, 2023).

funding for current and future facilities. Such a process could improve coordination to reduce concurrent downtimes from upgrades and provide both large and small neutron sources with the needed funding to maintain and grow operations, thereby allowing the United States to support a diverse portfolio of facilities.

Coordinated federal strategy for university reactors: RTI interviews with the neutron scattering community revealed a long-held need for a coordinated federal strategy with respect to university research reactors. The need for federal strategy was also raised by federal commissions and councils in 1988 and 2001. Regional consortia could be formed to serve advanced reactor needs and sustain and expand scientific pursuits that require neutrons such as neutron scattering. Universities interested in enhancing their existing facilities or in new construction could arrange consortia not just based on physical proximity, but on areas of research specialization or techniques. Material science, biological systems, and radiopharmaceuticals are all possible specializations among others.

Single entity leadership: Experts interviewed as part of this project and past federal evaluations have called for a single federal entity to improve coordination of funding, instrumentation, and fuel resources. Already, single-entity coordination occurs for nuclear science and engineering facilities through DOE’s NSUF Program, which categorizes members’ facility capabilities, helps users connect with needed research tools, and provides research funding (Nuclear Science User Facilities Program, 2023). A similar program through an appropriate coordinating agency could be established for national and university neutron scattering facilities. Such coordination could raise awareness of capabilities and activities at each facility, optimize facility usage, cultivate more formal collaborations between university facilities and national laboratories, and develop more extensive user networks.

9.4.2 Develop Mechanisms to Ensure Adequate Funding

Adequately staff and maintain current national facilities: Maintenance for neutron facilities should include gradual upgrades to instrumentation to maximize flux and keep facilities on the cutting edge of science as needs evolve. Funding should be provided for federal user facilities for instrumentation, staff, and support for early and midcareer professionals. Additional investment in computational and data analysis methods and computer hardware and architecture could greatly improve data collection and analysis of neutron scattering experiment data. Any funding plans need to account for inflation to maintain and grow capacity. This funding should be provided to federal user facilities and national laboratories as part of the annual appropriations process.

Reinvigorate university facilities: Recent interest in advanced and alternative reactors for nuclear power production has garnered increased federal support for university research reactors. For example, the CHIPS and Science Act called for the construction of up to four new university-based reactors. Although this proposal was not funded, it signals a willingness on the part of the federal government to reconsider the role of university research reactors in the landscape of federally supported science infrastructure. Strategic reinvestment in university reactors would make our neutron scattering facility inventory more similar to Europe’s. At least some of these facilities could develop specialized instrumentation to serve commercial clients and invaluable focus points for research and innovation for a wide range of scientific inquiries. Federal investments to upgrade power output and install core instrumentation for neutron scattering at university research reactors would provide redundancy when national user facilities are closed, offer researchers the ability to test-run experiments before visiting a national user facility, and let university research reactors serve as platforms to develop new instrumentation. Cross-institutional research programs between federal and university laboratories could further strengthen the pipeline of students interested in neutron scattering work.

Fund construction of one or more federal facilities: The need for a new research reactor was presented in the 2020 report, *The Scientific Justification for a U.S. Domestic High-Performance Reactor-Based Research Facility*, issued by BESAC (2020). The APS also has advocated for additional research reactors (APS, 2018). Although both ORNL and NCNR have done preliminary planning for new research reactors, the federal government must act to approve and fund new reactor sources. The extended planning and construction timelines for these facilities may mean that even if new facilities are immediately funded, the United States may be without one of the two existing sources before a new reactor can be completed (BESAC, 2020). Consensus building around the design and construction of this facility could be one of the first planks in a national roadmap for neutron scattering. This new facility could provide an opportunity to incorporate some of the features associated with other world-class facilities noted by our interviewees, such as:

- Collocation with an X-Ray source or other complementary research tools,
- Residential capacity for visiting researchers,
- Space and amenities to host graduate student summer camps and provide comprehensive new user support, and
- Accessibility by multiple modes of travel.

9.5 Key Takeaways

The research performed at neutron scattering facilities has advanced our fundamental knowledge of matter, leading to new and improved products. Yet the United States' neutron scattering research infrastructure has diminished since the 1960s. This places the country at a strategic disadvantage for current and future basic and applied research efforts.

Drawing on experience from other parts of the world, the U.S. neutron scattering ecosystem could be strengthened through the following actions:

- Forming a unified federal leadership committee or taskforce to develop a decadal plan or roadmap for neutron scattering facilities and national resilience, and
- Maintaining adequate funding for operating and improving existing facilities, strategically invigorating university facilities, and funding construction of new facilities.

An integral component of neutron scattering infrastructure is maintaining and strengthening university facilities. Significant improvements to the existing system can be achieved with a cohesive, federal strategy, single agency coordination, and facilitated decision-making for university investments. These interventions could support existing facilities and research staff and provide sufficient leadership to plan, fund, and construct new neutron sources to avoid further infrastructure loss. Timely action may avert research disruptions from uncoordinated or unanticipated facility closures and expand neutron scattering research opportunities for federal, academic, and industry users alike.

10. Summary of Findings

Case studies of the economic impact of four U.S. technologies influenced by research conducted at U.S. neutron scattering facilities highlight the substantial societal benefits generated from this research infrastructure. The PV benefits across the four case studies fully cover the PV of NCNR, HFIR, and SNS facility costs if even only 6-11% of these benefits are attributable back to neutron scattering research. Assuming neutron scattering research had an R&D acceleration effect of two years on case study technologies, the estimated BCR is 2.67 (range: 1.67 to 4.61), meaning that for every dollar invested in U.S. neutron scattering research facilities, $2.67 in benefits are realized. The estimated NPV is $29.4 billion (range: $11.8 billion to $63.6 billion). Results are similar when assuming that 20% of case study benefits are attributable to neutron scattering research.

These results are highly conservative as they only rely on benefits from four case studies of technologies influenced by neutron scattering research. These represent a small portion of total innovation influenced by U.S. neutron scattering research infrastructure, as we identified at least 22,808 research publications and 1,565 U.S. patents based on research conducted at U.S. federal neutron scattering research facilities from 1960 through 2020. We also identified at least 372 U.S.-based companies that are known to have used at least one U.S. federal neutron scattering source. These companies include both large-scale entities and SMEs across nearly every industry in the United States.

While facility use has been extensive, we heard from a variety of users that there is a need for increased neutron scattering research capacity in the United States. A survey of 247 facility users identified that 77% of these respondents experienced issues due to insufficient facility access in the five years before facility shutdowns in 2020. Issues included research quality reductions (32%) and lost or underutilized grant funds (25%) totaling $1.1 million per year in aggregate. Of the total survey sample, 19% successfully took research that they were not able to complete in U.S. neutron scattering facilities to an international facility.

Insufficient investment in neutron scattering research infrastructure generates long-term negative effects that are especially difficult to quantify, but could include loss of research capacity, outdated instrumentation, fewer individuals trained on and working with neutron scattering, and therefore reduced innovation and research quality.

Drawing on experience from other parts of the world, the U.S. neutron scattering ecosystem has the potential to be strengthened through the following actions:

- Forming a unified federal leadership committee or taskforce to develop a decadal plan or roadmap for neutron scattering facilities and national resilience, and
- Maintaining adequate funding for operating and improving existing facilities, strategically invigorating university facilities, and funding construction of new facilities.

11. Future Research Questions

Given the decades-long timeline for constructing a new neutron source, longer-term modeling would be needed to capture the economic impacts of major changes in U.S. neutron source investments. It could also be useful to fund comparative assessments of competitive and complementary materials assessment technologies, including spallation sources, reactors, synchrotrons, and other emerging X-ray technologies. Such assessments could further inform investment decisions to maximize the available U.S. materials research infrastructure.

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Appendix A: Additional Neutron Research Facility Information

A.1 Current Federal Neutron Facility Instruments and Uses

Table A-1. Current NCNR Instruments and Uses

Instrument	Uses
Residual stress diffractometer	Diffraction, used for studying residual and applied stress in engineering materials
Ultra-small-angle neutron scattering (USANS) diffractometer	Diffraction, small-angle neutron scattering
High-resolution powder diffractometer	Diffraction, crystallographic analysis
Filter analyzer spectrometer	Neutron vibrational spectroscopy
Triple-axis spectrometer	Spectroscopy
Double-focusing triple-axis spectrometer	Spectroscopy
MACS—ultra high efficiency cold neutron spectrometer (NSF-CHRNS)	Spectroscopy
Spin-polarized triple-axis spectrometer (SPINS)	Spectroscopy
High-flux backscattering spectrometer (NSF-CHRNS)	Spectroscopy, soft condensed matter, chemical physics, polymer dynamics, and biology
Disk-chopper time-of-flight spectrometer	Spectroscopy, materials studied include molecular and porous systems, layered materials, catalysts, glasses, polymers, metal-hydrogen, biological, and magnetic systems
Neutron spin echo spectrometer (NSF-CHRNS)	Spectroscopy, polymer dynamics
10 m small-angle scattering instrument (*n*Soft)	Small-angle neutron scattering, used for manufacturing, additive manufacturing, biomanufacturing, materials and polymers
30 m small-angle scattering instrument NG7	Diffraction
30 m small-angle scattering instrument NGB	Diffraction
Very small-angle scattering instrument (NSF-CHRNS)	Diffraction
Cold neutron reflectometer - Horizontal Sample Geometry	Reflection, polymer surfaces, thin films and multilayers of metals and semiconductors, both magnetic and nonmagnetic
PBR reflectometer with polarized beam option	Reflection, materials of interest in surface and interfacial science, including magnetic multilayers, polymer films, and artificial biological membranes
MAGIK off-specular reflectometer	Reflection, measurements of biological, battery/electrochemical, polymer, and magnetic thin films
CANDOR White-beam reflectometer (NSF-CHRNS)	Reflection
Neutron imaging (2 instruments)	Imaging, fuel cell experiments
Neutron interferometer and optics facilities	Fundamental neutron physics

Instrument	Uses
Prompt-gamma neutron activation analysis (2 instruments)	Chemistry
Cold neutron depth profiling	Chemistry
Radiochemical neutron activation analysis	Chemistry
Instrumental neutron activation analysis	Chemistry

Source: RTI based on information from the NCNR.

Table A-2. Current HFIR Instruments and Uses

Name	Instrument Type	Uses
Cold Neutron Imaging Facility	Imaging	Transmission imaging of natural and engineered materials
Biological Small-Angle Neutron Scattering Instrument (BIO-SANS)	Diffractometer	Used to examine proteins and complexes, pharmaceuticals, biomaterials
Cold Neutron Triple-Axis Spectrometer (CTAX)	Spectrometer	High-resolution inelastic scattering at cold neutron energies
Dimensional Extreme Magnetic Neutron Diffractometer (DEMAND)	Diffractometer	Small unit-cell nuclear and magnetic structural studies
Fixed-Incident-Energy Triple-Axis Spectrometer (FIE-TAX) HB-1A	Spectrometer	Low-energy excitations, magnetism, structural transitions
General-Purpose Small-Angle Neutron Scattering Diffractometer (GP-SANS)	Diffractometer	Small unit-cell nuclear and magnetic structural studies
High Intensity Diffractometer for Residual stress Analysis (HIDRA)	Diffractometer	Strain, texture, and phase mapping in engineering materials
Laue Diffractometer (IMAGINE)		Transmission imaging of natural and engineered materials
Neutron Powder Diffractometer (POWDER)	Diffractometer	Magnetic and crystal structure studies and phase analysis
Polarized Triple-Axis Spectrometer (PTAX)	Spectrometer	Polarized neutron studies of magnetic materials, low-energy excitations, structural transitions
Triple-Axis Spectrometer (TAX)	Spectrometer	Medium- and high-resolution inelastic scattering at thermal energies
Wide-Angle Neutron Diffractometer (WAND^2)	Diffractometer	Diffuse-scattering studies of single crystals and time-resolved phase transitions
Crystal alignment diffractometer	Diffractometer	Co-alignment of single crystals

Source: RTI based on information provided by ORNL.

Table A-3. Current SNS Instruments and Uses

Name	Instrument Type	Uses
Versatile Neutron Imaging Instrument (VENUS) Under Construction	Imaging	Energy selective imaging in materials science, engineering, materials processing, environmental sciences and biology
Wide Angular-Range Chopper Spectrometer (ARCS)	Spectrometer	Atomic-level dynamics in materials science, chemistry, condensed matter sciences
Fine-Resolution Fermi Chopper Spectrometer (SEQUOIA)	Spectrometer	Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
Vibrational Spectrometer (VISION)	Spectrometer	Vibrational dynamics in molecular systems, chemistry
Neutron Spin Echo Spectrometer (NSE)	Spectrometer	High-resolution dynamics of slow processes, polymers, biological macromolecules
Hybrid Spectrometer (HYSPEC)	Spectrometer	Measures excitations in small single crystals with optional polarization analysis
Fundamental Neutron Physics Beam Line (FNPB)		Operated as a user facility with all beam time allocated based on independent peer reviews. It is not an instrument but provides infrastructure for experiments.
Single-Crystal Diffractometer (TOPAZ)	Diffractometer	Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
Backscattering Spectrometer (BASIS)	Spectrometer	Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Cold Neutron Chopper Spectrometer (CNCS)	Spectrometer	Condensed matter physics, materials science, chemistry, biology, environmental science
Elastic Diffuse Scattering Spectrometer (CORELLI)	Spectrometer	Detailed studies of disorder in crystalline materials
Extended Q-Range Small-Angle Neutron Scattering Diffractometer (EQ-SANS)	Diffractometer	Polymers, soft materials and colloidal systems, materials science, life science, earth and environmental sciences
Liquids Reflectometer (LIQREF)	Reflectometer	Condensed matter, materials science, and magnetism of interfaces
Magnetism Reflectometer (MAGREF)	Reflectometer	Interfaces in complex fluids, polymers, chemistry
Macromolecular Neutron Diffractometer (MANDI)	Diffractometer	Atomic-level structures of proteins, macromolecules, and DNA
Nanoscale-Ordered Materials Diffractometer (NOMAD)	Diffractometer	Liquids, solutions, glasses, polymers, nanocrystalline, and partially ordered complex materials
Powder Diffractometer (POWGEN)	Diffractometer	Atomic-level structures in chemistry, materials science, and condensed matter physics, including magnetic structure
Spallation Neutrons and Pressure Diffractometer (SNAP)	Diffractometer	Materials science, geology, earth and environmental sciences
Ultra-Small-Angle Neutron Scattering Instrument (USANS)	Diffractometer	Life sciences, polymers, materials science, earth and environmental sciences
Engineering Materials Diffractometer (VULCAN)	Diffractometer	Deformation, phase transformation, residual stress, texture, and microstructure studies

Source: RTI based on information provided by ORNL.

A.2 Former Federal Neutron Facility Instruments and Uses

Table A-4. Former and Current Lujan Neutron Research Instruments

Name	Instrument Type	Still Operating
Asterix	Reflectometer/ cold neutron imaging	Yes
Energy-resolved neutron imaging (ERNI)	Imaging	Yes
High-Pressure-Preferred Orientation instrument (HIPPO)	Diffractometer	Yes
Neutron Powder Diffractometer (NPD)	Diffractometer	Yes
Spectrometer for Materials Research at Temperature and Stress (SMARTS)	Spectrometer	Yes
Pharos	Spectrometer	No
High Intensity Powder Diffractometer (HIPD)	Diffractometer	No
Filter Difference Spectrometer (FDS)	Spectrometer	No
Surface Profile Analysis Reflectometer (SPEAR)	Reflectometer	No
Low-Q Diffractometer (LQD)	Diffractometer	No
Single Crystal Diffractometer (SCD)	Diffractometer	No

Table A-5. HFBR Instruments and Uses

Instrument	Use
Polarized, beam-inelastic spectrometer	Condensed matter physics and materials science
Spectrometer, inelastic scattering	Condensed matter physics and materials science
Spectrometer, inelastic scattering, polarized beam	Condensed matter physics and materials science
Spectrometer, inelastic scattering cold neutrons	Condensed matter physics and materials science
Powder diffraction and inelastic scattering	Material science, neutron diffraction
Spectrometer, powder diffraction and inelastic scattering	Material science
3-axis pair spectrometer	Nuclear physics
TRISTAN mass separator	Nuclear physics
Powder diffraction new high-resolution power diffractometer	Neutron diffraction
Single-crystal diffraction H6-M has an analyzer axis and can be used in a three-axis mode if desired	Chemical crystallography, neutron diffraction
Single-crystal diffraction H6-S has a fixed monochromator scattering angle providing neutrons with fc=l. 16 A with a Ge (220) monochromator	Chemical crystallography, neutron diffraction
H3-A is a neutron spectrometer for protein crystallography	Structural biology

Instrument	Use
H3-B is an intermediate resolution SANS station that looks at the thermal part of the reactor spectrum	Structural biology
H9-B is a high-resolution SANS instrument situated at the cold source	Structural biology
Reflection spectrometer	Material interface studies using neutron reflectometry

Source: RTI International based on information from S.M. Shapiro, BNL

A.3 Isotope Production Collaborations and Oversight

At least 11 federal facilities or universities are engaged in isotope production (National Isotope Development Center (NIDC), n.d.). Because isotopes are critical for medical, national security, and scientific purposes, national production and distribution of isotopes are coordinated by the National Isotope Development Center, which is supported by DOE's Isotope Program. It serves as an interface with the user community and manages the coordination of isotope production across the program facilities at Argonne, Brookhaven, Idaho, Los Alamos, Oak Ridge, and Pacific Northwest National Laboratories (DOE, n.d.). DOE partners with universities to invest in R&D and to develop production capabilities. For instance, Michigan State University houses both the NSF's National Superconducting Cyclotron Laboratory, which is a national user facility, and the Facility for Rare Isotope Beams, a DOE-supported user facility. Together, these facilities can produce isotopes, conduct user experiments, and train future scientists (Michigan State University, n.d.). Isotope production can defray the cost of operating nuclear reactors for universities while increasing domestic production of critical materials. For instance, the University of Missouri has an exclusive agreement to supply radioisotopes for cancer therapy to a subsidiary of Novartis and was recently approved by the FDA to produce molybdenum-99, which is used in about 80% of medical imaging (Keller, 2020).

Appendix B: Additional Bibliometric and Patent Analysis Details

B.1 Dimensions Workflow for Identifying Publications

NCNR, ORNL, and Lujan each were able to provide RTI with full or partial publication archives. To associate the archived publication records with publications in the Dimensions database, we created a processing workflow using Python. This workflow took records from two formats: .CSV files consisting of text extracted from scanned images of paper archives using optical character recognition (OCR) and tabular data files (Excel spreadsheets) with publication reference metadata split into columns.

OCR extraction was used for NCNR records up to 2007 when digital archiving began, as well as for Lujan for all archival records. Acceptable matches were determined using an iterative automatic process comparing the difference between the matched title and the input title from the archival records.

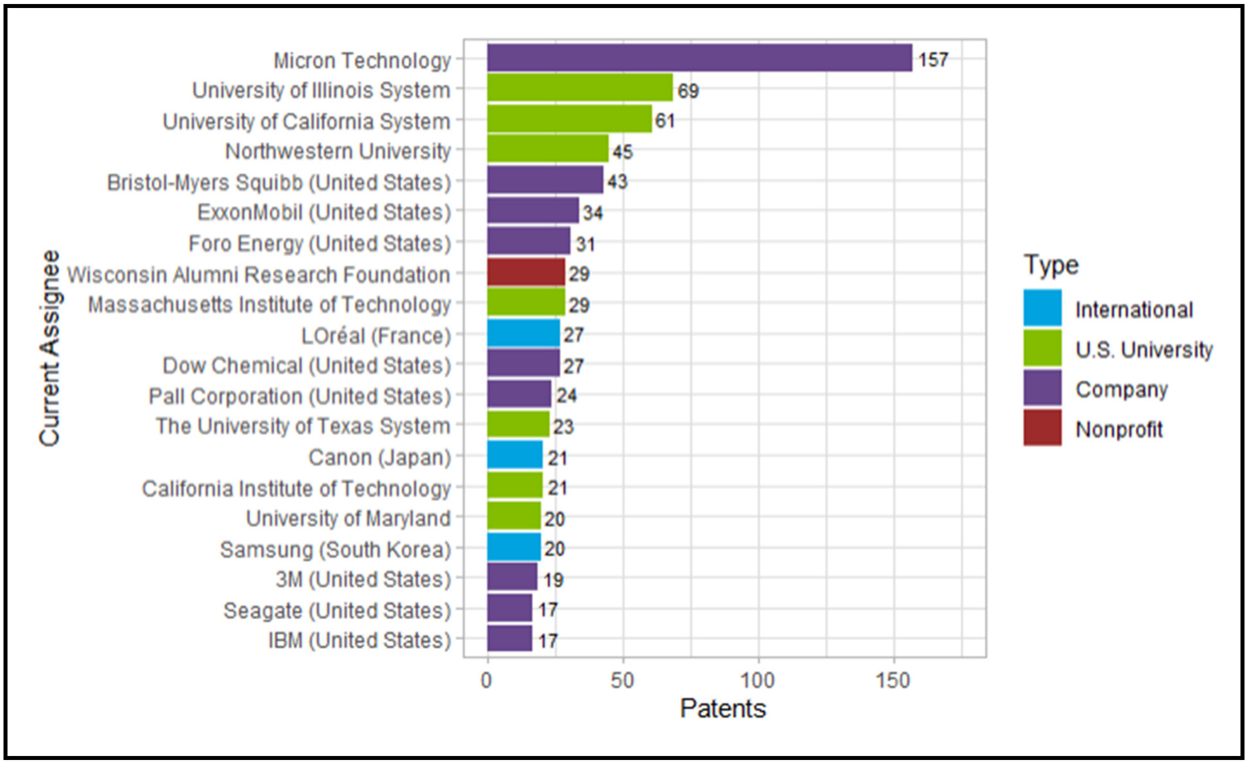
1. After loading records from both input formats, the primary sorting fields (publication title and year) were populated for each record and preprocessed as needed. This automated preprocessing step included removing or replacing specific characters, detecting any author names in the publication data, and combining hanging rows.
2. The records were then put through a basic automated query step using the associated title and year information. Because many of the OCR records contained spelling mistakes, a custom-made knockout algorithm (replacing random words in the query with wildcards) was implemented to re-attempt unmatched records. This step found acceptable matches for 50 to 60% of the records.
3. Using the Dimensions metadata from the acceptable matches, including author names and affiliations, the remaining unmatched records were reprocessed and put through a secondary query step. This step used the acceptable matches as a foothold to find secondary connections in the unmatched records. This step found acceptable matches for an additional 15 to 20% of the records.
4. Finally, additional information was extracted from Dimensions for each of the matched records. This information included all available fields from Dimensions, as well as breakouts for some of the author information and any patents associated with the matched records.

B.2 Additional Publication & Patent Analysis Findings

Since our patent data spans five decades, it is probable that the assignees of patents have changed over time. As such, patents by current assignees may serve as a better indicator of current activity in the user space. To account for patent transfers, reassignments, and mergers, we analyzed the same patent data using current assignees. As shown in Figure B-1, most top assignees were the same regardless of assignee status, but certain key differences are evident.

First, Micron Technology remains the top patent assignee, but with 60 fewer patents as current assignee than as original assignee. While patents are still highly concentrated with Micron Technology, the overall distribution of patents by current assignee is smoother than by original assignee. This suggests a transfer of patent ownership from Micron Technology to other assignees over time. Second, there is more diversity in key international players by current assignee than by original assignee. The emergence of Canon (Japan) and Samsung (South Korea) as top current assignees reflects the increase in innovation activity from East Asian companies in the neutron scattering space.

Figure B-1. Patents by Current Assignee



Looking at the distribution of current assignees by country, patent ownership remains concentrated with U.S. assignees, comprising 77% of total patents (Figure B-2). For international current assignees, Japan surpasses France with 98 and 74 patents respectively (Figure B-3). This indicates a shift in patent ownership away from European assignees and towards East Asian companies, further highlighting their entry into the user space.

Figure B-2. Patents by Current Assignee Country (U.S. Only)

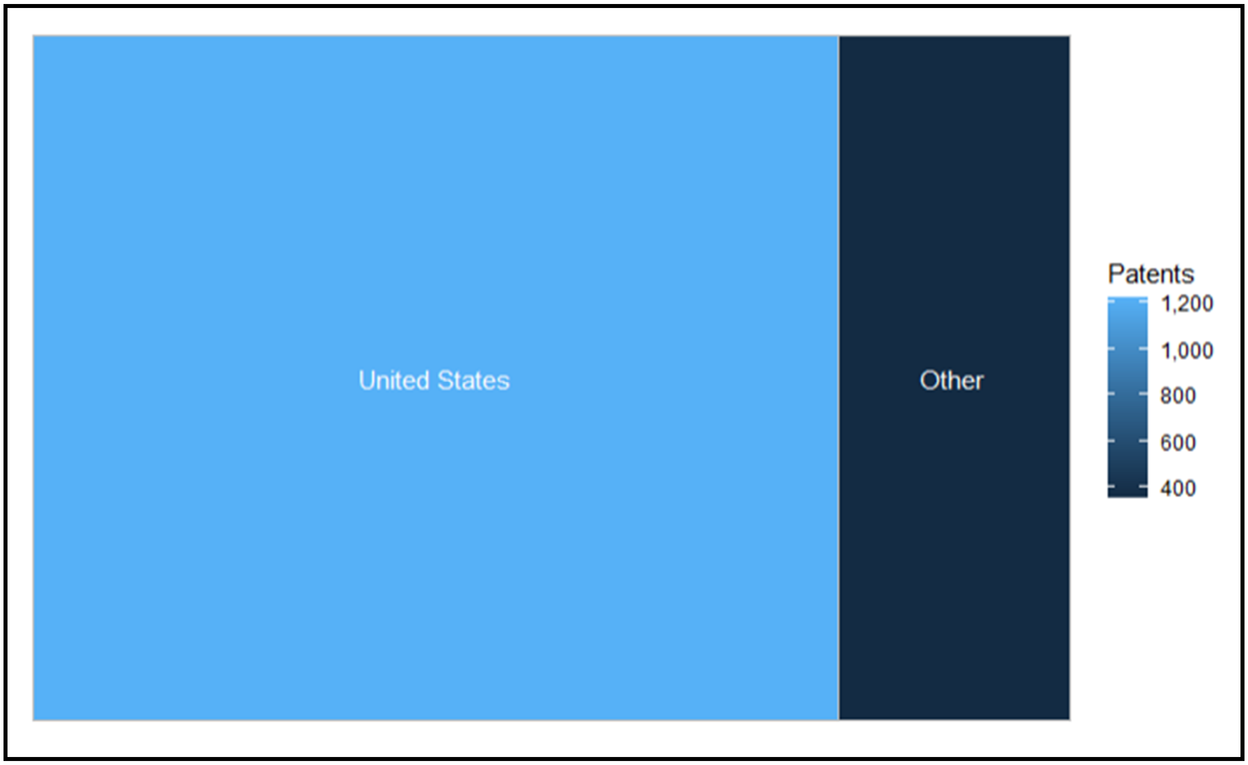
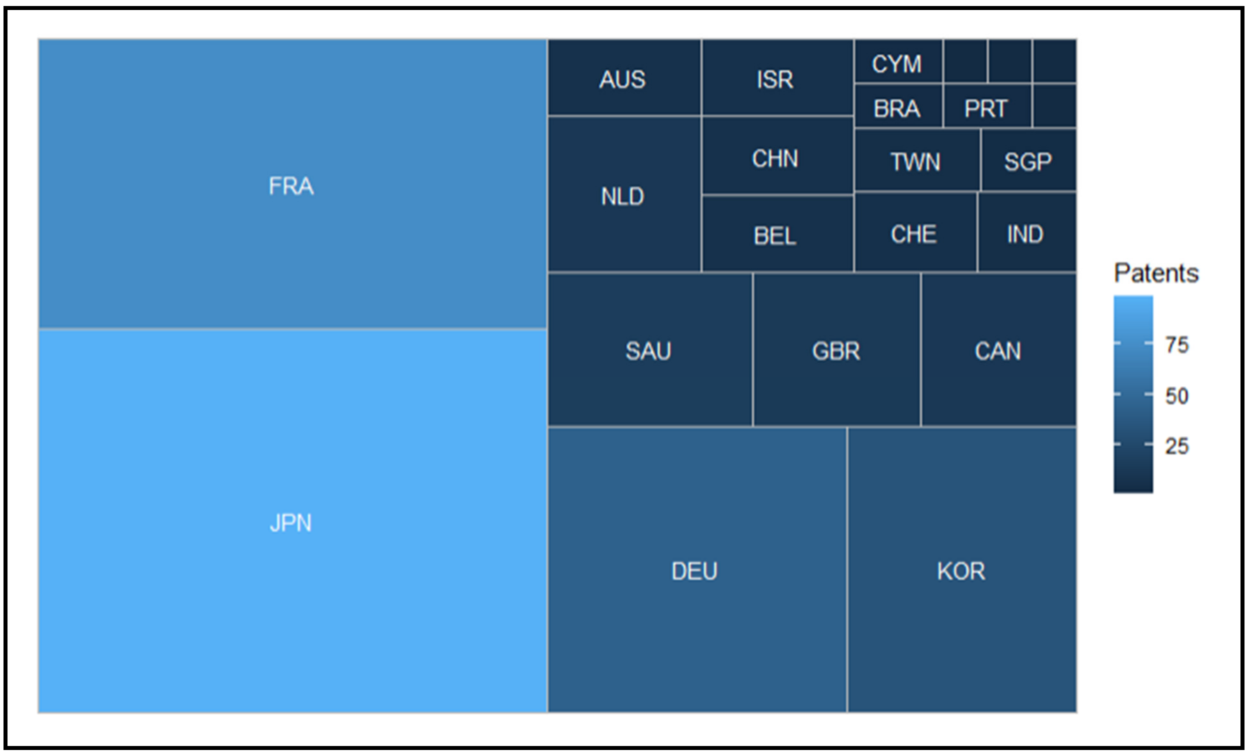


Figure B-3. Patents by Current Assignee Country (Without U.S.)



B.3 ISO Alpha-3 Country Codes

Table B-4. Countries Listed in Publication and Patent Figures

ISO Alpha-3 Code	Country Name
AUS	Australia
AUT	Austria
BEL	Belgium
BRA	Brazil
CAN	Canada
CHE	Switzerland
CHN	China
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
FRA	France
GBR	United Kingdom
GRE	Greece
HUN	Hungary
IND	India
IRL	Ireland
ISR	Israel
ITA	Italy
JPN	Japan
KOR	South Korea
MEX	Mexico
NLD	Netherlands
NOR	Norway
POL	Poland
PRT	Portugal
RUS	Russia
SAU	Saudi Arabia
SGP	Singapore
SWE	Sweden
TUR	Turkey
TWN	Taiwan

Appendix C: User Survey and Interview Guides

Below are the instruments that RTI used to conduct surveys and interviews with users of the NCNR and ORNL neutron scattering facilities. The survey instrument was developed using Alchemer. Red text indicates embedded survey logic that was not visible to the respondent. Survey invitations and reminders were sent from facility leadership via email to their user lists. Those who indicated at the end of the survey that they would be willing to participate in a follow-up interview were emailed by RTI using their provided contact information. Interviews occurred via video conference using either Zoom or Microsoft Teams.

C.1 2022 U.S. Neutron Scattering Facility User Survey Instrument

Welcome

RTI International is conducting an economic impact assessment of the nation's neutron scattering research facilities, using grant funds from the National Institute of Standards and Technology (NIST). Our goal is to determine the impact of federal neutron scattering facilities on the U.S. economy from 1968 to date, and to determine the potential impact of future investments in U.S. neutron scattering research infrastructure.

As a facility user, your participation in this survey will help inform our understanding of the benefits and outcomes associated with U.S. neutron scattering facilities along with the costs of insufficient research infrastructure. The survey will ask questions about you and your experience with using neutron scattering research facilities.

The survey should take approximately **10 minutes** to complete, and your participation is completely voluntary. You will not receive any payment or compensation for taking part in this study.

To the best of our knowledge, the questions you will be asked pose no more risk of harm than you would experience in everyday life. We will remove or code any personal information that could identify you before files are shared with other researchers to ensure that, by current scientific standards and known methods, no one should be able to identify you from the information we share. Despite these measures, we cannot guarantee against the reidentification of your personal data. De-identified data could be used for future research studies or distributed to another investigator for future research studies without additional informed consent.

If you have any questions about this study, you may email the RTI survey coordinator, Sara Nienow, at snienow@rti.org. If you have any questions about your rights as a study participant, you can call RTI’s Office of Research Protection at 1-866-214-2043 (a toll-free number).

By clicking "Next" below, you are consenting to participate in this study.

Logic: Show/hide trigger exists.

1) Please select your professional affiliations (select all that apply)

[ ] Academic Institution

[ ] Corporation

[ ] Government Institution

[ ] Research Foundation

[ ] Other (please specify): ____

Logic: Hidden unless: #1 Question "Please select your professional affiliations (select all that apply)" is one of the following answers ("Academic Institution")

2) Please select all titles that best describe you currently.

[ ] Graduate Student

[ ] Post-Doctoral Fellow

[ ] Adjunct Professor / Lecturer / Instructor

[ ] Assistant Professor

[ ] Associate Professor

[ ] Full Professor

[ ] Distinguished, Endowed, or University Professor

[ ] Department Head / Dean / Administrator

[ ] Researcher or Research Professor

[ ] Other (please specify): ____

3) In what year did you earn your terminal degree?

____

4) Over the past 5 years, about how many applications have you made for beam time at a U.S. federal neutron scattering facility?

____

5) At which neutron scattering facilities have you conducted research? (select all that apply)

[ ] Oak Ridge National Laboratory (ORNL)

[ ] NIST Center for Neutron Research (NCNR)

[ ] Los Alamos Neutron Science Center (LANSCE)

[ ] Other federal U.S. facility (please specify): ____

[ ] U.S. university-based facility

[ ] U.S. private facility

[ ] International facility (please specify): ____

6) Which technology areas best align with your neutron scattering research? (select all that apply)

[ ] Soft Matter

[ ] Biological Sciences

[ ] Energy Materials and Systems

[ ] Magnetic Materials

[ ] Infrastructure

[ ] Other (please specify): ____

7) What is the average amount of time it takes (in months) for you to prepare experiments for neutron scattering instrument beam-time (e.g., by conducting preliminary investigation or preparing samples)? In your response, please assume there are no facility-side delays in your ability to access beam time.

____

8) What is the average amount of grant funding that you allocate to each instance of beam-time allotment including travel expenses and experiment preparation?

____

9) How long do you estimate it takes on average for research to be submitted for publication after beam-time is complete?

____

Logic: Show/hide trigger exists.

10) Have you or any of your collaborators filed a U.S. patent that benefited from or was informed by research you conducted at a neutron scattering research facility?

( ) Yes

( ) No

Logic: Hidden unless: #10 Question "Have you or any of your collaborators filed a U.S. patent that benefited from or was informed by research you conducted at a neutron scattering research facility?" is one of the following answers ("Yes")

11) How many such patents have been filed or received?

Total patents filed: ____

Patents received: ____

Logic: Hidden unless: #10 Question "Have you or any of your collaborators filed a U.S. patent that benefited from or was informed by research you conducted at a neutron scattering research facility?" is one of the following answers ("Yes")

12) On average, how long after beam-time is complete has it taken you to file a patentable idea?

____

Logic: Show/hide trigger exists.

13) *In the years before the COVID-19 pandemic*, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)

[ ] Research delays

[ ] Reduced research quality

[ ] Sought to perform research elsewhere

[ ] Inability to perform research

[ ] None of the above

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Research delays")

14) Please consider a particular instance where you experienced research delays due to insufficient access to a U.S. federal neutron scattering facility. How many resources were lost?

Time (in months): ____

Grant funds (in dollars): ____

Other (please specify): ____

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Reduced research quality")

15) Please consider a particular instance where you experienced reductions in research quality due to insufficient access to a U.S. federal neutron scattering facility. Please indicate the type and magnitude of quality reductions you experienced.

	0% Reduction	**1% - 24% Reduction**	**25% - 49% Reduction**	**50% - 74% Reduction**	**75% - 99% Reduction**
Depth of information revealed from the research	( )	( )	( )	( )	( )
Applicability of information revealed from the research	( )	( )	( )	( )	( )
Number of publications resulting from the research	( )	( )	( )	( )	( )
Quality of publications resulting from the research	( )	( )	( )	( )	( )
Number of patents influenced by the research	( )	( )	( )	( )	( )

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Sought to perform research elsewhere")

16) For projects where you tried to seek access to another neutron scattering facility, what type of facility did you try to schedule time at? (select all that apply)

[ ] Another U.S. federal facility

[ ] U.S. university-based facility

[ ] U.S. private facility

[ ] International facility (please specify): ______________________________

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Sought to perform research elsewhere")

17) Where were you able to schedule time at? (select all that apply)

[ ] Another U.S. federal facility

[ ] U.S. university-based facility

[ ] U.S. private facility

[ ] International facility (please specify): ______________________________

[ ] Nowhere

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Inability to perform research")

18) Please consider a particular instance where you chose not to pursue a research topic because of a lack of access to a U.S. federal neutron scattering facility. How much resources were spent on the research before the decision was made to no longer pursue it?

Time (in months): ______________________________

Grant funds (in dollars): ______________________________

Other (please specify): ______________________________

Logic: Hidden unless: #13 Question "***In the years before the COVID-19 pandemic***, which of the following had you encountered because of insufficient access to a U.S. federal neutron scattering research facility? (select all that apply)" is one of the following answers ("Inability to perform research")

19) What were the anticipated research outputs?

Number of patents: ____

Number of publication submissions: ____

Other (please specify): ____

20) Are there any other thoughts you would like to share with us about your access to or experience with U.S. federal neutron scattering facilities?

____

____

____

____

Logic: Show/hide trigger exists.

21) Would you willing to participate in a 30-minute interview with RTI International to provide more information about your access to or experience with U.S. federal neutron scattering facilities?

( ) Yes

( ) No

Logic: Hidden unless: #21 Question "Would you willing to participate in a 30-minute interview with RTI International to provide more information about your access to or experience with U.S. federal neutron scattering facilities?" is one of the following answers ("Yes")

22) Please rank the available methods of contact below, with 1 being your most preferred option and 3 being your least preferred option.

________Zoom

________Teams

________Phone Call

Logic: Hidden unless: #21 Question "Would you willing to participate in a 30-minute interview with RTI International to provide more information about your access to or experience with U.S. federal neutron scattering facilities?" is one of the following answers ("Yes")

23) Based on your contact preferences, please provide your name and email address (for Zoom or Teams) or phone number.

Name (First & Last): ____

Title (Dr., Mrs., Mr., etc.): ____

Email address: ____

Phone number: ____

Thank You!

Thank you for taking our survey. Your responses have been recorded.

If you agreed to be contacted for a follow-up interview, someone from the RTI research team will contact you within two weeks of receiving your survey response.

If you have any other thoughts you would like to share, you may email the RTI survey coordinator, Sara Nienow, at snienow@rti.org.

C.2 U.S. Neutron Scattering Facility User Interview Guide

Interview Date	
Person Interviewed	
Title	
Organization	
RTI Staff Member 1	
RTI Staff Member 2	
Verbal Consent Provided	
Requested documentation from interviewee:	

Using funds from the National Institute of Standards and Technology (NIST), RTI International is assessing the economic contribution of U.S. neutron scattering research facilities to the U.S. economy. In support of this work, RTI is conducting a series of interviews with facility users to gain a better understanding of their use of and needs from these facilities.

This interview will last approximately 30 minutes, and your participation is completely voluntary. You will not receive any payment or compensation for taking part in this study. To the best of our knowledge, the questions you will be asked pose no more risk of harm than you would experience in everyday life.

Interview insights and themes will be aggregated from all responses before being shared with other researchers to ensure that, by current scientific standards and known methods, no one should be able to identify you from the information we share. No individuals or organizations will be directly quoted or cited without their permission. Despite these measures, we cannot guarantee against the reidentification of your personal data. De-identified data could be used for future research studies or distributed to another investigator for future research studies without additional informed consent.

If you have any questions about this study, you may email the RTI survey coordinator, Sara Nienow, at snienow@rti.org. If you have any questions about your rights as a study participant, you can call RTI's Office of Research Protection at 1-866-214-2043 (a toll-free number).

1. Can you briefly describe the types of research you do at neutron scattering facilities?

2. How frequently do you use neutron scattering facilities?

3. When was the last time you used a neutron scattering facility?

4. Which facilities have you used in the United States and abroad? Why were these facilities chosen?

5. If you have done neutron scattering research in other countries, how do the following factors compare to those at U.S. facilities?
   a. Instruments
   b. Source strength or intensity
   c. Support for sample handling and testing
   d. Administrative process (e.g., wait time)
   e. Cost
   f. Other factors

6. How do you measure the benefits you (or your company) receive from neutron scattering research? For example:
   a. Average number of samples examined per beam-time allotment?
   b. Average number of publications and/or patents resulting from each beam-time allotment?
   c. Enhancements to products or advancements in research knowledge base?
   d. Other metrics?

7. Has any research you conducted at a U.S. neutron scattering facility led to a commercial product or other field application?
   a. If so, please describe the product(s) or application(s) and the role of your facility research in the development process.

   b. In the absence of using a neutron scattering facility, would the work have still been commercialized or applied?

8. Could other techniques (e.g., X-ray scatterings, NMR, or light scattering) substitute for neutron scattering in your research?
   a. Would these alternatives be more costly to you?
   b. How available are these alternatives to you?
   c. What information would you lose using these other methods?

9. It is well documented that U.S. neutron scattering facilities are oversubscribed by a factor of 2-3.
   a. How has this affected your use of federal facilities (e.g., have you postponed or changed the direction of your research, looked for other facilities in the U.S. or abroad, or other)?
   b. What broader impacts do you think this has on U.S. industrial growth, innovation, and competitiveness?
   c. What types of commercial products have been or will be most adversely affected by this oversubscription of neutron scattering facilities?

10. If the research capacity of U.S. neutron scattering facilities were to increase by 50%, do you think that U.S. innovation and industrial growth would increase?
    a. If yes, by how much?
    b. Which scientific areas would be affected?

11. What barriers have prevented the U.S. neutron scattering community from performing at the same level as international competitors such as the EU?
    a. How do you think these barriers might be addressed?
    b. What role do you think private industry or universities should/could play in supporting neutron scattering facilities?

12. What new advances in science or technology might alter your needs for neutron scattering facilities in the next ten years?
    a. How would these affect your demand for neutron scattering facilities?

13. Are there other issues related to U.S. neutron scattering facilities that you think are relevant for NIST to consider?

Appendix D: Additional Data on Industry Users of Federal Neutron Scattering Facilities

Below is the full set of results from RTI's search of industrial neutron users. Individual companies were sorted into industries utilizing industry information from Pitchbook, which also provided information regarding firm revenue and employment. It should be noted that not all companies in the sample had revenue and employment information available.

Industry	Sample Count	Industry Count	Sample / Industry Ratio	Revenue	Employment
Aerospace and Defense	10	13,540	0.07%	$263,262	595,319
Automotive	5	135	3.70%	$346,633	414,017
BPO/Outsource Services	3	10,325	0.03%	$726	3,591
Building Products	1	383	0.26%	$49	350
Chemicals and Gases	19	20,612	0.09%	$95,939	123,271
Commercial Transportation	3	645	0.47%	$28,000	51,400
Communications and Networking	3	9,035	0.03%	$121,168	160,718
Computer Hardware	12	11,651	0.10%	$44,401	114,200
Construction and Engineering	9	37,234	0.02%	$27,191	118,080
Consulting Services	4	16,567	0.02%	$0	435
Consumer Durables	6	20,710	0.03%	$29,052	79,525
Consumer Non-Durables	8	6,340	0.13%	$194,524	272,065
Decision/Risk Analysis	1	118	0.85%	$5	164
Distributors/Wholesale	3	440	0.68%	$0	10
Education and Training Services	1	20,491	0.00%	$0	315
Electric Utilities	4	1,814	0.22%	$32,641	30,437
Electrical Equipment	18	39,166	0.05%	$7,676	34,586
Energy Equipment	11	780	1.41%	$32,312	116,950
Energy Services	7	70,740	0.01%	$55,515	30,427
Environmental Services	6	9,028	0.07%	$548	1,105
Exploration, Production and Refining	8	7,494	0.11%	$894,255	134,337
Healthcare Devices and Supplies	12	8,951	0.13%	$72,109	200,546
Healthcare Services	9	167,575	0.01%	$30,484	217,390
Human Capital Services	2	170,389	0.00%	$1,869	5,000
Industrial Supplies and Parts	16	5,013	0.32%	$10,039	33,666
IT Services	6	68,144	0.01%	$53,161	83,595
Leisure Facilities	2	77,619	0.00%	$0	0
Machinery	18	187,745	0.01%	$178,339	398,598

Industry	Sample Count	Industry Count	Sample / Industry Ratio	Revenue	Employment
Media and Information Services	4	10,662	0.04%	$25,291	1,948
Metals, Minerals and Mining	2	213	0.94%	$0	0
Other Business Products and Services	15	36,380	0.04%	$115,534	308,980
Other Commercial Products	22	6,085	0.36%	$17,021	66,509
Other Commercial Services	19	92,848	0.02%	$2,573	77,347
Other Financial Services	1	1,230	0.08%	$0	0
Other Materials	7	2,147	0.33%	$1	173
Pharmaceuticals and Biotechnology	30	126,144	0.02%	$362,164	514,690
Plastic Containers and Packaging	1	1,989	0.05%	$0	0
Printing Services	1	381	0.26%	$0	10
Raw Materials (Non-Wood)	1	8,673	0.01%	$0	249
Semiconductors	14	1,678	0.83%	$112,967	221,117
Services (Non-Financial)	3	38,078	0.01%	$33	220
Software	17	137,550	0.01%	$5,776	16,350
Specialty Retail	2	715	0.28%	$68	47,660
Total	**346**	**1,447,457**		**$3,161,326**	**4,475,350**