Preliminary Studies on A New Research Reactor and Cold Neutron Source at NIST

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Abstract. Upon the consequence of retirement of present NBSR by the mid-21st century, and also to compromise contingent challenges in LEU fuel conversion to NBSR, a LEU-fueled new research reactor design project is currently underway at NIST Center for Neutron Research (NCNR) with the primary purpose of providing cold neutrons for experimental instruments. The new design is targeting of at least two high quality cold neutron sources. A horizontal split compact core with a large D_2O reflector tank is proposed and studied in the first phase of the project, with the expectation of achieving better thermal and cold neutron performance than NBSR. The thermal power of the new reactor is designated at 20 MW and the operating cycle of the equilibrium core is set to be around 30 days. A preliminary core design has been completed with MCNP modeling and simulation. The performance of the new core is presented in the paper with the comparison to some world-wide lately built research reactors. Preliminary liquid deuterium cold neutron source design for the new reactor is also performed and presented in the paper. The design is optimized with calculations of CNS chamber heat load and cold neutron brightness performance. Monte Carlo simulation results have proven the superiority of the new reactor in terms of cold neutron performance with respect to the existing facilities.

1. Introduction

The present research reactor (NBSR) at National Institute of Standards and Technology (NIST) was built in the 1960s. Since then it has evolved into a major neutron source facility hosting over 2,000 guest researchers annually. The current operating license of the NBSR was extended by U.S. NRC in 2009, and the reactor will continue to be in service for an additional 20 years [1]. Although the NIST Center for Neutron Research (NCNR) may be able to obtain one more license extension in the future, the NBSR is eventually anticipated to reach its retirement around the middle of the 21th century. On the other hand, the demand of neutron users of the NBSR has continued to increase, especially after the addition of 5 cold neutron guides in 2012. Meanwhile, the conversion of the NBSR by replacing current high enriched uranium (HEU) fuel to low enriched uranium (LEU) fuel has been analyzed for years. However, various challenges appeared in engineering and technology make the NBSR conversion not be realized in the near term [2]. Upon the consequence of retirement of the NBSR, and also as a compromised solution to address the reactor conversion challenges, it is rational to look more forward and to build a new neutron generating facility on the NIST campus to sustain neutron source production capacity of the NCNR by the time NBSR is shutdown. Under all these circumstances, a research project on the design of a new LEU-fueled beam tube research reactor is currently underway at NCNR. In the first phase of the project, scoping studies on the new reactor are being carried out to demonstrate the feasibility of the reactor and cold neutron source (CNS).

Different from some lately designed multi-purpose research reactors around the world, the primary objective of the NIST new research reactor is to optimize the number and quality of cold neutron beams for experimental instruments. The new design is targeting at least two high quality cold neutron sources. To extensively leverage the knowledge gained from the NBSR, the new reactor is chosen to have a similar scale as the old one. However, LEU fuel with U-235 w/o less than 20% is used to comply with non-proliferation requirements. A horizontal split compact core configuration with large heavy water reflector is being studied the first phase with the purpose of achieving better neutron performance than the NBSR. The thermal power of the new reactor is designated at 20-30 MW and the operating cycle of the equilibrium core is expected to be around 30 days.

As the reactor is principally designed for neutron experiments, no facilities for material testing or radioisotope production are included in the first phase design. Instead, major design efforts are spent on the optimization studies of CNS design and placement. A 20 liter vertical liquid deuterium (LD2) CNS in the reflector of the reactor is studied. Preliminary calculation based on MCNP Monte Carlo simulation shows the heat load of the CNS is less than 4 kW when the center of the CNS is placed 40 cm away from the center of the reactor, and the cold neutron brightness/MW performance appears to be superior to similar cold sources.

The framework of the paper is organized as follows: the section following the introduction describes the design of the horizontal split core, which embraces the inverse flux trap principle and compact core design concept. The equilibrium end of cycle (EOC) core performance of the designed core is also presented in this section. Section 3 discusses the CNS design and performance evaluation. The heat load of the CNS and cold neutron brightness are calculated with Monte Carlo simulation with surface sources provided by criticality core calculation. Concluding remarks on studies of this stage are offered in last summary section of the paper.

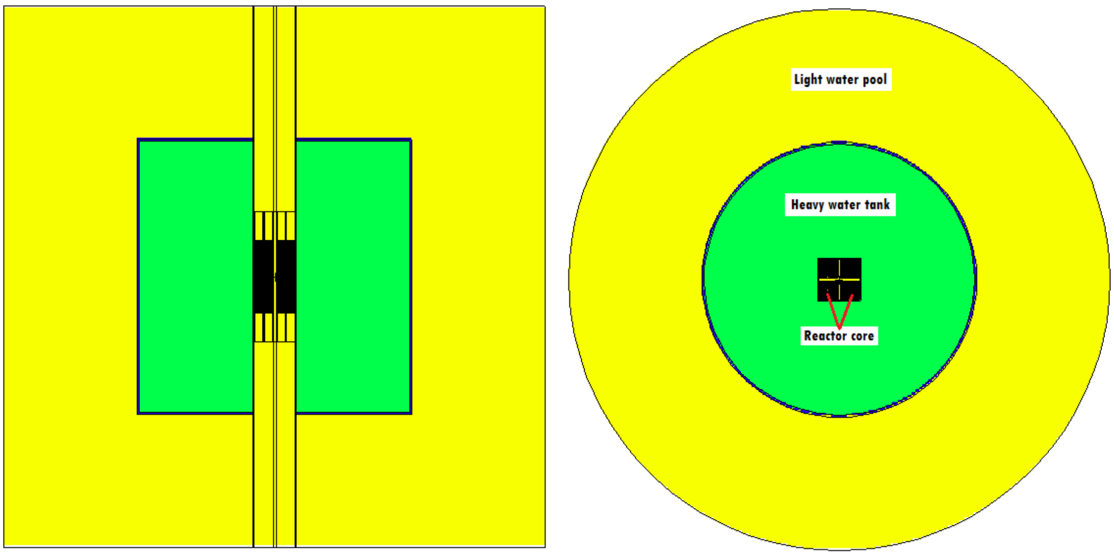
2. **Reactor Core Design**

The new reactor will be fueled with LEU material, therefore the first thing is to determine what fuel to be used in the reactor. Under practical consideration, U_3Si_2/Al dispersion fuel with U-235 enrichment 19.75% is selected as LEU fuel for the core feasibility study at this stage. To our knowledge, U_3Si_2 fuel is so far the only available LEU fuel certified by U.S. NRC for research reactors. Moreover, it has been successfully utilized in a few recently developed neutron beam research reactors. Some other advanced high density LEU fuels such as U-Mo alloy fuel will also be investigated under the study scope of this project, but their performance will not be reported in this paper. The power of the new reactor is 20 - 30 MW, where the definite number can be determined based on the design and performance of the LEU fuel elements (FEs). Building a beam tube type reactor in this power range can provide many benefits in the consideration of economic cost of construction and operation of the reactor as well as scientific utilization of the reactor [3]. With the designated fuel element/assembly and power rate, the operation fuel cycle of the new reactor is planned to be 30 days with about one week shutdown period between cycles. Some key design parameters of the NIST new reactor are summarized in Table I below. As a reference, the corresponding parameters of the present NBSR are also printed in Table I.

TABLE I: Some key design parameters of the new reactor.

Reactor	**New Reactor**	**NBSR**
Core configuration	Compactly packed	Loosely packed
Power (MW_{th})	20 - 30	20
Fuel cycle (days)	30	38.5
Fuel material	U_3Si_2/Al dispersion	U_3O_8/Al dispersion
Fuel enrichment (%)	19.75 (LEU)	93 (HEU)

The compact core concept and inverse flux trap principle [4-5] are fully applied in the design of the NIST new reactor to fulfil advantageous characteristics in producing high quality and reliable neutron flux [6]. Key features of compact core concept include: the active core volume should be made as small as possible for a given reactor power; the core should be surrounded with a moderator (reflector) of high quality and large volume to maximize the thermal flux production; the reactor power should be chosen as high as possible to obtain a high absolute value of the thermal flux. A typical compact core scheme can be seen in *Fig. 1*, in which a compact core is situated in the center of the reactor and is surrounded by large size of heavy water in a cylindrical tank. The reflector tank is immersed in a light water pool which is functioned as both thermal and biological shielding of the reactor.



(a) Cutaway side-plane *(b) Top view of mid-plane*

FIG. 1. Schematic view of compact core design

The compact core philosophy stands as a superior concept in the realm of research reactor development due to its excellent capability of producing large usable thermal neutron flux with favorable spectral property. The quality factor (which is defined as a ratio of maximum thermal flux to thermal power rate and is used as a figure of merit of neutron beam research reactor) of a reactor designed with a compact core is usually superior. All advanced high performance research reactors [7-9] developed in the world in last two decades have more or less incorporated the compact core idea.

The reactor we proposed also employs a compact core design pattern. It has a small core and is surrounded by large volume reflector. However, our reactor has special novelty in the core configuration, which differentiates it from all currently existing compact core designs. Originally inspired by the vertical split fuel element design in present NBSR [1], the 18 fuel elements in the new core are placed into two horizontally split regions, each region consists of 9 fuel elements and represents a half core of the reactor. The core regions are isolated from the reflector by core boxes in an irregular diamond shape (*See Fig. 2*). Those fuel elements in core regions are closed packed with a hexagonal lattice. The two core regions are cooled and moderated by light water, and surrounded with large volume of heavy water reflector. Therefore the core boxes separate heavy water and light water. The detailed schematics of the horizontal split core configuration is illustrated in *Fig. 2* with some key design parameters provided in Table II.

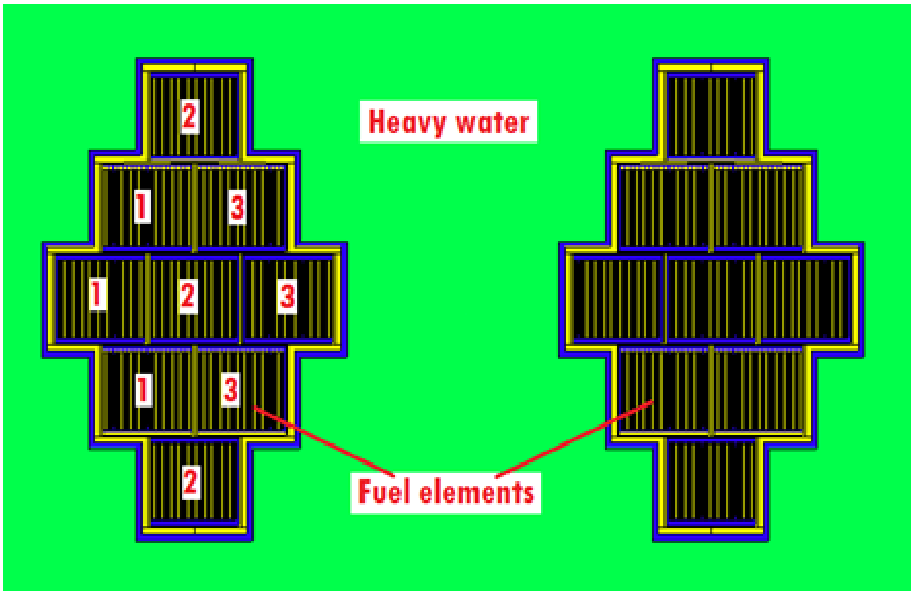


FIG. 2. Horizontal split core schematics

The horizontal split core configuration is desirable in that the primary purpose of the reactor is to produce the greatest possible unperturbed thermal neutron flux. Arranging fuel elements in two horizontal split regions naturally enhances the total leakage of fast neutrons, which consequently increases the absolute value of thermal neutron flux in the reflector. The space in the reflector between the two core regions is expected to have the maximum thermal flux, therefore it provides ideal locations for CNSs and cold neutron beams. In addition, those spaces do not directly view the core, which greatly improves the quality CNS beam tubes.

TABLE II: Design parameters for horizontal split core

Parameter	Data
Power rate (MW_{th})	20
Reactor type	Tank in a pool
Active core height (cm)	60.0
Fuel element lattice pitch (cm)	8.2
Number of fuel elements in the core	18
Core center horizontal gap distance (cm)	19.5
Water gap between box and fuel grid (cm)	0.5
Core box thickness (cm)	0.5
Heavy water tank diameter (m)	2.5
Heavy water tank height (m)	2.5
Heavy water tank thickness (cm)	2.0
Light water pool diameter (m)	5.0
Light water pool height (m)	5.0
Reactor coolant/moderator	Light water
Reactor reflector	Heavy water
Biological and thermal shielding	Light water pool

The standard MTR-type fuel plate is adopted in the design as it is widely used in high performance research reactors. Therefore the planar sectional geometry of the fuel in the new reactor is the same as the fuel element in NBSR [1]. However, the fuel meat thickness of LEU fuel plate is optimized to obtain a comparable enriched uranium (U-235) loading in each fuel plate. For the same reason, the fuel meat length is set to be 60 cm at this stage. Most of the important design parameters for the LEU fuel are presented in Table III with a referral comparison to the HEU fuel in NBSR.

TABLE III: Comparison of LEU fuel used in the new reactor with HEU fuel in NBSR

	Split core	NBSR
Fuel type	U_3Si_2/Al dispersion	U_3O_8/Al dispersion
Fuel geometry	MTR curved plate	MTR curved plate
Fuel cladding material	Al alloy 6061	Al alloy 6061
Fuel density (g/cc)	6.5244	3.612
Number of plates in FE	17	17
Fuel meat height (cm)	60	28 x 2[1]
Fuel meat width (cm)	6.134	6.134
Fuel meat thickness (cm)	0.066 (26 mil)	0.0508 (20 mil)
Fuel plate thickness (cm)	0.127	0.127
U-235 enrichment (%)	19.75	93.00
U-235 mass per FE (gram)	391.468	350.057

[1]Two 28-cm sections separated by a 18-cm gap.

As a proof of principle, an equilibrium EOC model of the core is developed using MCNP code [10]. The fuel inventories at EOC are achieved based on a simple fuel shuffling scheme indicated in *Fig. 2*. The red index shown in *Fig. 2* represents fuel cycle number, which also can be used to infer the fuel shuffling order for the core. The two halves of the split core are loaded symmetrically, thus there are 6 fuel elements replaced after each 30 days cycle.

Fig. 3 illustrates the unperturbed thermal flux distribution in the mid-plane of the split core at EOC. These results are obtained via mesh tally in a MCNP calculation. *Fig. 3* clearly shows that most desirable thermal flux with a magnitude of above $5x10^{14}$ n/cm2-s occurs in the place in-between two half regions of split core. These spaces are provisionally reserved for CNS placement.

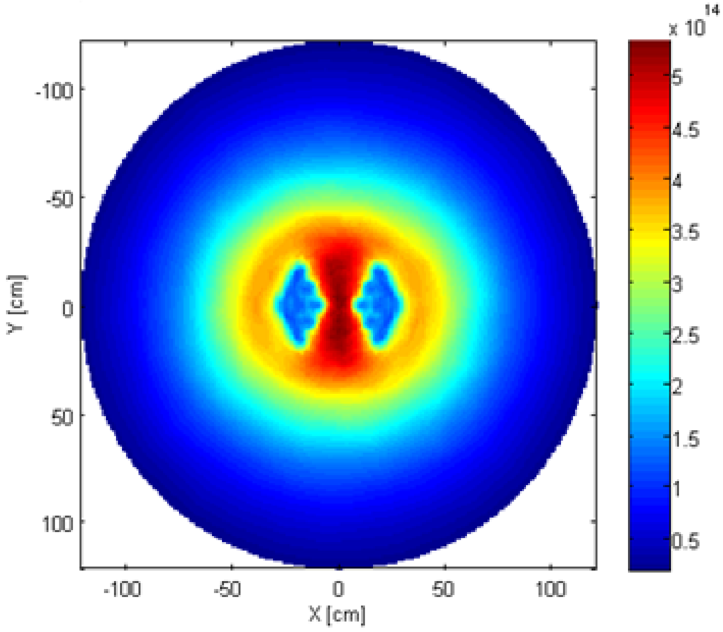


FIG. 3. Unperturbed thermal flux distribution in the mid-plane of the split core.

In order to highlight salient characteristics of the horizontal split core design, equilibrium EOC models were studied with core designs similar to the China Advanced Research Reactor (CARR) [7] with 20 FEs and the Australian OPAL reactor [9] with 16 FEs. For comparison, both of these cores are normalized to 20 MW_{th} with operational cycle length 30 days. For our simulations, the fuel element is identical to the one used in the split core. The equilibrium core is achieved by assuming 5 burnup cycles for the 20 FE core and 4 cycle burnup for the 16 FE core. In this regards, both reactors have 4 fuel elements to be replaced after every operational cycle.

The radial behavior of unperturbed thermal fluxes of the three reactors are depicted in *Fig. 4*. For consistent comparison purpose, all reactors are modeled with same size of reflector tank and light water pool. The radial fluxes illustrated in *Fig. 4* are selected as follows: for the 20 FE core and 16 FE core, it is chosen the radial flux that has the maximum thermal flux occurs in the reflector area;

for the split core, the radial flux is chosen in the direction along north south axis of the reactor. It is also in the line where the maximum thermal flux occurs (See *Fig. 3*).

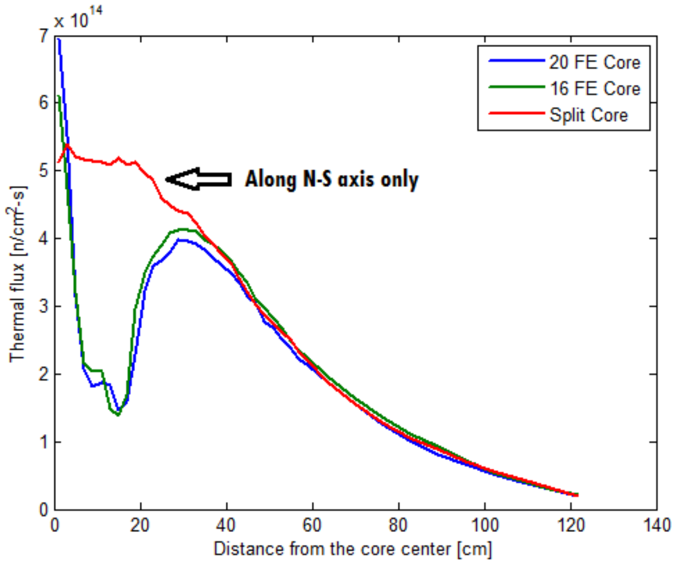


FIG. 4. Radial distribution of unperturbed thermal flux at EOC for three reactors.

As demonstrated in *Fig. 4*, all thermal flux curves were virtually identical at larger radius (R > 40 cm). However, the flux of the split core has superior performance in the reflector region along N-S axis with radius less than 40 cm from the core center. These are the fluxes we are highly interested to accommodate cold neutron sources. Moreover, as the core is horizontally split, it is possible that the CNSs and beam tubes avoid direct view of the core, which enhances the quality of cold neutron flux and reduces the heat load for CNS components. The analyses of CNS performance discussed in next section demonstrates this beneficial characteristic of the split core design.

Since the reactor core design is currently at a very early stage, much work remains to be done to further demonstrate the feasibility of the split core. The tasks consist of, but are certainly not limited to, thermal beam design, control element modeling, fuel burnup analysis with detailed power distribution, thermal hydraulics analysis at normal operation and accident scenarios, and so on. As always, all these tasks are subject to physics and engineering restraints which somehow likely diminish the overall performance of the final design.

3. Cold Neutron Source Design

As aforementioned, the highest priority of the new reactor at NIST is to optimize cold neutron beams to produce reliable and spectral favorable thermal and cold neutrons. To realize this objective, one of the most important tasks is to devise an appropriate cold neutron source and beam tube geometry in the reactor. Liquid deuterium is selected as the cold neutron moderator in the current design due to its advantageous physical property of interacting with thermal neutrons. In this paper, a vertical cylindrical CNS design, similar to the one utilized in OPAL reactor, is adopted and modeled for feasibility studies. The geometry of the vertical CNS is illustrated in *Fig. 5* and *Fig. 6*. The CNS chamber is modelled with a double-wall vessel and filled with about 20 liters of cryogenic liquid deuterium. It contains a large exit hole facing CNS beam, thus it has a re-entrant shape from the top view (see *Fig. 5*). The re-entrant hole is filled with deuterium vapor. The entire CNS chamber is isolated from heavy water reflector by a vacuum containment which is made by zircaloy. The material for CNS vessel is aluminum alloy 6061. The beam port is designed to have a full illumination of the surface of cold neutron exit hole and deliberately avoid direct view to the reactor core.

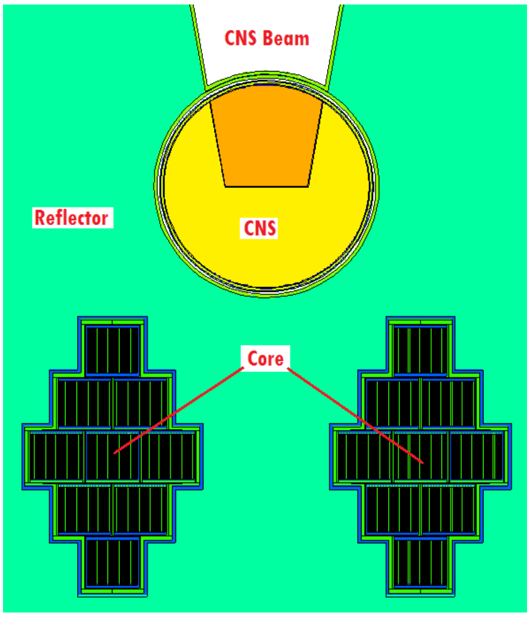


FIG. 5. Top view of the vertical cold neutron source to and split core

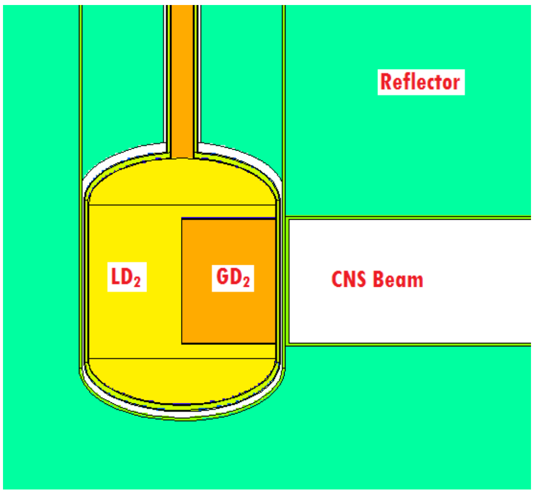


FIG. 6. Section view through the vertical cold neutron source

The geometry used in the vertical CNS model can be found in Table V. It is similar to the cold neutron source in the OPAL reactor. The distance from CNS chamber center to reactor center is an optimized parameter. To achieve as high as possible cold neutron brightness, it is hoped to place CNS as close as possible reactor center, but the closer to reactor, the higher nuclear heat load introduced to CNS chamber. The maximum allowed heat load of CNS chamber is limited by the heat removal capacity of the CNS heat exchange component. In this design, the heat load limit is 4kW to allow thermo-siphon cooling. Based on the heat and neutron brightness calculation presented later, the vertical CNS is placed at 40 cm away from the center of the reactor.

TABLE V. Geometric parameters of components in the vertical cold neutron source

Component	Parameter	Data
Vacuum containment	Center position (x, y, z) (cm)[1]	(0.0, 40.0, 0.0)
	Inner diameter (cm)	31.4
	Thickness (cm)	0.5
	Height (cm)	45.0
CNS chamber	Inner diameter (cm)	30.0
	Thickness (cm)	0.2
	Height (cm)	40
CNS beam	Water gap size (cm)	0.05
	Thickness (cm)	0.5
	Height (cm)	20.0
Reentrant hole	Exit surface width (cm)	12.0
	Exit surface height (cm)	20.0
	Cell tube thickness (cm)	0.12

[1]Position (0, 0, 0) is the core center

TABLE VI. Nuclear heat load calculation

Component	**Moderator – LD2**	**CNS vessel - Al**
Radiation source	**Heat (W)**	**Heat (W)**
Neutrons	721	6
Gamma rays	1276	1001
Beta particles	-	906
Subtotal	1997	1913

MCNP is also used to estimate the expected heat deposition in the moderator LD2 and the moderator vessel made of aluminum alloy 6061. The sources of energy are fast neutrons, prompt and delayed gamma rays, and beta particles from decay of Al-28 [11]. The estimated mass for LD2 and vessel aluminum are 3086 g and 2205 g, respectively. The calculated energy deposited in the CNS chamber from neutrons, gamma rays and beta particles, is summarized in Table VI. The total heat load is about 3.91 kW with the center of the CNS chamber placed 40 cm away from the reactor center, which is within the designated heat load limitation 4 kW.

The figure of merit to evaluate the performance of a cold neutron source is the “brightness” of the source in the direction of the guides to various instruments. The brightness, either in the unit of neutrons/cm2-s-A-ster or neutrons/cm2-s-meV-ster, can be obtained from the current tallies across a surface within a DXTRAN sphere in MCNP [10], and its value should not depend on the distance of the tally surface from the source. However, simulations of cold neutron production and transport depend heavily on the scattering kernels (cross sections for low energy neutrons, or S(α,β) data) of the cold moderators. The recently released ENDF/B-VII.1 data include continuous energy and angle S(α,β) data [12] and MCNP6.1 has improved interpolation routines that eliminate non-physical peaks and valleys in the current tallies with small energy and angle bins.

The calculated brightness (in the unit of neutrons/cm2-s-meV-ster) of the vertical CNS in the split core is presented in *Fig. 7*. It has been consistently compared to performances of former, present, and future planned cold neutron sources at NIST [11]. The large LD2 CNS is planned to be installed at NBSR in 2019 and represents the best performance we can achieve with the NBSR [13]. *Fig. 7* shows the average gain in brightness with respect to the large LD2 CNS is about 2.72 for neutron wavelength greater than 4 A. This gain factor will be lessened to some extent along with the full development of the core. However, since the present NIST liquid hydrogen CNS (Unit 2) has comparable performance to most existing world-wide cold sources, the preliminary results indicate the performance of the vertical CNS in the split core offers potentially significant gains in cold neutron performance.

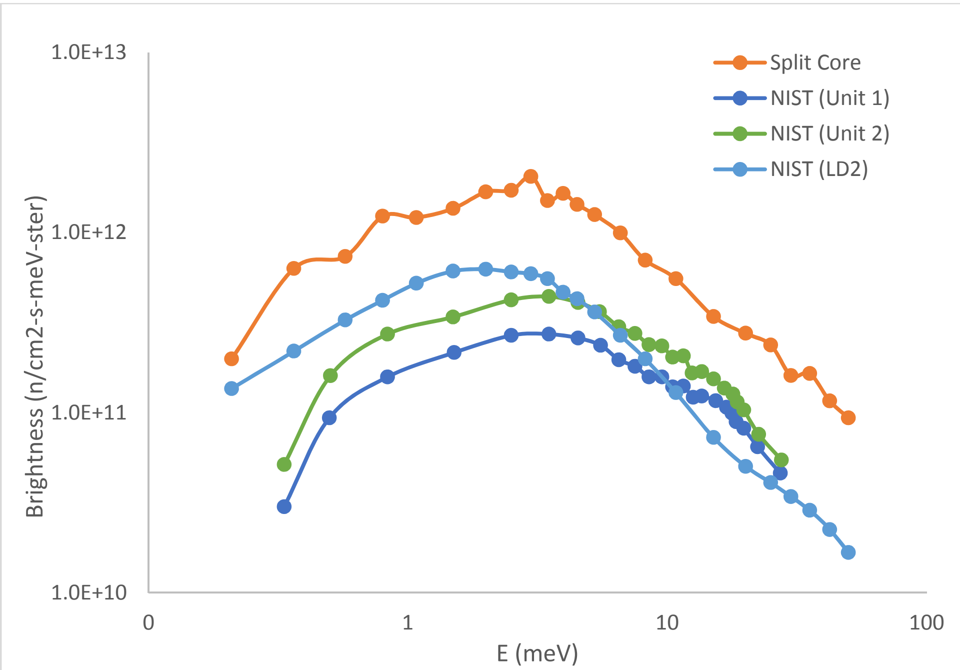


FIG 7. The comparison of cold neutron brightness in split core to CNS performance at NBSR

4. Summary

A research project on the design of a new LEU fueled beam tube research reactor is underway at NCNR. The primary objective of the new reactor is to optimize CNS beams for experiment instruments. The new reactor will operate at 20 – 30 MW_{th} with a cycle length of 30 days. A compact core design concept is adopted as a priority in the scoping study. Neutronics feasibility studies are completed on a horizontal split core design model. The preliminary predicted performance of the new reactor is competitive with most recent developed advanced research reactors around the world. A vertical LD2 CNS is also modeled in the reactor using MCNP. The heat load estimation of the CNS is acceptable and the cold neutron spectrum brightness/MW demonstrates some potential superiority to all existing sources.

5. Acknowledgement

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