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A RESEARCH REACTOR CORE DESIGN FOR ADVANCED NEUTRON SOURCE

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ABSTRACT

This paper presents the recent neutronics analysis results of a proposed LEU-fueled research reactor. The main goal of the research reactor is to provide advanced neutron source with a particular emphasis on high intensity cold neutron sources. A tank-in-pool type reactor with an innovative horizontally split compact core was developed in order to maximize the yield of the thermal flux trap in the reflector area. The reactor was designed with 20 MW thermal power and 30-day operating cycle. For non-proliferation purposes, the LEU fuel (U_3Si_2-Al) with 19.75 wt.% enrichment was used. The estimated maximum thermal flux of the reactor is ~5×10^{14} n/cm^2-s. The total peaking factor of the start-up (SU) core is ~2.5. The calculated brightness of the cold neutron source (CNS) demonstrates the superiority of the cold neutron performance of the design.

INTRODUCTION

The National Bureau of Standards Reactor (NBSR) [1] is a 20 MW thermal reactor that currently operates at the Gaithersburg Campus of the National Institute of Standards and Technology (NIST). Since it was built in 1960s, the NBSR has evolved into a major neutron source facility hosting over 2000 guest researchers annually. As of December 2015, NBSR provides beams to 28 neutron research instruments for various scientific experiments. 21 of these instruments use cold neutrons, which are neutrons slowed down by a cold moderator to energies less than 5 meV (wavelength greater than 4 Å). Cold neutrons are preferable for many sensitive scientific instruments because they have long wavelengths suitable to study large molecules and can be transported tens of meters in guides with very small losses.

The NBSR went first critical on Dec. 7th 1967 and was originally licensed to operate for 40 years. Its operating license was extended in 2009 for an additional 20 years, and it will likely achieve another license renewal in the future. Nevertheless, the reactor will eventually need to be replaced. However, the demand and number of neutron users of the NBSR has continued to grow in the past decade, particularly after the addition of 5 new cold neutron guides in 2012. Since the reactor is still operated with high enriched uranium (HEU) fuel, a plan for the safe conversion of the NBSR to low enriched uranium (LEU) fuel has been submitted, but various challenges have appeared in the development and fabrication of the high density LEU fuel (U-10Mo monolithic fuel). Conversions of U.S. high performance reactors such as NBSR have been delayed by at least a decade. [2]

Under these circumstances, there is strong interest to build a new neutron production facility at NIST in order to maintain and enhance the neutron science capacity when the NSBR is shutdown. A reactor replacement study was therefore initiated, and efforts to design a new research reactor optimized for cold neutron sources are currently underway at the NIST Center for Neutron Research (NCNR). Feasibility studies are being carried out to demonstrate the capability of the reactor as an advanced neutron source. The primary purpose of the proposed new reactor is to provide bright and reliable cold neutron beams for scientific experiments. The current design incorporates two high quality cold neutron sources and at least four thermal neutron beams. To leverage the existing site license and knowledge gained from the NBSR, the new reactor was chosen to be of similar scale to the existing one but will incorporate the latest proven research reactor design features. The material testing reactor (MTR) type fuel element was used in the conceptual design of the new reactor. However, LEU fuel with U-235 enrichment less than 20 wt.% was used to comply with non-proliferation requirements. An innovative 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 [3-4]. The new reactor was designed for 20 MW thermal power and a 30-day refueling cycle for an equilibrium core condition to provide a cost-effective research facility.

As part of the reactor design efforts, neutronics studies were performed to demonstrate the high intensity neutron production from the core design using a qualified LEU fuel while satisfying safety-related thermal limits during normal operation and abnormal events. The neutronics calculations were performed using the code MCNP6 [5] with an explicit geometric representation of the core. Specifically, a multi-cycle equilibrium core configuration with several representative burnup states was developed using the burnup feature in MCNP6. Detailed physics calculations were performed using the equilibrium core model to demonstrate the flux performance characteristics. Reactivity control and feedback were assessed to satisfy the standard reactivity control criteria and negative feedback requirements.

In the following section, the study objective is highlighted, followed with an overview of the LEU core design and an outline of the neutronics study procedure. Some recent core performance results different from Ref. 4, particularly the cold neutron source brightness performance, are discussed in the result section. Some summary and concluding remarks are offered in the last section.

DESIGN OBJECTIVE

The principal objective of this study is to demonstrate the superior neutron flux performance characteristics of the new design. One figure of merit to quantify the flux feature of a reactor is its quality factor, which is defined as the ratio of the maximum thermal flux to the total thermal power of the reactor. The quality factors of few well-established research reactors, including the NBSR, are shown in Table 1. The aim of the new reactor is to produce comparable or superior neutron fluxes to those already in existence. Note that some of the reactors shown in Table 1 still use high-enriched fuels and are currently studying fuel conversion options. The flux performance of these reactors will inevitably degrade by certain amount after the fuel is converted to LEU unless other design changes are made.

Table 1. The Performance Characteristics of Some Research Reactors

Reactor	NBSR [1]	BR-2 [6]	OPAL [7]	CARR [8]
Country	U.S.	Belgium	Australia	China
Power (MW_{th})	20	60	20	60
Fuel	HEU	HEU	LEU	LEU
Max Φ_{th} ($\times 10^{14}$ n/cm^2-s)	4[a]	12	3	8
Quality factor ($\times 10^{13}$ MTF[b]/MW_{th})	2.0	2	1.5	1.3

[a] The maximum beam accessible thermal flux in NBSR is ~1.5 $\times 10^{14}$ n/cm^2-s.

[b] MTF stands for maximum thermal flux.

CORE DESIGN OVERVIEW

All recently developed neutron beam reactors [7, 8] are based on compact core concept, which is characterized by a small core with a high power density. A compact core is capable of producing a high thermal neutron flux in a large volume outside of the reactor core such that beam tubes can be readily placed in this region to extract neutrons for scattering experiments. Characteristics of a compact core include: the active core volume is made as small as possible for a given reactor power; the core is surrounded with a reflector of high quality and large volume to maximize the thermal flux production, and the reactor power is set as high as possible to obtain the maximum thermal flux possible. Our core design employs a split compact core to create a thermal flux trap in an easily accessible location in the reflector tank and maximize the flux.

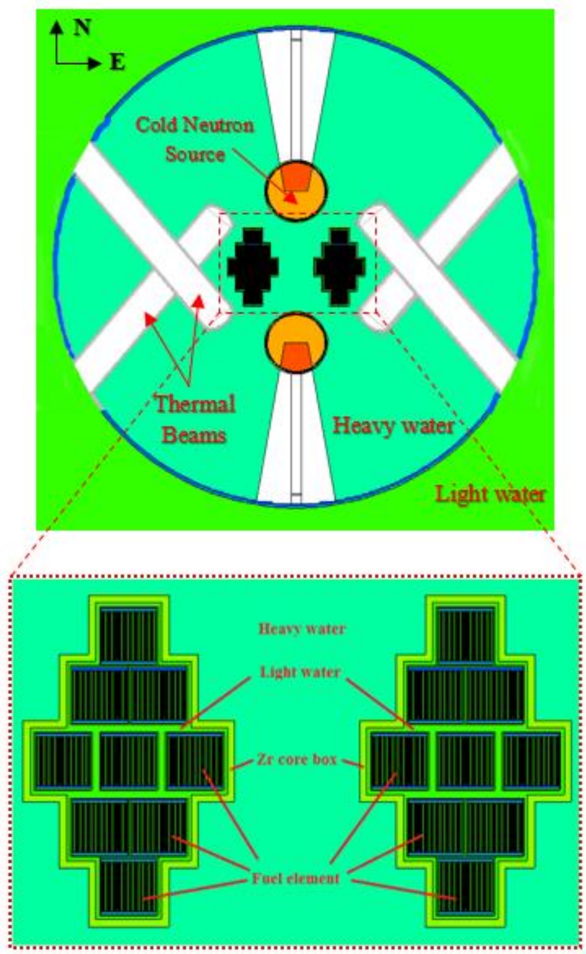

Figure 1. A schematic view of the mid-plane of the reactor with horizontally split cores

Fig. 1 illustrates the reactor components and the fuel element radial layout at the mid-plane of the split core. The commonly recognized ‘tank-in-pool’ design pattern is used in the new design. A cylindrical heavy water tank - 2.0 m in diameter and 2.0 m in height - is placed in the center of a large light water pool, which provides thermal and biological shielding to the reactor. To maximize the 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 provides ideal locations to place cold neutron sources [3]. The core itself is cooled and moderated by light water and surrounded by the heavy water reflector. The core halves are enclosed in two zirconium core boxes which separate heavy water and light water. Two vertical liquid deuterium cold neutron sources are placed in the flux traps 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 north and south. Four tangential thermal beam tubes are placed in the east and west sides of the core at different elevations. They are placed 20 cm above and below the core mid-plane in the present design. This number, however, might be increased if desired.

As shown in Fig. 1, the split core consists of 18 MTR-type fuel elements in two horizontally split regions. Each region consists of 9 fuel elements and represents one half of the reactor core. Each fuel element has 17 inside fuel plates and 2 end non-fuel plates. All plates have LEU fuel clad with Al. The fuel used in this study is U_3Si_2-Al dispersion fuel with U-235 enrichment 19.75 wt.%, which is currently the highest density (~6.5 g/cm^3) LEU fuel certified by the U.S. Nuclear Regulatory Commission (NRC). The fuel meat has a rectangular shape with dimensions of 60 cm long, 6.134 cm wide, and 0.66 mm (26 mil) thick. In this design, the U-235 mass in a fresh fuel element is 391 g. Note that the central fuel elements are separated by 1 cm water gaps (see the bottom figure in Fig. 1) for the purpose of accommodating control elements.

NEUTRONICS STUDIES

The Monte-Carlo based code MCNP6 was extensively used in the neutronics calculations. All the components in the core as well as the cold neutron moderator assemblies are explicitly modeled. The fuel plates are modeled without curvature for simplicity. The neutronics study started with an iterative search scheme to generate fuel inventories at four representative burnup states of a multi-cycle equilibrium core, and then continued with a refined calculation to obtain the physics performance characteristics of the core, with a particular interest on the cold neutron source performance. The safety analysis required power profiles and kinetics parameters are also provided. In this study, all the calculations performed in MCNP are criticality calculations (KCODE mode). For computational efficiency, the statistical uncertainties on the k_{eff} convergence at the equilibrium core search stage were much larger than the ones used for the detailed physics calculations. The k_{eff} statistical 1σ error is ~100 pcm (per cent mille) for the iterative search procedure and ~10 pcm at the detailed calculation stage. In both stages, however, sufficient inactive fission cycles are skipped to ensure the convergence of the fission source.

After the multi-cycle equilibrium core is generated, many key physics performance characteristics of the core such as neutron flux and power can be subsequently calculated by MCNP6. 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 [9], the total source of neutrons is calculated as follows:

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

This is the normalization factor used to estimate the absolute neutron flux and fission rates in the core.

PHYSICS PERFORMANCE

The flux is obtained via the standard MCNP FMESH tally. The cutoff energy for thermal neutrons is 0.625 eV. Due to the movement of the control blades, the axial behavior of the flux varies at different states during the cycle. This variation trend will have a direct effect 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 mid-plane of the core. The achievable unperturbed maximum thermal flux of the new core can reach ~5.0×10^{14} n/cm^2-s during the entire cycle. Since the core is presently designed at 20 MW, the quality factor of the neutron source is thereby approximately 2.5×10^{13} MTF/MW, which exceeds most of the well-known neutron sources currently operating in the world (see Table 1).

The power distribution in one of the most important physics performance parameters for a reactor calculation because it implies the hot spot inside the core. In the present study, the power density for a given position in the core is calculated by MCNP6, in which 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. In order to obtain a detailed power distribution for the core, the fuel meat 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 is 2 × 2 cm^2 and has a volume about 0.264 cm^3. The piece-wised power factor distribution for the mid-plane of the start-up (SU) core is shown in Fig. 2. Here the power factor represents the power generated in an individual piece that is normalized to the average power.

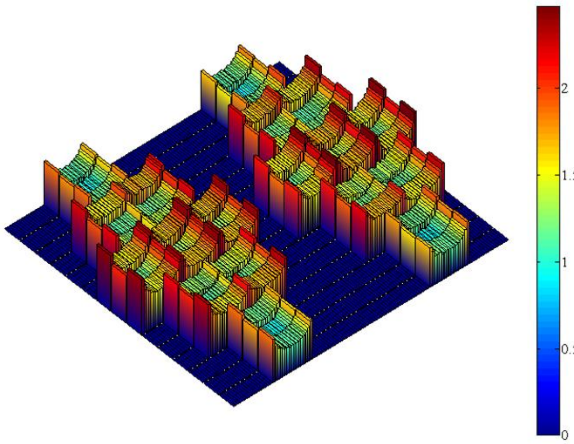

Figure 2. Power distribution at the mid-plane of the SU core.

As shown in Fig. 2, the plates located at both end regions of a fuel element generally have higher power factors. This is attributed to greater neutron moderation effect on the plates at these regions. The SU core is assumed to have the largest power peaking factor because the core is loaded with few fresh fuel elements. As indicated in Fig. 2, the peaking factor under this core configuration is about 2.5, which is acceptable for most plate-type research reactors. Note the plates in the north-south end fuel elements have shown mediocre power density because fuels at these locations have burned more cycles than others.

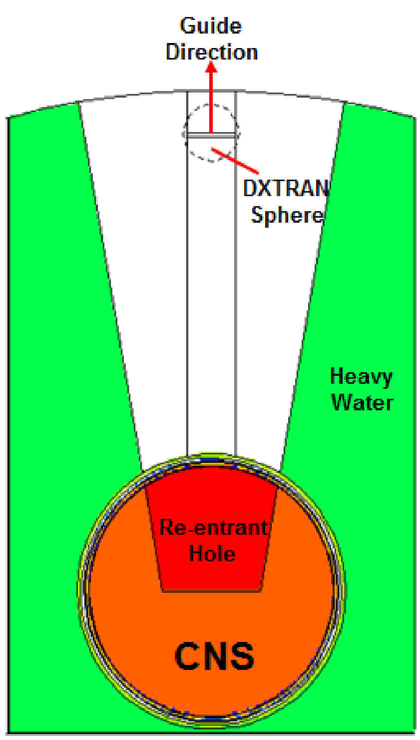

Figure 3. An illustration of the MCNP tally performed for the CNS brightness calculation.

As aforementioned, the principal design objective of the reactor is to generate advance cold neutron sources. One important 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 scientific instruments. For computational saving, the brightness, either denoted in the unit of neutrons/cm^2-s-Å-ster or neutrons/cm^2-s-meV-ster, is obtained from the current tallies across a surface within a DXTRAN sphere in MCNP (see Fig. 3), and its value should be independent of the distance of the tally surface from the source if the tally angle is chosen properly. Simulations of cold neutron production and transport depend heavily on the scattering kernels (cross sections for low energy neutrons, or $S(\alpha, \beta)$ data) of the cold moderators. The recently released ENDF/B-VII.1 data include continuous energy and angle $S(\alpha, \beta)$ data [10] and MCNP6.1 has improved interpolation routines that have reduced non-physical peaks and valleys in the current tallies with small energy and angle bins.

Fig. 4 presents the calculated brightness (in the unit of neutrons/cm2-s-meV-ster) of the vertical CNS in the split core. It is compared to the performance of the large liquid hydrogen (LH_2) CNS at NIST [11]. Fig. 4 clearly shows that substantial gains can be achieved in brightness with respect to the LH_2 CNS over the entire low energy range from 0 to 30 meV. Since the present NIST LH_2 CNS has comparable performance to almost all existing world-wide cold sources, the preliminary results indicate the performance of the vertical CNS in the split core has significant gains compared to all currently available cold neutron sources. Some preliminary efforts made to optimize the CNS and re-entrant hole geometry indicate another 20-40% gain is possible.

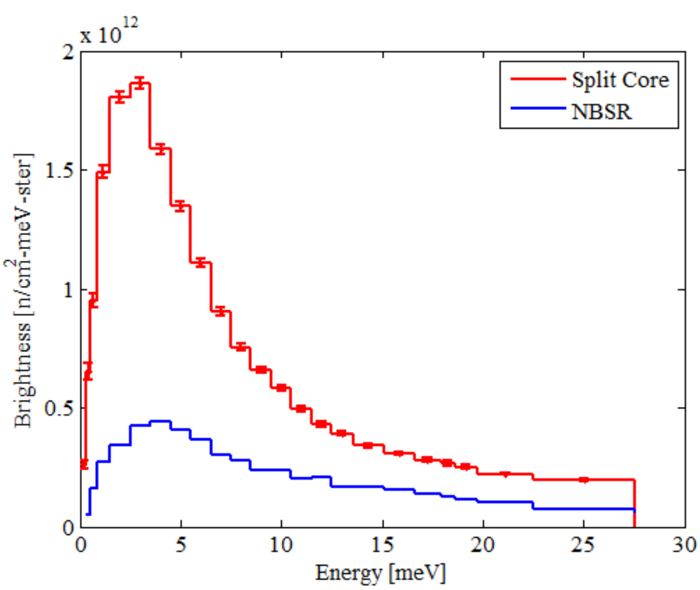

Figure 4. The comparison of CN brightness in the split core to that at NBSR.

CONCLUSIONS

The neutronics studies for a proposed new LEU-fueled research reactor optimized for cold neutron production have been performed. The reactor core has two horizontally split halves and each half consists of 9 MTR-type fuel elements. The core is surrounded with a 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. The neutronics studies were performed using MCNP6. The maximum unperturbed thermal flux can reach 5.0×10^{14} n/cm^2-s, which indicates the quality factor of the neutron source is 2.5×10^{13} MTF/MW and exceeds most of the well-known neutron sources currently operating in the world. The estimated brightness of the CNS confirmed the superiority of the new design.

The new reactor design is currently an on-going project at NIST. Several important tasks will be performed in the near future. For example, the safety analyses will be carried out with detailed flow conditions described. This work will be performed with a RELAP5 model [12]. The U-10Mo LEU fuel (a uranium alloy with 10% molybdenum by weight) is not yet qualified but its high uranium density is of great interest in research reactor community [13]. This fuel will be investigated in the next stage to assess the neutronics feasibility and safety performance under the split core concept. Research efforts will continue on the CNS geometry to achieve the maximum cold neutron gain under specified physical constraints. Some of these tasks are currently being carried out at NCNR while others will be undertaken in the near future.

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