Lead-based Radial Reflectors for Sodium-cooled Fast Reactor

Donny Hartanto and Yonghee Kim*
Korea Advanced Institute of Science and Technology
291 Daehak-ro, Yuseong-gu, Daejeon, Korea, 305-701
**Corresponding author: yongheekim@kaist.ac.kr*

1. Introduction

A small and compact 250 MWth sodium-cooled breed-and-burn fast reactor (B&BR), a CANDLE like reactor [1], for recycling PWR spent fuel has been studied from the neutronics point of view [2&3]. The PWR spent nuclear fuel (SNF) is used as the blanket fuel and the low-enriched uranium (LEU) is used in the initial core. In a B&BR, the neutron economy should be very good so that it can achieve an equilibrium breed-and-burn condition. One way to achieve the good neutron economy is by maximizing the fuel volume fraction in the core. At the same time, the neutron fraction should be improved. In particular, a good reflector is really important in a compact B&BR since the radial neutron leakage is relatively enhanced.

In this study, several alternative radial reflector materials are introduced and investigated. Particularly, lead-based radial reflectors are evaluated in terms of the core lifetime and the coolant void reactivity (CVR). The neutronic analyses were all performed by the Monte Carlo code McCARD [4].

2. Compact B&BR Concepts

The compact sodium-cooled B&BR core configuration is similar to the one in Ref. 3. The reactor power is 250 MWth. The fuel assemblies and the reflector assemblies are arranged in the 8-ring hexagonal core as shown in Fig. 1. The core consists of 78 fuel assemblies, 78 reflector assemblies, and 7 control rods assemblies. In the axial direction, a 40 cm axial HT-9 reflector is located at bottom of the core, while 40 cm-thick bonding sodium is placed at the top of the core. The equivalent core radius is 115 cm.

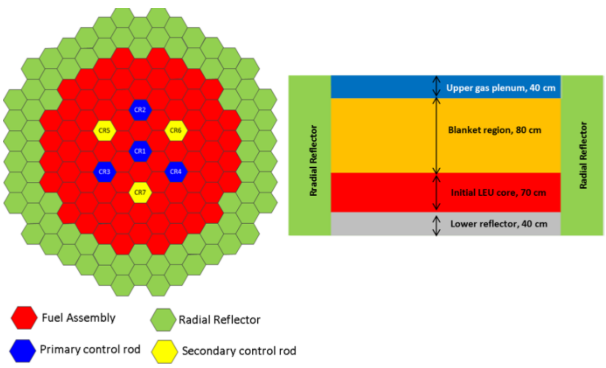

Fig. 1. Layout of the B&BR reactor

The fuel assembly (FA) consists of 127 fuel pins. The fuel pin diameter and P/D ratio is 1.9 cm and 1.064, respectively. The HT-9 cladding thickness is 0.06 cm. The radial reflector consists of 91 pins. The pin diameter is 2.32 cm. The HT-9 cladding thickness in the reflector pin is 0.10 cm.

For the initial LEU core, the U-7Zr metallic fuel with a 70% smear density is used, and a 75% smear density is used for the SNF-7Zr metallic fuel in the blanket region. The SNF in the blanket region is assumed to be metalized through a simple reduction process and the resulting metallic material is melted to fabricate a SNF-7Zr metallic fuel. The composition of the metalized PWR SNF is obtained by assuming that the discharge burnup is 50 GWd/MTU and the cooling time is 10 years.

3. Analysis Results and Discussion

Monte Carlo depletion analysis was first performed to see the impact of the reflector materials on the core lifetime. The fuel, cladding, and coolant temperature used in the calculation are 800 K, 700 K, and 700 K, respectively. These temperatures were obtained by using the one-dimensional single channel thermal analysis. For the Monte Carlo calculations, 25,000 histories and 150 cycles were considered, and ENDF/B-7.0 was used as the nuclear library.

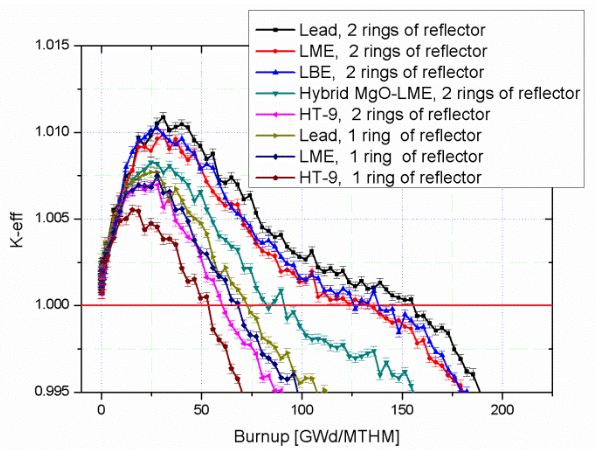

Fig. 2. Evolution of k-eff as a function of burnup.

Several reflector materials were considered in this study: lead, LME (Lead Magnesium Eutectic), LBE (Lead Bismuth Eutectic), hybrid MgO-LME, and the conventional HT-9 reflector. For the hybrid MgO-LME, the MgO reflector is utilized for the inner ring of the initial core, while an LME reflector is used for the blanket region and the outer ring of the radial reflector for the initial core. The purpose of using the MgO reflector for the initial core is to reduce the necessary U-235 enrichment for the initial core.

Fig. 2 shows the evolution of k-eff for several reflector materials and Table 1 shows the corresponding necessary U-235 enrichment and the core lifetime. The uranium enrichment is ~12% for the various reflector materials. To see the impact of the reflector thickness, a single ring of reflector is also considered in the comparison. It is shown in Fig. 2 and Table 1 that by using the lead-containing reflector when the reflector thickness is double, the core lifetime becomes 2-3 times longer. Meanwhile, for the HT-9 reflector, even though the reflector thickness is increased to double, the core lifetime is still short. The results clearly show that the HT-9 has the worst reflector performance and therefore is not suitable for a high-performance B&BR reflector. Another important thing to notice from Figure 2 and Table 1 is that a sufficient reflector thickness is necessary for a B&BR to make best use of the lead-based reflectors.

Table 1. The required U-235 enrichment and core lifetime for various reflector materials

Number of reflector rings	U-235 Enrich. [%]	Core lifetime [GWd/MTHM]
Single		
○ Lead	12.12	71.05
○ LME	12.14	67.96
○ HT-9	12.22	52.52
Double (Original design)		
○ Lead	11.95	154.46
○ LME	11.97	132.83
○ LBE	11.98	135.92
○ Hyb. MgO-LME	11.83	89.58
○ HT-9	12.15	58.96

The CVR was characterized at the EOC condition of each core with double ring reflector. Table 2 shows the CVR values of the cores at the corresponding discharge burnup or EOC condition. The CVR is defined as the reactivity difference between the flooded and the voided cores. Two types of CVR are considered: conservative one by voiding the active core only, and the other one by voiding the whole core.

Table 2. CVR at the corresponding EOC condition

Type of reflectors	CVR by voiding active core only [pcm Δρ]	CVR by voiding whole core [pcm Δρ]
Lead	2531.26 ± 18.60	1982.89 ± 13.45
LBE	2459.52 ± 19.32 (2456.13 ± 16.54)*	1882.53 ± 18.78 (1904.91 ± 18.01)*
LME	2455.05 ± 18.70 (2403.19 ± 17.91)* (2402.77 ± 18.84)**	1888.06 ± 19.45 (1845.26 ± 20.11)* (1772.15 ± 18.97)**
Inner hybrid MgO-LME	1962.50 ± 18.74 (2028.16 ± 17.27)*	1590.54 ± 18.81 (1405.63 ± 18.10)*
HT-9	1292.19 ± 19.62 (1325.55 ± 18.54)*	437.78 ± 20.42 (524.77 ± 19.42)*

* CVR when the original reflector was replaced with Pb reflector
** CVR when the original reflector was replaced with HT-9 reflector

It is clearly shown from Table 2 that the CVR is smaller when voiding of the whole core is considered. This is because the leakage is enhanced by voiding all regions in the core. Another interesting result available from Table 2 is that the CVR for the various reflectors such as Lead, LME, LBE, and HT-9 are comparable at the same burnup when the active core voiding is considered; they only differ in the neutron reflecting performance. But when the whole core voiding is considered, the HT-9 reflector provides a slightly smaller CVR compared to the reflector containing Pb. This is ascribed to the slightly increased neutron capture by the reflector when the HT-9 reflector is used.

In our previous study [2&3], the reflector for the B&BR was Pb, but it is considered to be unsuitable in this study because its melting temperature is rather high, 327.5^{o}C. The volume change caused by the phase change of the Pb during the reactor maintenance at low temperature (e.g., 200^{o}C) can potentially impose a high stress to the reflector cladding. LBE has the lowest melting temperature, but it is considered to be quite expensive, more corrosive than Pb, and produces hazardous Po-210 from bismuth. In the case of LME with a melting temperature of ~250^{o}C, it is expected that the possible phase change of LME may not cause any serious material issues. Regarding the corrosion of the LME reflector, it is considered that it will be rather comparable to the pure lead. Furthermore, the LME reflector may be replaced periodically, if necessary in order to secure the integrity of the radial reflector.

4. Conclusions

Several lead-based reflector materials for a small B&BR reactor have been investigated in terms of the neutronic performances. It was found that a sufficient reflector thickness is important to achieve high performance B&BR by using a lead-based reflector. It is also shown that the radial reflector has a small impact on the CVR: it mainly affects the neutronic performance. It is concluded that pure lead, LME and LBE provide much better neutron economy than the conventional steel reflector. Among the lead-based reflectors, LME reflector is considered as a favorable reflector for the small B&BR because it has a relatively low melting temperature and also it provides a good neutron economy.

REFERENCES

[1] H. Sekimoto, K. Ryu, and Y. Yoshimura, CANDLE: The New Burnup Strategy, Nuclear Science and Engineering, Vol.139, p.306, 2001.
[2] D. Hartanto and Y. Kim, A Compact Breed and Burn Fast Reactor Using Spent Nuclear Fuel Blanket, Proceedings of PHYSOR 2012, April 15-20, 2012, Knoxville, Tennessee, USA.
[3] D. Hartanto and Y. Kim, Characterization of a Metallic-Fuelled B&BR with Non-Uniform Smear Density, Transactions of the Korean Nuclear Society Autumn Meeting 2012, October 25-26, 2012, Gyeongju, Korea.
[4] H. J. Shim and C. H. Kim, "McCARD User's Manual", Version 1.0, Nuclear Design and Analysis Laboratory, Seoul National University, 2010.