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Experimental and Theoretical Study for the Effects of Different Reflector Types on the Neutronic Parameters of the MNSR Reactor

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Abstract

Nowadays, most research reactors utilizing highly enriched uranium fuel are planned to be converted to use low enriched uranium fuel. As a result of the conversion, the neutron thermal flux (Φ_{th}) decreased by 10%. Such lose in the neutron flux can be compensated by introducing a suitable reflector material around the reactor core. Three different type of reflectors have been investigated, graphite, heavy water and light water. The effect of each type on the reactivity and Φ_{th} distribution was investigate by monitoring the reactor parameters after inserting containers filled with a reflector material inside inner irradiation site. Furthermore, a theoretical analyses study has been conducted using the MCNP4C code. The analyses revealed that theoretical and experimental values are comparable. Our results indicate that graphite is the most preferred mateial among the studied reflector groups. The Φ_{th} in the Inner Irradiation Tube (IIT) was increased by 12, 11, and 2% for graphite, light water and heavy water, respectively. Moreover, heavy water introduced the highest reactor reactivity, 0.6 mk, followed by light water and graphite with the values: 0.323, and 0.127 mk, respectively. Finally, the graphite reflector can be a suitable reflector, since it compensates the decreasing in the Φ_{th} with minimum effect on the core reactivity.

Keywords: MNSR; Reflectors; MCNP; Neutron flux; Graphite; Heavy water

Introduction

MNSR stands for "miniature neutron source reactor". It is a research reactor uses light water as a moderator, pure beryllium as a reflector and highly enriched uranium as a fuel [1]. The reactor is mainly used for Neutron Activation Analysis (NAA). Ten vertical holes are designed for sample irradiation, five of them are located in the annulus beryllium reflector and called Internal Irradiation Sites (IISs) and the rest are the external irradiation sites (Figure 1). At the same power level, the neutron flux at an IIS for a generic the U-235 enriched 19.75% core is approximately 10% lower than that for the U-235 90% enriched core. The power therefore for the U-235 19.75% enriched core should be around 10% higher in order to retain a neutron flux of 1.0 × 10^{12} $cm^{-2}.s^{-1}$ at the IIS [2,3]. Many studies have been made for the MNSR conversion from the U-235 enriched 90% to U-235 19.75% enriched fuel [4,5]. This conversion process demands an increase in U-235 loading to achieve sufficient excess reactivity in order to overcome parasitic absorption in U-238 and to match the cycle length with U-235 90% enriched fuel. As a result of higher fuel loading, the neutron spectrum will become harder as well as Φ_{th} will decreased. The maximum relative decrease in the Φ_{th} of U-235 90% enriched and U-235 19.75% enriched fuels in the IIS was 10%.

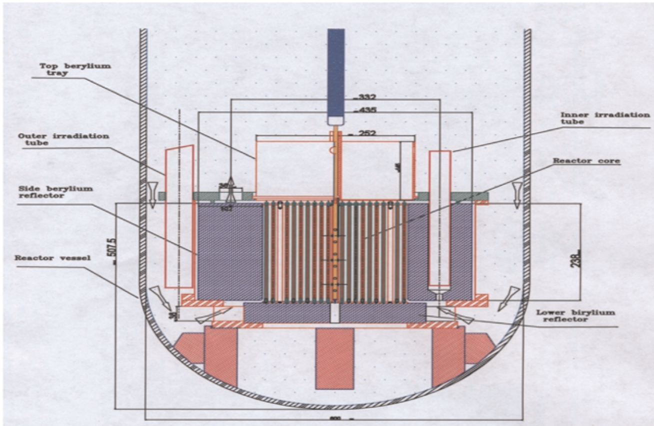

Figure 1: Location of inner and outer irradiation sites of the MNSR reactor.

These losses can be compensated by introducing a suitable reflector material. Such material will improve the average neutron flux thus increasing the excess reactivity in the core. In research reactors, different types of material are used as neutron reflectors in the reactor core. The reflector yield increases with the decrease in the absorption cross-section and increase in the scattering cross-section of the reflector [6,7]. The use of reflectors in the reactor core provides some advantages such as reduction in the critical size of the reactor core as well as reduction in the critical mass of the fuel. To assess the effect of different reflector materials on the neutronic parameters of the MNSR research reactor such as the reactivity and Φ_{th} in inner irradiation sites, a chain of TPCC filled of reflector material was used. The reactivity effects of flooded inner irradiation sites in the MNSR reactor were evaluated both numerically and experimentally [8]. It was found that the reactivity increase for each cm of the water is 4.5e^{-3} mk/cm. In this work, three reflector materials such as: Heavy water, graphite and light water were used to study the efficiency of the reflector on the MNSR parameters. The reactor reactivity and the neutron flux in inner radiation sites were calculated and compared for each reflector material. Several materials are traditionally used as neutron reflectors in the reactor. Such as water, graphite and hevy water [9-11].

Water is a universal material that could be used as a moderator, a coolant and a reflector at the same time. The scattering cross-section of hydrogen, and its ability to slow neutrons rapidly down to thermal energy makes water an obvious choice as a reflector. However, water has relatively low density and suffers from lack of structural functions. Graphite is widely used as a moderator or reflector in nuclear reactors due to its desirable nuclear, physical and chemical properties. Its properties include low cost, non-oxidation, simple manufacturing technology and high temperature stability. It is made up of layers of carbon atoms bound together in the form of repetitive hexagonal patterns. The separation between two consecutive layers is about 3.35 Å as shown in Figure 2.

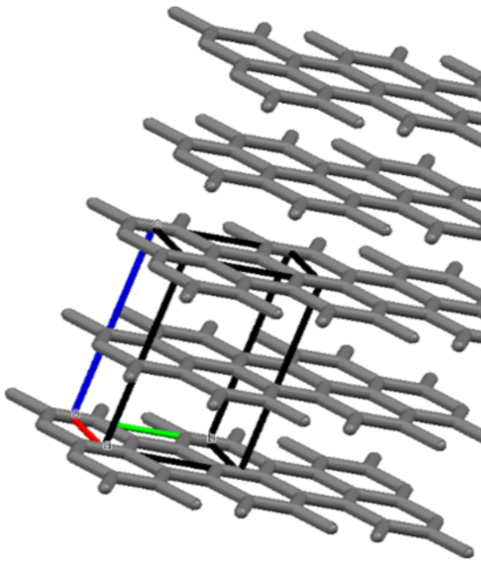

Figure 2: Crystal structure of graphite.

Dsiadvantages of graphite include: The return of fast neutrons from the graphite reflector to the reactor is relatively small, and chemical interaction of graphite with reactor coolant, could lead to a chemical reactions. Heavy water contains deuterium (an isotope of hydrogen) instead of hydrogen, it is also knows as deuterium oxide (DO_2). It is known to be used in low enriched reactor (CANDU) due to its ability to control the energy of prompt neutrons. Moreover, high-energy gamma rays resulting from some fission products such as (^{140}Ba-^{140}La) in irradiated fuel may induce the generation of light neutrons from heavy water according to the reaction D (γ, n) H, which increases the intensity of nitrous flux. This phenomenon is highly important in case of the reactor shut down.

Materials and Methods

Material characterization

The graphite sample was characterized by two different techniques, X-Ray diffraction and Raman spectroscopy. The XRD diffraction pattern was recorded on STADI-P STOE, with Cu K_α radiation (λ=1.54060 Å) and a germanium monochromatic operated at 50 kV and 30 mA in the range 5° to 70°. Figure 3 represents the collected XRD diffraction pattern (black dots) of the sample together with the simulated pattern of graphite (red line). A good agreement between and the experimental and simulated diffraction spectrums is clear. Raman analysis was carried at room temperature on a Thermo Scientific Nicolet 6700 Fourier transform Raman Spectrometer, Madison, USA. It is equipped with Nd: YAG laser operating with an exciting frequency at 1064 nm. Indium gallium-arsenide detector operating at room temperature is used for signal detection. Spectra were measured at 8 cm^{-1} resolution in the region from 100 to 4000 cm^{-1} and a total of 200 scans. A separate background spectrum was subtracted after pattern collection.

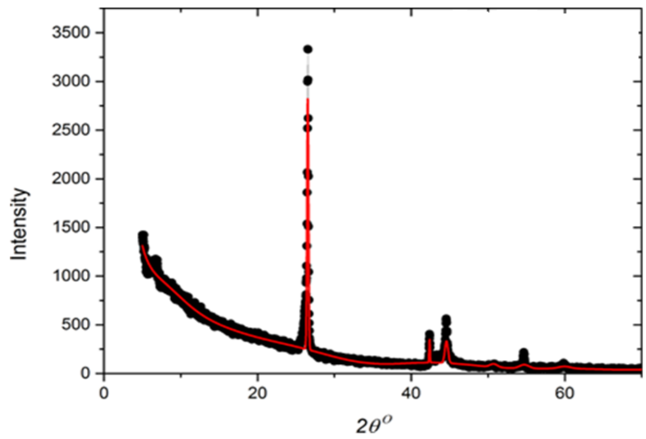

Figure 3: Comparison between experimental (black dots) simulated XRD patterns obtained for graphite sample. Note: ● Experimental — Simulated

Raman pattern of the graphite sample is displayed in Figure 4. It is clear that Raman shifts are fully consistent with the main frequencies over the entire spectrum field, indicating that the structure of the material used corresponds to the expected structure of graphite. The term 'heavy water' refers to a highly enriched water mixture that contains mainly deuterium oxide D_2O. For instance, the enrichement of heavy water used in CANDU reactors is 99.75%. Therefore, it is essiential to determine the enrichement of our sample. The heavy water content of the sample is determined by Deuterium dilution method using IRMS IZO prim mass sepctrometery from GV instrument. The results revealed that the ratio D_2O/H_2O is about 99.06%, which is close (and within the limits of error) to the percentage stated in the sample certificate of 99%.

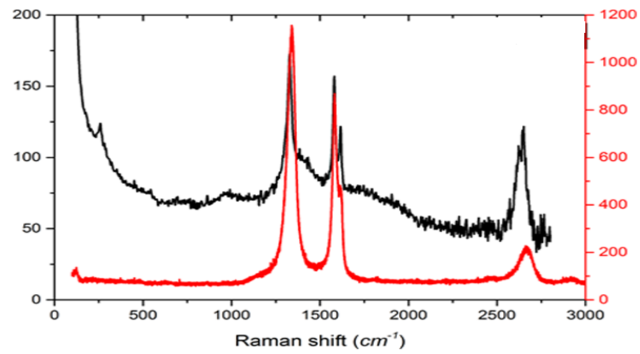

Figure 4: Comparison between experimental (red line) and black line) Raman spectra of graphite. Note: — Reference — Sample

For further investigation, we compared the proton NMR spectra of our samples with the spectra of a reference sample, where the concentrations of D_2O in reference is 99.6%. The width of the water resonance in a NMR spectrum depends on the amount of light water present. The larger concentration of H_2O the greater the width of the water line. This phenomenon is known as radiation damping. Figure 5 presents the 400 MHz proton NMR spectra of the two samples. It is clear that the width of the water resonance in a NMR spectrum of our sample is closer to that in the reference sample, indicating that the concentrations of H_2O in both samples are comparable.

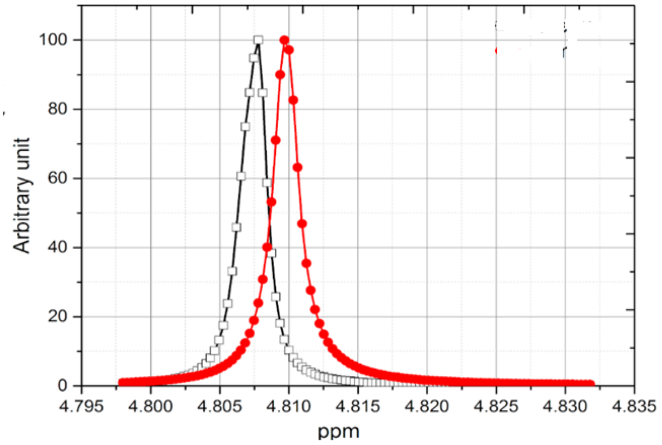

Figure 5: Comparison of NMR Spectroscopy of D_2O sample with 99.6% enrichment one. Note: ─ Reference ─ Sample

Experimental procedure

In this study, three different sets of experiments were conducte. In each experiment, as illustrated in Figure 6, chains of Interconnected Polyethylene Containers (TPCC) filled with the same reflector material, are inserted into the IIT form the top of the reactor using a long rop.

Therefore, the void inside the IIT will be filled with considered reflector materials. Consequently, a gain in excess reactivity and in the Φ_{th} will be obtained. The procedure form adopted for the experimental approach was the following:

All measurements were made on low power level. The initial reactor parameters were: Φ_{th} was 2×10^9 n.cm^{-2}.s^{-1}, the control rode position was 137 mm, and the IITs were empty.After adding the chains filled with reflector material into the IITs, the control rode position will be withdrawal into the reactor to compensate the reactivity gain caused by the reflector material. Stable critical position of the control rode before and after the loading of the chains gave the total reactivity worth of these chains.

The experimental relationship of the control rod reactivity (ρ) at different withdrawal positions (z) was evaluated as following:

$$\rho(z)=1.08 \times 10^{-5}+4.626 \times 10^{-4}.\ z+2.644 \times 10^{-4}.z^2+3.238 \times 10^{-7}.z^3-8.11 \times 10^{-9}.z^4+1.687 \times 10^{-11}.z^5$$

where: ρ-reactivity (mk), and z-height (mm).

The reactivity gain of each reflector material can be calculated using equation at two positions (reactivity with reflector material-reactivity without reflector material).

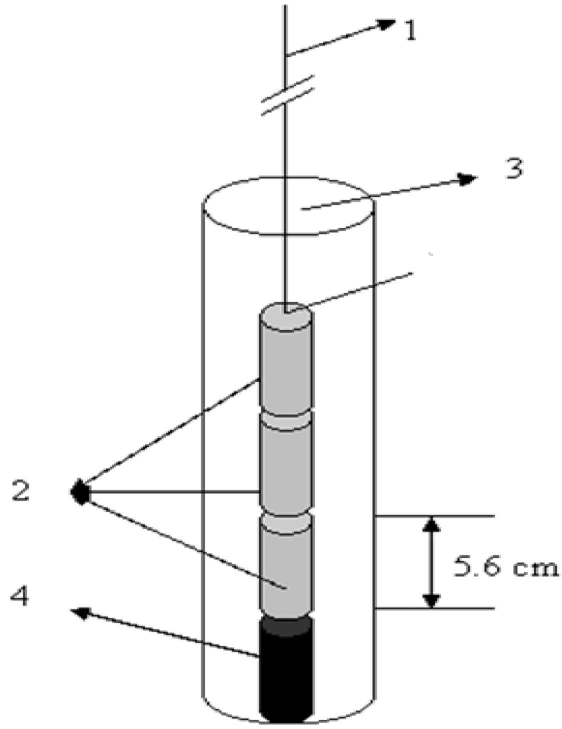

Figure 6: IIT filled with reflector material, where: 1-long rope, 2-a chain of TPCC filled with reflector material, 3-IIT, 4-irradiation capsule. Note: Φ=1.45 cm

Analytical study

In this work, MCNP (Monte Carlo N-Particle) version.4.0 simulation package has been used for reactor calculations [12]. MCNP is a general purpose transport code, which uses Monte Carlo method for modeling the interaction of different type of particles with materials. The Monte Carlo method has been practically useful for calculating the MNSR reactor parameters. A three dimensional model for MNSR reactor was prepared for evaluating the effect of reflector material type on both reactivity and neutron flux. In this model, the reactor geometry and the fuel configuration inside the core were kept unchanged as in safety analysis report. Whereas, the void inside the IISs was changed to account for the chains of polyethylene containers inserted in the IITs (Figures 7 and 8). KCODE card reflector is used to determine the keff (reactivity) parameter. A total of 400 cycles of iterations on a nominal source size were performed, in each cycle, 15000 particles were used in order to lower the estimation of the statistical error. Initially, the first 50 cycles were ignored to ensure the homogeneity distribution of the neutron source. The Φ_{th} distributions in the IIT was calculated using the F5 tally.

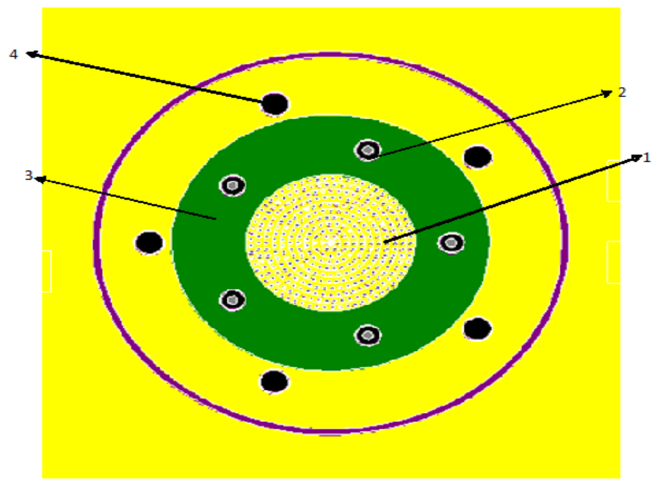

Figure 7: Horizontal cross section of MNSR by MCNP4C code, where: 1-inner irradiation site with chain of TPCC filled with reflector material, 2-fuel, 3-Be reflector, 4-outer irradiation site.

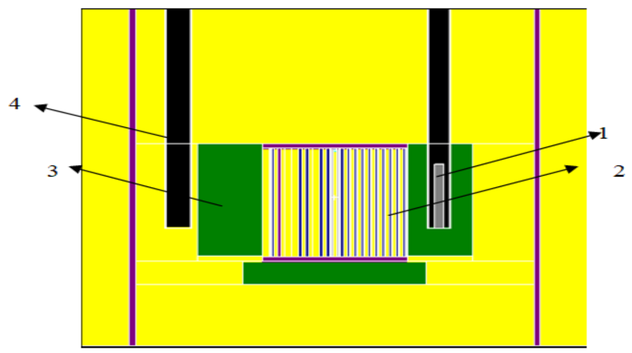

Figure 8: Vertical cross section of MNSR by MCNP4C code, where: 1-IIT with chain of TPCC filled with reflector material, 2-fuel, 3-Be reflector, 4-outer irradiation site.

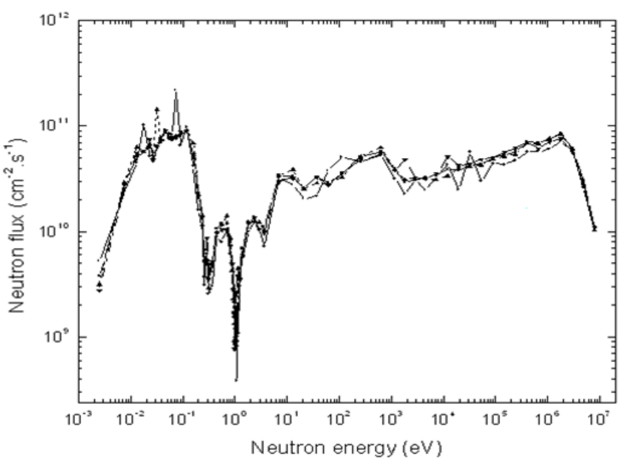

Figure 9: The neutron flux for 69 energy groups in the IIT of the MNSR reactor with chains of the potential reflectors (H_2O, D_2O and Gr).

Results and Discussion

The aim of this work is finding reflector material, which gives the maximum Φ_{th} and minimum effect on the reactor reactivity. Table 1 shows the experimental reactivity values for three reflector types. These values were calculated using experimental equation. The worth of reflector materials were 0.6, 0.323 and 0.127 mk for heavy water, light water and graphite respectively [13]. These values for one cm^3 of reflector material also calculated and found to be: 9.393E-3, 5.056E-3 and 2.946E-3 mk/cm^3. The heavy water was gave the maximum reactivity, followed by light water and graphite. Table 2 shows the analytical reactivity values for three reflector types. These values were calculated using MCNP4C code. The worth of reflector materials were 0.59, 0.339 and 0.125 mk for Heavy water, light water and graphite respectively. These values agree well to the experimental values as can be seen in this table.

Table 3 shows the MCNP results of the maximum Φ_{th} (in IIT). The maximum Φ_{th} were: 1.05E+12, 1.15E+12 and 1.16E+12 n.cm^{-2}.s^{-1}for the heavy water, light water, and graphite respectively. As it can be seen from this table, the graphite reflector gave the highest Φ_{th} followed by light water and heavy water reflectors. A comparison of these values with referenced values which were calculated by 2,3,13 can be seen in this Table as well. The calculated results have good agreements with the results calculated for U-235 90% enriched fuel without capsules. The results showed that the graphite reflector can be used since it compensated the decreasing in the Φ_{th} (from 1.03E12 n.cm^{-2}.s^{-1} for U-235 90% enriched, 90% UAl to 9.34 E11 n.cm^{-2}.s^{-1} for U-235 19.75% enriched, 12.6% UO_2). Figure 9 shows the Φ_{th} for 69 energy groups in the IIT of the MNSR reactor for the existing.

Reflector	Control rod position (mm)		Reactivity		
	Before adding capsules	After adding capsules	(mk)	(mk/g)	mk/cm^3
D_2O	137	110	0.6	8.66E-03	9.39E-03
H_2O	137	117	0.323	5.06E-03	5.06E-03
C	137	122	0.127	1.34E-03	2.95E-03

Table 1: Reactivity *vs.* control rod position for three reflector chains (each chine consists of three capsules).

Reflector	Reactivity					
	MCNP			Experimented		
	(mk)	(mk/g)	mk/cm^3	(mk)	(mk/g)	mk/cm^3
D_2O	0.59	8.40E-03	9.24E-03	0.6	8.66E-03	9.39E-03
H_2O	0.339	5.31E-03	5.31E-03	0.323	5.06E-03	5.06E-03
C	0.125	1.32E-03	2.90E-03	0.127	1.34E-03	2.95E-03

Table 2: Comparison between MCNP and experimental results for three reflector materials.

U-235 90% enriched fuel with beryllium reflector and the chains filled with potential reflectors (H_2O, D_2O and Gr). The max relative difference in the Φ_{th} in the IIT is less than 10%, depending on the reflector type.

Reflector type	Thermal flux (n/cm^2.s) (0-0.625 eV)			
	This work with capsules (U-235 90% enriched)	This work without capsules (U-235 90% enriched)	Without capsules (U-235 90% enriched)	Without capsules (12.6% UO_2)
		1.04E+12	1.03E+12	9.34 E+11
D_2O	1.05E+12	-	-	-
H_2O	1.15E+12	-	-	-
C	1.16E+12	-	-	-

Table 3: Φ_{th} for different reflectors in the IIT.

Conclusion

Experiment and analytical studies were successfully accomplished in order to evaluate the effects of the deferent reflector materials namely, D_2O, H_2O and Gr on the neutronic parameters of the MNSR core. Good agreements were noticed between the results of 3-D MCNP model (in this work and previously published results) and the experimental results for the MNSR reactor. The Graphite reflector has the most efficient in this reflector group since it gave the highest gain in Φ_{th} which was equal to 1.16E+12 n.cm^{-2}.s^{-1}. It followed by light water and heavy water respectively. The heavy water reflector gave the highest reactivity worth which was equal to 0.127 mk. It followed by the light water and graphite respectively. Finally, the results showed that, the graphite-beryllium reflector (Beryllium as annular reflector+chins of graphite in IIT) was the best material, since it compensated the flux losein IIS-due to the conversion of the MNSR U-235 90% enriched fuel to the U-235 19.75% enriched fuel- with minimum effect on the MNSR reactivity worth.

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