ALTERNATIVE REFLECTORS FOR THE NIST NEUTRON SOURCE

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A conceptual design of a replacement reactor at the NIST Center for Neutron Research (NCNR), referred to as the NIST Neutron Source (NNS), is underway in collaboration with the Brookhaven National Laboratory. The NNS reactor design favors the production of cold and thermal neutrons and in-core irradiation facilities are of secondary importance. Therefore, the focus of the neutronic core design is to maximize neutron leakage from the core to maximize the neutron flux in the beams. As a result, the NNS reactor core differs from typical modern multipurpose reactors which prioritize "in-core" (in-pool) irradiation over neutron beams. In the preliminary NNS design, a heavy water reflector tank was adopted based on "similar" core designs such as OPAL, HANARO, and RA-10. Such a heavy water tank becomes one of the most complicated and sophisticated systems of the reactor. Since the NNS reactor pre-conceptual design does not have any "in-core" (in-pool) radiation facilities, this work is focused on the investigation of an alternative reflector design, which explores the possibility of alternatives to the heavy-water tank and why the latter might be necessary for achieving our goals. The investigation involves using beryllium, graphite, and aluminum "blocks" arranged around the core, similar to what is utilized in the ETRR-2 and TRIGA reactors.

1. Introduction

Research reactors have a very wide variety of uses, including neutron scattering (in which beams of thermal neutrons are scattered by the atoms in a sample, revealing structure, dynamics, and magnetic properties); neutron activation analysis; radiography; irradiation testing of materials; and production of radioisotopes for medical, research, and industrial use. These capabilities are applied by researchers in many fields, ranging from archeology to materials science and from fusion research to environmental science. So-called test reactors, on the other hand, usually have been designed and built with more specialized purposes in mind, such as materials irradiation testing or particular experiments relating to power reactor safety issues. The main fleet of research as well as test reactors were built in the 60's and at that time there was a separation between the types. Unfortunately, over the past three decades, the number of new build reactors has significantly dropped and the new build reactors try to fulfill both missions making the reactor more complex, with associated compromises. Namely, the core size had to be reduced to allow more space for irradiation experiments without lowering the core power while preserving a compact reactor. For instance, the OPAL reactor [1], HANARO, and the RA-10 reactors do follow similar design criteria. These reactors are pool-type reactors. In such pool reactors, the core is often made up of what are called Materials Testing Reactor - (MTR) type fuel elements with aluminum cladding [2]. The fuel plates are arranged in long rectangular boxes, which are arranged between grid plates to form the core. Several positions in the grid are not occupied by fuel elements but by control rods or experimental capsules. Cooling may be by natural convection of the pool water, although this is augmented, for operation at higher power, by pumping pool water through the core. This design led to the "tank-in-pool reactor" or as in a more modern design the tank was converted to a chimney, like the open-pool type but with the core contained in an aluminum or zirconium tank or a chimney.

A typical core (grid) lattice size of these reactors is 5x5 and the reactor core is typically surrounded by a heavy water tank that houses the majority of the “in core” irradiation facilities. The heavy water tank is used as a high moderating ratio “neutron preserver”, simultaneously scattering fully-thermalized neutrons to external experimental stations and fulfilling core reactivity compensation as a reflector. Yet, the heavy water tank becomes one of the most complicated and sophisticated systems of the reactor [3].

The NNS reactor [4], which is designed by the Reactor Operations and Engineering Group (ROE) at the NIST Center for Neutron Research (NCNR) in collaboration with the Brookhaven National Laboratory (BNL), is primarily focused on providing thermal neutron and cold neutron beams. Therefore, the in-core radiation facilities are of secondary importance. Consequently, the neutronic core design favors high neutron leakage from the core to increase the neutron flux in the beams. As a result, the NNS core is very compact, with a 3x3 fuel element array as presented in Figure 1.

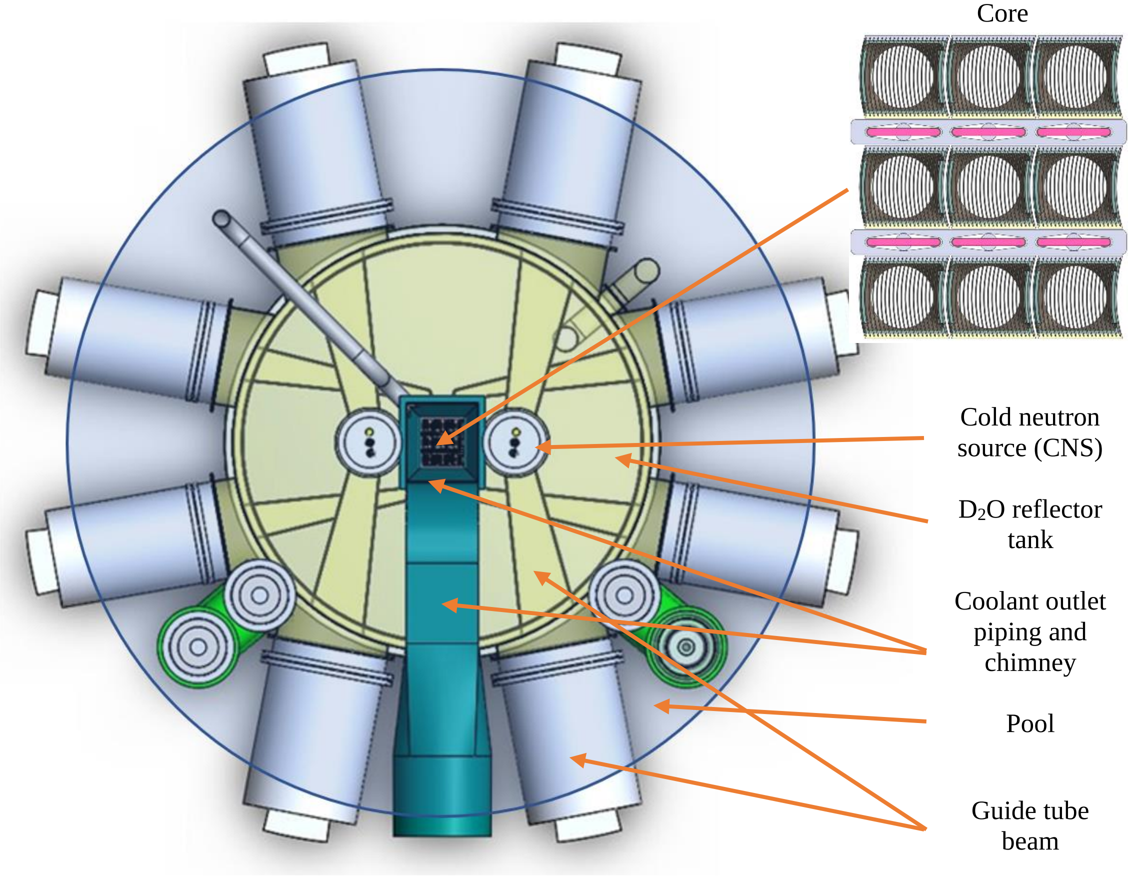


Figure 1: NNS preliminary core layout

In the preliminary NNS design, a heavy water reflector tank was adopted based on “similar” open-pool type core designs. Since the NNS reactor does not have any “in-core” (in-pool) radiation facilities an alternative reflector design may be considered. This includes Beryllium, Graphite, and Aluminum “blocks” surrounding the core as it is realized for example in the ETRR-2 reactor or TRIGA as presented in [5] and [6]. Such design can simplify the reactor design and contraction and enable future flexibility in experimental design such as an introduction of a hot neutron source or further modification of neutron flux in the guide tubes.

2. Methodology

The preliminary NNS core design is a 3x3 lattice having nine fuel assemblies and six absorber blades (2 control and 4 safety) in guide boxes. The fuel is based on U-Mo containing 21 slightly curvature plates fixed in 7.96cm × 8.05cm × 113.0cm fuel assembly (as shown in Figure 1). The core is designed to operate at 20MW with a nominal fuel cycle of about 40 days, and in every fuel cycle, three of the fuel assemblies are replaced. Those assets will be preserved over the investigation steps. The original NNS core design is surrounded by a reflector tank made of Zircaloy-4 and has a cylindrical shape with two flat plates across the top and bottom. It is approximately 6 m^3 in volume as shown in the three-dimensional view in Figure 2. The tank is filled with heavy water and the outside of the tank is covered by a pool filled with demineralized light water.

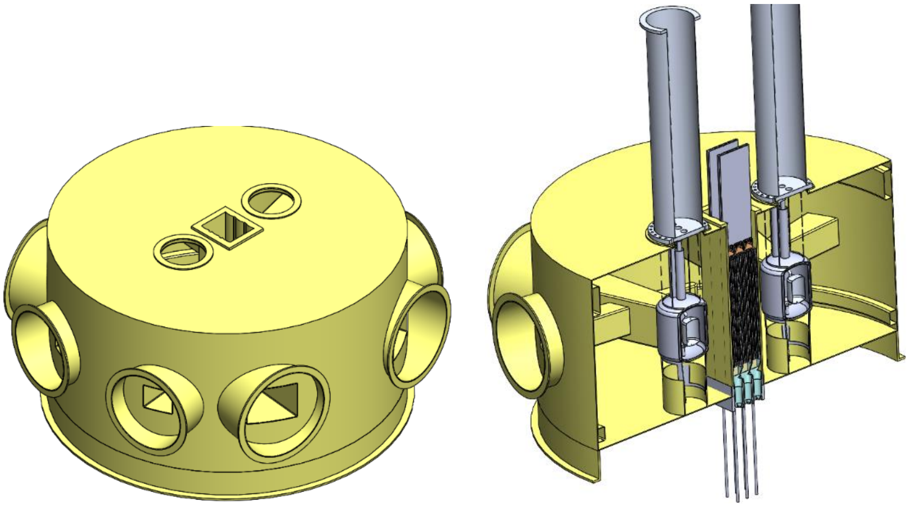


Figure 2: Reflector tank (left) and cutaway showing reflector tank internals (right)

The main goal of this work is to assess the possibility to replace the heavy water reflector tank with “block” type elements reflectors. The main output parameters of interest are:

1. The core eigenvalue (k_{eff}) – the goal is to adjust the alternative block type reflector to meet the original (D_2O reflector) eigenvalue up to ±250 percent mille (pcm).
2. The thermal spectral brightness at the thermal guide entrance (blue circle on the right side of Figure 3) - this quantity can be used for a first-round optimization. The primary goal is to keep the shifted thermal Maxwellian neutron flux distribution towards lower energies as in the original (D_2O reflector) design while preserving the designed performers.
3. The power density distribution in the fuel elements – this quantity can directly affect the thermal power limit of the core as well as the fuel cycle (depletion), the goal is to keep the power density destitution as in the original design (D_2O reflector) up to ±5%.

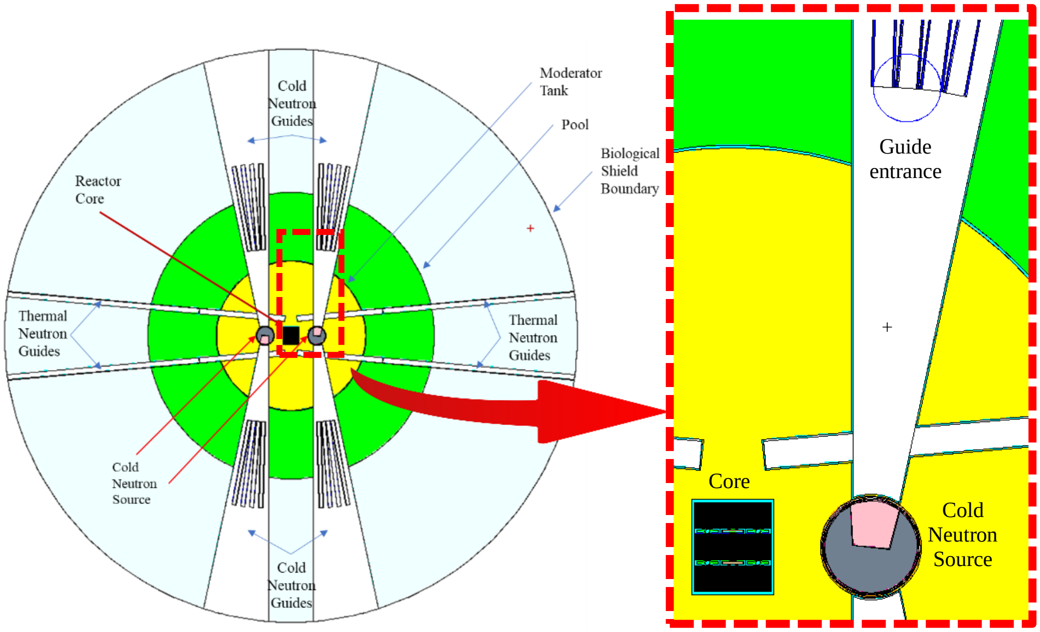


Figure 3: MCNP model planar view, the blue circle on the right side depicting DXTRAN region

2.1. Study stages

In the first stage, the D_2O reflector tank was removed, and it was replaced with de-mineralized light water from the reactor pool (H_2O). We expect that the core reactivity will drop significantly. Therefore, the next step was an investigation of “alternative” reflectors (beryllium, graphite, etc.) to compensate for the neutron leakage. In all these steps the thermal spectral brightness at the thermal guide entrance will be tallied. Based on the results the “optimal” core reflector configuration (mix between the “reflector” blocks) was chosen. Once the reflector was converged the heat production in the core was inspected.

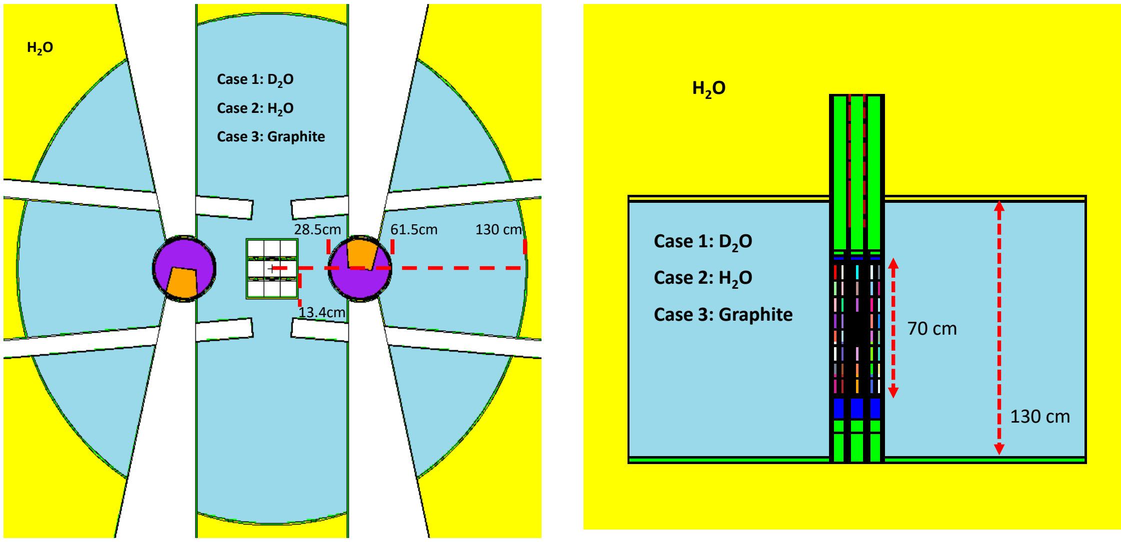
The study was performed with MCNP 6.2 Monte Carlo code package [7] using cross-section data from ENDF/B-VII.1 (ENDF71x) [8], a planar view of the MCNP model is presented in Figure 3. To improve the statistics of the thermal spectral brightness of the neutrons at the thermal guide entrance the DXTRAN [9] card was used. The DXTRAN variance reduction method enables Monte Carlo radiation transport calculations to deterministically place particle tracks on spheres surrounding geometric regions of interest. For the power density distribution, a mesh tally (FMESH card) with a tally multiplier (FM card) was implemented to account for fission energy deposition.

3. Results

This section is divided into two subsections, the first one is focused on the core eigenvalue (k_{eff}) convergence as a function of reflector design. The second section is dedicated to presenting the thermal spectral brightness at the thermal guide entrance and the power density distribution in the fuel elements. The results of the alternative reflector design are compared to the original design (D_20 reflector tank).

3.1. Core eigenvalue (k_{eff}) convergence

The prime goal of this study was to investigate the possibility to introduce a “block” type reflector elements around the core which will replace the heavy water reflector tank without changing the cold source position and the guide tubes. This section presents the evolution of alternative reflector design. The original heavy water reflector tank height and radius are about 130 cm, the cold source radius (including the coating) is 16.5 cm and its center is located 45 cm from the origin (0, 0, 0) while the reactor core at the origin and its active height is about 70 cm. At the preliminary stage, the heavy water in the reflector tank was replaced with demineralized light water used in the reactor pool. This was performed to evaluate the reflector’s contribution to the core reactivity. In the next stage, the heavy water reflector was converted to a Graphite (^{12}C) with a density of 1.7 g/cc. Figure 4 visualizes the above cases (Case 1-3) and the relevant dimensions while Table 1 summarizes the cases’ eigenvalues.



Radial

Axial

Figure 4: Visualization of the reflector tank and the cold source dimensions Cases 1-3

As it can be seen from Table 1, the NNS core indeed is designed for high leakage this is well emphasized by the difference in the eigenvalue between Case 1 to Case 2 (14000 pcm). Moreover, switching to a less effective reflector (Case 3), graphite, in the same dimensions as the original heavy water tank is not sufficient to maintain the core criticality.

Table 1: Case 1-3 core eigenvalue (k_{eff})

Case	**Description**	**k_{eff}**
1	Original – D_2O reflector tank of 130 cm radius	**0.99996**
2	Reflector tank of 130 cm radius is filled with H_2O	0.85944
3	Reflector tank of 130 cm radius is filled with Graphite	0.99479

Armed with the above deductions it was clear that in order to shrink the reflector up to the cold source a neutron multiplication material should be introduced. Therefore, beryllium was introduced since it is a good thermalization/reflector as well as its capability to multiply neutrons via n,2n reaction. Since the threshold of the Be(n,2n) reaction is 1.86 MeV, only a fraction of the fast neutrons produced during the fission process will be able to produce the reaction. Consequently, beryllium reflector coating should be positioned as close as possible to the reactor core. Cases 4 and 5 present a "block" type reflector around the core up to the cold source. In Case 4, only ^{9}Be with a density of 1.84 g/cc was introduced. In Case 5, a two-zone reflector was used with an inner reflector zone made of ^{9}Be and an outer reflector zone made of ^{12}C (graphite). Table 2 and Figure 5 present Cases 4 and 5, respectively. The dimensions of beryllium and graphite were adjusted so that the total thickness of the reflector will be 15 cm. While the outer reflector zone was made as thick as possible to thermalize the neutrons before reaching the cold source, the inner reflector zone (Beryllium) was adjusted correspondingly to assure core reactivity (match core eigenvalue).

Table 2: Case 4-5 core eigenvalue (k_{eff})

Case	**Description**	**k_{eff}**
4	Beryllium reflector box of 15cm	1.03685
5	Beryllium (5 cm) and Graphite (10 cm) reflector box[1]	**1.00223**

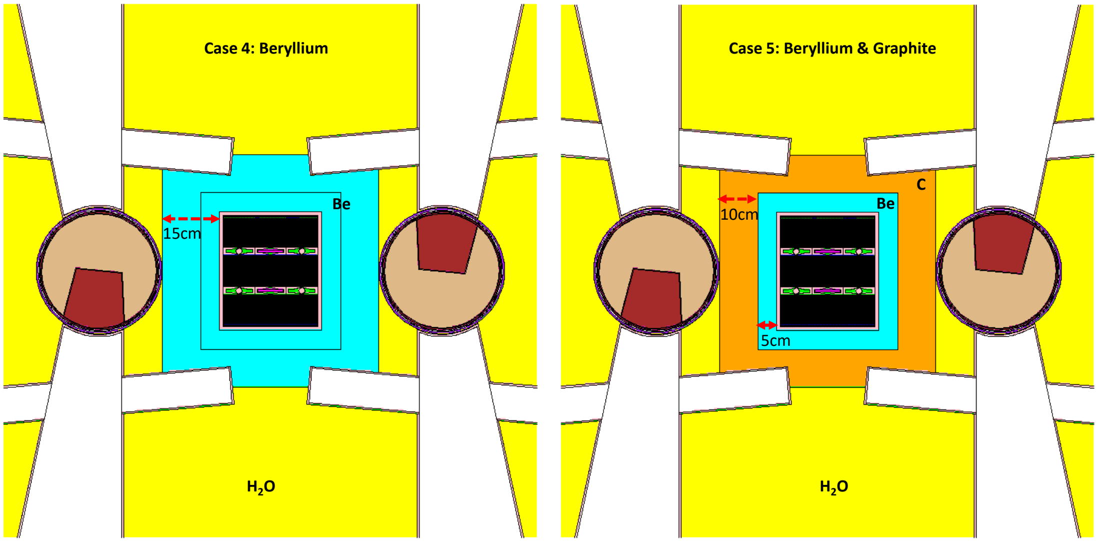


Figure 5: Visualization of the reflector dimensions Cases 4 (left) and Case 5 (right)

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[1] The best core eigenvalue (k_{eff}=1.00049) was achieved with a reflector box where beryllium size was 4.7 cm and graphite size was 10.3 cm. Since the goal was to reach a match between the cases in the limit of 250 pcm for further analysis, Case 5 dimensions will be adopted.

3.2. Thermal spectral brightness at thermal guide entrance and the power density distribution

Above section described how the core eigenvalue was matched by introducing a reflector mix with an inner zone made of beryllium and an outer zone made of graphite while the total dimension of such reflector was limited up to the cold source. This section is focused on two main parameters: (1) The neutron thermal spectral brightness at the thermal guide entrance, (2) The power density distribution in the fuel elements. Results presented below are the results of Case 1 – the heavy water reflector tank (the original NNS design) and Case 5 – the block-type reflector made of beryllium and graphite.

Figure 6 presents the thermal neutron spectral brightness at the thermal guide entrance (as described in Figure 3), Case 1 vs. Case 5. While the thermal neutron spectral brightness distribution shape is preserved the magnitude of the cold neutron, noted in the red rectangular in Figure 6, is almost one order of magnitude lower in Case 5 (block type reflector) compared to Case 1 (heavy water reflector tank). Since the primary goal of the NNS cold neutron sources is to provide cold neutrons, with wavelengths greater than 4 Å, such reduction (almost one order of magnitude) may be of significant impact on the cold neutron instruments and experiments.

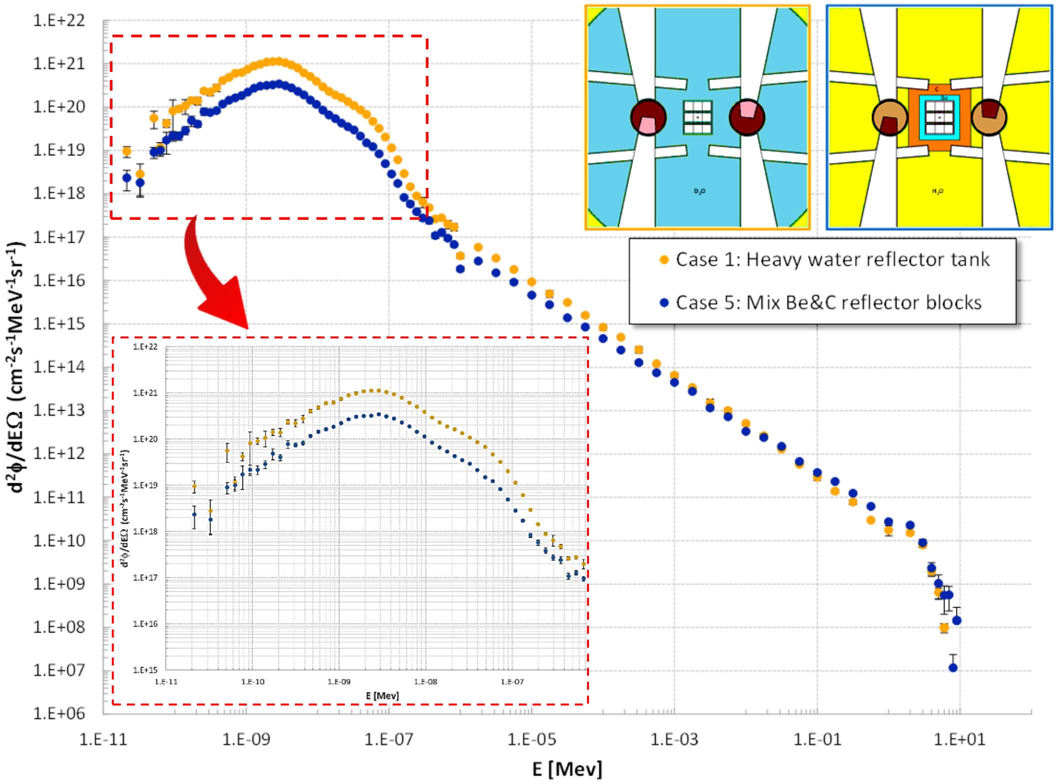

Figure 6: The thermal spectral brightness at the thermal guide entrance Case 1 vs. Case 5

Figure 7 presents the radial normalized power density (normalized with respect to maximum power density) in fuel elements for Case 1 and Case 5 at the center of the core. Figure 8 depicts the difference in power density in percentage compared to Case 1. As it can be seen in Case 5, the mixed “block” type reflector, the fission density shifter towered the core center and it is about 25% higher compared to Case 1. Congruently, the shift in generated power is due to a less thermalized neutron at the core edges which are produced by the Be(n,2n) reaction. Such a shift in power may affect the core thermal power limits as well as the fuel burnup which in turn will disturb the fuel cycle and will require a more detailed investigation yet, this is out of scope at this point of the study.

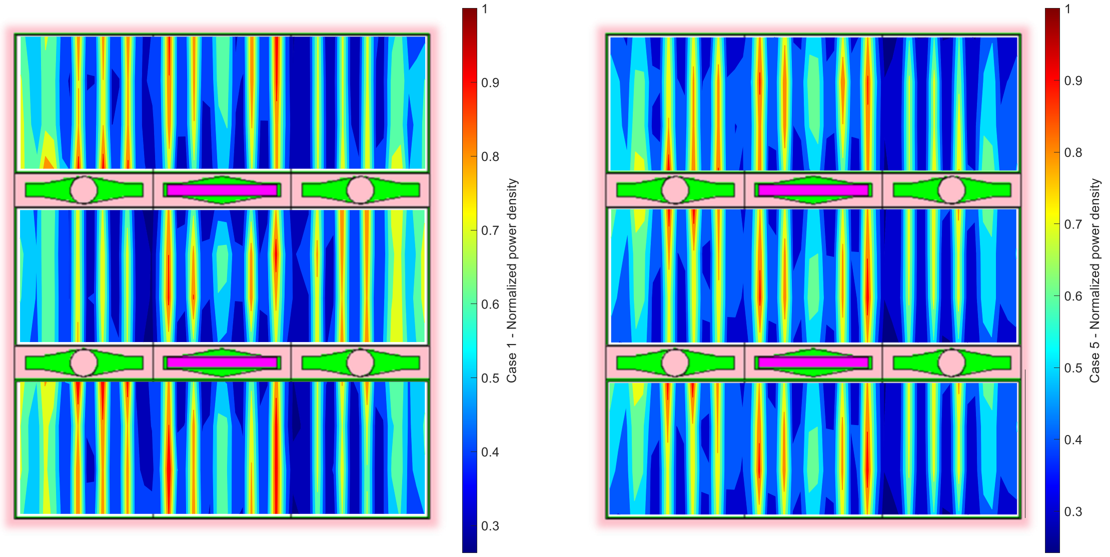

Figure 7: Case 1 (left) and Case 5 (right) normalized power density distribution

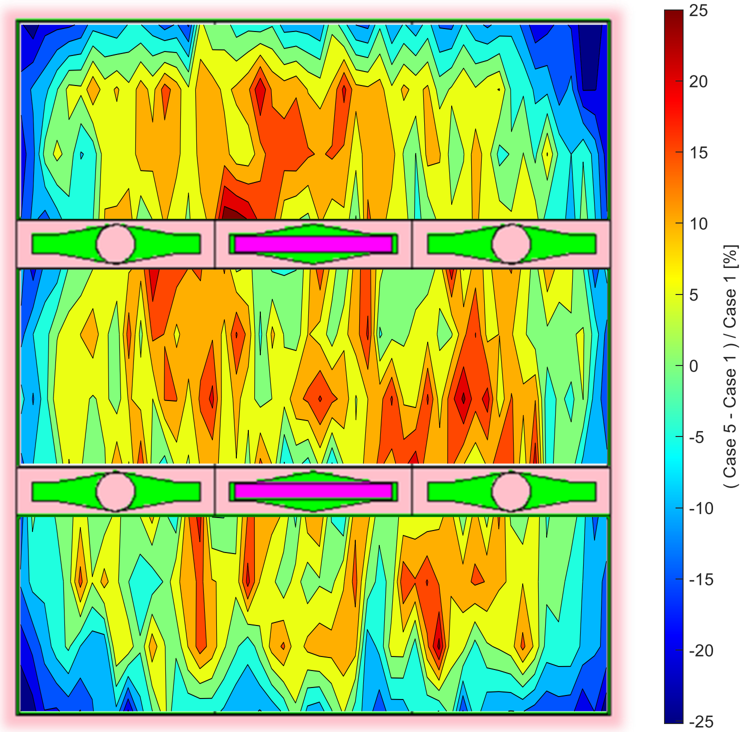

Figure 8: Relative power density difference of (Case 5 - Case 1)/Case 1 in percent

4. Conclusions

This study was focused on examining the implementation of an alternative reflector for the NNS. The current NNS design feature of a heavy water reflector tank which is comparable to a “block” type reflector is intricate in means of design and manufacture. Therefore, in this study, a compact block-type reflector was proposed. The primary goal was to introduce an alternative reflector design to the NNS core without impairing neutronic performance. Since the NNS core is designed as a very compact core with high leakage a compact block-type reflector required the implementation of neutron multiplication material in the reflector region. This was achieved by an introduction of beryllium as neutron compensation, and a graphite filler was followed to further thermalize the neutrons before reaching the cold source. For such a layout, the core eigenvalue was matched by adjusting the beryllium and graphite thickness respectively. Since the primary objective of the NNS is to supply cryogenically-cooled neutrons at high flux intensity the thermal neutron spectral brightness at the thermal guide entrance was examined. While the shape (spectra) of the cold neutrons was preserved the magnitude was decreased by almost one order of magnitude in the block-type reflector design compared to the original heavy water tank. Such degradation may be of significant impact on NNS performance. An additional parameter of interest was the core power density distribution had to be unperturbed, which in turn dictates the core power limit (hot spot) as well as the cycle length (burnup). For the proposed “block” type reflector the power density distribution had shifted by about 25% toward the core center compared to the original heavy water design which may significantly affect both the core power limit as well as the core shuffling scheme.

In summary, it was observed that the current NNS design which embraces a heavy water reflector tank is a superior one compared to the proposed compact “block” type reflector options.

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.

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