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Sensitivity analyses of the use of different reflector materials on the main neutronic parameters of the TRIGA Mark-II research reactor

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Abstract

This article discusses the effect of changes in the neutron reflector material on the neutron parameters of the TRIGA Mark-II research reactor. Since changing reflector materials critical – some of the safety and neutron parameters of the reactor core, sensitivity analyzes for four reflector materials commonly used in nuclear reactors have been selected. These reflectors are namely: beryllium, beryllium oxide, heavy water, and light water. Their integral effects on the main neutronic parameters have been investigated. The related neutronic parameters are as follows: effective multiplication factor, neutron flux, power distribution, hot rod power peaking factor F_{HR}, and shutdown margin (SDM). The calculation results for all proposed reflectors in comparison with the conventional graphite reflected core was performed. Sensitivity analysis is shown to be of great relevance for the determination of the best reflector material and thus to establish its full impact on the neutronic parameters under investigation, whereby reactor modeling and optimization can be carried out effectively. Actually, it was found that the beryllium has been considered to be the most effective reflector material among other candidates since it gave good results from neutronic point of view, followed by beryllium oxide, graphite, heavy water, and light water.

Keywords: Sensitivity analysis; TRIGA Mark-II core; reflector material; neutronic parameters; data libraries

Introduction

The efficiency of a reflector is measured by the ratio of the number of neutrons reflected back into the reactor core to the number entering the reflector. In nuclear applications, it is a combination of a small atomic weight, a small absorption of thermal neutrons a higher slowing down power, and a height scattering cross-section together with the thickness that make a good reflector material. Material such as graphite, thanks to its reflection feature, the neutrons that leave the reactor core will collide with carbon nuclei and be scattered back into the reactor core via elastic scattering reaction [1]. By reducing neutron leakage, the reflector increases the effective multiplication factor (k_{eff}) in the reactor core and decreases the amount of fuel necessary to make the reactor critical. Consequently, in the present paper, a set of four reflector materials (beryllium, beryllium oxide, heavy water and light water against the conventional graphite reflected core (**Table 1**)) were selected to discuss the sensitivity of the reflector on the TRIGA Mark-II research reactor without changing the reflector thickness. The effective multiplication factor, neutron flux, power distribution, hot rod power peaking factor F_{HR} and shutdown margin (SDM) were calculated for each reflector material which allows then to investigate the sensitivity of the selected reflector to those parameters.

Table 1. Characteristics of selected reflectors at room temperature [2,3].

	Parameters	Graphite	Beryllium	Beryllium oxide	Heavy water	Light water
	Atomic weight	12.0	9.0	25.0	20.0	18.0
	Density, g/cm^3	1.600	1.850	3.025	1.100	1.000
Thermal properties	Scattering cross-section (Σ_s), cm^{-1}	0.38	0.76	0.72	0.35	1.47
	Thermal absorption cross-section (Σ_a), cm^{-1}	0.00036	0.0011	0.00066	0.000036	0.0220
	Diffusion coefficient (D), cm	0.86	0.54	0.59	0.85	0.16
Epithermal	Logarithmic Energy decrement (ξ)	0.158	0.206	0.173	0.504	0.925
	Diffusion length (L)	49	22	30	154	2.70
	Slowing down power ($\xi\Sigma_s$)	0.060	0.16	0.12	0.18	1.36

Basic Reactor Description

The 2 MW TRIGA Mark II (TM2) research reactor is a pool-type reactor cooled and moderated by light water. The fuel is composed of a mixture of uranium (8.5% wt., enriched at 19.7% with ^{235}U), zirconium hydride and encapsulated in a stainless steel cladding. Five control rods containing boron carbide control the reactor. The TM2 core consists of 101 fuel elements and

17 graphite elements; the core is mainly reflected by graphite. Further description of TM2 can be found in [4]. The reactor general description was listed in **Table 2**.

Table 2. Reactor general description of TM2 [5,6].

Operating condition	
Power (MW)	2
Geometric parameters	
Fuel rod diameter (cm)	3.746
Fuel active length (cm)	38.1
Cladding thickness (cm)	0.0508
Diameter of zirconium rod (cm)	0.6350
Outer reflector thickness (cm)	21.0
Kinetic parameters	
Effective delayed neutron fraction β_{eff} (pcm)	723
Mean neutron generation time Λ (μs)	53

Methodology

In this study, the MCNP6.2 [7] computer code was selected for the sensitivity analyses. The MCNP6.2 input for the TRIGA reactor was prepared (Figure1) in such a way to preserve as far as possible all the characteristics related to the geometry, dimensions, and compositions. Furthermore, ENDFB-VII.1, FENDL-3.0 and JENDL-4.0u data libraries [8,9,10,11,12] with the appropriate thermal neutron treatment s(α, β) were selected to investigate the effect of nuclear data library on the calculated results such as effective multiplication factor. The so-called s(α, β) treatment was used for the light and heavy water, beryllium, and oxygen in beryllium oxide, beryllium metal, crystalline graphite, and zirconium hydride to accurately modeling the neutron interactions within this material at energies below then 4~eV.

The sensitivity assessment aims to determine how changes of reflector material as an independent variable will affect particular dependent variables (neutronic parameters) under a given set of assumptions. For that purpose, the MCNP6.2 calculation was conducted using the same history of neutrons per generation (50000 histories per generation and 1000 active generations of neutrons) and the number of skipped generations. The statistical uncertainties associated with the MCNP6.2 calculations were almost 20 pcm.

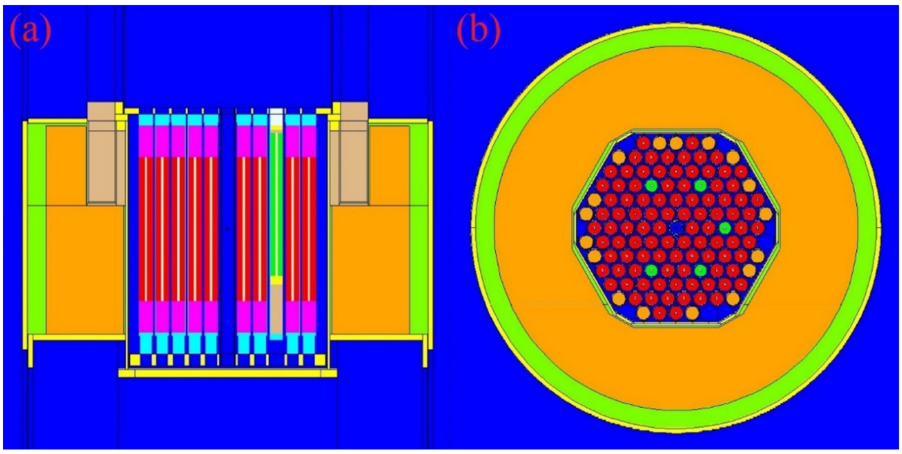

Figure 1. Side (a) and top (b) view of the TM2 modeled by the MCNP6.2 code.

Figure 2. The reflector assembly of the TM2 reactor.

Results and discussion

Effective multiplication factor

The calculations of effective multiplication factor (k_{eff}), excess reactivity (ρ_{ex}), and the gain in reactivity ($\Delta\rho$) using different reflector elements material types have been done with MCNP6.2 code. Results, together with k_{eff} estimated uncertainty using ENDFB-VII.1, FENDL-3.0 and JENDL-4.0u data libraries are presented in **Table 3.** It can be noticed from this Table, the k_{eff} of the reactor (with graphite reflector) using the ENDFB-VII.1 data library was 1.07559 ± 16 pcm. It has a good agreement with the referenced values reported by [5] and [13] which were 1.07382 ± 10 pcm and 1.07902 ± 5 pcm, respectively. As it can be seen also, the beryllium followed by beryllium oxide were found to be the most efficient reflector among other candidates since they gave the highest gain in reactivity for all the proposed libraries, thanks to the good combination between height scattering cross-section and low thermal absorption cross-section (see **Table 1**). However, light water adds minimum excess reactivity. The highest thermal absorption cross-section related to light water is mainly responsible for this behavior. When comparing heavy water and graphite, the excess reactivities added are nearly comparable. Both the materials are better than light water but are less effective than beryllium and beryllium oxide.

Table 3. Calculation results of effective multiplication factor (k_{eff}), excess reactivity (ρ_{ex}), and the gain in reactivity ($\Delta\rho$) with different nuclear data libraries.

	ENDFB-VII.1			FENDL3.0			JENDL-4.0u		
	k_{eff}	ρ_{ex}^*	$\Delta\rho^*$	k_{eff}	ρ_{ex}^*	$\Delta\rho^*$	k_{eff}	ρ_{ex}^*	$\Delta\rho^*$
Graphite	1.07559	7028	-	1.07586	7051	-	1.07468	6949	-
Beryllium	1.08117	7508	480	1.08190	7570	519	1.08121	7511	562
Beryllium oxide	1.08055	7455	427	1.08143	7530	479	1.08039	7441	492
Heavy water	1.07240	6751	-277	1.07263	6771	-280	1.07207	6723	-227
Light water	1.06325	5949	-1079	1.06330	5953	-1098	1.06260	5891	-1058

* (pcm)

The excess reactivity (ρ_{ex}), and the gain in reactivity ($\Delta\rho$) can be calculated using the following formulates:

$$\rho_{ex} = \frac{(k_{eff} - 1)}{k_{eff}} \quad (1)$$

$$\Delta\rho = \rho_{ex} - \rho_{ex\,(\text{for Graphite})} \quad (2)$$

Flux distribution

Figures 2 and 3 show the integral effects of neutron reflector on the neutron flux distributions in both fuel and reflector volume. As plotted in **Figure 3**, the thermal and the epi-thermal neutron flux increases with changing the graphite reflector to either beryllium, beryllium oxide or heavy water. Because of the good combination between a higher scattering cross-section (thermal) and a higher slowing down power (epi-thermal). The slowing down power for beryllium is close to heavy water and nearly 2.7 times better than graphite (**Table 1**). The presence of oxygen in beryllium oxide makes it is slowing down power smaller than beryllium. Additionally, the increase in neutron flux for beryllium and beryllium oxide in the fast energy range was due to the (n, 2n) reaction [14]. Conversely, a decrease in the neutron flux when changing the graphite with light water because of its higher thermal absorption cross-section. On the other hand, a slightly higher peak value is observed in the reflector region (**Figure 4**), when heavy water is used instead of graphite flowed beryllium and beryllium oxide because of its higher slowing down power.

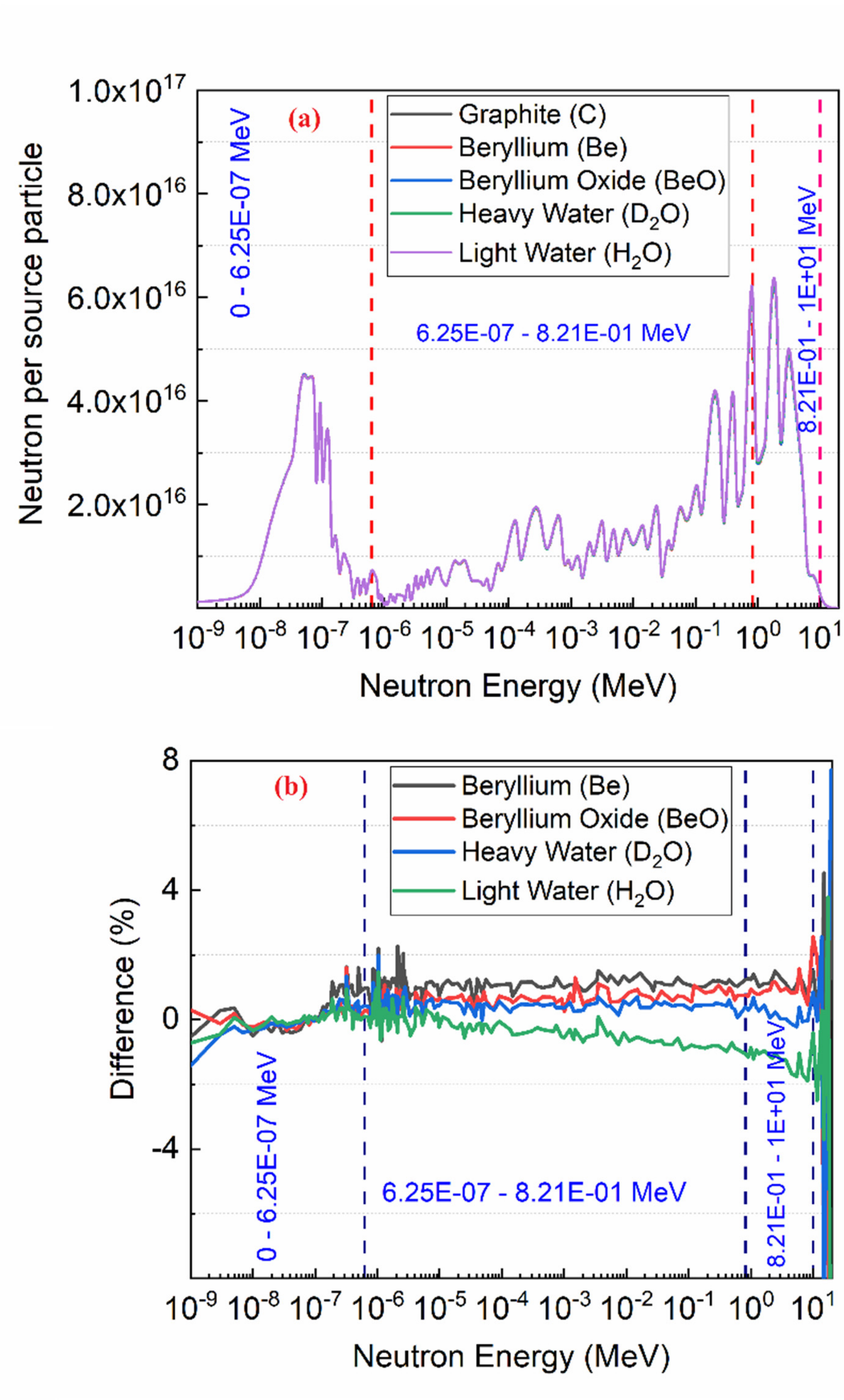

Figure 3. (a) Comparison of the neutron flux spectra obtained in the fuel volumes using five different reflector types, (b) Difference in neutron flux spectra between configuration with graphite and other configurations.

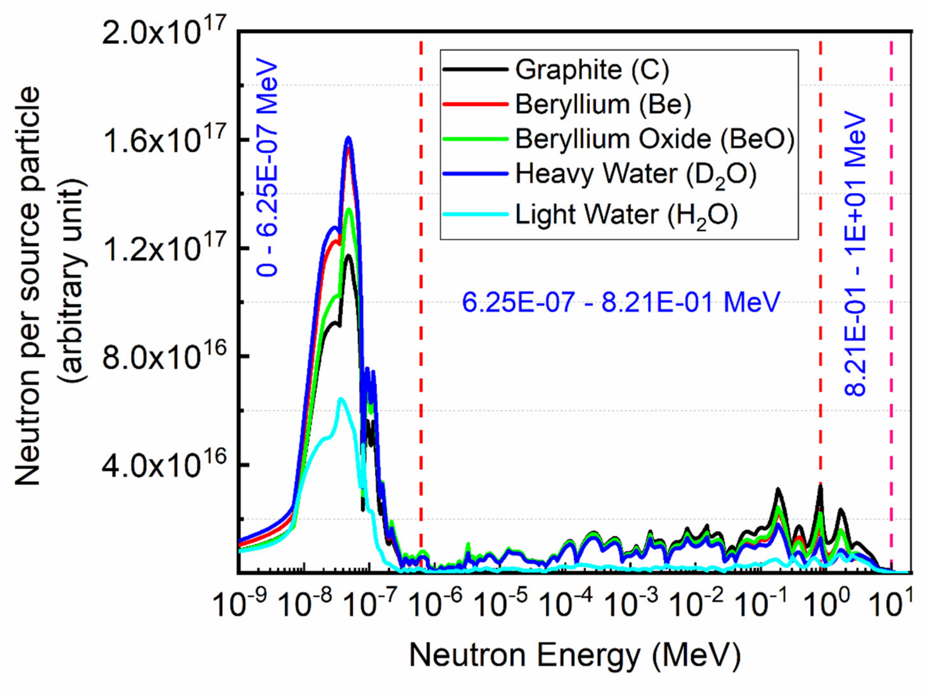

Figure 4. Comparison of the neutron flux spectra obtained in the reflector volumes using five different reflector types.

The profile of neutron flux (Φ) was calculated using the tally F4: N normalized to the steady-state thermal power of the system. The source normalization factor F4 was estimated as follows [15]:

$$\Phi\left(\frac{\text{neutron}}{\text{cm}^2.\text{s}}\right) = \text{S} * \Phi_{\text{F4 tally}}\left(\frac{1}{\text{cm}^2}\right) \tag{3}$$

Where:

$$\text{S} = \frac{\bar{\nu}\left(\frac{\text{neutron}}{\text{fission}}\right) * \text{p[W]}}{\epsilon\left(\frac{\text{MeV}}{\text{fission}}\right) * 1.602.10^{-13}\left(\frac{\text{J}}{\text{MeV}}\right) * \text{k}_{\text{eff}}} \tag{4}$$

And the difference:

$$\Delta\Phi = \left(\frac{\Phi - \Phi_{\text{graphite}}}{\Phi}\right) * 100 \tag{5}$$

Power distribution and radial hot rod power peaking factor (F_{HR})

Table 4 shows the hot rod power peaking factors F_{HR} [6] and its changes, in percent, due to replacing the graphite reflector with other reflectors. As can be seen from the table, the F_{HR} factor is slightly reduced when using beryllium and beryllium oxide, while it is slightly increased using light water due to its highest slowing down power [16]. The maximum average power values in fuel volume were 19.36 kW and 19.35 kW using beryllium and beryllium oxide respectively (see **Figure 5**). The large scattering cross-section and the lowest thermal absorption cross-section associated with beryllium (pure beryllium or beryllium oxide) were mainly responsible for this behavior by increasing the fission at the edge of the fuel region through neutron multiplication reflection.

Table 4. The F_{HR} factor and its variation due to core reflector.

Reflectors material	Hot Rod Identifier	F_{HR}	Changes in (%) of F_{HR} due to core reflector variation
Graphite	B3	1.61	-
Beryllium	B3	1.56	3.03
Beryllium oxide	B3	1.57	2.48
Heavy water	B3	1.61	-0.11
Light water	B3	1.67	-3.69

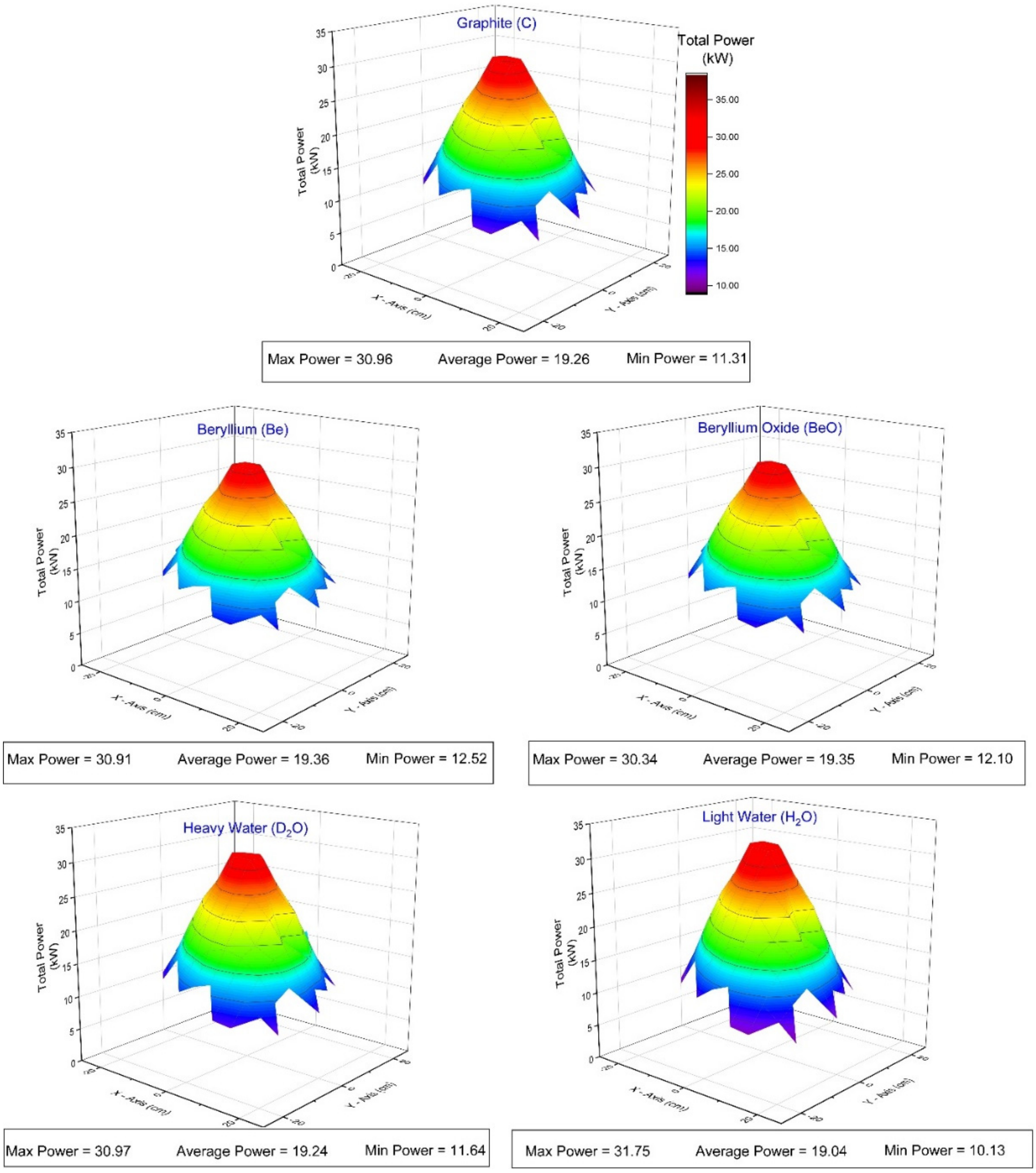

Figure 5. Core power distribution using the four reflectors.

It is worthy to notice that, the power distribution and radial hot rod power peaking factor (F_{HR}) results were based on the F7 tally (track length estimator of fission energy deposition) multiplied by normalization scaling factor as shown in Eq (4) [15].

Shutdown margin (SDM)

The SDM was evaluated as the difference between the core excess reactivity and the combined reactivity of 4 out of the 5 control rods, and assuming that the highest worth rod is stuck, and it can be calculated using the following formulate [17].

$$\rho_{rod}^{i} = k_{out}^{i} - k_{in} \tag{6}$$

Where:

k_{out}^{i}: All rods except the highest worth rod inserted (4 out of the 5 control rods).

k_{in} : All control rods fully inserted.

Regarding the definition, **Table 5** reports the SDM factor and its changes when altering the reactor core. The calculation results show that changing the reflector increases the amount of shutdown margin, where light water is the most effective reflector material; it can be used to gain a greater shutdown margin. It is followed by beryllium and beryllium oxide.

Table 5. The SDM factor and its variation due to core reflector changes.

Reflectors material	SDM	Changes in (%) of SDM due to core reflector variation $[(SDM - SDM_{Graphite}) * 100]$
Graphite	1.96	-
Beryllium	2.03	-3.49
Beryllium oxide	2.04	-3.84
Heavy water	1.99	-1.52
Light water	2.08	-5.97
SDM reported by Chham et al., 2016 (Graphite as a reflector)	1.82	

Conclusions

In this paper, a sensitivity analysis of the use of different reflector materials on the main neutronic core parameters of the 2 MW TRIGA Mark-II research reactor was performed. The following quantities were examined: effective multiplication factor, neutron flux, power distribution, hot rod power peaking factors F_{HR}, and shutdown margin (SDM).

The results show that:

The beryllium reflector was found to be the most efficient reflector since it showed the highest excess in the reactivity of 7508 pcm. It followed by beryllium oxide and graphite with excess reactivity of 7455 pcm and 7208 pcm, respectively.

The beryllium reflector, followed by beryllium oxide and heavy water, demonstrated the highest neutron flux in fuel volumes especially. On the contrary, in the reflector volume, a more increase in the thermal neutron flux was assessed when changing the graphite reflector to heavy water.

The average power values are similar in all reflectors and differ slightly from each other because it depends sensually on the fuel and the number of fuel rods.

Light water was found to be the most effective material to gain a greater shutdown margin. It followed by beryllium and beryllium oxide.

Finally, it is worthy to notice that the beryllium followed by beryllium oxide were the most efficient elements in these reflector element material families (beryllium, beryllium oxide, heavy water, and light water) according to their neutronic results. However, problems associated with beryllium, such as its availability, and very high cost should be given due consideration [18]. Moreover, it can be concluded that changing the core reflector, leads to noticeable changes in neutronic parameters such as effective multiplication factor, neutron flux, power distribution, hot rod power peaking factor F_{HR}, and shutdown margin (SDM).

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