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Original Article

Preliminary Study on Alternative Reflectors for LOTUS Reactor

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Abstract: LOTUS reactor - a compact lead-cooled fast reactor is currently being studied to generate 200 MWth of capacity and operate for 20 years without refueling for the floating nuclear power plant (FNPP) application. Therefore, it would be a big advantage to achieve a long operation without refueling. However, a small reactor usually has a higher neutron leakage, and a good neutron reflector is essential to maintain the neutron economy. The main objective is selecting potential reflectors materials for the LOTUS reactor using Monte Carlo code, Serpent. The various candidate reflector materials, including Al_2O_3, BeO, MgO, PbO, SiO_2, and ZrO_2 are calculated from the neutronics characteristics to determine a good neutron reflector. In this work, we have investigated the parameters of neutronics characteristics, such as core neutron flux spectrum, evolution of k_{eff} due to burn-up, power distribution, and lead coolant void reactivity with each reflector. From the comparison of those parameters, MgO material was found to be a good candidate for the relector of LOTUS reactor.

Keywords: LOTUS reactor, fast reactor, reflectors, FNPP, Serpent.

1. Introduction

The design goal of LOTUS reactor is to provide a reactor core concept design that is compact in size, light in weight, and safe that can be applied to the floating reactor model. The LOTUS reactor is designed based on the Micro Modular Reactor (MMR) [1] after removing the drum-type secondary

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control rods and adding a fuel ring to reduce the core size and increase the capacity and life of the core. The fuel and control form design are a cylindrical fuel rod in the hexagonal lattice, which is surrounded by the gap and cladding. This reactor design uses U^{235} under 15% enrichment and lead as the coolant. It aims to have the ability to generate 200 MWth and operates for 20 EFPY without refueling.

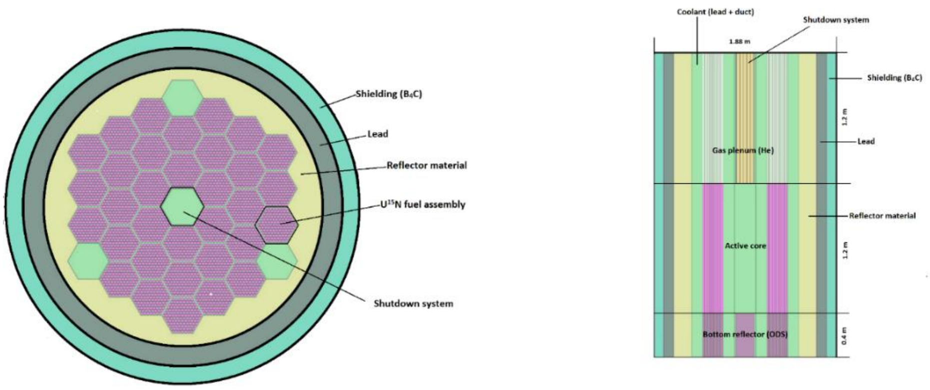
Since the LOTUS reactor has relatively high neutron leakage, selecting an effective reflector is necessary to maintain the neutron economy. Therefore, the reactor design can obtain stable conditions and a long-term core lifetime. It is neccessary to investigate several candidate reflector materials, including Al_2O_3, BeO, MgO, PbO, SiO_2, and ZrO_2, based on several characterizations including neutron flux spectrum, evolution k_{eff} due to burn-up, power distribution, coolant void reactivity (CVR) [3-5].

In the investigation and analysis, the continuous energy Monte Carlo code Serpent is used with the ENDF/B-VIII.0 nuclear data library. Serpent is a multi-purpose three-dimensional continuous-energy neutron and photon transport code developed at VTT Technical Research Centre of Finland since 2004. Unlike MCNP code, Serpent has a built-in depletion routine; thus, it can be used as a stand-alone for the core depletion analysis [2].

This work is organized as follows. Section 2 briefly describes the LOTUS reactor. Section 3 illustrates a brief description of alternative reflector materials. The analysis results and discussion are provided in Section 4. Finally, the conclusions are drawn in Section 5.

2. Compact 200 MWth Lead-cooled Fast Reactor Model

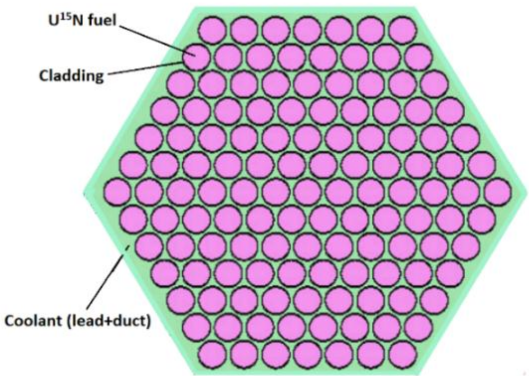
The LOTUS reactor configuration is designed based on the ALMANAR reactor configuration [1] and considered in this work is shown in Figs. 1 and 2, and the basic configurations and design parameters of the fuel and control assemblies are shown. Table 1 shows the major core design parameters. The core consists of 33 hexagonal fuel assemblies, 127 fuel rods for each assembly, 4 hexagonal control assemblies, and 19 control rods for each assembly. The equivalent core diameter is about 1.88 m. The total active core and the gas plenum height are both 120 cm, while the bottom reflector zone is 40 cm. The main features of the core structure are the helium (He) gas plenum and oxide-dispersion-strengthened (ODS) core support (bottom reflector) [1]. The reactor power is set to 200 MWth, and it is expected to operate at 20 EFPYs without refueling.



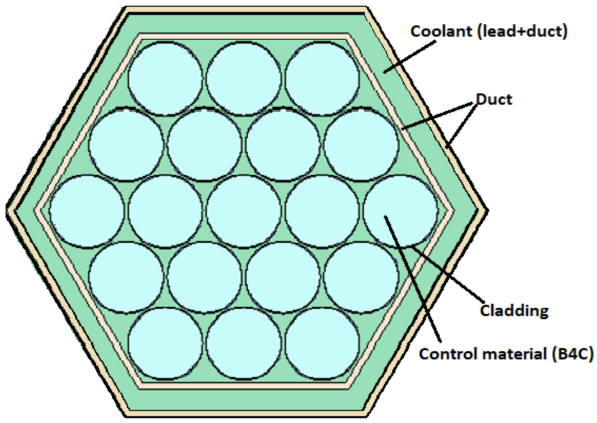
(a) (b)

Figure 1. Radial and axial configurations of reactor with uniform enrichment:
(a) Radial configuration; (b) Axial configuration.

In this design, the fuel and control materials used are UN (100%-enriched ^{15}N and 14.84%-enriched ^{235}U) and B_4C (98%-enriched ^{10}B), respectively. The hexagonal shape of the fuel and control assemblies is adopted in order to increase the compactness of the reactor core, the neutron economy, and the control rod worth (Fig. 2). The control system placed one in the center and three in the outer fuel ring, as shown in Fig. 1a. The control rods used in this design are rod-type instead of the drum-type that was adopted in the reference reactor. Such replacement is considered in order to increase the compactness of the reactor and to allow the passive insertion of the control rod, that driven by gravity, which will contribute to enhancing the safety of the reactor. In general, a high fuel volume fraction and control material volume fraction is required for this compact reactor to achieve a long-life core as well as enhance the control rod worth. In order to increase the fuel and control fraction, a relatively large pin and a tight lattice are utilized in this work. Through a sensitivity analysis of the neutronic performance, the diameter of the fuel pin and the Pitch/Diameter (P/D) ratio are 0.69 cm and 2.39, respectively, and the diameter of the control rod and P/D ratio are 1.69 cm and 2.1331, respectively.



(a)



(b)

Figure 2. Fuel and control assembly layout: (a) Fuel assembly layout; (b) Control assembly layout.

For this model, the best coolant material was found to be Pb due to its superior properties, including high boiling point, high density, high scattering cross-section, low absorption cross-section, and benign chemistry (no interaction with water or air) in addition to its wider range of applicability. Using lead as coolant can result in some constraints that arises with the use of lead and that should be considered in the reactor design. The most prominent constraint is related to the erosion and corrosion issue, which is solved by controlling the corrosion rate of the structure steel through the parameters that impact it: the temperature, the nature of the steel, the dissolved oxygen concentration and the molten lead coolant speed which is reduced to be less than 2 m/s. Part of the needed 3 modification achieved through calculations related to temperature distribution in addition to neutronic calculations. The simulation work of this project is done with the help of Serpent Monte-Carlo Code which enables us to develop the model of the LOTUS. Some of the lead-cooled fast reactors use LBE (Pb-Bi eutectic) coolant because the melting point of lead is slightly high, about 327.5 °C. However, Bi is costly and considered as a rare element. Additionally, Bi produces a considerable amount of Po which is a highly radioactive element that can contribute to contamination issue. Based on these factors, Pb is chosen as the primary coolant for LOTUS.

Table 1. Core design parameters

Parameters	Value	
Total power, MWth	200 MWth	
Active core radius/height, cm	73.74/120	
Core equivalent radius/height, cm	188/280	
Parameters	Fuel assembly	Control assembly
Number of pins/assemblies	127/33	19/4
Pin diameter, cm	0.69	1.69
Cladding thickness, cm	0.05	0.06
Duct thickness, cm	-	0.3
P/D	2.3913	2.1331
Assembly pitch, cm	18.9473	16.1981
Flat to flat distance, cm	19.2473	16.7981
Fuel/Absorber volume fraction, %	59.1781	53.1112
Coolant volume fraction, %	30.0825	37.7065
Structure volume fraction, %	10.7393	9.1823
Material	$U^{15}N$	B_4C
Cladding	ODS steel	ODS steel

3. Reflector Materials

The reflector plays an important role in a fast reactor due to the reduction of net neutron leakage (improving neutron economy) and flattening the power distribution. In search of alternative reflector materials for the LOTUS reactor, six alternative reflector materials are considered, which are Al_2O_3, BeO, MgO, PbO, SiO_2, and ZrO_2. The reflector material properties are shown in Table 3, and the elastic and capture cross-sections of major nuclides of the reflectors are shown in Figs. 3 and 4. It is clearly noticed that the lead is a good reflector compared with the others because lead has a relatively low capture cross-section but high scattering cross-section. Besides, lead also has a very high material density. This is both advantage and disadvantage for a small reactor due to its weight. It makes the installation and transport of the modular reactor less flexible. Table 3 shows that all of the reflector materials have a relatively higher melting temperature than PbO, in which BeO and MgO have a very high melting temperature (2507 ^oC and 2852 ^oC, respectively), and their density is rather low (3.01 g/cm^3 and 3.6 g/cm^3 respectively).

Several important core characteristics influenced by the various reflector materials have been investigated in this work in comparison with the PbO reflector, which includes the neutron spectrum, k_{eff} at the beginning of cycle, the evolution of k_{eff} due to burn-up, core power distribution, and coolant void reactivity coefficient. These characteristics will provide a better understanding of the physics and performance of each material as a reflector in this model.

Table 3. Material properties of the reflector materials [3-5]

Properties	Al_2O_3	BeO	MgO	PbO	SiO_2	ZrO_2
Melting temperature, ^oC	2072	2507	2852	888	1713	2715
Boling temperature, ^oC	2977	3900	3600	1477	2950	4300
Density, g/cm^3	3.987	3.01	3.6	9.53	2.196	5.68
Thermal conductivity, $W.m^{-1}.K^{-1}$	30	330	45-60	1.3-2.2	1.4	2-2.5

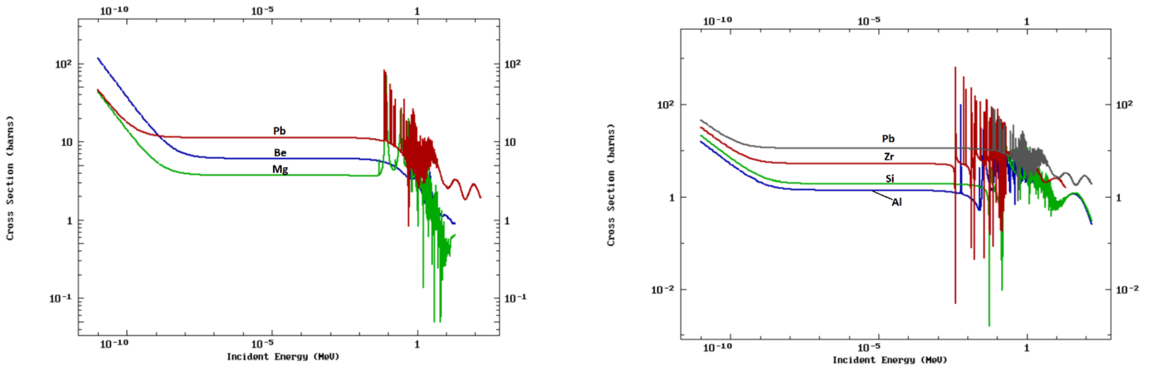


Figure 3. Elastic cross-sections of the major isotopes of reflector materials [6].

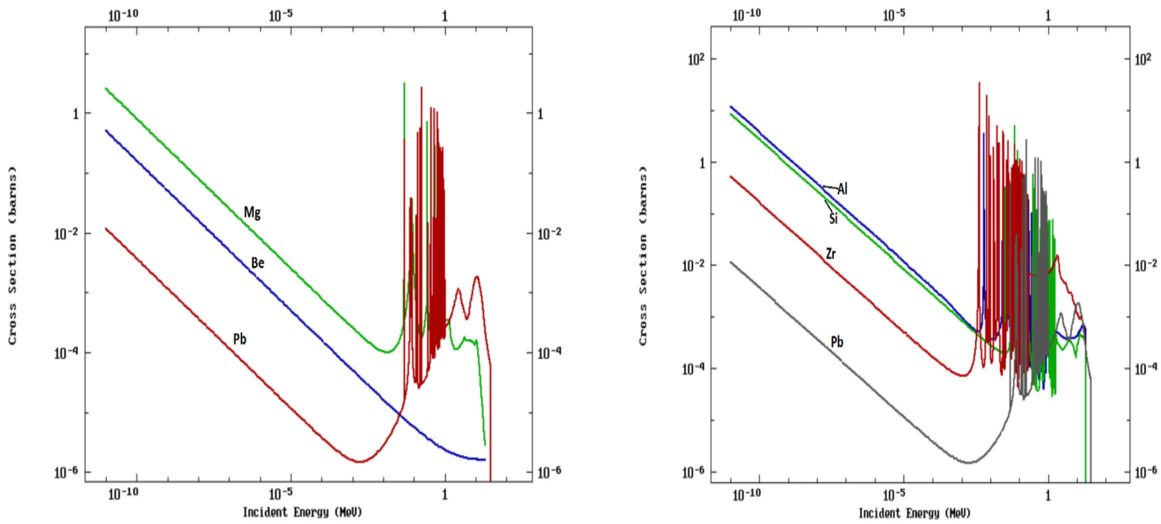


Figure 4. Capture cross-sections of the major isotopes of reflector materials [6].

4. Reflector Performance in View of Core Lifetime

4.1. Neutron Spectrum

The neutron spectra for cores with different reflector materials are plotted for two core regions: active core and reflector one. These results are shown in Figs. 5 and 6 for the beginning of cycle (BOC). Obviously, the neutron spectrum in reflector region clearly depends on the reflector material, and the neutron flux in the active core region is always higher than in the reflector region. For BeO material, the neutron flux is very high in the energy range from 10^{-7} keV to 10^{-6} keV but lowest in fast neutron range in both of the reflector and active core region. It can be understood that most of the fast neutrons leaking from the core region are converted to thermal neutrons after encountering with BeO reflector and reflected back to the core region due to BeO as a light material (3.01 g/cm^3) and the very high elastic cross-section of BeO in the thermal energy region. Because of the large neutron flux in the thermal region, the fission reaction rate is fast, as a result, the fuel is depleted faster.

In addition, the neutron flux in Figs. 5 and 6 also implies the neutron leakage in the reactor core. Figure 6 illustrates the amount of neutron leakage for PbO is the largest. Therefore, PbO is not the optimal choice for this reactor design. It can be seen that with approximately the same neutron flux value in the core, the amount of neutron leakage from the core region to the reflector region for the MgO is relatively low in comparison to other materials. Therefore, MgO could be a good reflector material for this reactor core.

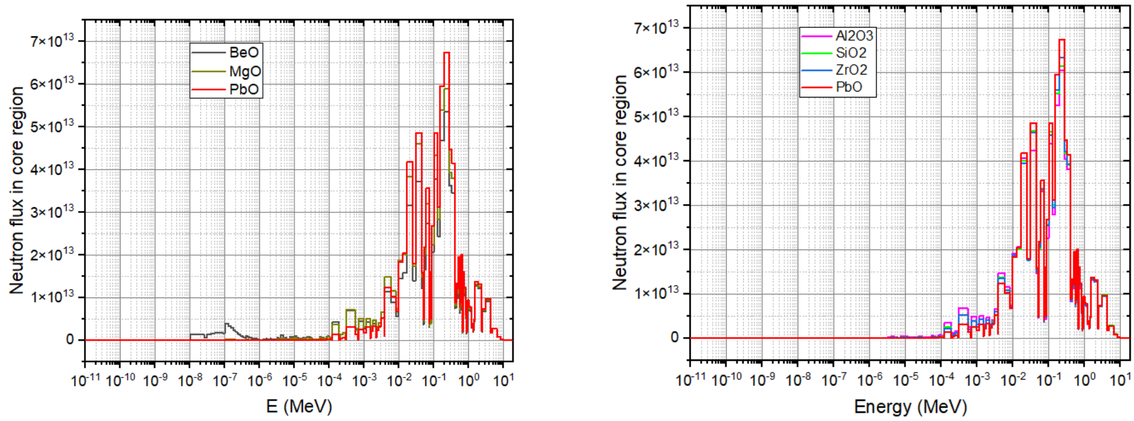


Figure 5. Neutron spectrum in the active core region at BOC for various reflector materials.

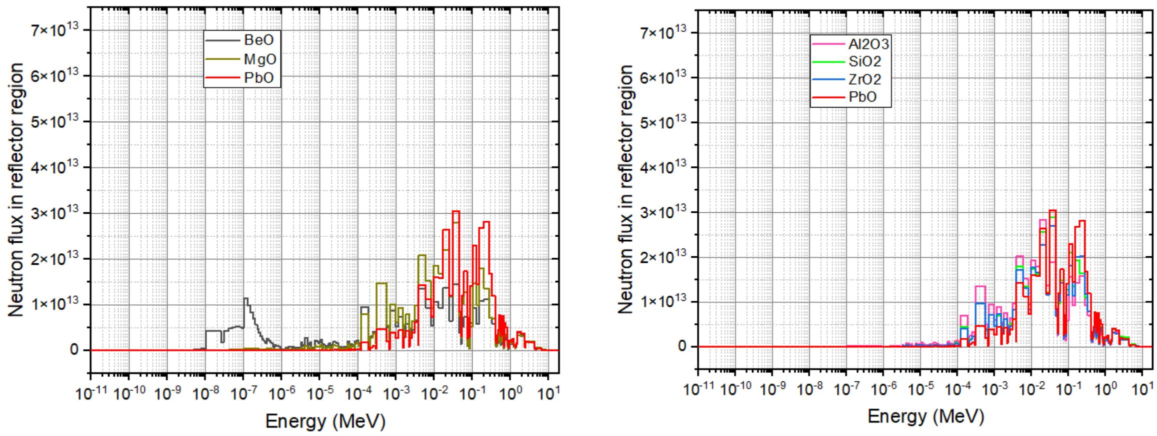


Figure 6. Neutron spectrum in the reflector region at BOC for various reflector materials.

4.2. Evolution of k_{eff} Due to Burn-up

Figure 7 illustrates the effective multiplication factor evolution in the burn-up unit (MWd/kgU) and the effective full power days (EFPD). Obviously, the effective multiplication factor experiences a downward trend during the fuel burning, and all of the alternative reflector materials have the multiplication value after the core lifetime of 20 EFPY (7,300 days) remain in the supercritical state. Evolution of k_{eff} due to burn-up for alternative reflector materials are linear lines that are almost parallel to each other except for BeO. Figure 7 shows that for BeO, k_{eff} has the largest slope, which also means that with the BeO reflector, k_{eff} has the largest reactivity swing. In order to explain this, it is obvious that the neutron flux spectra in Figs. 5 and 6 for BeO in the thermal neutron region is much more significant compared to that of the other materials; thus, the fission rate for BeO occurs faster than others, leading to a rapid reduction in the multiplication factor due to the larger in the amount of U^{235} being burned. After excluding BeO materials, it is obvious to see from Table 4 that MgO is a material with a higher multiplication factor than other materials and a small reactivity swing due to burn-up. Thus, the reactor core uses MgO as a reflector material promising in order to extend the core operation time compared to other materials.

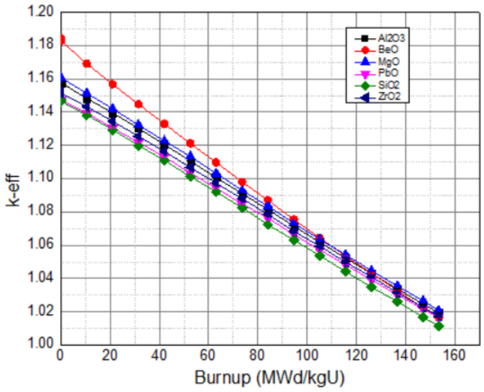


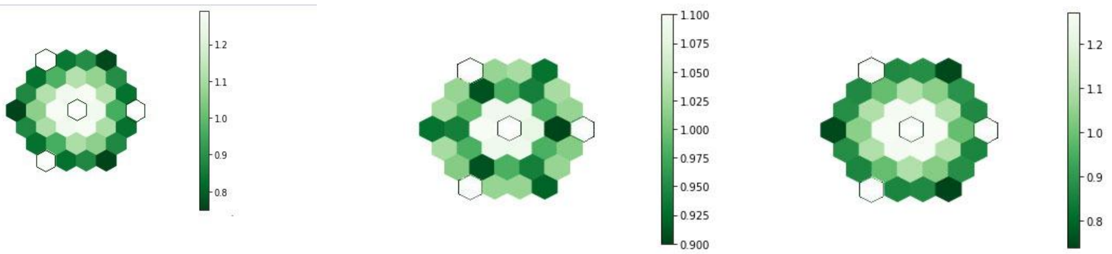
Figure 7. Evolution of k-eff due to burn-up for various reflector materials.

Table 4. Reactivity swing for alternative reflector materials

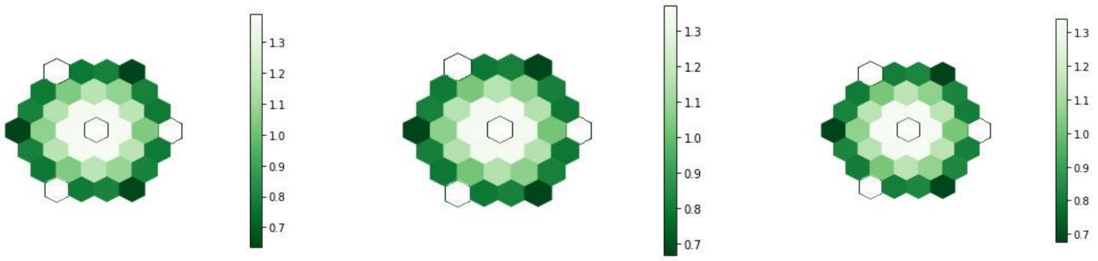
Reflector material	k_{eff}		
	BOC	EOC	Reactivity Swing
Al_2O_3	1.15756±0.00013	1.019431±0.00015	0.11705±0.00020
BeO	1.18429±0.00014	1.01635±0.00015	0.13953±0.00021
MgO	1.16049±0.00012	1.02083±0.00015	0.11789±0.00019
PbO	1.14738±0.00013	1.01679±0.00016	0.11194±0.00021
SiO_2	1.14733±0.00014	1.01151±0.00016	0.11703±0.00021
Zr_2O_3	1.15233±0.00012	1.01725±0.00015	0.11524±0.00019

4.3. Core Power Distribution

The power distribution in the reactor core is closely related to the lifetime of the core. Therefore, a good reflector material would maintain the flat power distribution along with the core life. Figure 8 and 9 show how the assembly-wise power is radially inside the LOTUS reactor at BOC and EOC. Based on our observation, the radial power peaking factor of each one at BOC and EOC is located near the center. Comparing the power distribution at BOC and EOC, the power sharing at EOC slightly increases in the peripheral region and slightly decreases at the center because more fissile fuels in the center were burnt compared to the one in the peripheral region, which results in a more uniform distribution of power at EOC than at BOC. Particularly, for the BeO reflector material, there is an uneven radial power distribution. The reason is that a large number of fast neutrons are generated and converted to thermal neutrons after scattering with BeO material, leading to higher power distribution in the outer ring than in the second ring. Table 5 shows that the MgO reflector material gives a flatter power peaking factor value in comparison to other materials. With a power peaking factor difference of only 0.02, this shows the uniform power distribution not only at EOC but also at BOC when using MgO material. These results demonstrate that MgO material can be considered a good reflector candidate for the LOTUS reactor.

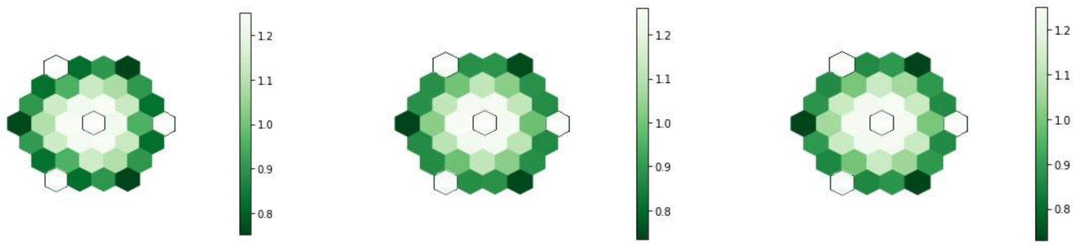


Al2O3 reflector BeO reflector MgO reflector

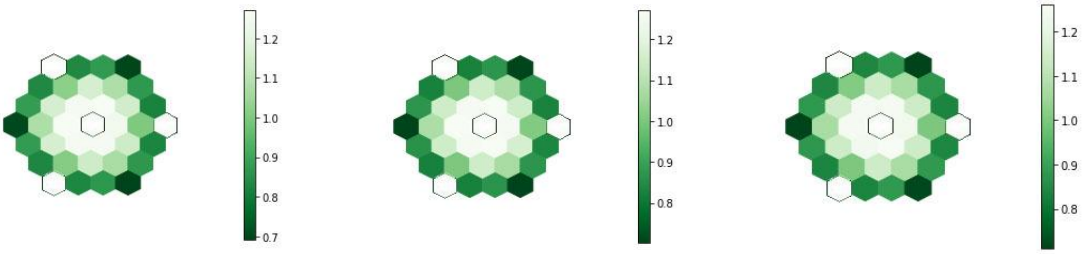


PbO reflector SiO2 reflector ZrO2 reflector

Figure 8. Normalized assembly power distribution at BOC for various reflectors.



Al2O3 reflector BeO reflector MgO reflector



PbO reflector SiO2 reflector ZrO2 reflector

Figure 9. Normalized assembly power distribution at EOC for various reflectors.

Table 5. Power peaking factor for various reflectors

	Time	Reflector materials					
		Al2O3	BeO	MgO	PbO	SiO2	ZrO2
Power peaking factor	BOC	1.29	1.10	1.27	1.39	1.37	1.34
	EOC	1.25	1.26	1.25	1.27	1.27	1.26

4.4. Coolant Void Reactivity (CVR)

The CVR is one of the most important safety parameters in a lead-cooled fast reactor. It is defined as the change in reactivity per percent change in the void volume. The CVR formula is presented by equation (1):

$$CVR = \quad \Delta \rho \qquad (1)$$

where ρ is the reactivity of the core.

Table 6 shows the coolant void reactivity results for various reflector materials. It is clear that all void coefficient for 6 materials are negative. The negative void coefficient means that the reactivity decreases as the void fraction inside the reactor increase andit can be considered as the intrinsic safety feature of the core. As the result, all reflective materials have advantages in voiding with negative reactivity feedback.

Table 6. Coolant void reactivity for various reflector materials.

Time	Coolant void reactivity (CVR) (pcm)	
	BOC	EOC
Al_2O_3	-1948±19.85	-1182±36.25
BeO	-1010±36.25	-715±36.25
MgO	-1862±18.44	-982±36.25
PbO	-2494±19.85	-1240±37.58
SiO_2	-2482±20.52	-1300±38.48
ZrO_2	-2281±19.21	-1052±37.16

5. Conclusion

We have investigated several reflector materials, including Al_2O_3, BeO, MgO, PbO, SiO_2, and ZrO_2, to recognize the reflexibility of alternative candidate reflectors. The candidate reflectors have been identified based on the nuclear physics parameters, including distribution of flux, effective multiplication factor due to burn-up, power distribution, and coolant void reactor. Regarding the material properties (Table 3), it can be clearly seen that BeO and MgO are two materials that meet the criteria of the reflector well material, including high melting point, high boiling point, high thermal conductivity, and low density. However, in terms of neutron spectrum, the evolution of k_{eff} due to burn-up, power distribution, and CVR coefficient, MgO is a suitable reflector material for the LOTUS reactor with such advantages as the largest neutron flux in the core region, the low neutron leakage, the higher multiplication factor than other materials (accept BeO), a small reactivity swing due to burn-up, the most uniform power distribution during core life, and the positive CVR value. Based on the investigated parameters, MgO material can be considered proper candidate reflector for the LOTUS reactor.

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