PRE-CONCEPTUAL DESIGN OF THE NIST NEUTRON SOURCE

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ABSTRACT

The National Bureau of Standards Reactor (NBSR), a 20 MW thermal power Material Test Reactor (MTR), is located at the NIST Center for Neutron Research (NCNR), providing a safe and reliable neutron source for the thousands of visiting U.S. and international researchers annually. The NCNR has a long-standing reputation for scientific productivity, as measured by the abundance of scientific publications and research participants. The measurement facilities are perennially over-subscribed with a continually increasing demand from the scientific community. There are also increasing maintenance demands associated with aging NBSR reactor systems and components. A new state-of-the-art research reactor utilizing high assay low enriched uranium (HALEU), curved, MTR-type fuel plates, is being conceptualized. The proposed reactor is designated as the NIST Neutron Source (NNS). Eventually, the NNS will be constructed adjacent to the NCNR and replace the currently operational, but aging, NBSR. The NNS concept design is a light water-cooled pool-type compact reactor with a heavy water reflector to operate at 20 MW thermal power. The NNS core is primarily optimized to leak neutrons out of the core toward cold neutron sources and thermal neutron beams. This paper provides pre-conceptual design characteristics for the proposed NNS, a brief description of the user facilities, thermal neutron guides, cold neutron sources, cold neutron guide network, highlights of reactor core neutronics, and recent thermal-hydraulics analysis results. The initial neutronic analysis results imply a total cold neutron current gain at the guide entrances of about 10 when compared to the existing NBSR liquid hydrogen cold source, and at least a factor of two increase in the thermal neutron Maxwellian brightness with respect to the NBSR thermal beam tubes. At the initial startup (commissioning), the NNS would deliver measurement capabilities that are at least equivalent to those existing at the NBSR. However, once at full capacity, the new facility should provide significantly enhanced measurement capabilities, thereby substantially alleviating the current over-subscription of scientific instruments at the NCNR.

1. Introduction

The NIST Center for Neutron Research (NCNR) houses the National Bureau of Standards Reactor (NBSR), which is one of the high-performance research reactors in the U.S. and is the primary source of cold neutrons for thousands of visiting national and international researchers annually. The NBSR has a long history of successful operation since its startup in 1967 [1], and it is licensed to operate until 2029 at which point it will need to be relicensed. Currently, it is one of only two major steady-state neutron scattering facilities in the U.S.

An assessment of the NCNR by the National Academies of Sciences, Engineering, and Medicine [2] recognized that *“Loss of this facility [the NBSR] 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 report [3] on neutron sources had the following recommendation: *"The United States should initiate an effort to competitively design and build a new generation of LEU-fueled [low-enriched uranium fueled] high-performance research reactors that would satisfy all needs presently met by current HEU-fueled [high-enriched uranium fueled] 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 issued by the Swiss Academies [4] and the U.S. Department of Energy [5].

A study on future options for the NCNR neutron source found that a replacement reactor is the best option to ensure a reliable neutron source in the long term. Another option considered was to rehabilitate the existing reactor [6]. This latter option could address the issue of aging management and possibly expand user facilities. However, the many unknowns involved with removing and replacing the reactor vessel, and the long downtime required, make this option undesirable. A third option, keeping the existing reactor operational, was also deemed undesirable because of the high uncertainty in the long-term condition of the reactor vessel and thermal shield and because it would not allow for the expansion of neutron beams.

A new reactor located at the NCNR can be constructed while the NBSR 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 cost-effective neutron science facility. At initial startup (commissioning), the NNS would deliver measurement capabilities equivalent to those of the existing NBSR neutron source by operating, at minimum, one cold source delivering cold neutrons to one of the guide halls. Once at full capacity, the facility would provide new measurement opportunities and should substantially alleviate the current over-subscription of scientific instruments by operation of both cold sources on two guide halls.

With a primary focus on neutron beam experiments, an essential aspect of the proposed NNS user facility is the provision of cold and thermal neutron beams as well as several irradiation positions to meet the diverse needs of the neutron research community [7]. Cold neutrons have energies below about 5 meV [8], which, due to the quantum nature of the neutron, corresponds to a range of neutron wavelengths, λ, greater than about 0.4 nm. The challenge for neutron sources is to furnish collimated neutron beams of sufficient intensity to satisfy the demand for experimental throughput. The NNS intends to provide not only a replacement for an aging facility but aims to offer significantly increased scientific output through not only enhanced beam intensity and an expansion in the number of experimental stations available, but through advanced state-of-the-art cold neutron sources, guide networks, and optimized scattering instruments. This paper provides up-to-date pre-conceptual design characteristics for the proposed NNS, highlights the reactor core neutronics and thermal-hydraulics, and a brief description of the user facilities, neutron guide network, cold neutron sources, and a list of potential advanced neutron scattering instruments.

2. Functional Requirements

Regardless how unusual the technology is, a design team for a new nuclear reactor should prioritize the reactor's purpose (i.e., the reason for building a reactor). Several generic core features, like size, shape, and neutron spectrum, will probably be determined by the reactor's intended use. Currently, the functions of the NIST Neutron Source are defined by the NCNR and the scientific community that utilizes the NCNR. The functions identify what the NNS should be designed to do, and be derived that will satisfy these functions. When possible, the requirements are quantified as either a bounding value or a range of values. Requirements may be modified (and certainly will be added) in the future when more feedback is obtained from experimenters/users, architect-engineers, and other involved parties. There are other design features that, although not requirements, are desirable and they are discussed herein as well.

There are five functions (F1-F5) that the NNS must satisfy, all of which can be found below.

F1 – Neutron Science: The NNS must: (1) Provide cold and thermal neutron beams[1] that meet the current and anticipated needs of the neutron science community with high availability (capacity factor); (2) alleviate present and future over-subscription of scientific instruments; (3) be competitive and complementary with other premier neutron scattering facilities; and (4) provide future expansion capabilities; (5) provide irradiation capability with negligible detriment to (1).

F2 – Reactor Safety: The NNS must be able to be licensed by the U.S. Nuclear Regulatory Commission (NRC).

F3 – Reactor Manufacturability: The neutronic, thermal-hydraulic, and mechanical design, and the materials chosen to build the reactor must not challenge the manufacturability of the NNS and should not increase the risk for the project completion. The materials must also be chosen to help minimize the cost of construction and the lifetime cost of the NNS.

F4 – Operational Reliability: The neutronic, thermal-hydraulic, and mechanical design, and the materials chosen to build the reactor must not challenge operational reliability; that is, the ability to operate without interruption in each fuel cycle and the ability to do routine maintenance in a fixed schedule between fuel cycles.

F5 – Adequacy of Balance-of-Plant: The reactor supplies the neutrons and is the central system. There are many structures, systems, and components (SSC) that complete the plant and allow the reactor to be a useful neutron source. The balance-of-plant SSC must be consistent with all functional requirements above.

3. Design

The current NNS reactor concept was influenced by several reactors designed for neutron science, particularly the Open Pool Australian Light water (OPAL) reactor design, which was used extensively to ensure the use of realistic parameters for the pre-conceptual core and fuel assembly geometry [9]–[11]. The NNS is proposed to be an open-pool research reactor with a nominal power of 20 MW_{th}. It consists of a light-water-cooled compact reactor core located inside a vertical channel (the “core chimney”) that is surrounded by a heavy-water reflector tank. These components/structures are located at the bottom of the reactor pool filled with demineralized light water.

The reflector tank encompasses the cold neutron sources and associated beam tubes as well as beam tubes for thermal neutron beams. The core is cooled by an upward flow of demineralized light water, which also acts as a neutron moderator. The core chimney channels the coolant to the outlet, where it is pumped away by the primary cooling system (PCS) for heat removal by the secondary cooling system (SCS). The PCS and SCS are isolated from each other, at the plate-type heat exchanger. The PCS has four centrifugal pumps and four heat exchangers, each housed in separate rooms to lower common cause failures and allow maintenance, with only three units used for normal operation. The fourth pump and heat exchanger can either be in standby mode or under maintenance.

The general layout of the reactor including the PCS is shown in Figure 1. At the center of the figure (in yellow) is the reflector tank. The internals of the reflector tank, including the reactor core at the center, two cold neutron sources, and beam tubes are shown in Figure 1.

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[1] Thermal neutrons are defined herein as having energies less than 1 eV and cold neutrons are defined as having wavelengths greater than 4 Å.

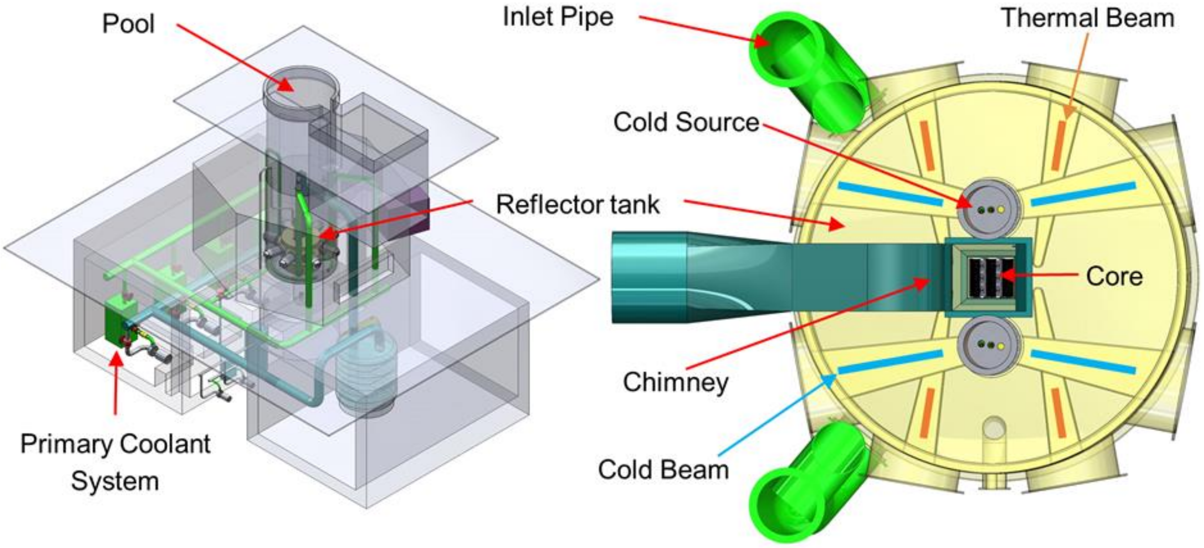


Figure 1. Reflector tank with core, cold sources, and beam tubes.

4. Core Design

There are 9 fuel assemblies in the current NNS core design, which are arranged in a 3x3 square lattice as shown in Figure 2. Separating each row of fuel assemblies are a combination of safety and control blades, all of which are composed of Hafnium. There are 2 control blades separating the elements in the middle column of the core, which are adjusted throughout the cycle to maintain sufficient excess reactivity. On the peripheral fuel assemblies, 4 safety blades act as emergency shutdown devices (scram), which have identical material composition to the control blades. All blades are contained within aluminum guide boxes, which act as the physical separation between each row in the core. Each fuel assembly contains 21 high-assay low-enriched (19.75 wt% ^{235}U) U-10Mo fuel curved fuel plates, which yield a total of 64 coolant channels in any given row in the core. Per Figure 3, the fuel plates consist of the U-10Mo fuel meat, a ~8 µm thick zirconium foil interlayer (to prevent fuel-clad chemical interactions [12], [13]), and the aluminum-6061 cladding encasing the meat and interlayer.

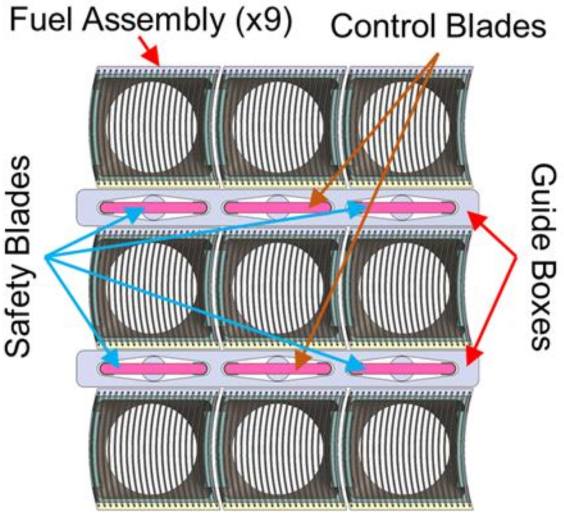


Figure 2. Core design for the NNS.

Within each of the fuel assemblies, there are burnable cadmium (Cd) poison wires (0.5 mm in diameter) placed on each side of the fuel plates. The Cd wires fit into a water-filled T-slot channel that provides some level of cooling for the burnable poison. The Cd wires help in suppressing the higher flux of the reactor at the initial stages of the fuel cycle. The core design is set-up to optimize the length of the fuel cycle and satisfy all thermal limits while maximizing the leakage of thermal neutrons out-of-the-core. The square lattice coupled with the compact core design is expected to assist in neutron leakage, which is desirable to supply neutrons to out-of-core instruments.

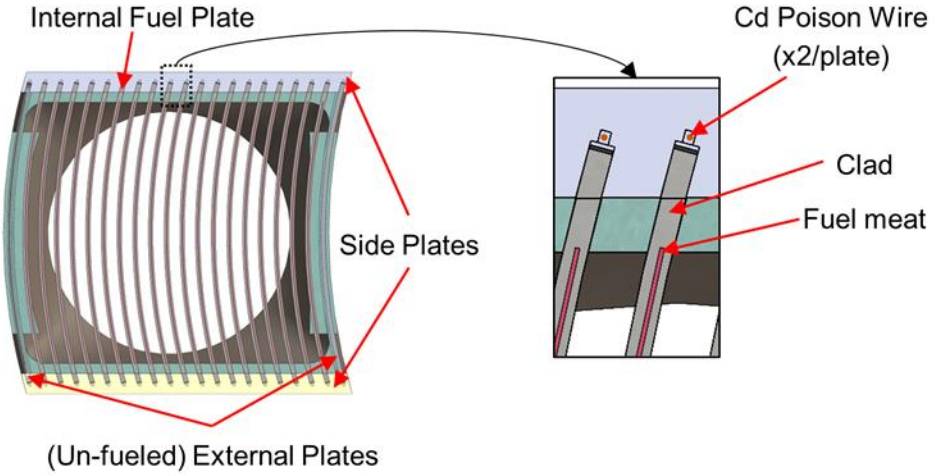


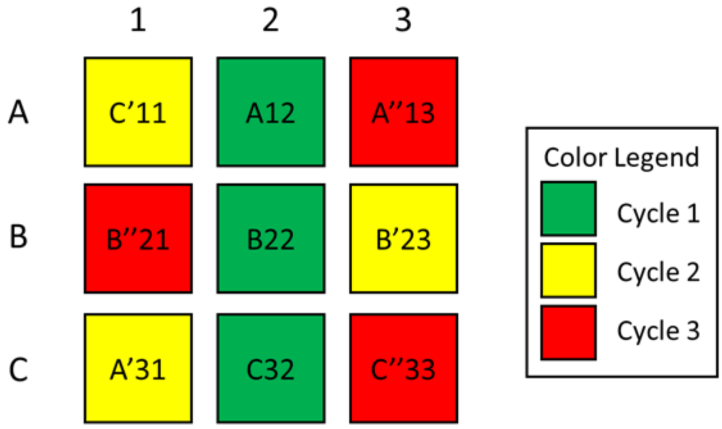
Figure 3. An illustration of a single fuel assembly.

5. Status of Core Neutronics Analyses

The neutronics model utilizes the MCNP code package [14] to simulate the reactor behavior, where the fuel plates are assumed flat for computational efficiency. The model discretizes the fuel meat in each plate into axial and radial zones to account for spatial variations in the fuel composition and to perform more accurate equilibrium core computations. The fuel meat is discretized into 10 axial zones such that the top and bottom zones are 2 cm high, and the remaining zones are each 8.25 cm high. The fuel meat is also radially discretized into three uniform zones each with a width of 2.167 cm. The total thickness of any fuel plate in the core is 0.63 mm, where the fuel meat is 0.25 mm thick (with the zirconium interlayer).

The preliminary neutronics analyses [15] yielded a fuel management scheme as illustrated in Figure 4, which can be summarized by the algorithm shown below. At the beginning of each cycle, the inner column of the core (identified as A12, B22, and C32 and green in Figure 4) is loaded with three fresh fuel assemblies that contain 19.75% enriched U-10Mo, which are then moved to their second cycle locations (yellow), and then to their final and third cycle positions (red). The naming convention adopted in Figure 4 describes the original and current location of the assembly in the core, where the first letter describes the original row where the assembly was first inserted; which is then followed by an apostrophe to define the assembly's age in the core (i.e., 1 apostrophe means it has been burned for 1 cycle). The pair of digits in each of the names corresponds to the row and column numbers, where row A is equivalent to row 1 in this convention. Per this management scheme, any U-10Mo fuel assembly will have a lifetime of no more than 3 cycles, where each cycle is estimated to be 40 days of continuous 20 MW_{th} operation.

A12 → A'31 → A''13
B22 → B'23 → B"21
C32 → C'11 → C"33

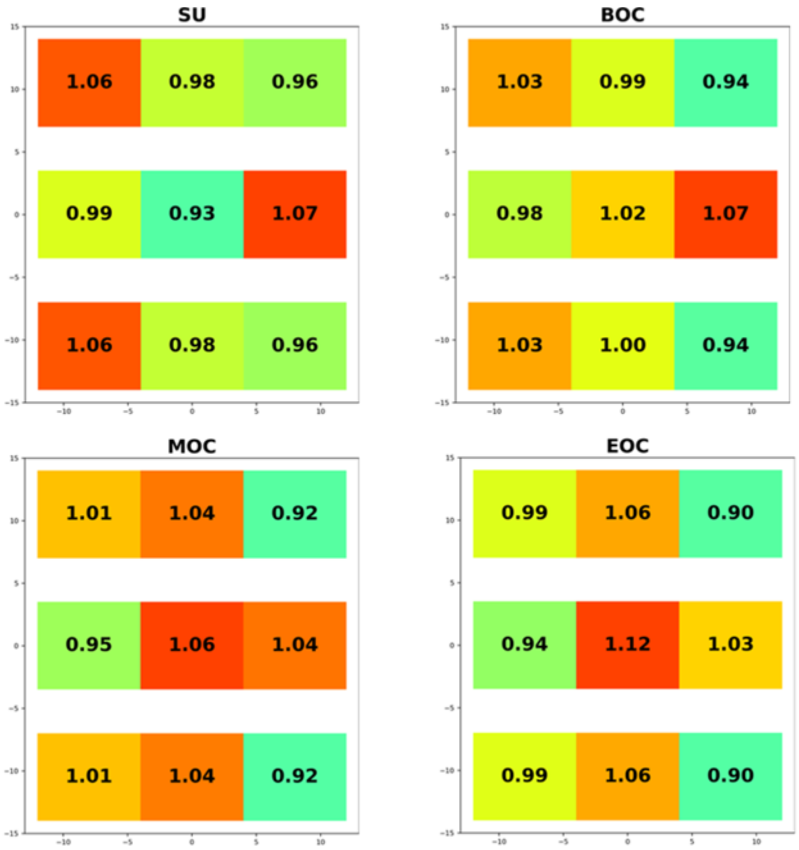


	1	2	3
A	C’11	A12	A’’13
B	B’’21	B22	B’23
C	A’31	C32	C’’33

Color Legend
🟩 Cycle 1
🟨 Cycle 2
🟥 Cycle 3

Figure 4. The current fuel management scheme for the NNS.

Each cycle is decomposed into multiple stages as adopted by previous works [15], which begin at startup (SU), progress into the beginning of cycle (BOC), middle of cycle (MOC), and then finally to the end of cycle (EOC). Figure 5 shows the normalized power heatmaps of the assemblies in each cycle state. Note that the hottest assemblies in earlier stages of the cycle are the 2nd cycle assemblies (C’11, B’23, and A’31). However, towards the end of the cycle the fresh fuel elements (A12, B22, and C32) become hotter as their fission densities increase. As per previously published works on the NNS [15], [16], the peak fission density achieved by any fuel assembly throughout its life in the NNS is 4.4×10^{21} cm^{-3}. Plate-wise, it is found that the outer plates get hottest with their maximum power peaking at the axial center and the radial edges.



SU

1.06	0.98	0.96
0.99	0.93	1.07
1.06	0.98	0.96

BOC

1.03	0.99	0.94
0.98	1.02	1.07
1.03	1.00	0.94

MOC

1.01	1.04	0.92
0.95	1.06	1.04
1.01	1.04	0.92

EOC

0.99	1.06	0.90
0.94	1.12	1.03
0.99	1.06	0.90

Figure 5. The normalized power heatmap of the assemblies in each cycle state.

6. Core Thermal Hydraulics

Previous thermal-hydraulics analyses can be found in the literature [17], [18], which revealed a minimum critical heat flux ratio of 2.18 at the BOC state and a minimum onset of flow instability ratio of 12.9 at the SU state. The maximum bulk temperature remained below 333 K whereas the maximum cladding temperature reached nearly 370 K during the SU state. The bulk temperature was found to be nearly uniform in all channels (to within 3 K). Simplified computational fluid dynamics (CFD) models revealed nearly uniform velocity distributions throughout the core, but ongoing studies with more precise CFD models of the inlet to the NNS revealed some variations between the channels [19], [20].

Figure 6 shows a summary of the current CFD studies for the inlet of the NNS, where Reynolds Averaged Navier Stokes (RANS) models are utilized to yield the results illustrated. The contour plot corresponds to the initialized realizable k-ϵ model results using OpenFOAM code [21]. The visualized results correspond to the normalized streamwise velocities (V/V_∞). Note how the results are notably sensitive to the selected RANS turbulence model, where standard k-ϵ yields nearly 26% higher velocities than standard k-ω at the center assembly. Additional analyses are currently ongoing regarding the statistical variations and sensitivities of the thermal safety margins to variations in inlet temperatures, mass flow rates, and reactor power [22].

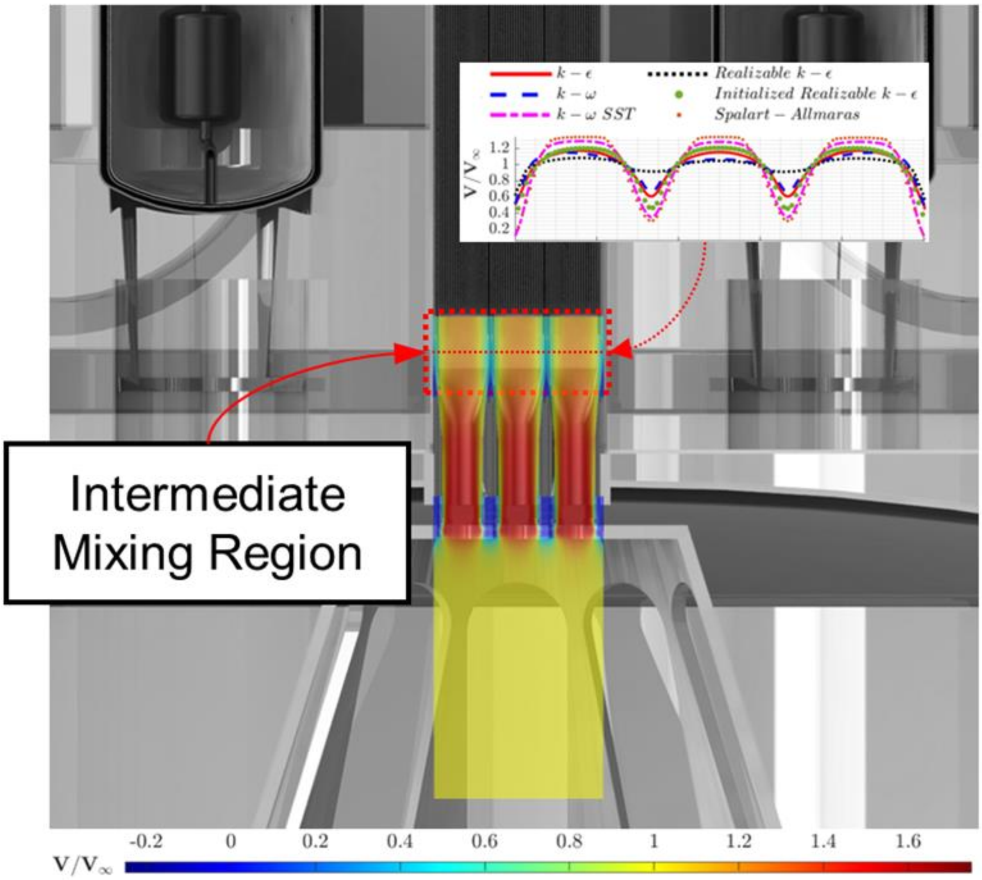


Figure 6. A summary of current CFD studies at the inlet of the NNS with results for the normalized streamwise velocities (V/V_∞).

7. Neutron Guides, Instrumentation and Facilities

The NNS, much like the existing NBSR, is designed for maximum leakage to accommodate instruments and facilities connected to the thermal and cold neutron guides outside of the core. Although discussed in prior works [16], the list of potential instruments considered for the NNS are unchanged thus far, and are presented in Table 1 for the cold beams and Table 2 for the thermal beams. Further details on the instruments and guide descriptions are given in previous works [7], [16].

Table 1: Instruments being considered for the NNS cold beams.

Instrument Type	**Total Number**	**End Position**
Small-Angle Neutron Scattering (SANS)	2-3	YES
Reflectometer (CANDOR type)	2	YES
Cold Neutron Imaging (CNI)	2	YES
Cold 3-Axis (CN3X)	2	YES
Backscattering (BS)	2	YES/NO?
Neutron Spin-Echo (NSE) (Mezei-type)	1	YES
Neutron Spin-Echo (NSE) (WASP type)	1	YES
High current physics experimental position (Physics)	1	YES
Prompt Gamma Activation Analysis (PGAA)	1	YES
Neutron Depth Profiling (NDP)	1	YES
Materials Diffractometer ($\lambda > 0.3$ nm)?	1?	YES
Interferometer	1?	NO
Monochromatic Physical Measurements Laboratory (PML) positions	2-3?	NO
Miscellaneous monochromatic/ test positions	2-3?	NO
Very Small-Angle Neutron Scattering (vSANS)	1	YES
TOTAL	22-25	16-18

Table 2: Instruments being considered for the NNS thermal beams.

Instrument Type	**Abbreviation**
Prompt Gamma Neutron Activation Analysis	PGNAA
Neutron Microscope	Imaging
High-Resolution powder diffractometer	D
Triple Axis Spectrometer	3X
Ultra-Small Angle Neutron Scattering	USANS
High Throughput Fast Powder Diffractometer	D
White Beam Engineering Diffractometer (with CANDOR-type detector)	ENG
High Current Physics Experimental Position	PHYS

A relevant update in the activities relating to experimental facilities at the NNS is the pursuit of a neutron activation analysis (NAA) facility with access to thermal neutrons. The NBSR utilizes rabbit tubes to meet this experimental need [23], which is a common feature in research and test reactors. The inclusion of a rabbit system or a rabbit substitute can support standard reference materials certification at NIST and would meet the functional requirement set by **F1**(5). Current studies are looking at either incorporating a rabbit system into the core, or outside of the core in the reflector (which may require core and chimney design variations) or incorporating an alternative like a hot source similar to the one present in FRM-II in Germany [24]. The addition of a hot neutron source will likely be the more costly option, but it would help maintain the compact core design. Both alternatives are currently being investigated.

8. Discussion and Future Work

As seen, the pre-conceptual reactor design of the NIST promises expanded cold neutron utilization and facilities that almost doubles the available equipment for scientific research. According to preliminary neutronic analysis results, the thermal neutron Maxwellian brightness compared to the NBSR thermal beam tubes will increase by at least a factor of two, and the total cold neutron current gain at the guide entrances will increase by about 10 when compared to the current NBSR liquid hydrogen cold source. The NNS would give measuring capabilities that are at least comparable to those already present at the NBSR at the first startup (commissioning). When the new facility is fully operational, however, it should offer remarkably sophisticated measurement capabilities, greatly reducing the NCNR's existing overabundance of scientific instrumentation. Nevertheless, there are many areas under investigation to improve the design to a complete pre-conceptual state. Future studies are planned to include Computational Fluid Dynamics (CFD) Verification and Validation via experiments. A system code model of the NNS reactor is being implemented in collaboration with the Brookhaven National Laboratory to evaluate potential accident scenarios and reactor feedback. Detailed accident analysis scenarios are being drafted along with probabilistic risk assessment strategies. Alongside, alternative fuel types, such as silicide-based LEU is being evaluated. NIST is also planning to initiate pre-application engagement meetings with the NRC to understand current licensing needs.

9. Disclaimer

Certain commercial equipment, instruments, or materials are identified in this study in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

10. REFERENCES

[1] J. J. Rush and R. L. Capelleti, *The NIST Center for Neutron Research: Over 40 Years Serving NIST/NBS and the Nation*. National Institute for Standards and Technology, 2011.

[2] N. A. Sciences, “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.

[3] J. D. Wells, *Neutrons for the Nation: Discovery and Applications while Minimizing the Risk of Nuclear Proliferation*. American Physical Society Panel on Public Affairs, 2019.

[4] “Neutron Science Roadmap for Research Infrastructures 2025–2028 by the Swiss Neutron Science Community, Swiss Academies Reports, Vol. 16, No. 7,” 2021. [Online]. Available: https://boris.unibe.ch/156933/1/327_Neutron_Science_Roadmap_2021.pdf

[5] “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. [Online]. Available: https://doi.org/10.2172/1647598

[6] T. H. Newton, P. C. Brand, and D. Hughes, “Future Options for the Neutron Source at the NIST Center for Neutron Research,” National Institute for Standards and Technology, 2017.

[7] J. C. Cook *et al.*, “Proposed NIST Neutron Source User Facility,” *ANS Winter Meeting 2022, Arizona, USA*, vol. In Press.

[8] F. J. Webb, “Cold neutron sources,” *Journal of Nuclear Energy. Parts A/B. Reactor Science and Technology*, vol. 17, no. 4, pp. 187–215, Jul. 1963, doi: 10.1016/0368-3230(63)90021-1.

[9] G. Braoudakis, “OPAL nuclear reactor: Reactor specification,” vol. 46, no. 20, Feb. 2015, Accessed: Jun. 09, 2021. [Online]. Available: http://inis.iaea.org/Search/search.aspx?orig_q=RN:46046717

[10] S. J. Kennedy, “Construction of the neutron beam facility at Australia’s OPAL research reactor,” *Physica B: Condensed Matter*, vol. 385–386, pp. 949–954, Nov. 2006, doi: 10.1016/j.physb.2006.05.280.

[11] S.-J. Kim, “The OPAL (open pool Australian light-water) reactor in Australia,” *Nuclear Engineering and Technology*, vol. 38, no. 9, pp. 443–448, 2006.

[12] A. B. Robinson, G. S. Chang, J. Keiser, D. M. Wachs, and D. L. Porter, “Irradiation Performance of U-Mo Alloy Based ‘Monolithic’ Plate-Type Fuel – Design Selection,” Idaho National Lab. (INL), Idaho Falls, ID (United States), INL/EXT-09-16807, Aug. 2009. doi: 10.2172/968567.

[13] D. J. Turkoglu, Z. Wu, R. E. Williams, and T. H. Newton, “COMPARISON OF NEUTRONICS PERFORMANCE CHARACTERISTICS OF THE PROPOSED NIST REACTOR WITH DIFFERENT LEU FUELS,” in *Proceedings of the PHYSOR 2018*, Cancun, 2018.

[14] C. J. Werner *et al.*, “MCNP Users’ Manual Code Version 6.2,” Los Alamos National Laboratory, LA-UR-17-29981, Sep. 2017. Accessed: Jul. 07, 2021. [Online]. Available: https://mcnp.lanl.gov/pdf_files/la-ur-17-29981.pdf

[15] O. S. Celikten, D. Sahin, and A. G. Weiss, “Highlights of Neutronics Analyses for the Pre-conceptual NIST Neutron Source Design,” *Trans. Am.Nucl.Soc.*, vol. In Press, Arizona, USA..

[16] D. Şahin *et al.*, “NIST Neutron Source Preconceptual Design,” in *RERTR 2022 – 42ND International Meeting on Reduced Enrichment For Research And Test Reactors*, Vienna, Oct. 2022. [Online]. Available: https://www.rertr.anl.gov/RERTR42/pdfs/S7-P6_Sahin_paper.pdf

[17] I. R. Baroukh, A. Gurgen, J. S. Shen, and A. G. Weıss, “A Preliminary Thermal-hydraulics Analysis for the NIST Neutron Source,” in *Transactions of the American Nuclear Society*, Phoenix, AZ, Nov. 2022.

[18] I. R. Baroukh, A. Gurgen, J. S. Shen, and A. G. Weıss, “Preliminary CFD Investigations for the NIST Neutron Source,” in *Transactions of the American Nuclear Society*, Phoenix, AZ, Nov. 2022.

[19] Shen, Joy, Weiss, Abdullah G., Gurgen, Anil, and Baroukh, Idan R., “A Turbulence Model Sensitivity Analysis of Thermal-Hydraulic Properties on the Pre-conceptual NIST Neutron Source Design,” in *Proceedings of the International Conference on Nuclear Engineering*, Kyoto, Japan, May 2023.

[20] Weiss, Abdullah G., Shen, Joy S., and Gurgen, Anil, “A Turbulence Model Sensitivity Analysis on the Hydraulic Behavior in the INlet Plenum of the Proposed NIST Neutron Source Design,” presented at the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), Washington, DC.

[21] H. G. Weller, G. Tabor, H. Jasak, and C. Fureby, “A tensorial approach to computational continuum mechanics using object-oriented techniques,” *Computers in physics*, vol. 12, no. 6, pp. 620–631, 1998.

[22] Weiss, Abdullah G., Gurgen, Anil, Baroukh, Idan R., and Shen, Joy, “Sensitivity Analyses of the Thermal-hydraulics Safety Margins in the Proposed NIST Neutron Source Design,” in *Proceedings of the International Conference on Nuclear Engineering*, Kyoto, Japan, May 2023.

[23] D. Şahin, V. Radulović, R. M. Lindstrom, and A. Trkov, “Reevaluation of neutron flux characterization parameters for NIST RT-2 facility,” *Journal of Radioanalytical and Nuclear Chemistry*, vol. 300, pp. 499–506, 2014.

[24] C. Mueller, E. Gutsmiedl, and A. Scheuer, “Status of the FRM-II hot neutron source,” 2001.