## A New Neutron Source for NIST and the Nation

The mission of the NCNR is to "Assure the availability of neutron measurement capabilities to meet the needs of U.S. researchers from industry, academia, and other government agencies.". The NBSR reactor at NIST first went critical in 1967. In the 55+ years since the facility has undergone multiple source, facility, and instrument upgrades to remain at the forefront of neutron research. In 1985 the NBSR was relicensed to double power (from 10MW to 20MW). NIST broke ground on a major cold neutron research facility in 1987 which led to a rapidly increasing demand from the research community as state-of-the-art cold neutron instruments came online throughout the 1990s. The performance also improved significantly from upgrades to the cold neutron source (CNS) in 1995 and 2002.

In 2011, the cold neutron experimental area was nearly doubled, allowing the installation of five serving seven new beamlines additional instruments, and a small liquid hydrogen (LH<sub>2</sub>) CNS was dedicated to the MACS instrument. Each improvement led systematically to an increased demand beyond available capacity from the scientific community. Since 1985, the number of participants in neutron research at the NCNR soared from a few hundred to nearly three thousand, leading to nearly 350 publications each year. This trend is expected to continue as NIST is currently preparing for the installation of a liquid deuterium (LD<sub>2</sub>) CNS which will provide significant gains in the cold neutron spectrum below 5 meV and more than compensate for eventual conversion to low enrichment uranium (LEU). Concurrently, the three oldest cold neutron beamlines at the facility will be renewed and upgraded.

This impressive growth has occurred because neutron measurements play a key role in the discovery and development of new materials, advancing technologies that promise to improve the quality of life for all Americans. These areas include biopharmaceuticals, drug delivery systems, personal care products, advanced

energy conversion and storage polymers, technologies, chemical production, and separation, advanced data storage systems, quantum information technologies, dissipationfree electronics, and advanced engineering materials such as those produced through additive manufacturing. In the era of big data, AI, and combinatorial materials synthesis, neutron scattering is a leading tool for guiding the design, discovery, and characterization of new materials. It is therefore not surprising that despite continual performance upgrades, the requested-to-available neutron beam time has increased to nearly 3.

Overarchingly, the aging reactor requires longer outages and larger reactor maintenance expenditures to maintain safe and reliable operations. Some reactor components are not easily replaceable or serviceable, or they depend on obsolete technology.

Therefore, the central question of how NIST can best provide a source of neutrons into the future must be addressed. A 2018 assessment of the NCNR by the National Academies of Sciences, Engineering, and Medicine [<sup>i</sup>] recognized that

"Loss of this facility would have a strongly negative impact on neutron science within the United States and the scientific disciplines that the NCNR serves."

Furthermore,

"NCNR should commission a detailed assessment of the current facility and begin the conceptual design of a new reactor."

The American Physical Society in their 2018 report [ii] entitled "*Neutrons for the Nation*" recommended:

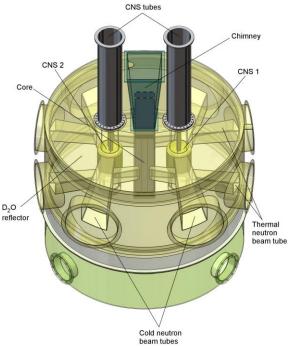
"The United States should initiate an effort to competitively design and build a new generation of LEU-fueled [low-enriched uranium] high-performance research reactors that would satisfy all needs presently met by current HEU-fueled [high-enriched uranium] U.S. high-performance research reactors and provide new capabilities." Other recent reports that highlight the important contributions of neutron scattering and imaging techniques to a broad range of scientific disciplines and technology have been published by the U.S. Department of Energy (2020) [<sup>iii</sup>] and the Swiss Academies (2021) [<sup>iv</sup>].

Prior to these recommendations, a NIST study on future options for neutrons at NIST was already underway. This study concluded that keeping the existing reactor operational is undesirable not only because of the long-term uncertainty in the condition of the reactor vessel and thermal shield but more importantly because it could not allow any further expansion of the neutron beams. A rehabilitated reactor would address the issue of aging management and may expand user facilities. However, the many unknowns involved with removing and replacing the reactor vessel and thermal shield, and the long downtime required make this option less desirable. The overall conclusion was that a replacement reactor is the best option to ensure a reliable neutron source at NIST over the long term.

A new reactor located at NIST can be constructed while the current one continues to operate and would take advantage of the infrastructure and personnel in place at the NCNR with a proven track record of running a world-class and costeffective neutron science facility. In anticipation of the need to plan for its replacement, NIST assembled a NIST/NCNR - Brookhaven National Laboratory (BNL) collaborative group to define top-level functions and requirements and to develop a pre-conceptual design of a replacement reactor and neutron scattering facilities.

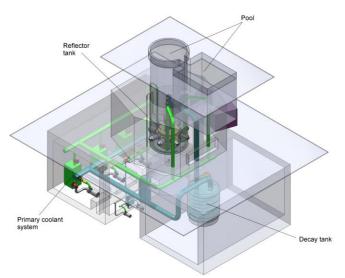
Foremost, the reactor operation must be safe, reliable, and efficient with a high availability and built on a time scale that minimizes disruption to US neutron research. The current global nuclear policy also mandates the use of "low-enriched" uranium as the reactor fuel. The design should promote straightforward maintenance, accessibility to serviceable components, and upgradability. A ground-up reconfiguration incorporating lessons learned from the design and facility layout of the NCNR and other installations around the world allow significant performance upgrades over the present facility. Importantly, these gains can be realized with a reactor design including established safety analysis models and construction solutions which are key to an efficient regulatory review, licensing, and construction process.

An appealing option that satisfies these combined conditions is a forced-cooled reactor core in a pool with a heavy water reflector surrounding a compact core for optimum neutron delivery. The emphasis is on increasing both facility capacity and performance through optimized beam extraction, neutron optics. state-of-the-art instrumentation. and signal-to-noise enhancements which have the potential to produce order-of-magnitude gains. Note that increasing the reactor power is less cost-effective, complicates the licensing process, and increases the scale and challenges associated with core heat extraction while only generating gains that scale linearly. As such, the present concept (dubbed the NIST Neutron Source, or NNS) (Fig.1) would operate at 20 MW with a compact, light water-



*Figure 1.* Isometric view of the present concepts of the NNS core (with two LD<sub>2</sub> CNSs) and the reactor building.

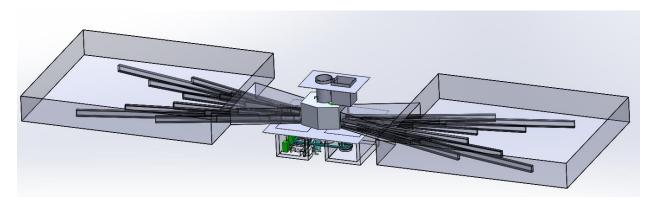
cooled LEU fuel array surrounded by a heavy water-reflector tank containing two (verticallyintroduced)  $LD_2$  CNSs and beam tube penetrations. Tangential beam arrangements mitigate fast neutron and gamma contamination and twin CNSs in vertical thimbles greatly facilitate serviceability and upgradability over the present horizontal thimble arrangement of the current reactor (Fig. 2).



*Figure 2. The present concept of the reactor building.* 

An initial facility layout concept extracting cold neutron beams in opposing directions from each CNS, with thermal beams in an approximately perpendicular direction is illustrated in figure 3. From initial studies up to perhaps 50 cold and thermal neutron instruments could be accommodated with high-performance, lowbackground cold neutron guides, with additional end-positions provided by benders on side locations at multiple levels from tall guides, together with monochromatic beam positions.

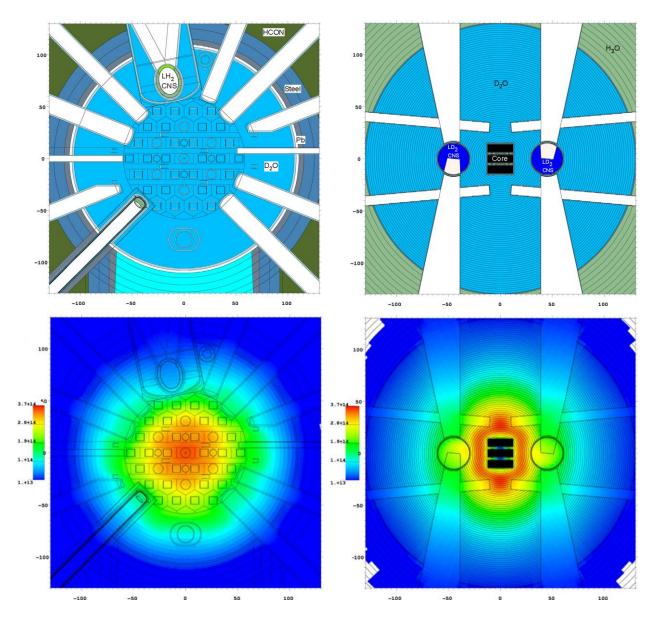
The under-moderated compact core eliminates the compromises of the sparse NBSR fuel assembly array allowing the NNS CNS to be placed in, and thermal beams extracted from, regions much closer to the thermal flux peak in the  $D_2O$  reflector (peak unperturbed<sup>1</sup> thermal flux of  $5.3 \times 10^{14}$  cm<sup>-2</sup>s<sup>-1</sup>) that are unincumbered by fuel assemblies. This is illustrated in figure 4. Despite comparable simulated perturbed thermal flux peaks of about 3.55×10<sup>14</sup> cm<sup>-2</sup>s<sup>-1</sup> (NBSR) and  $3.63 \times 10^{14} \text{ cm}^{-2}\text{s}^{-1}$  (NNS), simulations based on an  $LD_2 CNS$  design predict a cold neutron (< 5 meV) brightness 3.5 times greater for the NNS than currently available at the NCNR. Factoring in solid angle and illumination improvements of the cold neutron guide array yields an order of magnitude increase in transmittable cold neutron current is achievable at the same reactor power.



*Figure 3.* Conceptual facility layout with opposing cold neutron guide halls shown with 16 cold neutron guides viewing two CNSs. The reactor block is at the center. Thermal beams (not shown) emerge approximately perpendicular to the cold neutron beams.

neutron sources. Conversely perturbed flux is assessed with these features introduced.

 $<sup>^{1}</sup>$  Unperturbed flux is assessed with the bare core and D<sub>2</sub>O reflector without the beam penetrations and cold



*Figure 4.* Top row: MCNP models for the current (left) and NNS (right) shown on the same spatial scales. Bottom row: Thermal neutron flux (< 300 meV) shown on the same spatial scales and normalized to the same intensity scale for ease of comparison. The horizontal and vertical scales are in cm.

Additional brightness gains are possible from moderate increases in the CNS vessel diameter and further intensity and signal-to-noise gains are achievable at the instruments with instrumentoptimized neutron optics unlocking areas of research previously restricted by time and data quality constraints. Radiation heat load simulations confirm that the CNSs can be placed as close to the fuel as shown. At initial startup (commissioning), the NNS would deliver measurement capabilities comparable to those of the existing NBSR neutron source by operating, at a minimum, one cold source delivering cold neutrons to one of the guide halls. Once both guide halls are fully operational, the facility would provide new measurement opportunities and substantially increase the neutron measurement capacity for the nation. https://nap.nationalacademies.org/catalog/25282/an-assessment-of-the-center-for-neutron-research-at-the-nationalinstitute-of-standards-and-technology

<sup>ii</sup> Neutrons for the Nation: Discovery and Applications while Minimizing the Risk of Nuclear Proliferation. American Physical Society Panel on Public Affairs, 2019. <u>https://www.aps.org/policy/reports/popa-reports/heu.cfm</u>

<sup>iii</sup> Scientific Justification for a U.S. Domestic High-Performance Reactor-Based Research Facility, Report of the Basic Energy Sciences Advisory Committee, U.S. Department of Energy, Office of Science.," 2020. https://doi.org/10.2172/1647598.

<sup>iv</sup> Neutron Science Roadmap for Research Infrastructures 2025–2028 by the Swiss Neutron Science Community, Swiss Academies Reports, Vol. 16, No. 7," 2021. <u>https://boris.unibe.ch/156933/1/327\_Neutron\_Science\_Roadmap\_2021.pdf</u>.

<sup>&</sup>lt;sup>i</sup> An Assessment of the Center for Neutron Research at the National Institute of Standards and Technology: Fiscal Year 2018, The National Academies Press, Washington, DC, 2018.