Neutrons for the Nation

Discovery and Applications while Minimizing the Risk of Nuclear Proliferation

A Report by the APS Panel on Public Affairs

July 2018

APS physics

ABOUT APS & POPA

Founded in 1899 to advance and diffuse the knowledge of physics, the American Physical Society (APS) is now the nation's leading organization of physicists with approximately 55,000 members in academia, national laboratories and industry. APS has long played an active role in the federal government; its members serve in Congress and have held positions such as Science Advisor to the President of the United States, Director of the CIA, Director of the National Science Foundation and Secretary of Energy.

This report was overseen by the APS Panel on Public Affairs (POPA). POPA routinely produces reports on timely topics being debated in government so as to inform the debate with the perspectives of physicists working in the relevant issue areas.

REPORT COMMITTEE

James Wells, Co-Chair, *University of Michigan Physics Department*

Julia Phillips, Co-Chair, *Sandia National Laboratory (retired)*

William Barletta, *Massachusetts Institute of Technology Department of Physics*

Robert Birgeneau, *University of California, Berkeley*

Robert Dimeo, *National Institute of Standards and Technology*

Francesco Ganda, *Argonne National Laboratory, Nuclear Engineering Division*

William Martin, *University of Michigan, Nuclear Engineering & Radiological Sciences*

John Sarrao, *Los Alamos National Laboratory*

Antoinette Taylor, *Los Alamos National Laboratory*

Norman Wagner, *University of Delaware, Chemical & Biomolecular Engineering*

APS STAFF

Francis Slakey, *APS Chief Government Affairs Officer*

Jeanette Russo, *Manager of Operations*

Allen Hu, *Policy Analyst*

AUTHORSHIP

The American Physical Society has sole responsibility for the contents of this report, and the questions, findings, and recommendations within.

ACKNOWLEDGEMENTS

We thank Frank Bates, Bill Buyers, David Dean, Alex Glaser, Geoff Greene, Jenny Heimberg, Mark Johnson, John Katsaras, Julia Kornfield, Patrick Lemoine, Dan Neumann, Sean O'Kelly, Ray Orbach, Winfried Petry, Roger Pynn, Kate Ross, and J. Michael Rowe for their contributions to this report.

PUBLICATION DATE: JULY 2018

Cover and report designed by Meghan White.

For additional information, including the participant bios and the workshop charge and agenda, please visit: www.aps.org/policy/reports/popa-reports/

Table of Contents

Executive Summary i

Key Findings ii

Key Recommendations iii

Introduction 1

1. Why Neutrons? 3

Neutrons for Research 3

Neutrons for Industry and Medicine 6

2. The Neutron Facilities Landscape 9

Worldwide Neutron Scattering Facilities 9

European Facilities 9

Asia-Oceania Facilities 10

U.S. Facilities 11

Worldwide Neutron Irradiation Facilities 13

3. Reactors and Spallation Sources: Challenges and Opportunities 15

Research Reactors 16

Spallation Sources 17

Costs of Neutron Sources and Societal Benefits 18

Summary: The Path Forward 21

Key Recommendations 22

References 23

Executive Summary

For many decades, neutron fluxes from civilian nuclear research reactors have been important in the advancement of science and industry. Since 1978, the policy of the United States has been to reduce and ultimately eliminate the use of highly enriched uranium (HEU)[1] in civilian research reactors, encouraging by example worldwide efforts to reduce nuclear proliferation risks. Significant progress has been made on this front, with many reactors having been converted to low enriched uranium (LEU)[2] fuel or shut down.

However, there still exist HEU-fueled reactors in the United States and abroad. An important reason for their continued use is their capability to produce intense sources of neutrons that can probe matter and trigger interactions at a level that no other technique currently can achieve. This capability is critical to scientific research and industrial applications. HEU-fueled reactors are used in materials research that engenders economic development, tests of fundamental laws of the physical world that enrich our understanding of nature, and advanced treatments that improve medical outcomes.

This report, commissioned by the American Physical Society's Panel on Public Affairs (APS POPA), focuses on the competing goals of reducing nuclear proliferation risk while maintaining intense controlled sources of neutrons for vital scientific and industrial work.

In developing this report, several issues were examined, including the current and future needs of neutrons for science and industry; the landscape of neutron facilities in the United States and worldwide; the complementary merits of spallation sources and nuclear reactors; the prospects for converting research reactors from HEU to LEU fuel usage; and the economic motivations for maintaining and growing neutron science and its industrial applications.

1 Natural uranium is 99.284% ^{238}U isotope, with ^{235}U only constituting about 0.711% of its mass. Enriched uranium is a type of uranium in which the percent composition of uranium-235 has been increased. Highly Enriched Uranium is fuel enriched to at least 20% U-235 concentration and has “direct use” for the manufacture of a nuclear explosive device.
2 Low Enriched Uranium is fuel enriched to less than 20% U-235 concentration.

The examination culminated in the following key findings and recommendations:

KEY FINDINGS:

1. Investigations performed at neutron sources are essential components of R&D in numerous areas of science and engineering.

2. Neutron scattering is often an essential part of a broader experimental study that uses a complementary suite of tools (e.g., light sources, high-performance computers). Thus, neutron sources play a key role in overall U.S. innovation capacity.

3. The United States has lost important capability in neutron R&D in the last two decades and is no longer the world leader. The United States cannot afford to lose its remaining capacity and capability without significant detriment to the quality and quantity of science, engineering, and even medical and manufacturing processes that rely on neutron sources.

4. Reactor fuels containing HEU represent a risk for proliferation, which should be considered when planning for the future infrastructure for neutron R&D.

5. Current HEU-fueled research reactors provide unique R&D capabilities relative to other neutron sources available today. Eliminating them without developing and deploying alternative methods of producing neutrons with the same properties (e.g., from high-density LEU-fueled reactors and/or a new generation of spallation sources) would compromise U.S. innovation capacity.

6. World-class neutron science and engineering require the comprehensive benefits of spallation facilities, research reactors, and high-performance instrumentation. While there is some overlap in the capabilities provided by spallation and reactor sources, each provides certain capabilities that cannot now be duplicated by the other type of source.

RECOMMENDATIONS:

1. The United States should continue to support its diversity of neutron R&D capabilities, including both research reactors and spallation sources, for scientific, engineering, and economic capacity and capability. Decisions regarding potential new neutron sources should be guided by the principle of reducing and ultimately eliminating the use of HEU while retaining or enhancing current neutron capabilities.

2. The United States should sharply increase its investments in neutron instrumentation development and deployment to partially compensate for the country's dramatic decrease in neutron R&D capacity and capability in recent decades; to offset any loss of capability arising from the elimination of HEU fuel from research reactors; and to complement continuing investments in complementary tools such as light sources and high-performance computing.

3. The United States should reaffirm its commitment to the timely development and deployment of high-density LEU fuels for use in existing high-performance research reactors. Any transition from HEU to LEU reactor fuel must not compromise neutron research and engineering capabilities, especially those that cannot be duplicated using spallation sources. The United States should also consider options to cost-effectively maintain reactor performance and simultaneously reduce HEU consumption while awaiting a suitable LEU fuel.

4. The United States should initiate an effort to competitively design and build a new generation of LEU-fueled high-performance research reactors that would satisfy all needs presently met by current HEU-fueled U.S. high-performance research reactors and provide new capabilities.

Introduction

Neutrons are essential, precious, and powerful. Their unique properties as a probe of the structure and dynamics of materials have led to numerous advances and discoveries in basic materials science and made them invaluable tools in industrial product development and manufacturing. They are vital to a number of scientific disciplines, including condensed matter and materials research, and nuclear physics. In addition, they are essential for materials irradiation testing and the production of materials, especially radioisotopes. Thus, neutrons not only enable scientific advances, but also are crucial to the development of applied technologies and other industrial uses important to the U.S. economy.

Neutrons for civilian scientific and engineering uses are generally produced in either spallation sources or research reactors. Research reactors provide a continuous stream of neutrons and are well suited for applications requiring a high "time-averaged flux." Spallation sources typically provide a pulse of neutrons, where instruments are optimized for applications requiring high "peak flux." These two types of sources are complementary in their scientific capabilities. Since neither alone is capable of providing neutrons with the properties to meet all needs, both are indispensable components of a vibrant infrastructure for frontier research and development (R&D).

Highly enriched uranium (HEU) fuel, which is defined as an enrichment of the uranium-235 (^{235}U) isotope to greater than 20%, is currently used in many of the highest performance research reactors.[3] Since HEU can be used as a nuclear explosive, it presents a nuclear proliferation risk. For decades, a goal of U.S. policy has been the worldwide reduction toward elimination of the civilian use of HEU.

HEU fuel is classified as a "direct-use material" by the International Atomic Energy Agency (IAEA), whereas low enriched uranium (LEU) fuel, with less than 20% uranium-235, is classified as an "indirect-use material" that cannot be used for "the manufacture of nuclear explosive devices without transmutation or further enrichment" [1]. Hence, the policy objective of reducing/eliminating proliferation risks gave rise to the goal of converting HEU-fueled reactors to LEU-fueled reactors.[4] However, while converting all research reactors to operate using LEU fuel would meet U.S. policy goals, it is not currently feasible to make this conversion and maintain the unique capabilities provided by existing facilities for critical scientific

---

3 For a list of all HEU-fueled reactors operating worldwide in 2016, see table 2.2 of ref. [2].

4 The goal of reducing the enrichment of uranium in civilian applications to 20% or less was established in the earliest years of the U.S. program to remove HEU from civilian applications around the world. An enrichment level of less than 20% was established as balancing overall proliferation concerns with the ability to continue important civilian programs [3]. That standard was soon adopted internationally, as well [4]. See also [5].

investigations and engineering applications. Those reactors that cannot be converted to LEU fuel without significantly degrading their capabilities are the high-performance research reactors discussed in this report. Therefore, there is a current challenge in meeting both the needs of the scientific and engineering communities and the U.S. policy goal to reduce proliferation risks.

Meeting both future U.S. R&D needs and policy goals requires decision makers and stakeholders to answer several important questions, including:

- What are the unique contributions of existing HEU-fueled reactors to the U.S. scientific enterprise, technology development, and industrial competitiveness?
- Can the use of HEU fuels in reactors be reduced or eliminated while preserving needed characteristics of neutrons produced by these reactors?
- What functions currently performed by research reactors can be assumed by spallation neutron sources?
- What complementary roles do spallation neutron sources and nuclear reactors play?
- What are the economics of various paths that can be taken to meet future U.S. needs for neutrons?
- What policies could contribute to a healthy, cost-effective, and safe neutron science enterprise in the United States?

This report considers these questions, describes the unique roles neutrons play in scientific and engineering endeavors, and discusses the neutron source characteristics that constitute a world-class R&D enterprise. This report also examines the need for investments in U.S.-based neutron sources in order for the United States to both remain globally competitive and to remove the proliferation threat of HEU-fueled neutron sources.

Why Neutrons?

1

Neutrons have unique properties that enable a number of critically important scientific investigations and engineering applications. Unlike X-rays and light, they only interact with the atomic nuclei in a material, which makes many dense materials nearly transparent to neutrons. For example, neutrons pass through titanium and aluminum easily such that water flow can be observed within fuel cells, lubricant flow can be imaged in engine blocks, and stress flaws can be observed in welded metals. Because of their large scattering cross section with hydrogen and especially deuterium, neutrons can reveal the interior structure of complex fluids, polymer nanocomposites, and biopharmaceuticals. The magnetic spin of neutrons enables scientists and engineers to measure the magnetic nanostructure of materials such as superconductors and magnetic storage devices. As a consequence of all these applications, sources of neutrons are used broadly by industry as well as researchers in many fields of science and engineering including hard condensed matter physics, soft matter physics, biology, and materials science. Neutron sources are also critical for answering fundamental science questions pertaining to the underlying structure and properties of the neutron and the subatomic structure of matter.

NEUTRONS FOR RESEARCH

Spanning the full breadth of neutron contributions to scientific research is beyond the scope of a short report; however, some examples presented here illustrate the range and depth of their impact. As a first example, research conducted using neutrons played a critical role in the discovery of giant magnetoresistance (GMR) by providing direct information on the role of interlayer coupling of ferromagnetic layers. This was critical to understanding the mechanism relating the dramatic changes in resistance with small changes in magnetic field. The discovery led to a Nobel Prize in Physics [6], rapid growth in the magnetic storage industry, and entirely new areas of exploration including spintronics.

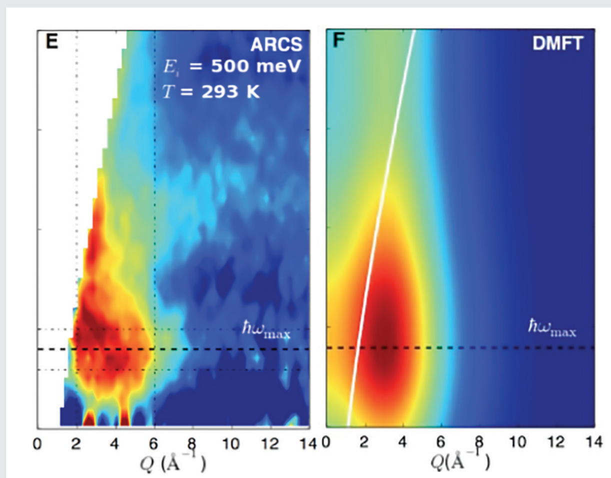
In materials research, neutron scattering has played a key role in understanding many of the fundamental concepts that enable the design and discovery of new materials and material properties. Neutron scattering helped to establish the reality of quantized collective excitations, such as phonons and magnons, as well as the idea of broken symmetry in phase transitions. Due to the sensitivity of neutron scattering to both magnetic and lattice degrees of freedom, studies involving neutrons have underpinned our understanding of the role of magnetism in quantum materials used in high temperature superconductors, the emergence of quantum states from specific structures, and the relationship between magnetism and heat transport.

Neutron scattering experiments made it possible for scientists to solve the puzzle of the missing magnetism in plutonium (*see inset 1*). Neutrons also enable determination of the atomic structure and vibrational modes of novel materials, essential for connecting structure to functionality. For example, in 2008, researchers in China and Japan discovered a new and completely unexpected family of high-temperature superconductors. Research at U.S. neutron facilities contributed to elucidating the microscopic magnetic properties of these new superconductors, thereby giving the United States a leading role in this emerging field.

INSET 1
SOLVING THE MYSTERY OF MISSING MAGNETISM

Inelastic neutron scattering experiments enabled researchers to solve the decades' old puzzle of the missing magnetism in plutonium and hence the large sensitivity of its volume to small changes in temperature and pressure. Elemental plutonium is the most electronically complex of any element in the periodic table and has defied understanding for well over seven decades. This complexity arises because its 5f electrons cannot be described as being either localized (magnetic) or itinerant and nonmagnetic. Because of this electronic complexity, plutonium adopts six different phases, with the large-volume, face-centered cubic δ-phase being important for national security.

Conventional electronic structure calculations that predict the correct atomic volume of δ-Pu do not predict the correct magnetism from the 5f electrons. However, recent dynamical mean-field theory (DMFT) electronic calculations suggested a subtle quantum-mechanical superposition of electronic configurations that gives rise to magnetic fluctuations. Inelastic neutron scattering experiments were the only way to definitively test these predictions. Indeed, neutron scattering measurements [7] found a large magnetic moment of $0.8\mu_B$/Pu that fluctuates on a characteristic time scale of 0.015 psec. This discovery of evidence for valence fluctuations and associated magnetic fluctuations in δ-Pu resolves a long-standing controversy over an appropriate description of Pu's 5f electrons and provides an explanation for the large sensitivity of plutonium's volume to small changes in temperature, pressure, and alloying.



Left image: Measured energy- and momentum-dependent magnetic scattering in δ-Pu. *Right image*: DMFT-calculated magnetic scattering that accounts for dynamic fluctuations in $5f^4$ and $5f^5$ configurations. From [7].

Inelastic neutron scattering experiments have been vital to the development of thermoelectric materials, which are used broadly for converting heat to electricity and vice versa, allowing for an understanding of a material's thermal conductivity via measurements of phonon dispersion (*see inset 2*).

The study of fundamental properties of the neutron at neutron sources is critical to our understanding of the fundamental laws of nature. These include searches for an electric dipole moment of the neutron, measurements of the neutron lifetime, and the search for matter-antimatter oscillation in the form of neutrons oscillating to antineutrons [8]. Furthermore, the study of neutron cross-sections yields important quantitative understanding of nuclear fission reactions.

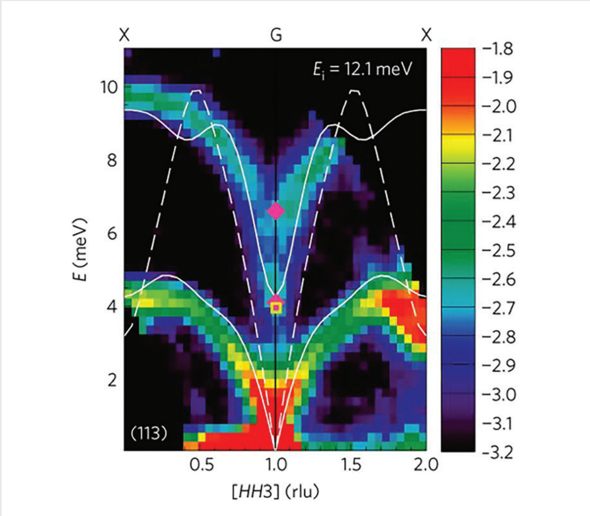


Figure: Anomalous features of phonon dispersions observed for PbTe at 300 K. From ref. [9].

Neutrons have also been essential to the modern scientific exploration of nanomaterials, soft matter, and biological systems because they enable isotopic labeling [10], which provides critical information for structure determinations and enables study of chemical and mass exchange kinetics. Neutrons can also be used to access the relevant length and time scales that govern the structure and properties of such materials. They are most powerful when used as part of a larger study that combines them with other radiation sources (e.g., X-rays and light), as well as direct imaging (optical and electron microscopy), and high-performance computing for simulation and data processing. Neutrons are an essential "eye" into the nanoscale world; they can penetrate deep into soft materials, such as polymers, proteins, colloids, and nanoparticles, as well as biological systems, to resolve the atomic-to-nano-to-mesoscale structure nondestructively.

Neutron scattering can be used to probe the microstructure of thermoelastic polymers, while the material is deformed mechanically (*see inset 3*). Such measurements are needed to design new materials with improved mechanical response.

Importantly, the examples presented above all involve the use of multiple measurements and/or computational methods to obtain a more complete picture of the phenomena being investigated. Neutrons complementary yet essential role is highlighted in many of the examples of the research described in the insets of this report. This multi-pronged approach is a key aspect of forefront condensed matter and materials research.

INSET 2

UNDERSTANDING HEAT CONDUCTION AT THE MICROSCOPIC LEVEL

Understanding thermal conductivity is important in various energy-related technologies from building insulation, to heat exchangers, to nuclear reactor fuels. Modern inelastic neutron scattering instruments enable a microscopic view of thermal conductivity via measurements of phonon dispersions and lifetimes over a full Brillouin zone. Thermoelectric materials, which require low thermal conductivity, offer great potential for superior energy efficient devices. For example, measurements in PbTe revealed a giant anharmonic coupling between a "ferroelectric" optic mode and longitudinal acoustic mode, explaining the low thermal conductivity of PbTe, and more generally why many good thermoelectric materials occur near ferroelectric lattice instabilities [9].

This example illustrates also the critical importance of recent progress in instrumentation (here: time-of-flight spectrometers) and also the catalyzing role of computational progress to enable direct comparisons of theory with experiment, which enabled the discovery.

INSET 3

MEASURING MOLECULAR REARRANGEMENT IN MICROSCOPIC BENDING OF POLYMERS

Elastomers' mechanical properties are greatly influenced by their microstructural features, e.g., cross-link density, type of crosslinking (physical or chemical), concentration and morphology of hard domains and/or nanofillers. Therefore, engineering new elastomers with improved properties requires deep understanding of the interrelations between mechanical response and microstructure evolution during deformation. To achieve this, in-situ nanostructure probes integrated with mechanical probes are needed. This can be accomplished by a combination of small-angle neutron scattering (SANS), as the microstructure probe, along with an extensional rheometer that provides uniaxial deformation and measures the stress response from the sample.

Such in-situ tensile-SANS measurements were performed on thermoplastic elastomers consisting of ABA-type triblock copolymers with styrenic end blocks and a rubbery middle block, specifically sphere-forming blends of a styrene-isoprene-styrene (SIS) block copolymer with a low molecular weight deuterated polystyrene (dPS) [11]. The Figure shows the stress-strain curve of the SIS/dPS blend measured in the rheometer, along with the 2D SANS profiles measured during the deformation. The initially isotropic circular profile becomes elliptical in the elastic and yield regimes, which indicates that the lattice is extended in the stretching direction and compressed in the transverse direction.

An important new quadrulobe microstructural feature was observed at high elongations, which originates from the rearrangement of the glassy spheres into strings that orient into preferential angles inclined towards the stretching direction. Further, this technique revealed that strain-hardening, hysteresis, permanent set, as well as the affine to non-affine deformation transition are the result of rearrangement in the nanostructure of the sphere-forming block copolymer thermoplastic elastomers.

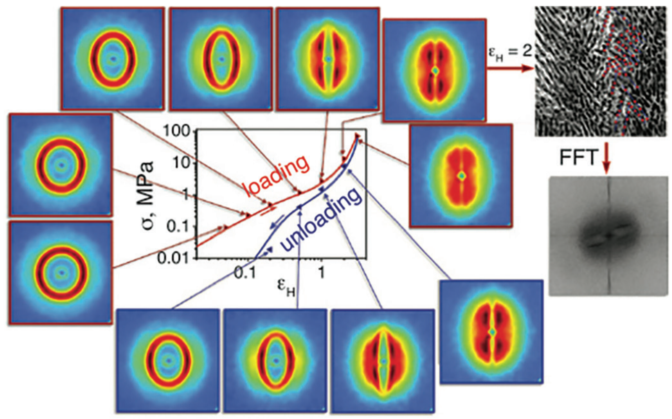


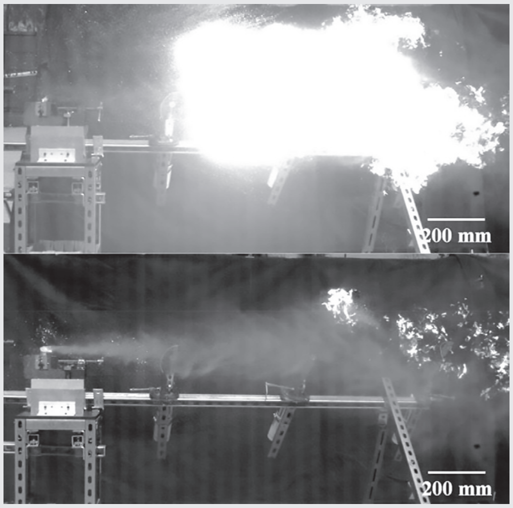
Figure: The stress-strain curve of the SIS/dPS blend measured in the rheometer, along with the 2D SANS profiles measured during the deformation. From ref. [11].

NEUTRONS FOR INDUSTRY AND MEDICINE

Intense sources of neutrons are used to produce medical isotopes. The medical community is the largest consumer of radioisotopes, especially for diagnostic purposes. The dominant radioisotope is an isotope of technetium, over 95 percent of which is produced through neutron irradiation in an HEU-fueled high-performance reactor. Worldwide, more than 30 million patients annually benefit from diagnostics based on this radioisotope [12].

Neutrons played a key role in resolving the challenge to design and synthesize a new jet fuel additive that prevents the fluid from becoming a flammable mist upon impact, while still maintaining performance and efficacy (*see inset 4*). The design and synthesis invoked a multi-pronged approach, and the characterization of the resulting material required multiple techniques—including structural measurements using small-angle neutron scattering—in order to verify that the synthesized material met the design criteria.

In addition to serving as a probe of the structure and properties of matter, intense sources of neutrons are also useful for modifying and testing materials. Irradiation of a material with a very high neutron flux is important for inducing radioactivity, introducing radiation damage, and irradiation testing of proposed nuclear fuel designs (*see inset 5*). All nuclear power plants make use of fuel that was developed, tested, and qualified in the neutron irradiation environments produced by research reactors. A handful of reactors around the world provide this service, which also enables capability for much of the $300B semiconductor industry.



Still frames captured from high-speed video showing the flammability of a sheared mixture of jet fuel with (top frame) a commercial anti-misting agent (ultralong polymer polyisobutylene), and with (bottom frame) an anti-misting agent based on megasupramolecules. In both cases, the mixtures were subjected to a high-speed impact and attempts were made to ignite the resulting spray. From ref. [13].

INSET 4
SAFER JET FUEL

Designing and synthesizing materials fit for a specific purpose is a key goal of materials science and engineering. Scientists have successfully synthesized a new material based on self-assembling “megasupramolecules” that demonstrate a remarkable ability to prevent misting in fluids such as jet fuel that have been subjected to large impact and can contend with the harsh shearing environment experienced in the fuel injection process [13]. The secret to the additive’s effectiveness is that these megasupramolecules are composed of ultra-long polymers which have end associations enabling them to self-assemble after breaking apart, mitigating the destructive effect of shear.

Successfully designing, synthesizing, characterizing, and verifying the desired functional properties was an investigative tour-de-force. In addition to small angle neutron scattering measurements, success required a number of other powerful investigatory methods including theoretical statistical mechanics, computational methods, light scattering, nuclear magnetic resonance, rheology, and materials synthesis in order to develop this material. The neutron measurements ensured that the end associations of the ultra-long polymers were suitable to prevent the additive chains from collapsing—crucial knowledge that could only be measured using neutron methods.

U.S. industry relies on neutron scattering and imaging for discovery, development, and processing of superior materials. These include semi-crystalline polyethylene [14] polymers with branched topologies [15], filled elastomers (*see inset 3*), paints and coatings [16], and a variety of commonly used consumer products [17]. The biopharmaceutical industry utilizes the unique capabilities of neutron scattering to develop stable formulations for improved drug delivery [18, 19] and improvements in drug processing and formulation [20, 21]. The oil and gas industries employ neutron scattering to improve enhanced oil recovery [22] and methods of shale gas production [23]. Fuel cell development has been greatly accelerated by the unique capabilities of in situ neutron imaging [24], as well as the development of high-performance turbine blades [25] and detecting corrosion in aluminum aircraft components [26]. In the United States, the Shull Wollan Center, a Joint Institute for Neutron Sciences [27], provides a gateway for U.S. industry to use the High Flux Isotope Reactor (HFIR)/Spallation Neutron Source (SNS). Additionally, the n-SOFT consortium at the NIST Center for Neutron Research (NCNR) enables U.S.-based manufacturers to access neutron tools to solve manufacturing challenges [28], and the LANSCE accelerator at Los Alamos provides a test-bed for semiconductor irradiation damage used by many aerospace and computing companies [29]. These U.S.-based consortia have European [30] and Japanese counterparts [31], further demonstrating the importance of neutron research facilities to international industrial competitiveness.

INSET 5
THE ROLE OF RESEARCH REACTORS IN DEVELOPING PROLIFERATION-RESISTANT REACTOR FUEL

The research, development, and qualification of proliferation-resistant low-enriched uranium (LEU) fuel for high-performance research reactors requires a type of reactor known as a materials test reactor. Candidate fuel materials, as well as full-scale fuel elements and assemblies are irradiated in environments that closely mimic the conditions the fuel will experience during use. Significant radiation doses must be delivered over large areas in a relatively short time to allow timely determination of fuel performance, lifetime, and limits of safe operating conditions. Only research reactors can meet these requirements. Even in a research reactor, the time required to irradiate a test fuel assembly for a single test can take 6–12 months. The most closely equivalent test in an accelerator-based system would take many times longer.

Materials often undergo significant, sometimes catastrophic changes during irradiation. They can experience swelling, transformation into unstable forms, creep, and degradation of mechanical properties.

Substituting LEU fuel in an existing research reactor requires a much higher density (up to a factor of 5 or so) of uranium in the fuel in order to maintain the same or even greater amount of the fissionable ^{235}U in the fuel in the same volume. Such a dramatic increase in the amount of uranium in the same volume means that an entirely new type of fuel must be developed—either so-called "monolithic" fuel or high-density dispersion fuel, both using an alloy of uranium and molybdenum. The fuel "meat" must be clad with additional materials in order to ensure safe and sustained operation. The entire fuel element package must retain mechanical, geometric, and hermetic integrity throughout its use in the extreme environment of the reactor.

Testing under reactor conditions is critical to identify and qualify any fuel, and particularly one that differs so significantly from previously developed fuels. The figure (modified fig. 21 from Ref. [32], to highlight features of interest) shows the development of blisters and delamination in a test monolithic fuel assembly irradiated under conditions beyond those expected in a high-performance research reactor. Understanding the conditions that give rise to such features is essential if safe and proliferation-resistant fuels are to be available for current and future high-performance research reactors.

As we see from these many applications of neutron sources, HEU-fueled research reactors serve the dual purposes of providing crucial high-flux neutron sources that currently cannot be generated by any other means, and they contribute to overall neutron science capacity, which is being increasingly squeezed and oversubscribed. Increasing capacity through advances in instrumentation at existing facilities and developing new sources that do not require HEU fuel to achieve similar performance are two of the themes discussed below with the goal of reducing reliance on HEU fuel.

KEY FINDING 1

Investigations performed at neutron sources are essential components of R&D in numerous areas of science and engineering.

KEY FINDING 2

Neutron scattering is often an essential part of a broader experimental study that uses a complementary suite of tools (e.g., light sources, high-performance computers). Thus, neutron sources play a key role in overall U.S. innovation capacity.

The Neutron Facilities Landscape

2

Given the large variety of uses for neutrons, with the different characteristics required by each, it is not surprising that a spectrum of facilities is needed to meet all needs. Countries with strong neutron-based R&D typically host a variety of neutron sources—from small sources based at universities or smaller research institutes catering to local and regional needs, to state-of-the-art reactors and spallation sources that attract users from around the world. As with other R&D capabilities such as light sources and high-performance computer centers, a combination of facilities that provides diverse and complementary capabilities is most effective.

WORLDWIDE NEUTRON SCATTERING FACILITIES

As a matter of international scientific and economic competitiveness, it is useful to compare the U.S. facilities with those available overseas. Though a detailed technical comparison of specific neutron measurement capabilities is beyond the scope of this report, we can draw some reasonable conclusions using available facility data.

EUROPEAN FACILITIES

Europe has dominated neutron scattering science in recent decades as measured by capabilities, capacity to support users, and scientific output. European laboratories operate two world-class facilities: the Institut Laue-Langevin (ILL) in France and the ISIS Neutron and Muon Source in the United Kingdom. A third facility, the Swiss Spallation Neutron Source (SINQ) at the Paul Scherrer Institut (PSI) near Zurich, provides a continuous source of neutrons that was the world's first spallation source to operate in excess of 1 MW for a proton beam on a liquid metal target. ISIS was upgraded with a second target station that began operation in 2008, and the United Kingdom is considering an additional major upgrade of ISIS to MW-class operation in a short pulse mode. In addition to the ILL, ISIS, and SINQ, a network of other sources—both reactors and spallation sources—provide for the health of the European neutron scattering ecosystem [2]. One example is the 20 MW FRM II research reactor at the Technical University of Munich that began operation in 2005 and features cold neutron (<0.025 eV energy) flux comparable to that of ILL. FRM II operates 22 neutron scattering instruments with four more scattering instruments currently under construction [33].

The European Union is now constructing what will be the world's highest power spallation source, the 5 MW European Spallation Source (ESS) in Lund, Sweden. The ESS will be co-located with the groundbreaking, diffraction-limited, synchrotron radiation source MAX-IV. In 2014, PSI officially started the SINQ upgrade project to deliver a significant increase in instrument performance and to evaluate all integral parts of SINQ for their upgrade potential. ISIS is building out instrument capacity at its second target station, and ILL is in the middle of a 60 M€ upgrade program.

Europe has taken a strategic look [2] at its future capabilities in neutron scattering for the coming era in which the ESS is projected to be the world's leading facility for neutron research. In developing its strategic plan it recognized various challenges: 1) intense competition for European research funds, 2) limited availability of funds from European members of the ESS necessary to construct a major international neutron user facility with a commensurate budget for operations, and 3) an aging fleet of neutron sources. With respect to the aging fleet, it is projected that the majority of operating neutron sources in Europe constructed in the 1960s and 1970s are likely to close within the next decade [2]. The highly productive reactor-based sources, Orphée in Saclay and BER-II in Berlin, are scheduled to cease operations in the next few years. A special concern regarding such closures, as noted by the *European Strategy Forum on Research Infrastructures* (ESFRI), is the important role that the network of neutron facilities—not just the flagship-class facilities—has played in the overall health of the European scientific community.

ASIA-OCEANIA FACILITIES

The Asia-Oceania region has hosted significant recent neutron facility developments. Over the past decade, new major neutron sources have been built in both China and Japan. The China Advanced Research Reactor (CARR) is a 60 MW LEU reactor located outside of Beijing. It was commissioned with nine scattering instruments, although it is not yet in routine operation. The China Mianyang Research Reactor (CMRR) is a 20 MW LEU reactor located at Mianyang in Szechuan Province that began operations in 2013. It operates routinely with eight scattering instruments and two imaging instruments. The Chinese Spallation Neutron Source (CSNS) is a 120 kW spallation source located at Dongguan in Guandong Province. The CSNS produced its first neutrons on August 28, 2017 and is expected to commence regular operations in 2018. It has capacity for 18 beam instruments although only three are currently funded [34].

The most important new neutron source in Japan is the Japan Proton Accelerator Research Complex (J-PARC), located in Tokai. J-PARC has a dual programmatic functionality: powering the Japan Spallation Neutron Source (JSNS) for neutron physics and providing a powerful source of neutrinos for a world-class program in high-energy physics. JSNS started operation in 2008, but the Great East Japan Earthquake (March 2011) and a Hadron Facility accident interrupted operations. During 2017, JSNS has been operating at ~160 kW (similar to ISIS) on target, although operation at its design level of 1 MW operation is foreseen. JSNS is designed with 23 beam ports; 17 scattering instruments are presently available to outside users.

Australia's OPAL reactor is a 20 MW LEU-fueled light-water-moderated reactor that serves 12 scattering instruments and one imaging instrument. It came on line in 2006 and provides for in-core irradiations, as well as commercial production of isotopes for medicine and other needs.

Another noteworthy neutron source is the pulsed, fast reactor IBR-2 at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. IBR-2 hosts 13 scattering instruments that perform 150 experiments annually, mostly in condensed matter physics and biophysics.

MAP

MAJOR NEUTRON SCATTERING FACILITIES WORLDWIDE

Map of the major neutron scattering facilities worldwide and the number of neutron scattering and imaging instruments from each region in 2017 [37]. A major neutron scattering facility is defined in this report as having eight or more beam instruments and a thermal power of 10 MW or more if the source is reactor based. Pins ( ) denote reactor-based facilities and stars (★) represent spallation neutron sources. Green, orange, and red symbols represent facilities that are currently operational, under construction, and not operational at present, respectively.

U.S. FACILITIES

In contrast with other parts of the world, the United States has not benefited from a similar, vibrant network of smaller neutron facilities that contribute to overall national scientific productivity. The peak of U.S. capacity (based on number of neutron scattering instruments) occurred in 1996, when there were 55 scattering instruments available at the nation's major facilities. The last 20 years have seen a net decrease in this capacity, with some fluctuations, as the United States ceased operations at neutron facilities such as the HFBR (High Flux Beam Reactor), IPNS (Intense Pulsed Neutron Source), and the BES (Basic Energy Sciences program of the Department of Energy) user program at the Lujan Center. No high-performance research reactor has been commissioned in the United States since 1969, a period of nearly 50 years. On a positive note, the world-leading SNS was constructed at Oak Ridge National Laboratory (ORNL) and commenced operations in 2006. In addition, the National Institute of Standards and Technology (NIST) Center for Neutron Research, with its National Bureau of Standards Reactor (NBSR), has enjoyed a significant expansion of its cold neutron capacity and capability.

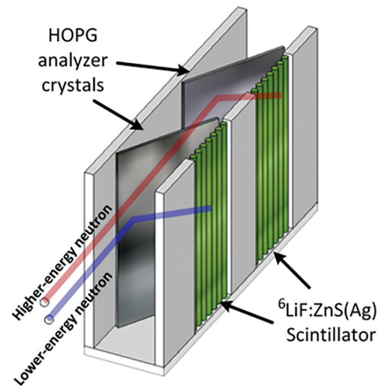
The net result of these developments over the last ten years is that the U.S. capacity has grown back to 45 scattering instruments (plus three imaging instruments); nevertheless, it is well below the peak U.S capacity of over 20 years ago. This has led to oversubscription rates in recent years of a factor of ~2–3 at facilities of NIST [35] and ORNL [36].

INSET 6
A REVOLUTION IN NEUTRON SCATTERING

Progress in neutron scattering science is the result of developments in neutron source technology, advances in instrumentation, ancillary equipment and materials synthesis. Arguably most of the progress in the last two decades has been due to advances in neutron instrumentation and the ingenuity of instrument builders. Consider for example that the performance of the triple-axis spectrometer, invented in the 1950s [39], has improved approximately 4 orders of magnitude (data rate) since its invention [40]. Instrument performance improvements as measured by increases in data rates have been due to advances in neutron optics and improvements in solid angle coverage of neutron detectors. See the accompanying figure and caption for an example.

To make optimal use of the neutrons produced by the source, the neutrons are now transported to the instruments via a highly efficient system of (low-loss) neutron guides, including additional beam-conditioning optical devices such as converging guides, choppers, and/or lenses that have been tailored to provide beam characteristics that matches instrument requirements. Modern scattering instruments at reactor sources can be equipped with large double-focusing monochromators that capture and focus large monochromatic neutron beams towards the sample position. The back end of a scattering instrument is often equipped with large analyzer and detector systems that can capture a significant fraction of a solid angle of the scattered neutrons.

The results of these improvements are evident in the science being performed. For example, inelastic neutron- scattering measurements had been limited in application due to low data rates for systems with small cross-sections of inelastic features. This situation has improved dramatically. The performance improvements described above now make it routine to measure things that just two decades ago could only be performed in very special and limited circumstances: measuring spectral features of systems with small magnetic moments, determining the magnetic structure of a single atomic layer in a buried interface, measuring thickness fluctuations in a biomembrane, and collecting vibrational spectra in a minute. Simply put, advances in instrumentation have revolutionized the window on the world accessible to the scientific community.



Schematic illustration of a new energy-dispersive neutron detector for use in an advanced neutron reflectometer on a reactor-based neutron source. In this instrument a polychromatic neutron beam is reflected from a sample and the energy-dispersive detector selects many different reflected wavelengths simultaneously, thus resulting in significantly higher data rates than on a conventional reactor-based reflectometer.

The scientific productivity of a facility, as measured by peer-reviewed publications (especially high-impact publications), depends on the number of high-quality neutron instruments available. Generally, the number of users and proposals to use the facility are also correlated with the number of instruments available [38]. In the last 40 years, the neutron measurement capacity of the U.S. facilities has declined, failing to keep pace with the capability and capacity of both Europe and the Asia-Oceania region.

Nevertheless, the United States has significant capabilities. Major neutron scattering facilities at ORNL and NIST are essential elements of the U.S. research enterprise. The SNS at ORNL provides intense pulsed neutron beams, and the reactor-based sources at NIST and ORNL provide high-flux continuous beams of neutrons. Decades of operating experience with neutron science facilities has shown that the most important aspects of a neutron source are flux, signal-to-noise ratio, availability, reliability, capacity for instrumented beamlines, and cost-effectiveness. Though flux is mentioned first, it is important to note that neutron source improvements have been evolutionary, not revolutionary. As neutron flux is closely related to the power density in the source, the primary obstacle to subsequent revolutionary advances in source development is the removal of heat, whether neutrons are produced through spallation or fission. Therefore, advances in neutron instrumentation related to neutron optics, detectors, and devices (*see inset 6*) have driven the progress of the scientific capabilities of neutron sources over the past two decades. Though the importance of a world-leading neutron source should not be underestimated, the global competitiveness of the ORNL and NIST neutron facilities is attributed largely to the continual development of technologies that support new, advanced neutron instruments.

Though no plans for new U.S. facilities have received construction funding, ORNL has proposed a second target station for the SNS and has received some funding for conceptual design. In addition, a preliminary conceptual design effort is underway at NIST for an LEU-fueled, reactor-based neutron science facility that could replace the existing reactor source.

In summary, considering all major facilities, the United States currently has about one-third of the neutron scattering instruments of Europe and one-half those of the Asia-Oceania region.

WORLDWIDE NEUTRON IRRADIATION FACILITIES

At present, nuclear reactors are capable of producing much higher continuous radiation environments than spallation sources. Therefore, facilities specializing in producing the highest neutron irradiation environments all have a nuclear reactor as their centerpiece. The neutron fluxes in the highest performance facilities are used for materials irradiation needs, including materials testing in neutron environments, isotope production, and transmutation for analytical and other needs. The reactors used for these purposes are called "irradiation facilities." They tend to have very compact cores to maximize peak power densities and peak neutron fluxes. The most powerful of these reactors are found in the United States, Russia, and Europe.

There are four high-performance reactors in the United States that have significant irradiation capability, all of which operate on HEU fuel to achieve the fluxes needed. The HFIR at ORNL is now used primarily for neutron scattering, though it was originally constructed for the production of heavy transuranic isotopes requiring multiple neutron captures, for example, Californium-252 (^{252}Cf).[5] It is still the only reactor outside of Russia to efficiently produce such isotopes.

The Advanced Test Reactor (ATR) at Idaho National Laboratory is the only U.S. research reactor capable of providing large-volume, high-flux neutron irradiation in a prototype environment. This capability is particularly useful for studying the effects of intense neutron and gamma radiation on reactor materials and fuels. ATR was specifically designed for in-core irradiation to test the performance of materials under naval reactor conditions. However, since 2007, approximately 50 percent of the irradiation positions in ATR have been made available for civilian use as part of a national science user facility for broader materials testing applications.

5 Californium-252 is essential for the start-up of nuclear reactors by the navy, in detectors of hazardous materials by the U.S. Customs and Border Control, Homeland Security, and the U.S. Armed Forces, and oil and gas exploration, among other critical uses.

The MIT Research Reactor (MITR-II) is used primarily for the investigation of advanced materials, fuel, and instrumented irradiation tests using in-core experimental facilities. The University of Missouri Research Reactor (MURR) is specifically designed for in-core irradiation. While the reactor still performs this mission, its focus has shifted to medical isotope production in recent years.

The most significant materials irradiation capabilities in Russia (SM-3 and MIR. M1) are at the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad. SM-3 is designed primarily for the production of heavy transuranic elements (this is the Russian source of ^{252}Cf), but its mission has expanded to include the production of isotopes with high specific activity and to test materials. The MIR.M1 is also located in RIAR and is mainly used to test materials.

There are two operating high-performance reactors in Europe with a significant role in materials testing and irradiation. The Belgian Reactor 2 (BR2) focuses primarily on in-core irradiation experiments, with focus on radiation damage of materials and accelerated testing of materials for nuclear energy applications. It is also used for radioisotope production. Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II reactor (FRM-II) in Garching, Germany hosts five irradiation facilities and a medical application facility, in addition to neutron beam capabilities. Other operating reactors in Europe, for example, the High Flux Reactor (HFR) in the Netherlands, also produce intense irradiation environments, but they are dedicated to purposes such as production of medical isotopes and do not support as much R&D. The Jules Horowitz Reactor (JHR) is under construction at CEA Cadarache and is scheduled to begin operations in 2020. The mission of JHR will be material and fuel testing as well as radionuclide production for medical applications.

KEY FINDING 3

The United States has lost important capability in neutron R&D in the last two decades and is no longer the world leader. The United States cannot afford to lose its remaining capacity and capability without significant detriment to the quality and quantity of science, engineering, and even medical and manufacturing processes that rely on neutron sources.

Reactors and Spallation Sources: Challenges and Opportunities

3

As discussed in Section 1 of this report, neutrons are essential to science and engineering, especially materials research, nuclear physics, isotope production, and materials irradiation testing. Neutron sources not only lead to scientific advances and discoveries, but are also essential to the development of applied technologies and industrial uses. Thus, the availability of a diverse suite of neutron sources is a measure of scientific competitiveness and economic vitality for a country. As Section 2 indicates, there are threats to U.S. competitiveness in neutron science that should motivate enhancement of the nation's neutron capabilities.

Today, neutrons for civilian scientific and engineering use are produced in research reactors and spallation sources. Research reactors have at their heart a nuclear chain reaction in which neutrons induce nuclear fission of a radioactive element (usually uranium), producing neutrons that both propagate the reaction and are available for the uses discussed in this report. Spallation sources are accelerator facilities, rather than nuclear facilities. Here, bombarding a heavy metal target, such as tungsten or mercury, with an accelerator-produced beam of protons produces neutrons.

As discussed in the introduction, research reactors and spallation sources have relative advantages with respect to each other depending on the desired source attributes for a particular problem or challenge. The commencement of full operation of the European Spallation Source (ESS), planned for the middle of the 2020s, will be the dawn of a new era, in which a spallation source will produce roughly the same average neutron flux as today's most powerful research reactor. At that time, the relative merits of the two types of neutron sources for scattering experiments may shift. Even then, the needed capacity of facilities to support large quantities of neutron scattering work is likely to require the continued availability of scattering stations at research reactors. A research reactor can provide neutrons for up to 50 neutron scattering stations, whereas a pulsed spallation facility is limited in practice to about 20 such stations.

RESEARCH REACTORS

Research reactors are the facilities of choice for the irradiation of materials and isotope production. Both are typically performed in the core of the reactor at locations where the neutron flux (#neutrons/cm^2-s) is high and the spectrum (neutron energy) is appropriate for the specific phenomenon being studied. Other uses depend on beams of “slow” neutrons (energy ~ 1–10 eV) extracted from the reactor through beam tubes to an experimental station where they are used as a probe to study fundamental properties of materials; spallation sources are also suitable for many beam studies. Since neutron flux levels are directly proportional to the reactor power density, high-performance research reactors (HPRRs) are needed to provide sufficiently intense neutron fluxes for many applications, particularly material irradiation and fuel testing, isotope production, and multiple simultaneous extracted beam applications.

Because of their use of enriched radioactive material, research reactors are nuclear facilities, which brings a particularly high level of rigor to their design, licensing, construction, and operation. Nearly all of the HPRRs in operation today, including five in the United States (ATR, HFIR, MITR, MURR, and NBSR) operate using HEU fuel.

Minimization, and ultimately elimination, of HEU in civilian uses worldwide, including in research reactors, has been a goal of U.S. policies and programs since 1978, resulting in the conversion of many civilian reactors to LEU fuel usage and the shutdown of others [41]. The HPRRs operating in the United States were constructed before the decision to move away from use of HEU in civilian applications. These reactors continue to operate using HEU fuel because they either cannot operate at all or would experience very significant degradation in performance with any currently available LEU fuel. While R&D efforts to develop and certify a suitable LEU fuel are ongoing, current projections state that a suitable fuel will not be available until 2028 or later and that these reactors will not be converted to LEU until the mid-2030s at the earliest.

KEY FINDING 4:

Reactor fuels containing highly enriched uranium represent a risk for proliferation, which should be considered when planning for the future infrastructure for neutron R&D.

Despite the extremely long delays and technical difficulties in transitioning the remaining HPRRs from HEU to LEU, a continuing research opportunity exists to design LEU fuels with characteristics that enable HPRRs to be retrofitted to operate with LEU fuel at a level that replicates most, if not all, of their HEU-fueled performance. While such efforts have been initiated in the United States and abroad [42], these efforts have encountered both unanticipated technical challenges and insufficient financial and political support to make rapid progress. To accelerate progress, increased investments in the research, development, and manufacturing of suitable LEU fuel are required, as are incentives to motivate individual research reactors to convert to LEU. One should also take note of the important role of existing research reactors in the development of proliferation-resistant reactor fuel (*see inset 5*).

KEY FINDING 5:

Current HEU-fueled research reactors provide unique R&D capabilities relative to other neutron sources available today. Eliminating them without developing and deploying alternative methods of producing neutrons with the same properties (e.g., from high-density LEU-fueled reactors and/or a new generation of spallation sources) would compromise U.S. innovation capacity.

Given the long lead time to either develop and qualify LEU fuel for existing research reactors or to build new reactors that are designed to operate on LEU, a National Academies study suggested the possibility of converting existing HPRRs to a currently qualified fuel enriched to a level between LEU (<20% enrichment) and the ninety-three percent enrichment in use today [41]. Such a step would only be taken as an intermediate one between the current situation and the final state of full elimination of HEU usage. It would have the advantage of lowering the level of enrichment, and hence the risk of proliferation, at least one decade sooner than full LEU conversion is expected to occur. The primary disadvantage is the need for two conversions, which would bring associated costs and regulatory requirements. Nevertheless, given the timeline for conversion of these reactors to LEU fuel, which has expanded by 17 years since 2009 (from target 2018 to current target 2035 for full conversion), it would be prudent to investigate whether or not such intermediate conversions can be done cost effectively.

SPALLATION SOURCES

Spallation sources are an attractive alternative to reactors as sources of neutrons, in particular because they do not require HEU fuel to produce neutrons. Techniques to exploit their capabilities as time-dependent neutron sources have been developed, yielding important scientific results at the SNS as well as at other international spallation neutron sources. Because nuclear material is not used, the waste footprint and proliferation risk of a spallation source are qualitatively different than those of a reactor source. On the other hand, as discussed in the economics section below, maintenance and operations costs can be higher because a working accelerator is required to produce the neutrons and the heavy-metal target needs to be replaced on a regular basis.

The structure of data from spallation sources is very complex due to the time dependence of their neutron scattering spectra. The advent of advanced computing and data analytics methods has been a boon to the interpretation of such data and creates greater opportunity for spallation sources to increase their impact on neutron-based science and engineering. Over time, spallation sources are likely to fulfill an increasing percentage of the need for neutrons.

KEY FINDING 6:

World-class neutron science and engineering require the comprehensive benefits of spallation facilities, research reactors, and high-performance instrumentation. While there is some overlap in the capabilities provided by spallation and reactor sources, each provides certain capabilities that cannot now be duplicated by the other type of source.

COSTS OF NEUTRON SOURCES AND SOCIETAL BENEFITS

The costs of HPRRs and spallation neutron sources accrue in somewhat different ways. The total cost of owning and operating a research reactor includes the initial investment, the annual costs of the fuel and of the non-fuel operation and maintenance (O&M), regulatory costs associated with designing, constructing, and operating a nuclear facility, and the cost of decommissioning after the facility has ceased operations. Spallation sources without subcritical multipliers do not have the fuel cost (including the cost of disposal of spent fuel) but do have the additional costs of the electricity to power the accelerator and of periodically replacing the target. The sophistication and limited lifetime of targets mean that the target cost is significant [43]. They do not experience, however, the level of regulation associated with nuclear reactor facilities. The cost of operating the instrumentation for the users and of conducting experiments depends on the type of applications and instrumentation provided to the users and is not directly attributable to the type of neutron source.

Fuel Costs. Reactor fuel costs include the cost of natural uranium, its enrichment, and its manufacture into a fuel assembly. These costs are substantially higher for a kg of HEU fuel relative to a kg of LEU fuel. However, high-density LEU fuels require a factor of five or more uranium per unit volume than HEU fuel. The cost of achieving this higher density in LEU fuels partially cancels the cost saving of not having to enrich to HEU levels. The cost difference may narrow further since the manufacturing complexity for high-density LEU fuels is likely to be more complicated than for low uranium density HEU fuel, due to the greater challenge of preserving fuel integrity of the higher uranium content LEU during reactor irradiation.

In summary, while the actual fuel cost differential can only be determined after detailed analysis of the manufacturing cost of advanced fuels, including learning effects, it is likely that the overall fuel cost will be higher with LEU fuel than with HEU fuel, at least initially. If the manufacturing process of LEU fuel achieves a similar level of mastery as that of today's HEU fuel, the cost of LEU fabrication is likely to be similar, or even slightly lower, to that of HEU fuel in the future due to the lower criticality control challenges and lower requirement for safeguards for LEU fuels as compared to HEU fuel.

Capital Costs. Comparing the capital costs of new research reactors and of new spallation neutron sources, it appears that, based on the limited information on construction costs publicly available for a number of recently constructed facilities, state-of-the-art spallation sources are roughly a factor of two more expensive to construct than the most capable reactors. For example, publicly available information on the European Spallation Source (ESS) under construction in Lund, Sweden [2] put the total construction cost at €1.85 billion (i.e., approximately $2.1 billion) for the source itself (no beamlines or instrumentation), with an operational date for the facility of 2019. Costs of a similar order of magnitude were reported for the ORNL Spallation Neutron Source (SNS), at $1.4 billion, completed in 2006 [44]. On the other hand, the PALLAS reactor, under construction at Petten in the Netherlands, is expected to cost €600 million (i.e., approximately $680 million) [45]. Similarly, the FRM-II reactor in Germany [2] has a replacement value of €600 million (i.e., approximately $680 million). However, it is not obvious how to normalize these to the cost of a potential new high-performance research reactor in the United States because no HPRRs have been constructed in the United States since 1969.

Operations and Maintenance Costs. Annual budget information for research reactors and spallation sources is rather sparse, but the data suggest that the O&M costs of reactors and spallation sources are fairly comparable.[6] A similar conclusion is reported in [2]: "Interestingly there does not appear to be a significant difference between the figures for spallation sources and those for reactor facilities. This is explained by the fact that annual costs are heavily influenced by staff numbers and that the cost of the fuel cycle of a reactor source (increasing on every future scenario) is balanced by electricity costs for a spallation source (also a resource that is becoming more costly). Of course, the statistics are rather low to be able to extract statistically significant differences in the two kinds of source. Instead they provide a guideline that indicates equality." Unfortunately, it is not always possible to assess whether the annual budget information includes the fuel cost for reactors or the cost of electricity and annualized target replacement costs for spallation sources, among other data points.

Decommissioning Costs. One final economic consideration for neutron facilities is the cost of decommissioning, especially in light of the fact that several of the current sources are approaching the end of their expected lifetimes. The amount and type of activation that generates radioactive isotopes from neutron capture (and consequently increases the complexity and costs of the decommissioning operations and of the required waste disposal) are unique to each facility, requiring analysis of its detailed design and operational history. The complexity and cost of the decommissioning operations are not expected to be substantially different between spallation sources and reactors, as activation products will be present in both types of facilities. Reactors will have high-level wastes that contain both fission products and transuranics, which require geologic disposal. This adds to decommissioning costs, in addition to having to manage the disposal of the activated material. Spallation sources will have extra decommissioning costs related to the activated material associated with the accelerators and the associated shielding. Typical estimates of the total cost of decommissioning neutron facilities are of the order of $200–300 million, for both reactors and spallation sources.

---

6 Annual budgets for research reactors range from €22M (~$25M) for BERII to €95M (~$107M) for ILL. Annual budgets for spallation sources range from €30M (~$34M) for SINQ to $178M for SNS (see refs. [2,46,47,48]).

Societal Benefit. While the costs of constructing, operating, and decommissioning neutron sources of any type are significant, the positive societal and direct economic impact of neutron R&D is enormous. One example is the role of neutron scattering in the development of biologic medicines, including the development of the first FDA-approved virus-based cancer therapy formulation [49]. And as has been alluded to earlier, the penetrative ability of the neutron has been used by the paints and coatings industry to gain a fundamental understanding of paint under flow conditions, leading to advanced product formulations. The total estimated global market for nanomagnetics, paints and coatings, and biologic medicines is in the hundreds of billions of dollars [50]. Additional applications of neutron research with broad societal and direct economic impact include advances in automotive lightweighting, the development of safer jet fuel, formulation of new materials in body armor for law enforcement and the military, advances in materials for energy storage, and improving personal care products. These are just a few of the many advances enabled through the use of neutrons.

Likewise, the use of neutrons in more applied areas has also had significant economic and societal impact, ranging from radioisotopes used for medical diagnostics to the testing and qualification of fuels for power-generating nuclear reactors and on to doping of bulk semiconductor crystals vital for the semiconductor industry. It is clear that neutron science and technology continues to be an essential part of the nation's innovation engine and a key tool for technological progress. It is equally clear that the availability of a suite of neutron sources to meet these needs is a measure of the scientific competitiveness and economic vitality of a country.

Summary: The Path Forward

Research reactors and spallation sources provide different and complementary capabilities for science and engineering. Both are needed for a world-class neutron R&D enterprise. Economic data (construction and operating costs plus the number of studies that can be supported at a facility) suggest that research reactors are somewhat less expensive to build and operate per unit of R&D output, but the difference is small. Advances in the capabilities of new spallation sources may change this equation over the next decade. Still, some applications of neutrons will continue to require high-performance research reactors for the foreseeable future. While most of today's highest performance research reactors present a proliferation risk since they operate using HEU fuel, it is possible to design and build reactors that operate on non-proliferant LEU fuel that provide almost all of the capabilities of today's highest performance HEU-fueled reactors, with the potential exception of materials performance testing in some reactor environments. Further, it is possible to develop an LEU fuel that can be used in existing reactors, although it is likely to be nearly two decades before such a conversion can be carried out.

To ensure the continued availability of neutrons from research reactors for science and engineering, while also being responsive to the proliferation risk, investment is needed to reduce and ultimately eliminate reliance on HEU. A multi-track substitution and replacement strategy is appropriate. As already discussed, many scientific investigations that rely on beams of neutrons can be performed using neutrons from either research reactors or spallation sources. When possible, spallation sources should be used for such research efforts. This will not, however, eliminate the need for research reactors. For those applications that demand the unique characteristics of the neutrons provided by research reactors, two paths should be pursued. First, qualification and manufacture of fuels that can meet the performance requirements of existing HPRRs at lower levels of enrichment should be pursued with renewed vigor, including the intermediate pursuit of fuels with lower enrichment levels en route to LEU. Second, any new research reactors should be designed to operate using LEU fuel. Although the policy advantages of LEU are evident, little progress has been made in reducing the U.S. HEU footprint for civilian reactors in recent years. Policy and financial incentives may be required to change the status quo.

We recommend the following steps be taken:

RECOMMENDATION 1: The United States should continue to support its diversity of neutron R&D capabilities, including both research reactors and spallation sources, for scientific, engineering, and economic capacity and capability. Decisions regarding potential new neutron sources should be guided by the principle of reducing and ultimately eliminating the use of HEU while retaining or enhancing current neutron capabilities.

RECOMMENDATION 2: The United States should sharply increase its investments in neutron instrumentation development and deployment to partially compensate for the country's dramatic decrease in neutron R&D capacity and capability in recent decades; to offset any loss of capability arising from the elimination of HEU fuel from research reactors; and to complement continuing investments in complementary tools such as light sources and high-performance computing.

RECOMMENDATION 3: The United States should reaffirm its commitment to the timely development and deployment of high-density LEU fuels for use in existing high-performance research reactors. Any transition from HEU to LEU reactor fuel must not compromise neutron research and engineering capabilities, especially those that cannot be duplicated using spallation sources. The United States should also consider options to cost-effectively maintain reactor performance and simultaneously reduce HEU consumption while awaiting a suitable LEU fuel.

RECOMMENDATION 4: The United States should initiate an effort to competitively design and build a new generation of LEU-fueled high-performance research reactors that would satisfy all needs presently met by current HEU-fueled U.S. high-performance research reactors and provide new capabilities.

References

[1] IAEA Safeguards Glossary, 2001 Edition. Intl. Nuclear Verification Series, No. 3, 2002.

[2] Neutron scattering facilities in Europe, Present status and future perspectives, ESFRI Physical Sciences and Engineering Strategy Working Group, Neutron Landscape Group, ESFRI Scripta Volume I, Published by Dipartimento di Fisica - Universita degli Studi di Milano, September 2016, ISBN: 978-88-901562-5-0

[3] Travelli, A. 1978. The U.S. Reduced Enrichment Research and Test Reactor (RERTR) Program. Presented at the International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR), November 9–10, 1978, Argonne, IL, USA.

[4] International Nuclear Fuel Cycle Evaluation (INFCE). 1980. Report of INFCE Working Group: Advanced fuel cycle and reactor concepts, Volume 8 of Report of INFCE Working Group, International Nuclear Fuel Cycle Evaluation. Vienna, Austria: International Atomic Energy Agency.

[5] Glaser, A. 2006. On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels. Science & Global Security 14(1):1–24.

[6] Albert Fert and Peter Grunberg won the 2007 Nobel Prize in Physics “for the discovery of Giant Magnetoresistance.”

[7] M. Janoschek, P. Das, B. Chakrabarti, D. L. Abernathy, M. D. Lumsden, J. M. Lawrence, J. D. Thompson, G. H. Lander, J. N. Mitchell, S. Richmond, M. Ramos, F. Trouw, J-X. Zhu, K. Haule, G. Kotliar, and E. D. Bauer, “The valence-fluctuating ground state of plutonium”, Science Advances, 1, 6, e1500188 (2015).

[8] Greene, Geoff. Fundamental Neutron Physics. Presented at Scientific Challenges to Elimination of HEU in Civilian Research Reactors Workshop, Washington DC, April 3, 2017. http://www.aps.org/policy/issues/energy/upload/FundamentalNeutronPhysics.pdf

[9] O. Delaire et al., “Giant Anharmonic Phonon Scattering in PbTe,” Nature Materials 10, 614 (2011).

[10] Isotopic labeling most often involves substitution of deuterium for hydrogen, which enables unique experiments to resolve nanoscale structure and kinetic processes not accessible by any other means.

[11] C. R. López-Barrón, A. P. R. Eberle, S. Yakovlev, and A. Bons, “Structural origins of mechanical properties and hysteresis in SIS triblock copolymers/polystyrene blends with spherical morphology,” Rheologica Acta 55, 103 (2016).

[12] Molybdenum-99 for Medical Imaging, THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001, 2016, ISBN 978-0-309-44531-3 I DOI: 10.17226/23563.

[13] M.-H. Wei et al., “Megasupramolecules for safer, cleaner fuel by end association of long telechelic polymers,” Science 350, 72–75 (2015).

[14] Lopez-Barron CR, Zeng YM, Schaefer JJ, Eberle APR, Lodge TP, Bates FS. Molecular Alignment in Polyethylene during Cold Drawing Using In-Situ SANS and Raman Spectroscopy. Macromolecules. 2017;50(9):3627–36.

[15] Zeng YM, Lopez-Barron CR, Kang SH, Eberle APR, Lodge TP, Bates FS. Effect of Branching and Molecular Weight on Heterogeneous Catalytic Deuterium Exchange in Polyolefins. Macromolecules. 2017;50(17):6849–60.

[16] Van Dyk AK, Chatterjee T, Ginzburg VV, Nakatani AI. Shear-Dependent Interactions in Hydrophobically Modified Ethylene Oxide Urethane (HEUR) Based Coatings: Mesoscale Structure and Viscosity. Macromolecules. 2015;48(6):1866–82.

[17] Basavaraj MG, McFarlane NL, Lynch ML, Wagner NJ. Nanovesicle formation and microstructure in aqueous ditallowethylesterdimethylammonium chloride (DEEDMAC) solutions. J Colloid Interface Sci. 2014;429:17–24.

[18] Garidel P, Kuhn AB, Schafer LV, Karow-Zwick AR, Blech M. High-concentration protein formulations: How high is high? Eur J Pharm Biopharm. 2017;119:353–60.

[19] Yearley EJ, Godfrin PD, Perevozchikova T, Zhang HL, Falus P, Porcar L, et al. Observation of Small Cluster Formation in Concentrated Monoclonal Antibody Solutions and Its Implications to Solution Viscosity. Biophysical Journal. 2014;106(8):1763–70.

[20] Abdul-Fattah AM, Truong-Le V, Yee L, Nguyen L, Kalonia DS, Cicerone MT, et al. Drying-induced variations in physico-chemical properties of amorphous pharmaceuticals and their impact on stability (I): Stability of a monoclonal antibody. J Pharm Sci. 2007;96(8):1983–2008.

[21] Mazzer AR, Clifton LA, Perevozchikova T, Butler PD, Roberts CJ, Bracewell DG. Neutron reflectivity measurement of protein A-antibody complex at the solid-liquid interface. J Chromatogr A. 2017;1499:118–31.

[22] Pomerantz AE. Toward Molecule-Specific Geochemistry of Heavy Ends: Application to the Upstream Oil Industry. Ind Eng Chem Res. 2016;55(16):4403–14.

[23] King HE, Eberle APR, Walters CC, Kliewer CE, Ertas D, Huynh C. Pore Architecture and Connectivity in Gas Shale. Energy Fuels. 2015;29(3):1375–90.

[24] Owejan JP, Trabold TA, Jacobson DL, Arif M, Kandlikar SG. Effects of flow field and diffusion layer properties on water accumulation in a PEM fuel cell. Int J Hydrog Energy. 2007;32(17):4489–502.

[25] Heller AK, Brenizer JS. Neutron Radiography. Anderson IS, McGreevy RL, Bilheux HZ, editors. New York: Springer; 2009. 67–80 p.

[26] Berger H, Dance WE. Accelerator-based neutron radioscopic systems. In: Duggan JL, Morgan IL, editors. Application of Accelerators in Research and Industry, Pts 1 and 2. Aip Conference Proceedings. 475. Melville: Amer Inst Physics; 1999. p. 1084–7.

[27] https://neutrons.ornl.gov/users/industry (accessed 16 January 2018)

[28] https://www.nist.gov/nsoft (accessed 16 January 2018)

[29] http://lansce.lanl.gov/facilities/wnr/index.php (accessed February 25, 2018)

[30] http://www.stfc.ac.uk/research/nuclear-physics/neutrons/neutrons-industry/ (accessed 16 January 2018)

[31] http://www.riken.jp/en/research/labs/rap/adv_photon/neutr_beam/ (accessed 16 January 2018)

[32] M. K. Meyer et al., “Irradiation Performance of U-Mo Monolithic Fuel”, Nuclear Engineering and Technology, 46, 2, 169–182 (2014).

[33] Private communication, Thomas Brückel.

[34] China Spallation Neutron Source. http://csns.ihep.ac.cn/english/index.htm (accessed 21 October 2017).

[35] https://www.ncnr.nist.gov/call/proposal_stats.html (accessed February 16, 2018)

[36] Private communication, Crystal Schrof.

[37] Graphic provided courtesy of Dr. Dan Neumann (NIST).

[38] R.J. Briber, H. Glyde, and S. K. Sinha, “Access to Major International X-Ray and Neutron Scattering Facilities,” Committee on International Scientific Affairs of the American Physical Society, p. 33 (2009).

[39] Bertram Brockhouse received the Nobel Prize in Physics in 1994 with Clifford Shull for “pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.”

[40] D. Neumann. “Status of Neutron Facilities in the U.S.” APS Workshop on Scientific Challenges to Elimination of HEU in Civilian Research Reactors. Washington, DC (April 3, 2017).

[41] Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors, THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001, 2016, ISBN 978-0-309-37918-2 | DOI: 10.17226/21818.

[42] “Joint Statement on Quadrilateral Cooperation on High-density Low-enriched Uranium Fuel Production,” White House (March 26, 2012). https://obamawhitehouse.archives.gov/the-press-office/2012/03/26/joint-statement-quadrilateral-cooperation-high-density-low-enriched-uran (accessed May 29, 2018)

[43] Neutron Science Directorate, “Target Management Plan,” Oak Ridge National Laboratory 106010000-PN0005, R00, March 2017. https://conference.sns.gov/event/65/picture/114.pdf (accessed September 15, 2017).

[44] “Spallation Neutron Source Features Superconducting Linac,” APS NEWS, May 2000. https://www.aps.org/publications/apsnews/200005/sns.cfm

[45] van der Keur, H. “The Pallas business case -- between dream and reality,” Laka Foundation, June 2013. http://laka.org/pallas/2013-Pallas_business_case_resume.pdf

[46] Report from the ILL Associates’ Working Group on Neutrons in Europe for 2025, June 27, 2013

[47] Murphy, J.B. Follow-up report from the Office of Basic Energy Sciences Scientific User Facilities Division budget and operational review of the Spallation Neutron Source and High Flux Isotope Reactor at Oak Ridge National Laboratory (19–20 November 2013). May 20, 2014.

[48] Mustain, C.J, McNaull, A.D. “Physics in the FY 2015 budget.” In AAAS Report XXXIX: Research & Development FY 2015.

[49] See http://www.amgen.com/media/news-releases/2015/10/fda-approves-imlygic-talimogene-laherparepvec-as-first-oncolytic-viral-therapy-in-the-us/ (accessed August 25, 2017).

[50] See http://www.transparencymarketresearch.com/pressrelease/nanomagnetics-market.htm, https://www.pharmasalmanac.com/articles/biologics-driving-force-in-pharma, and http://www.pcimag.com/articles/103790-kusumgar-nerlfi-growney-releases-global-paint-and-coatings-study (accessed August 25, 2017).

APS physics