CORE DESIGN STUDIES ON A LOW-ENRICHED URANIUM REACTOR FOR COLD NEUTRON SOURCES AT NIST

Zeyun Wu[1, 2*] and Robert E. Williams[1]

[1]NIST Center for Neutron Research
100 Bureau Drive, Mail Stop 6101, Gaithersburg, MD 20899 USA

[2]Department of Materials Science and Engineering
University of Maryland, College Park, MD 20742 USA
*Corresponding author: zeyun.wu@nist.gov

ABSTRACT

A LEU-fueled research reactor for cold neutron sources is currently being studied at NIST. The new design is targeting at least two high quality cold neutron sources. A tank-in-pool type reactor with a horizontally split compact core cooled by light water and reflected by heavy water is proposed and investigated, with the expectation of achieving extraordinary flux performance. The thermal power of the new reactor is designated at 20 MW and the operating cycle of the equilibrium core is set to be 30 days. Core design studies were performed mainly using the Monte Carlo code MCNP-6. The core performance characteristics at several representative burnup states of an equilibrium cycle including startup (SU) and end of cycle (EOC) are presented in the paper to demonstrate the performance of the new design. The calculated surface current at the exit hole of the cold neutron source is expected to achieve a gain factor of three compared to the cold neutron performance of the existing NIST reactor.

Key Words: **Low-Enriched Uranium, Research Reactor, Cold Neutron Source**

1. INTRODUCTION

The NBSR (National Bureau of Standards Reactor) [1] is a 20 MW research reactor that currently operates at the Gaithersburg Campus of the National Institute of Standards and Technology (NIST). It is a major neutron source facility around the world and hosts over 2,000 guest researchers annually. As of December 2014, NBSR provides beams to 28 neutron research instruments for various scientific experiments, and 21 of them use cold neutrons. The NBSR first went critical on Dec. 7th 1967. It was re-licensed in 2009 to continue operating for additional 20 years, and it is expected that an additional re-licensing will be possible after that. Nevertheless, the reactor is eventually anticipated to reach its retirement around the middle of the 21st century. On the other hand, the demand and number of neutron users of the NBSR has continued to grow in the past decade, particularly after the addition of 5 cold neutron guides in 2012. Meanwhile, a plan for the safe conversion of the NBSR from high enriched uranium (HEU) fuel to low enriched uranium (LEU) fuel has been submitted, but various challenges appeared in the development and fabrication of the U-Mo fuel delaying the NBSR conversion at least a decade.

Under these circumstances, there are strong interests to build new neutron production facility at NIST in order to sustain neutron source production capacity by the time NSBR is completely decommissioned. A reactor replacement study was therefore initiated and efforts on the design of a new research reactor optimized for cold neutron source are currently underway at NIST Center for Neutron Research (NCNR). Feasibility studies are being carried out to demonstrate the capability of the reactor as a neutron source for the next century. The primary purpose of the new reactor is to provide bright and reliable cold neutron beams for scientific experiments. The new design is targeting at least two high quality cold neutron sources and four thermal neutron beams. To leverage the knowledge gained from the NBSR, the new reactor is chosen to be of similar scale to the existing one but incorporates the latest proven research reactor design features. The MTR-type fuel element was used in the conceptual design of the new reactor. However, LEU fuel with U-235 enrichment less than 20% is used to comply with non-proliferation requirements. A horizontally split compact core cooled and moderated by light water while reflected by heavy water is being investigated at this stage to achieve better flux performance. [2] The thermal power of the new reactor is designated at 20 MW and the operating cycle of the equilibrium core is set to be 30 days at this stage.

This paper presents the recent results of the core design studies for the new reactor, which were mainly performed using the Monte Carlo code MCNP-6. An overview of the LEU core is given in Section 2. It is followed by a brief description of the computational procedure that generates the fuel inventories for a multicycle equilibrium core based on a simplified three-batch fuel management scheme using an iterative search procedure. Section 4 discusses the physics performance characteristics of the core such as neutron flux and power density at several representative burnup points of a cycle including startup (SU) and end of cycle (EOC) results. The high performance of the new design is verified by the flux performance, particularly the cold neutron characteristics, of the reactor compared to the NBSR. Some concluding remarks on the study are provided at the end of the paper.

2. OVERVIEW OF THE LOW-ENRICHMENT URANIUM CORE

The standard ‘tank-in-pool’ design pattern is chosen for the new design. A cylindrical heavy water tank 2.5 m diameter and 2.5 m height is placed in the center of a large light water pool, which functions as a thermal and biological shield. The core design embraces the compact core concept and creates a thermal flux trap in an easily accessible location in the reflector tank to maximize the flux. The reactor core is enclosed by two zirconium core boxes to separate heavy water and light water. To maximize useful flux trap volume in the reflector, an innovative horizontally split core is employed in the design such that the thermal flux trap between the core halves would provide ideal locations to place cold neutron sources (CNS). [2] Two vertical liquid deuterium CNS are placed in the flux trap located in the north and south sides of the core. The distance between the center of the CNS and the reactor center is 40 cm, which is a tradeoff between the cold neutron performance and the estimated heat load for the CNS. Two CNS beam tubes are connected to the CNSs with guides pointing in the north and south directions. Four thermal beam tubes are placed in the east and west sides of the core at different elevations (20 cm above and below core mid-plane) with the pointing direction tangential to the core face. A schematic view of the reactor components and the fuel element radial layout in the split core is illustrated in Fig. 1.

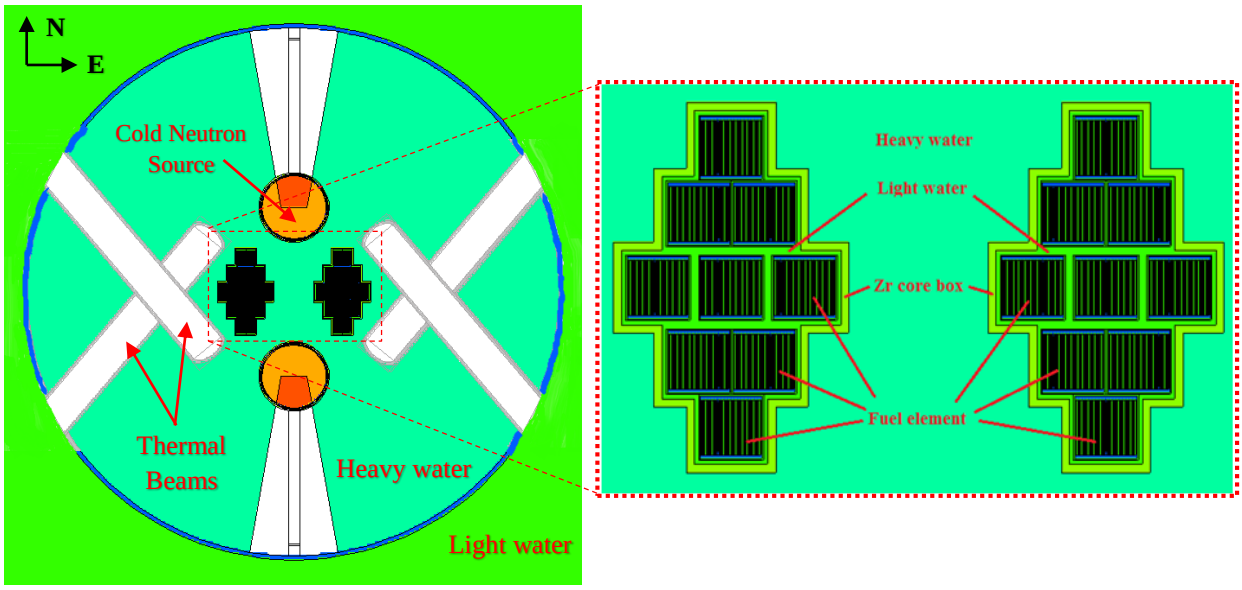

Figure 1. A schematic view of the mid-plane of the reactor with horizontally split cores.

As shown in the figure, the split core consists of 18 MTR-type fuel elements in two horizontally split regions. Each region consists of 9 fuel elements and represents a half core of the reactor. The fuel elements in those core regions are close-packed in a hexagonal lattice. The fuel plate is made of Al clad LEU fuel. The LEU fuel used in this study is U_3Si_2-Al dispersion fuel with U-235 enrichment 19.75%, which is the only LEU fuel certified by US NRC so far. For simplification, the fuel plates are modeled without curvature in MCNP. The fuel meat has a rectangular shape with dimensions of 60 cm long, 6.134 cm wide, and 0.066 cm (26 mil) thick. Under this design, the U-235 mass in a fresh fuel element is 399 grams. Note that the central fuel elements are separated with 1 cm water gaps (see the right figure in Fig. 1) for the purpose of accommodating control elements.

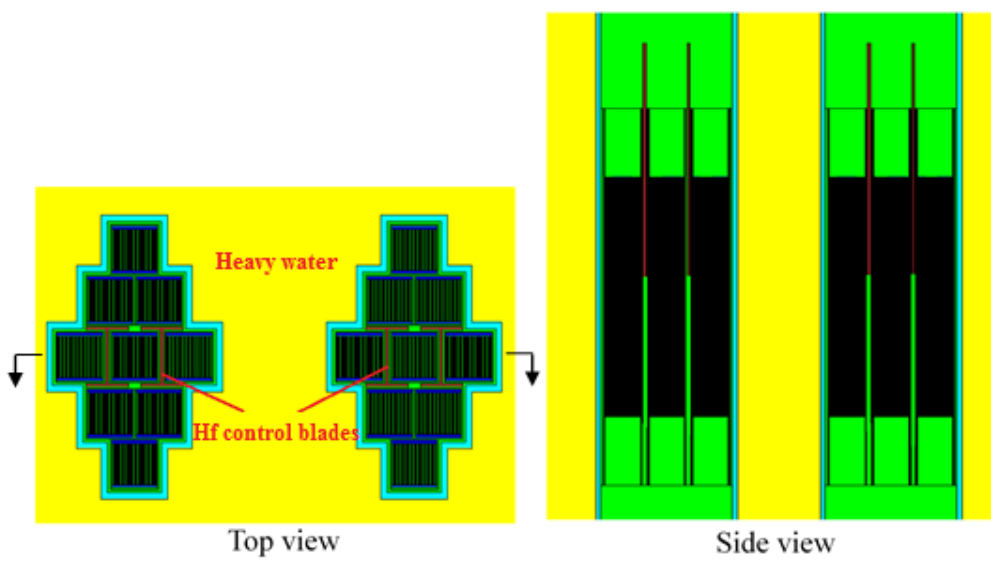

Figure 2. Arrangement of the control element.

Four sets of H-shaped hafnium control blades are utilized as both criticality and safety control elements for the reactor. Due to the limited space in the core, all control blades are made about 0.5 cm thick and 60 cm long (the same length as the active fuel length). The blades are controlled by a mechanical driver located at the bottom of the core (not shown) but with the fully withdrawn positions at the top of the core. A top and side view of the control element placement for a critical core is illustrated in Fig. 2.

3. THE MULTICYCLE EQUILIBRIUM CORE GENERATION

A three-batch fuel management scheme is employed in the study to achieve a multicycle equilibrium core. The fuel shuffling scheme for the 18 fuel elements is depicted in Fig. 3, in which the fuel elements indicated with green numbers have fresh fuel in the startup (SU) core, elements indicated with black numbers have once burnt fuel, and fuel indicated with red numbers will be discarded at the end of cycle (EOC). Thus there are 6 fuel elements be replaced at each cycle under this fuel management scheme.

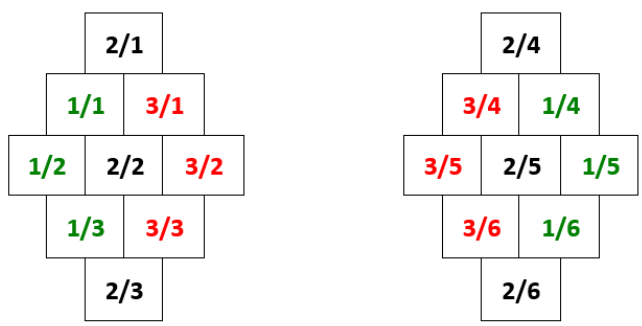

Figure 3. Three-batch fuel element shuffling scheme: The green color indicates fresh fuel at SU and the red color indicates spent fuel at EOC. For each number pair, the first number stands for the batch number and the second is the fuel element ID number.

To achieve a multicycle equilibrium core, an iterative search procedure is performed following the methodology introduced by Hanson and Diamond [3]. In the depletion calculation, each fuel element is divided into 6 axial zones, resulting in 18 × 6 = 108 fissionable zones in the entire core. To obtain a result in a manageable computational time, only four representative burnup states are considered in a cycle in the equilibrium search procedure:

- The startup (SU) state, which is initiated with all fresh fuel,
- The beginning of the cycle (BOC) state, which has burned 1.5 days into the cycle and assumed to have equilibrium xenon concentration,
- The middle of the cycle (MOC) state, which has burned 15 days into the cycle,
- The end of cycle (EOC) state, which has burned a full cycle length (30 days).

The fuel compositions at EOC is allowed to decay for one week after EOC before the elements are shuffled into the SU core for the next iteration (except the discarded fuel). The iterative procedure continues until k_{eff} converges for each state. Note that the control rod positions for each state must be adjusted in order to maintain critical status during the equilibrium search process. A diagram briefly

illustrating the search procedure is shown in Fig. 4 with the k_{eff} behavior curves in the search process presented in Fig. 5.

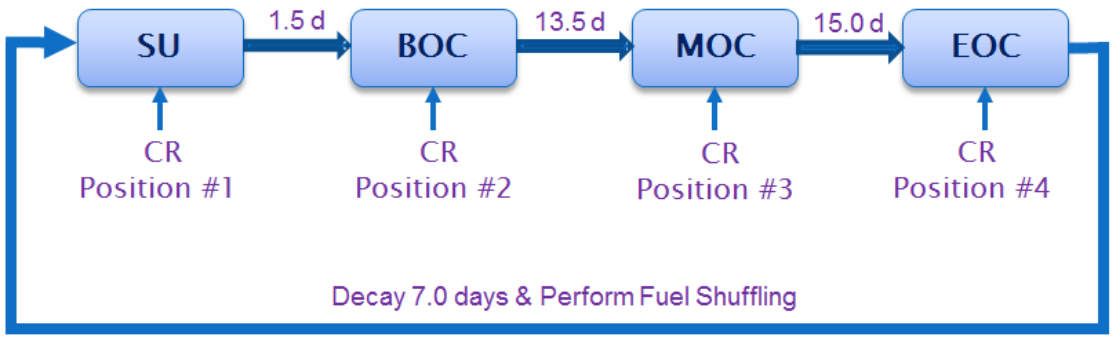

Figure 4. Flow diagram of the multicycle equilibrium core search procedure.

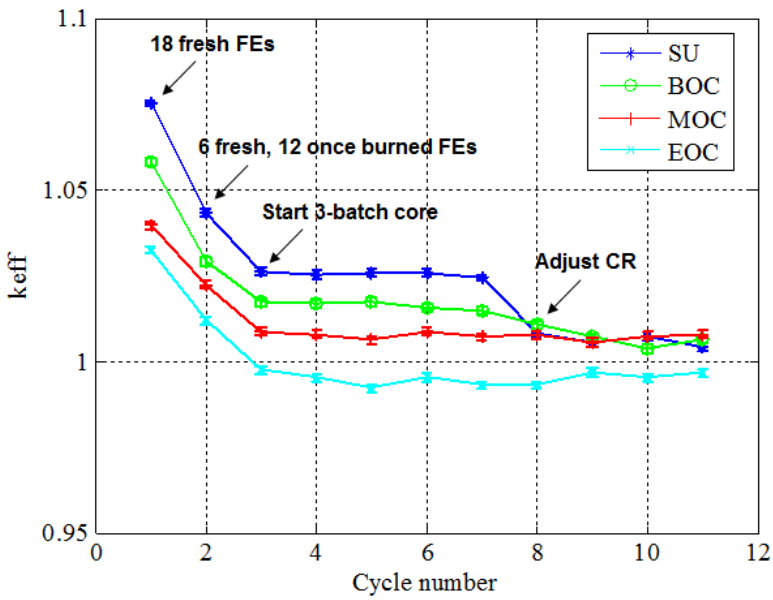

Figure 5. The k_{eff} convergence curves in the iterative search process.

All the control blades were operated together within the cycle. To achieve critical status for each state, the inserted length of control blades had to be adjusted correspondingly to compensate the reactivity loss due to the burnup of fissile material and the buildup of fission product poisons. The search procedure begins with critical control rod (CR) positions approximately estimated for each state based on prior knowledge on the CR worth. The abrupt change of k_{eff} in the 8th cycle for the SU curve is mainly due to external CR adjustment for this state because the CR critical position initially assumed for SU was not very accurate (see Fig. 5). The converged k_{eff} values and the control blade withdrawal lengths for the four states are summarized in Table 1.

Table 1. The Critical Status of the Burnup States for the Equilibrium Core.

Burnup State	k_{eff}	CR Withdrawal Distance
SU	1.00466 ± 0.00120	35 cm
BOC	1.00668 ± 0.00097	45 cm
MOC	1.00826 ± 0.00119	55 cm
EOC	0.99705 ± 0.00101	65 cm

4. PHYSICS CHARACTERISTICS OF THE CORE

After obtaining the material inventories of the equilibrium core, many key physics performance characteristics of the core such as neutron flux and fission rate can be subsequently calculated by MCNP-6. However, to obtain the absolute flux information, tallies from MCNP calculations must be normalized to the real reactor power (20 MW in this study). With the assumption that the recoverable energy per fission is approximately 200 MeV and the average number of neutrons generated per fission is 2.44 [4], the total source of neutrons is calculated as follows:

$$\text{Total source} = (2.44 \text{ neutrons/fission})(20 \times 10^{6} \text{ J/s})/[(200 \text{ MeV/fission})(1.602189 \times 10^{-13} \text{ J/MeV}]$$
$$= 1.523 \times 10^{18} \text{ neutrons/s}$$

This is the normalization factor used to estimate the absolute neutron flux and fission rate in the core. Note if the actual system is slightly off-critical, the normalization factor also needs to take k_{eff} into account, though this effect may be insignificant as the eigenvalue of a practical system is always close to unity.

4.1. Neutron Flux

The flux was obtained via the standard MCNP FMESH tally. Fig. 6 shows the axial flux distribution (including fast flux and thermal flux) at the center of the core for the four different states. The cutoff energy for the thermal neutron is 0.625 eV. Due to the movement of the control blades, the axial behavior of the flux varied at different states during the cycle. As clearly observed in Fig. 6, the peak flux gradually shifted from the bottom region of the core to the center from the SU to the EOC. This variation trend would have direct effects on the flux performance of the thermal beams as they are located off the mid-plane of the core. It should, however, be less significant for the cold neutron beams because the two vertical CNSs are located at the middle portion of the core. This is actually verified by the resultant CNS beam surface current tallies. The achievable maximum thermal flux of the new core can reach about 4.50×10^{14} n/cm^2-s in the entire cycle as shown in Fig. 6.

Fig. 7 shows the radial flux distribution along the north-south axis at the mid-plane of the core. These results are of interest as the CNSs are located at these locations. As can be seen, the thermal fluxes are greatly perturbed at CNS locations. The fast fluxes at these locations are very low in the flux trap of the split core. This is beneficial for the CNS design because the heat load caused by fast neutrons is significantly reduced and the fast neutron background in the cold neutron beams is also greatly

reduced. Although the axial flux behavior has apparent variations along the burnup cycle, the radial flux exhibits nearly identical distributions at different states, which is desirable to achieve consistent performance for CNS throughout the cycle.

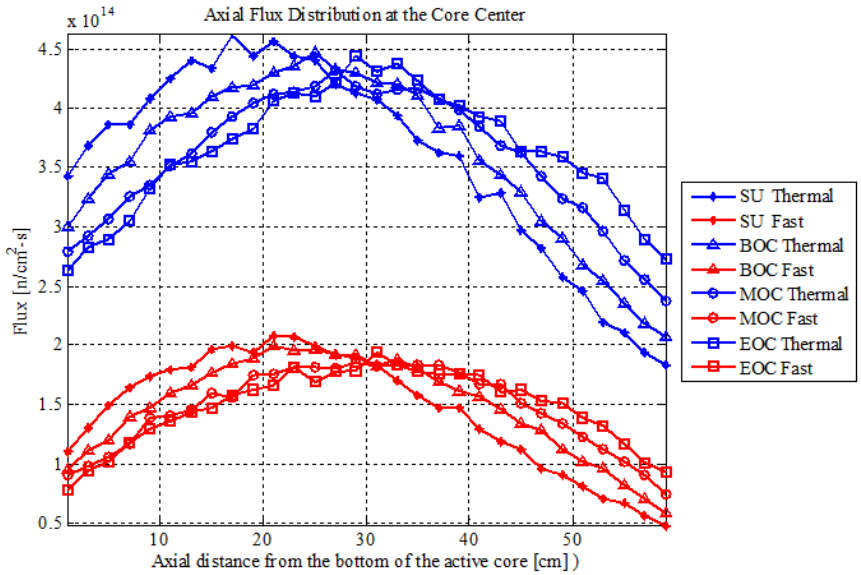

Figure 6. The axial flux distribution at the center of the core.

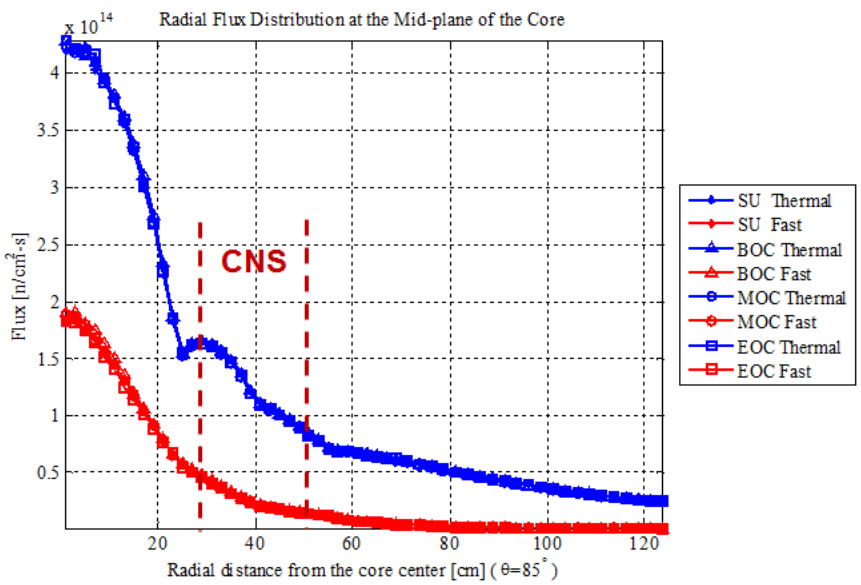

Figure 7. The radial flux distribution in the mid-plane of the core along the north-south axis.

4.2. Power Density

The power density for a given position in a core is determined by the effective recoverable fission energy deposited at that position. In power density calculations with MCNP, we conservatively assume that all the recoverable fission energy is deposited at the point of fission, and the power density

is proportional to fission density. Thus the power factor of a position is directly proportional to the fission density at that position. Table 128 of the MCNP output file is employed to perform the power calculation as discussed in Ref. 5. In order to obtain a detailed power distribution for the core, the regions that contain fissionable material in the core must be computationally divided into small pieces. For this study, the fuel plate (really the fuel meat inside the plate) is evenly divided into 3 stripes, and each stripe is evenly divided into 30 axial pieces. As a result, the smallest unit for power calculation has a volume about 0.264 cm^3. The core averaged axial power distribution at different burnup states is shown in Fig. 8. The axial power curves shift toward the core center similar to the axial flux.

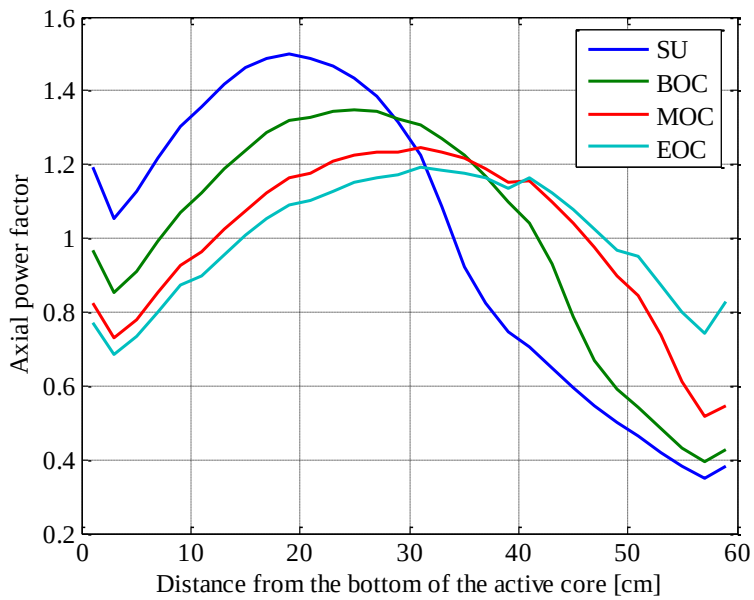

Figure 8. The core averaged power distribution at different burnup states.

Table II summarizes the power peaking factors (PPF[1]) estimated for the core at different states. The hot spot PPF (also referred to total PPF) for SU is slightly high but it remains at an acceptable level. Moreover, the peaking factors may be further mitigated with more optimized studies on the design.

Table 2. Power Peaking Factors at Different Core State

Core State	SU	BOC	MOC	EOC
Hot spot PPF	3.16	2.91	2.68	2.60
Hot stripe PPF	2.24	2.21	2.13	2.04
Plate-wise PPF	2.15	2.15	2.06	1.98
Fuel Element-wise PPF	1.08	1.11	1.12	1.14

4.3. CNS Beam Performance

Cold neutrons have kinetic energies less than 5 meV and wavelengths greater than 4 Å. They can be transported over tens of meters through super-reflecting neutron guides with minimal losses, and

[1] The PPF is defined as the peak power divided by the average power in the associated domain.

thereby provide high intensity beams to a large number of special scientific experimental instruments. Intense beams of cold neutrons are obtained from cryogenic moderator such as liquid deuterium (LD_2) that further slowdown thermal neutrons produced in the reactor. Fig. 9 illustrates a generic vertical cold neutron source in which the gaseous deuterium (GD_2) provides a re-entrant hole between the CNS and beam port that facilitates cold neutron transport to the guides.

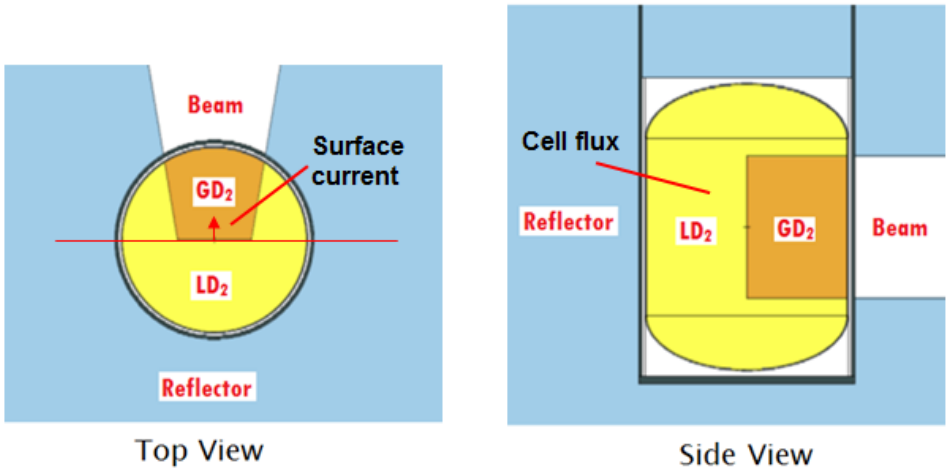

Figure 9. A schematic of the vertical cold neutron source.

One of the important measures of the CNS performance is the cold neutron surface current (in the unit of n/cm^2-s) at the exit surface of the re-entrant hole as shown in the left figure in Fig. 9. The estimated surface current for the CNSs of the new reactor is summarized in Table 3. The result is compared to the value from the existing CNS in NBSR. As can be seen, the surface current for both north and south CNSs have marginal differences between SU and EOC, and they all obtained a gain factor ~3 to the current of the existing CNS in NBSR, which is operated at the same reactor power (i.e., 20 MW). No effort has yet been made to optimize the CNS geometry.

Table 3. Cold Neutron Surface Current at the Exit Surface of the CNS Beams

	North CNS	**South CNS**	**NBSR**
SU	2.25×10^{11}	2.26×10^{11}	8.18×10^{10}
EOC	2.18×10^{11}	2.22×10^{11}	N/A

5. CONCLUSION

An LEU-fueled research reactor optimized for cold neutron production is proposed and studied. The reactor core has two horizontally split halves and each half consists of 9 MTR-type fuel elements. The core is surrounded with a large heavy water reflector that provides a large volume thermal flux trap. Two cold neutron beams and four thermal neutron beams are located in the reflector area to extract intense neutron beams. The LEU core design studies were performed using MCNP-6. A multicycle equilibrium core is achieved based a three-batch fuel management scheme and an iterative

search procedure. The core performance characteristics at four representative burnup states are presented and discussed to demonstrate the feasibility of the new core in terms of flux, power density and beam performance. The calculated surface current at the exit hole of the cold neutron source will achieve a gain factor of three compared to the cold neutron performance of the existing NIST reactor.

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