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Neutronic Performance Evaluation of Reflector Materials for LEU+ Fueled SMR

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1. Introduction

The development of advanced SMR designs has increased interest in using Low Enriched Uranium Plus (LEU+) fuel. Although LEU+ fueled SMR have not yet been implemented in Korea, they offer advantages in fuel cycle efficiency and sustainability [1]. One of the key aspects of LEU+ fueled SMR design is selecting appropriate reflector materials. Due to its small size, an SMR has greater neutron leakage compared to a large-scale reactor. To mitigate this neutron leakage, a solid reflector with higher neutron reflection performance than light water can be considered. This approach minimizes neutron leakage, contributing to improved neutron economy, extended cycle length, and flattened power distribution, ultimately leading to a reduction in spent nuclear fuel discharge.

Effectiveness of reflectors depends on factors such as neutron reflection capability, absorption cross-section, and thermal properties. This study evaluates various reflector materials placed adjacent to an LEU+ fuel assembly using neutron transport analysis. The goal is to identify suitable reflector materials that enhance neutronic performance, providing useful insights for future LEU+ core development.

2. Method

2.1. Code and Reflector Model

Neutron transport calculations were conducted to analyze the effect of different reflector materials on LEU+ fuel assemblies. This study utilized STREAM, a neutron transport code developed at UNIST [2]. STREAM employs the pin-based pointwise energy slowing-down method (PSM) [3], which accurately accounts for resonance interference effects. This ensures high precision regardless of fuel enrichment.

Fig. 1 shows the reflector model which consists of a 2×1 region, where one region contains an LEU+ fuel assembly, and the other region contains different candidate reflector materials. Because the neutron flux drops significantly with distance from the fuel region, a 2×1 model is sufficient to represent the performance of the reflector neighboring the fuel. Boundary condition of farther edge of reflector is black, and boundary conditions of other edges are reflective.

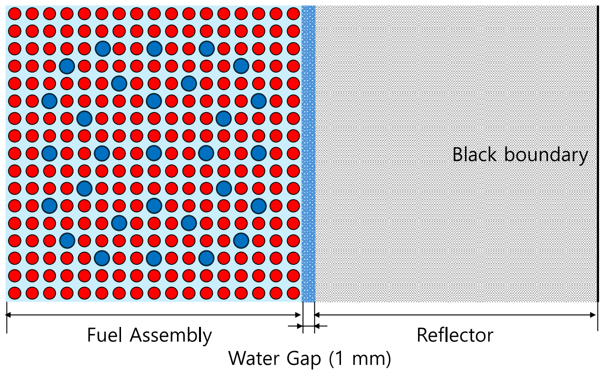

Fig. 1 Reflector model neighboring LEU+ fuel assembly

The description of the LEU+ fuel assembly and reflector model is described in Table I. Assuming an LEU+ fuel applied Soluble-Boron-Free (SBF) SMR, a U-235 enrichment of 7 w/o% and a boron concentration of 0 PPM were applied.

Key parameters analyzed in this study include multiplication factor, pin power distribution. Temperature effects on reactivity was also analyzed. In general, coolant flows from the bottom to the top of the reactor, resulting in a temperature increase along the axial direction. Consequently, the temperatures of both the coolant and the reflector can vary depending on their axial position. To assess the impact of temperature changes on reflector performance, the reactivity changes were analyzed for cases where the temperature increased by 10, 20, and 30 K from the baseline conditions described in Table I.

Table I. Description of the reflector model neighboring LEU+ fuel assembly

Parameter	Value
Number of fuel pins	260
Number of GT/IT	28/1
U-235 Enrichment (Fuel)	7 w/o%
Fuel Temperature	810.5 K
Moderator Temperature	584 K
Reflector Temperature	584 K
Boron Concentration	0 PPM

2.2. Reflector Materials

The reflector materials were chosen based on the following criteria: (1) Low thermal neutron absorption cross-section, (2) High atomic number density, (3) High melting point. The 15 selected reflector materials are listed in Table II. The selected reflector materials include well-known neutron reflector candidates such as beryllium-based materials [4] and graphite. Zirconium-based metals, commonly used as cladding materials, and SS304, which has favorable mechanical properties and neutron reflection characteristics, were also considered [5]. Other materials such as various oxides, as well as SiC and FeCrAl, are also included.

Since the reactor operates under high-temperature and high-pressure coolant conditions, melting or chemical reactions may occur. To evaluate this effect, both cases with and without SS304 coating model were considered for the non-metallic materials.

Table II. Selected reflector materials

No.	Metal/Non-metal	Material
1	Non-metal	BeO
2	Non-metal	Graphite
3	Non-metal	MgO
4	Non-metal	PbO
5	Non-metal	Al_2O_3
6	Non-metal	SiC
7	Non-metal	Bi_2O_3
8	Metal	Beryllium Metal
9	Metal	Zirconium Metal
10	Metal	ZIRLO
11	Metal	HANA-6
12	Metal	Zircaloy-4
13	Metal	SS304
14	Metal	FeCrAl C26M
15	Metal	FeCrAl APMT

3. Results and Discussion

3.1. Multiplication factor

Depending on the reflector materials, complex phenomena occur simultaneously, including the neutron leakage, collisions, and absorption in reflector region, and spectral shift due to the moderation effects. Since it is difficult to separately analyze the impact of each factor, the multiplication factor, which comprehensively accounts for these effects, is used to evaluate the neutron reflection performance of different reflector materials.

Fig. 2 shows evaluated multiplication factors of reflector materials under fresh fuel and reflector condition. The black bar at the top represents a reflective condition.

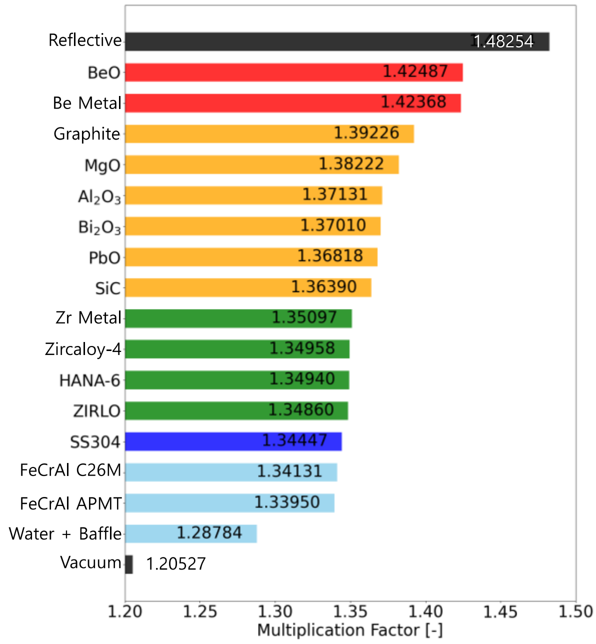

Fig. 2 Multiplication factor of reflectors

Beryllium-based materials (BeO and metallic Be), represented in red, exhibit the highest multiplication factors, demonstrating their strong neutron reflection capabilities. Graphite and other non-metallic oxides, represented in orange, also demonstrate notable neutron moderation and reflection effects, though slightly lower than those of beryllium-based materials.

Among the metallic reflectors, zirconium-based alloys (green), SS304 (blue), FeCrAl-based materials (light blue), and Water+Baffle (light blue) show the different degrees of neutron reflection performance. Although FeCrAl materials have the lowest multiplication factors among the selected candidates, they still show a significant improvement compared to the Water + Baffle case. The reflection performance of various reflector materials can be evaluated by comparing with vacuum condition (black bar). These results highlight the superior performance of beryllium-based reflectors while also showcasing the diverse characteristics of different materials.

3.2. Be-based reflector

Among the candidates, BeO and Beryllium indicate superior neutron reflection properties. However, an important limitation was observed when accounting for long-term transmutation effects in Be-based reflectors. Fig. 3 shows the multiplication factor of BeO reflector model against fuel assembly burnup with and without considering the transmutation of reflector material. More than 500 pcm of difference was observed.

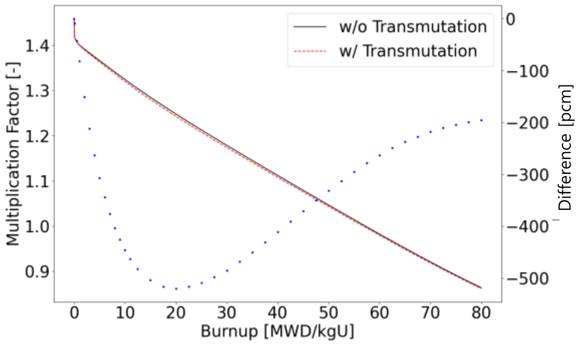

Fig. 3. Multiplication factor of BeO reflector against burnup

The results indicate that transmutation in beryllium leads to a decrease in reflection performance over time, resulting in larger than 500 pcm of difference in multiplication factor. This phenomenon, which was not observed in other materials, suggests a potential disadvantage for Be-based reflectors in long-term core applications. Also, Be-based reflectors have the drawback of being toxic, making them difficult to handle.

3.3. Non-metallic reflectors with SS304 coating

To prevent melting and chemical reactions with the coolant, a 4 mm SS304 coating was applied to the non-metallic reflector materials. Fig. 4 shows the multiplication factors of reflectors with and without coating, with the results for SS304 (bulk material) as a comparable candidate.

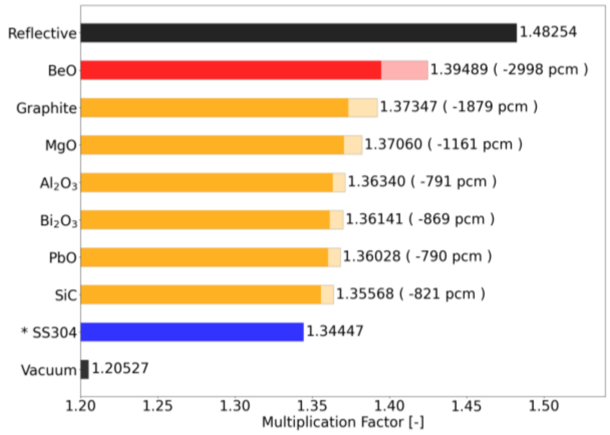

Fig. 4 Multiplication factor of non-metallic reflectors w/ SS304 coating

Reflectors with higher neutron reflection capability tend to experience a more significant reflection performance reduction when coated. While some reflectors such as Bi_2O_3 shows relatively bigger reductions compared to Al_2O_3, the differences are on the order of tens of pcm, making them negligible in practical terms.

3.4. Power distribution

Fig. 5 shows the pin power distributions and pin peaks of reflector facing fuel assemblies. BeO, SiC, and SS304 were analyzed alongside the Water+Baffle reflector.

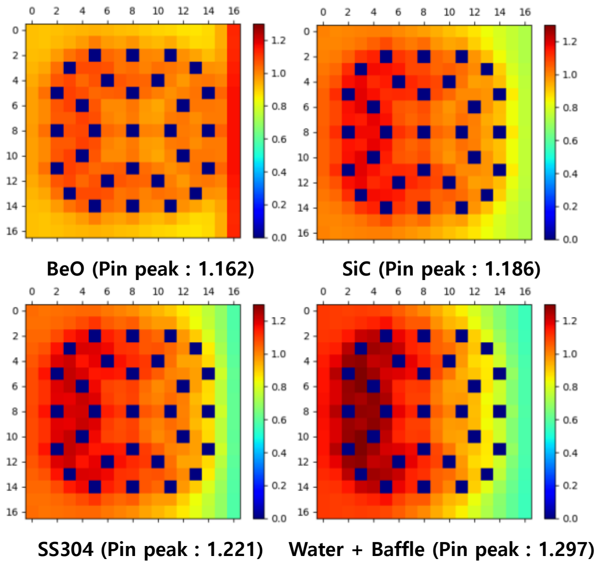

Fig. 5 Pin power distribution of reactor neighboring FA

For BeO, which exhibited the highest reflection performance, the east side adjacent to the reflector showed the highest pin power. This is attributed to neutron reflection and moderation effects from the reflector, as well as the additional neutron supply from the (n,2n) reaction of ^{9}Be, which distinguishes Be-based reflectors from other candidate reflectors. SiC and SS304 exhibited pin peak values of 1.186 and 1.221, respectively, demonstrating a flattening effect in the power distribution compared to the Water + Baffle reflector.

3.5. Moderator and reflector temperature variations

Table III shows the reactivity change against moderator and reflector temperature change and the average reactivity change with temperature with and without considering thermal expansion.

Reflectors with higher neutron reflection capability showed smaller reactivity changes with increasing temperature. Under conditions where neutron spectrum hardening increases the probability of fast neutron escape, the reflection capability becomes more significant issue. The difference in reactivity changes between the cases with and without thermal expansion consideration was observed to be negligibly small.

Table III. Reactivity change against moderator and reflector temperature change

Material	Δ ρ [pcm]			Avg. ρ/T [pcm/K]	
	+10 K	+20 K	+30 K	Ignore THE	Consider THE
Reflective	-273	-601	-1013	-30	-30
BeO	-321	-705	-1183	-34	-34
Beryllium	-311	-684	-1148	-35	-35
Graphite	-382	-838	-1409	-42	-42
MgO	-403	-886	-1491	-44	-44
Al_2O_3	-420	-924	-1554	-46	-46
Bi_2O_3	-436	-959	-1615	-48	-48
SiC	-436	-960	-1615	-48	-48
Zirconium	-471	-1037	-1747	-52	-52
SS304	-474	-1043	-1754	-52	-52
Zircaloy-4	-474	-1043	-1757	-52	-52
HANA-6	-475	-1045	-1760	-52	-52
ZIRLO	-477	-1048	-1766	-53	-53
FeCrAl C26M	-483	-1062	-1787	-53	-53
FeCrAl APMT	-487	-1071	-1803	-54	-54
Water+Baffle	-610	-1342	-2263	-67	-67

4. Conclusion

This study evaluated the impact of various reflector materials neighboring a LEU+ fuel assembly using neutron transport analysis with STREAM. The results demonstrate that Be-based materials show the highest neutron reflection performance, however, their transmutation effects lead to performance degradation over time, larger than 500 pcm of multiplication factor difference was observed. Other oxides and SiC showed high reflection capability without any degradation. Zirconium-based alloys, SS304, and FeCrAl also showed effective neutron reflection while maintaining structural stability, making them viable candidates for reflector applications.

The analysis further revealed that coated non-metallic reflectors showed that more effective reflector made more reductions in performance. Additionally, reflectors with stronger neutron reflection capabilities exhibited lower reactivity sensitivity to temperature increases, highlighting their role in mitigating neutron spectrum hardening effects.

Future work should include full-core simulations to validate these trends at the reactor scale. Experimental validation and multi-physics simulations incorporating thermal-hydraulic and material behavior under irradiation are also necessary to assess the feasibility of these materials in LEU+ fueled reactors.

ACKNOWLEDGEMENT

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