Performance of Burnable Poison in $ZrH_{1.6}$ Moderated Driver Zone of a Long-Cycle Fast-Spectrum SMR

Yanuar Ady Setiawan [a,b], Douglas A. Fynan [a*]
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Eonyang-eup, Ulju-gun, Ulsan, 44919, Republic of Korea*
[b]*Department of Nuclear Engineering and Engineering Physics, Faculty of Engineering, Universitas Gadjah Mada (UGM), Yogyakarta, 55281, Indonesia*
[*]*Corresponding author: dfynan@unist.ac.kr*

1. Introduction

Long-cycle fast-spectrum small modular reactors (SMRs) are being proposed to fulfill marine transportation, off-grid/remote electricity production, and proliferation-resistant nuclear power export roles [1]. In the breed-burn configuration of fast-spectrum SMRs, long-cycle operation with low reactivity swing can be achieved for over 30 effective full-power years without refueling nor fuel shuffling. However, the long mean-free-path of fast spectrum requires thick radial reflector (>40 cm) for neutron economy and more material for radiation shielding, all increasing the overall diameter affecting manufacturability, transportability, and weight of the SMR. Performance of the breed-and-burn core is also limited by the zoned enrichment scheme and the power peaking that usually occurs at the core center at end-of-cycle (EOC).

This paper investigates the adoption of the dense moderating material $ZrH_{1.6}$ as a reflector material and in internally moderated fuel pin for a long-cycle lead-bismuth (LBE) cooled fast reactor, forming a moderated driver fuel zone in the outer radius of the core. With the shifted spectrum in the moderated zone, the performance of integrated Gd_2O_3 burnable poison (BP) for controlling local power peaking, global 3D power distribution, and reactivity swing is assessed using an R-θ Monte Carlo model of the core with depletion analysis using the MCS code [2]. The radial enrichment zoning and fuel lattice of MicroURANUS (MU) [1, 3] are the reference design parameters for the study.

2. Model Geometries and Moderator Configurations

2.1 R-θ 3-Zone Model

Figure 1 shows the simplified R-θ model of the MU core as a 1/6th slice, 2D radial model with 2-cm height. Reflective boundary conditions are applied at all sides except for black/vacuum condition at the outer radius of the 50-cm thick reflector, so the model closely approximates the core mid-plane of a 3D core. The reflector is either a "fast spectrum" reference reflector comprised of 50%stainless steel-50% LBE (SS-LBE) or the strongly moderating type with $ZrH_{1.6}$. Less than 25-cm thickness of $ZrH_{1.6}$ is required to achieve the maximum albedo. The UO_2 fuel temperature is set as 900 K, while other material temperatures are set as 600 K. The right panel of Fig. 1 shows the tight-pitch, UO_2 fuel pin lattice of MU [1] which adopts large 2.0-cm diameter fuel pins owing to the low specific power density of the long-cycle core.

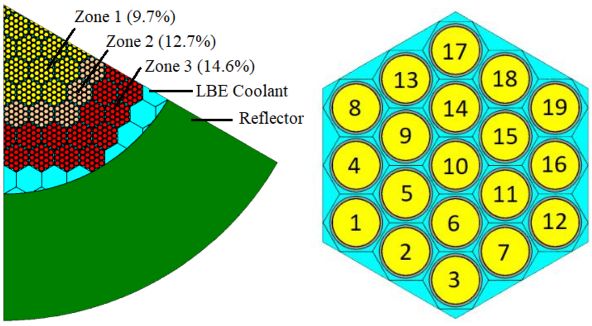

Fig. 1. Left: R-θ core model with 3 enrichment zones; Right: Fuel pin indexing in fuel assembly.

To create a moderated radial driver fuel zone, the outer 10% radius of the UO_2 pellets in the zone 3 assemblies (14.6% ^{235}U enrichment zone) are replaced with $ZrH_{1.6}$ ring illustrated in Fig. 2. For cases with BP, 5wt% or 1wt% Gd_2O_3 is integrated (homogenously mixed) into the UO_2 of all fuel pins in the 8th ring of fuel assemblies (the outermost zone 3 assemblies). The 7th ring still contains the moderated fuel pins but does not have the integrated BP. Table 1 summarizes the seven combinations of reflector, moderated fuel, and BP studied.

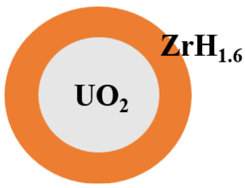

Fig. 2. Fuel pin with 10vol% $ZrH_{1.6}$ moderator (not to scale).

Table I: Summary of the Study Cases

Case Name	Reflector	Moderated Fuel	Burnable Poison
FR	SS-LBE	-	-
FR-BP	SS-LBE	-	5 wt% Gd_2O_3 in Ring-8 Fuel
FR-MF	SS-LBE	10vol% $ZrH_{1.6}$ in Ring 7 & 8	-
FR-MF-BP	SS-LBE	10vol% $ZrH_{1.6}$ in Ring 7 & 8	1 wt% Gd_2O_3 in Ring-8 Fuel
MR	$ZrH_{1.6}$	-	-
MR-MF	$ZrH_{1.6}$	10vol% $ZrH_{1.6}$ in Ring 7 & 8	-
MR-MF-BP	$ZrH_{1.6}$	10vol% $ZrH_{1.6}$ in Ring 7 & 8	1 wt% Gd_2O_3 in Ring-8 Fuel

3. Influence of Moderated Fuel and BP in Fast Reactor

3.1 Fast-Reflector (FR) Case

The result from 30-year MCS burnup simulation of this simplified 2D model (FR case) gives accurate insights of burnup behavior of MU core design requiring less than 48-hour simulation time using pin-wise depletion, 2 year burn steps, and semi-predictor-corrector method. The number of histories was optimized such that the highest absolute error of k_{eff} is 7.8 pcm and the relative error of the pin power is <1% compared to case with much higher number of histories. Figure 3 shows that the power distribution is shifted from the outer ring at beginning-of-cycle (BOC) to the core center at EOC. This power shift to the core center decreases the net leakage of neutron compensating for the fuel depletion effect during the burn cycle which eventually results in the ~600 pcm increase of reactivity during the core lifetime as shown in Fig. 4.

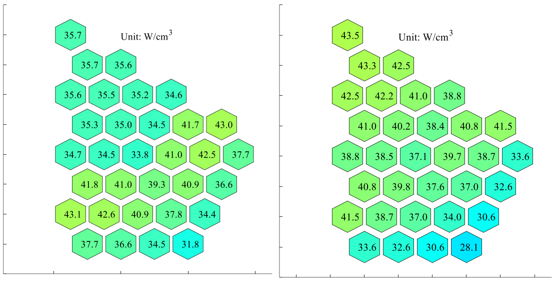

Fig. 3. Left: BOC power distribution FR case; Right: EOC power distribution of reference case.

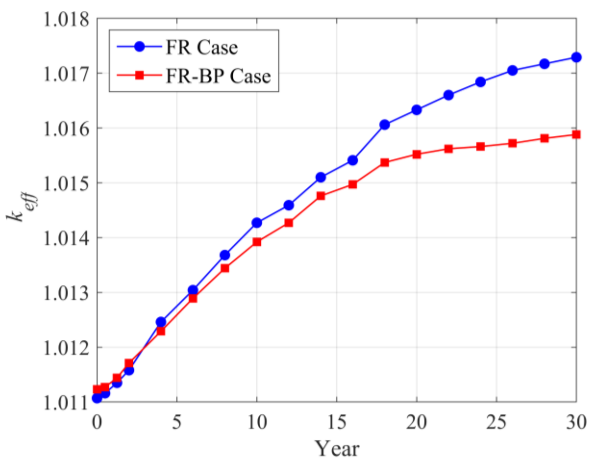

Fig. 4. Comparison of 30-year burnup k_{eff} between FR case and FR-BP case.

3.2 Fast-Reflector with Burnable Poison (FR-BP) Case

For the FR-BP case, 5wt% Gd_2O_3 is homogeneously mixed with the UO_2 fuel in ring-8 assemblies. The 30-year burnup simulation in Fig. 5 shows that the power distribution also shifts from the outer ring at BOC to the core center at EOC, with ~450 pcm increase of reactivity swing (Fig. 4).

Figure 6 shows that the Gd_2O_3 is not performing as a BP because the gadolinium isotopes (^{157}Gd and ^{155}Gd) are only depleted by ~7% and ~25% in 30 years. Although the gadolinium depletion rates are more than 2 times faster than ^{238}U, most of the BP inventory remains at EOC when it should be fully depleted as in a thermal spectrum. This shows that Gd_2O_3 is not an effective burnable poison in fast spectrum.

Compared to the FR case, Fig. 5 shows lower power in the ring-8 assemblies and higher powers in zones 1 and 2. This power shift is mainly due to the ~7% reduction in U number density in the ring-8 fuel assemblies and not due to flux depression caused by the presence of the BP. Due to the power shift, the FR-BP case has a smaller net neutron leakage early in the cycle and thus a slightly higher k_{eff} in the first 3 years compared to the FR case.

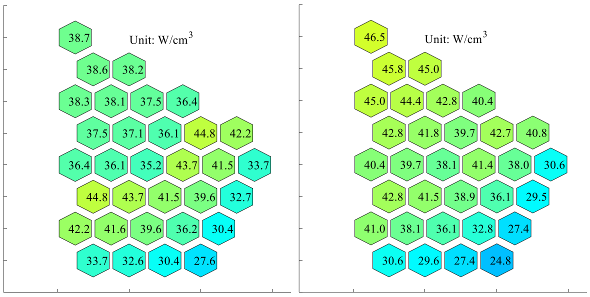

Fig. 5. Power distribution of FR-BP case; Left: BOC; Right: EOC.

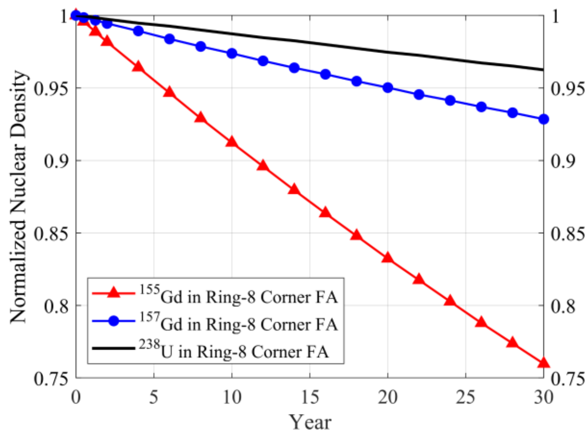

Fig. 6. Depletion of ^{155}Gd, ^{157}Gd, and ^{238}U in 30 years of FR-BP case.

3.3 Fast-Reflector Moderated-Fuel (FR-MF) Case

The FR-MF case has ~1700 pcm higher k_{eff} at BOC (1.02384) than the FR case (1.01101), despite 10% reduction of uranium mass in those 2 fuel rings. The $ZrH_{1.6}$ softens the spectrum resulting in shorter mean-free-path (mfp) of the neutrons near the core periphery, which in turn reduces (significantly) the net leakage. However, Fig. 7 shows the FR-MF case has a large negative reactivity swing (~3000 pcm) during its 30-year burnup cycle due to the fissile material net depletion effect while the change in the net leakage is smaller in magnitude.

Figure 8 shows the addition of $ZrH_{1.6}$ material in the outer rings gives higher zone 3 power throughout the whole burn cycle. This higher power means higher fuel utilization because the assemblies with the highest enrichment—the most expensive fuel—will have higher discharge burnups. Table 2 provides pin-wise power densities using with fuel pin indexing (Fig. 1) and fuel assemblies in rings 7 and 8 numbered in ascending order from left to right. The BOC pin power distribution within the moderated fuel assemblies are relatively flat.

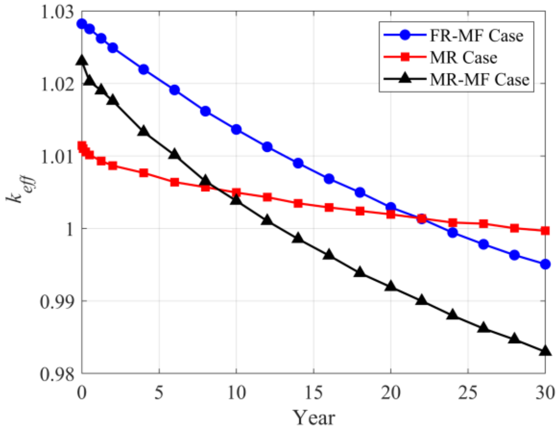

Fig. 7. Burn cycle k_{eff} of FR-MF, MR, and MR-MF cases

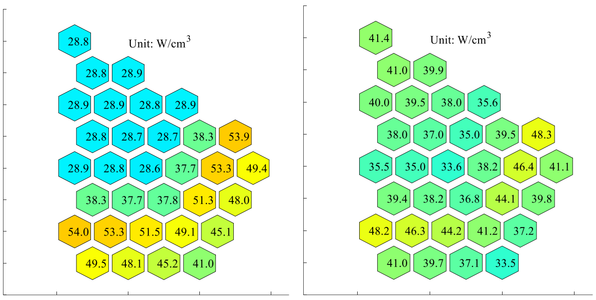

Fig. 8. Power distribution of subsection FR-MF case; Left: BOC; Right: EOC.

3.4 Fast-Reflector Moderated-Fuel with Burnable Poison (FR-MF-BP) Case

Figure 9 shows ~3000 pcm negative reactivity swing and higher Gd depletion rates, but the BP is still not fully depleted at EOC. The addition of $ZrH_{1.6}$ moderator only shifts the spectrum until the epithermal region (Fig. 10) which increases the resonance absorption in the large low-lying resonances of the Gd isotopes (Fig. 11). ^{155}Gd is the more effective BP (~1.3 times higher flux-weighted 1-group cross section than ^{157}Gd) in this spectrum because it has more resonances in the shifted region.

Overall, Gd_2O_3 addition to the ring-8 fuel assemblies does not give the desired burnable poison performance here. Gd_2O_3 addition to the ring-7 fuel assemblies would not have the desired effect either because the spectrum is harder there.

Table II: FR-MF BOC Pin-Power Distribution in Ring 7 and 8

Ring-7 Fuel Assembly Pin Power Density (W/cm^3)							
Pin#	FA1	FA2	FA3	FA4	FA5	FA6	FA7
1	54.6	54.4	53	49.9	49.9	51.9	53.1
2	54.1	53.7	51.8	48.3	51.2	53.6	54.5
3	53.5	52.7	50.6	46.6	50.6	53.3	54.6
4	54.7	54.6	53.4	50.6	49.4	51.2	52
5	55.2	54.8	53	49.9	51.6	53.8	54.6
6	55	54.1	52.1	48.5	51.8	54.2	55.1
7	54.1	53.2	50.7	46.8	50.6	53.2	54.3
8	52.9	52.9	51.7	49.7	48.5	49.9	50.5
9	54.9	54.3	52.9	50.6	51.8	53.5	54.1
10	55.5	54.6	52.7	49.8	52.6	54.5	55.3
11	55.2	54.2	51.8	48.5	51.9	54	54.8
12	54.6	53.3	50.6	46.7	50.4	52.7	53.4
13	52.1	51.8	50.3	49.2	50.3	51.6	52
14	54.3	53.6	51.8	50.3	52.6	54.5	54.6
15	54.9	54	51.8	49.9	52.7	54.8	55.1
16	54.7	53.8	51.3	48.4	51.7	53.4	54.3
17	50.6	49.9	48.7	49.6	51.6	53	53.1
18	52.1	51.3	49.7	50.4	53.1	54.5	54.5
19	52.9	52.1	50.1	49.8	52.7	54.3	54.6
Avg.	54	53.3	51.5	49.1	51.3	53.3	53.9
Ring-8 Fuel Assembly Pin Power Density (W/cm^3)							
Pin#	FA1	FA2	FA3	FA4	FA5	FA6	FA7
1	47.8	46.9	44.8	41.1	45.4	49	51.1
2	46.8	45.7	43.3	39.6	43.4	46.9	49.1
3	46	44.8	42	38.7	41.9	45.3	47.3
4	49.6	48.8	46.4	42.3	47.2	50.4	52.2
5	48.3	47.4	44.9	40.7	45.4	48.4	50.2
6	47.4	45.9	43.2	39.2	43.2	46.6	48.2
7	46.6	44.9	41.8	38.4	41.7	45	46.5
8	51.7	50.8	48.4	44.2	48.8	51.9	53.2
9	50.6	49.5	46.6	42.4	47	50	51.4
10	49.4	48	45.1	40.6	45	48	49.3
11	48.2	46.5	43.4	39.1	43.1	46.1	47.3
12	47.2	45.4	42	38.6	41.9	44.8	46.2
13	52.6	51.4	48.7	44.2	48.6	51.5	52.7
14	51.5	50.1	47.1	42.4	46.5	49.5	50.4
15	50.3	48.6	45.2	40.7	44.7	47.2	48.2
16	49	47.1	43.5	39.6	43.3	45.7	46.8
17	53.3	51.8	48.8	44.3	48.2	50.8	51.6
18	52.2	50.5	47.3	42.4	46.4	48.7	49.5
19	51.2	49.2	45.3	41.1	44.8	46.9	47.7
Avg.	49.5	48.1	45.2	41	45.1	48	49.4

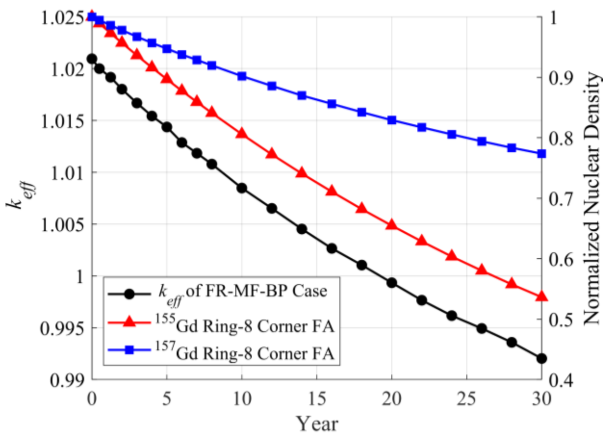

Fig. 9. Burn cycle k_{eff} and BP depletion of FR-MF-BP case.

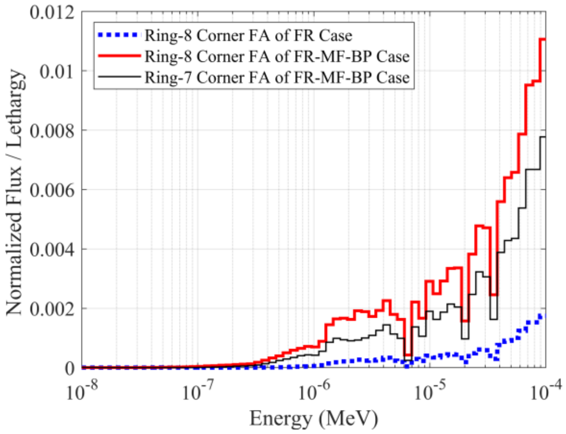

Fig. 10. Comparison of BOC epithermal flux spectrum showing moderated fuel has higher flux in resonance region.

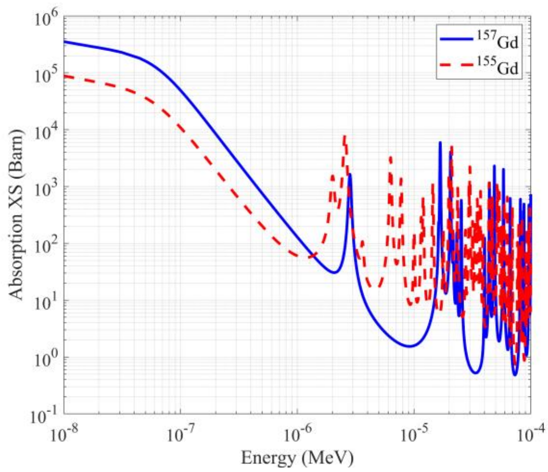

Fig. 11. Absorption cross section of ^{155}Gd and ^{157}Gd (ENDF VII.1).

4. Parametric Study of Moderating Reflector Cases

4.1 Moderated-Reflector (MR) Case

If thick hydrogenous moderating material such as $ZrH_{1.6}$ is adopted as a reflector for a fast spectrum core, the effectiveness of the reflector is function of two coupled parameters, the reflector albedo (ratio of incoming current to the outgoing current) and the spectrum shift of the incoming current. The MR case reactivity at BOC (Fig. 7) is slightly higher than the FR reference case by 38 pcm. The moderating reflector has strong influence on the power distribution shown in Fig. 12 with significantly higher powers in the outer ring and extreme power peaking in the ring-8 corner fuel assembly at BOC. A closer examination of the pin power distribution of the ring-8 corner fuel assembly in Table 3 shows that there is pin power peaking up to ~250% of assembly average (which is already high). This extreme power peaking issue is because the high enriched periphery fuel pins (#1, #2, #3, #7, #12, #16, #19) directly see the incoming thermal flux returning from the $ZrH_{1.6}$ reflector region.

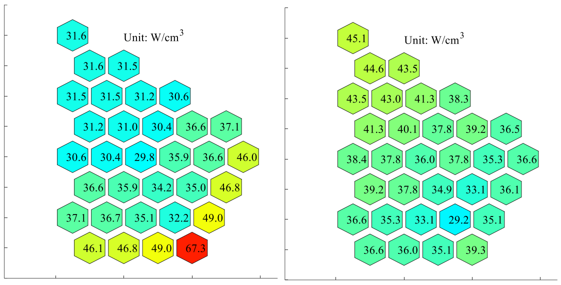

Fig. 12. Power distribution of MR case; Left: BOC; Right: EOC.

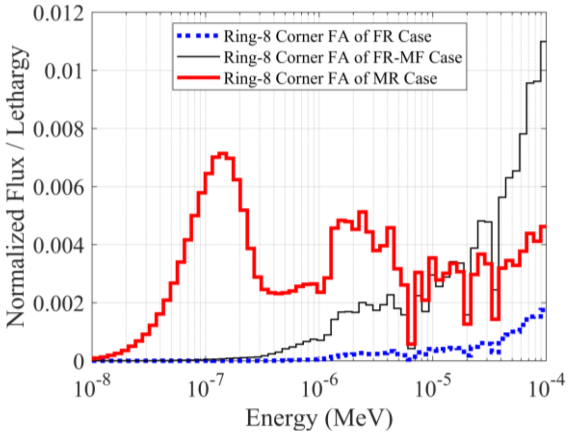

Fig. 13. BOC flux spectrum of FR, FR-MF, and MR cases

Figure 13 compares the flux spectrum in the corner assembly for the FR, FR-MF, and MR cases. The moderating material is only in the reflector for the MR case, so the thermal peak and relative flux increase in the epithermal and low-energy resonance region are entirely attributed to the incoming current from the reflector. In 30 years, the fuel pins seeing thermal flux are significantly depleted resulting in much lower pin powers at EOC (see column 3 of Table 3). Secondly, the EOC power distribution is somewhat flat with higher powers in the ring-8 assemblies than the FR case indicating better fuel utilization of the high enrichment zone. The reactivity swing is larger in magnitude than the FR case but smaller than all other cases using moderating material at -1176 pcm. A moderating reflector concept appears to have some positive attributes if the extreme local power peaking issues can be mitigated.

4.2 Moderated-Reflector Moderated-Fuel (MR-MF) Case

For the MR-MF case, Fig. 7 shows a large negative reactivity swing (~4000 pcm), from k_{eff} 1.02288 at BOC. Figure 14 and Table 3 shows that this MR-MF case still suffers extreme pin power peaking issue in the ring-8 corner fuel assembly and significantly higher zone 3 assembly powers at BOC. The depletion effect results in flat power distribution and suppression of the local power peaking issues at EOC. Results from MR and MR-MF cases indicate that there might be an optimal combination between $ZrH_{1.6}$ volume percentage and the enrichment level in zone 2 and 3 to manage the power peaking issue at BOC.

Table III: Ring-8 Corner Fuel Assembly Pin-Power Distribution of MR, MR-MF, and MR-MF Cases

Ring-8 Corner FA Pin Power Density (W/cm^3)							
Pin	MR Case		MR-MF		MR-MF-BP		
#	BOC	EOC	BOC	EOC	BOC	6-Y	EOC
1	82.4	51.5	84.3	50.6	39.7	71.1	50.8
2	106.6	58.4	105.0	56.3	43.7	89.5	57.4
3	170.2	53.9	159.8	52.8	57.9	131.1	55.8
4	35	28.4	41.8	32.2	30	34.2	31.2
5	37.5	32.1	43.3	34.2	28	34.3	33.6
6	50.1	46.7	54.2	45.2	28.6	43	44.8
7	138.6	59.1	132.8	56.9	49.7	111.2	59.2
8	29.6	24.6	38.1	29.8	31.8	33.8	28.9
9	29.1	23.6	36.4	28	28.6	31.6	27
10	31.8	26.4	37.8	29.6	26.6	31.2	28.2
11	50.1	46.3	54.4	45.5	28.8	42.7	45.5
12	170	53.5	160.1	53.2	58.2	130.5	55.8
13	28.7	23.9	37	29.2	31.6	33.4	28.6
14	29.1	23.7	36.4	28	28.8	31.6	27
15	37.5	31.9	43.4	34.4	27.9	34.4	33.5
16	106.1	58.4	105.3	56.8	43.7	88.7	57.5
17	29.7	24.7	38.1	29.8	31.7	33.9	28.9
18	34.9	28.6	41.7	32.5	30	34.3	31.1
19	82.7	51.9	84.1	51.2	39.9	71.1	51.2
Avg.	67.3	39.3	70.2	40.9	36.1	58.5	40.8

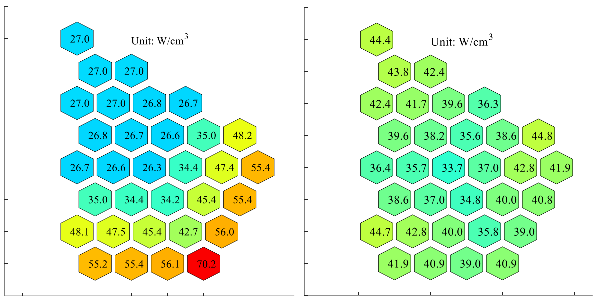

Fig. 14. Power distribution of MR-MF case, Left: BOC; Right: EOC.

4.3 Moderated-Reflector Moderated-Fuel with Burnable Poison (MR-MF-BP) Case

For MR-MF-BP case, the 1wt% Gd_2O_3 is added to the ring-8 fuel to test if reactivity swing can be reduced and extreme local power peaking be suppressed at BOC. Figure 15 and Table 3 shows that the Gd_2O_3 addition in the soft neutron spectrum region around ring-7 and ring-8 is suppressing BOC k_{eff} to 0.9804 and ring-8 corner FA pin power. Here the BP is behaving similar to those in light water reactor lattice. As the gadolinia rapidly burns out (~50% depleted) in the first 6 years, the core reactivity reaches its maximum point with ~2000 pcm reactivity swing, before decreasing with similar rate as other previous cases (MR and MR-MF cases). This rapid depletion of gadolinium isotopes is due to the relatively high amount of thermal and epithermal neutron flux, especially compared to the FR case, as shown by Fig. 16. Figure 16 also shows the Gd_2O_3 addition in ring-8 assemblies greatly suppress the thermal flux compared to the MR-MF case.

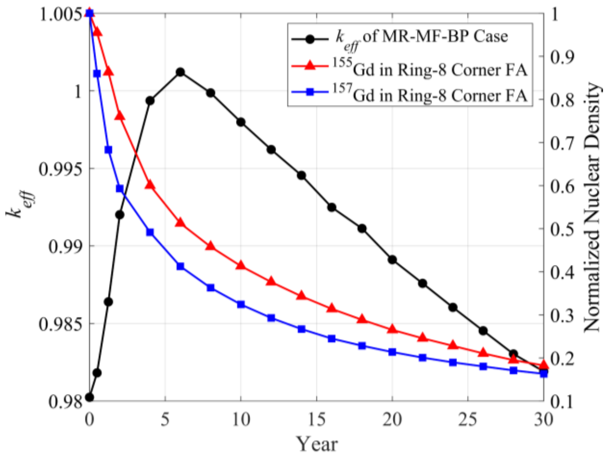

Fig. 15. Burn cycle k_{eff} and BP depletion of MR-MF-BP case.

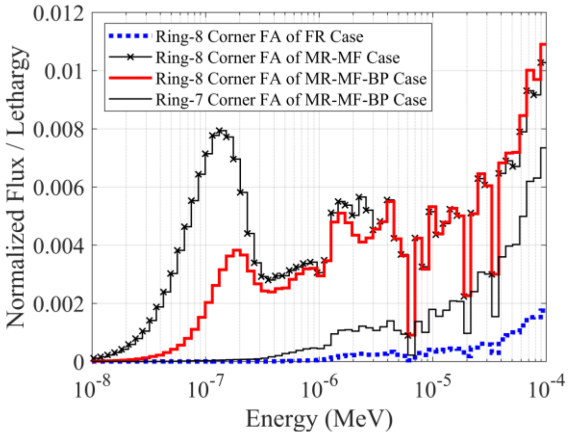

Fig. 16. Comparison of BOC flux spectrum showing MR-MF-BP case has higher flux in thermal, epithermal, and resonance region.

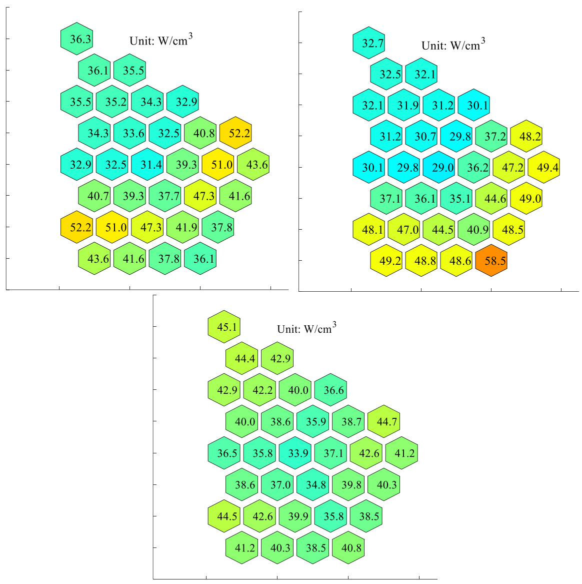

Fig. 17. Power distribution of MR-MF-BP case, Upper Left: BOC; Upper Right: 6-year burn cycle; Below: EOC.

The gadolinia depletion behavior affects the local power peaking and power shift behavior throughout the burn cycle as shown by Fig. 17 and Table 3. At BOC, the local power peaking is fully suppressed but returns at 6 years—after BP depletion. However, the power peaking at 6 years is not as extreme as the BOC of the MR case because some of the fissile inventory in those fuel pins has been burned during the first six years. At EOC, the power distribution is also flat. This case suggests the incorporation of the BP in softened/thermalized zone provides additional degrees of freedom for controlling reactivity swing, local power peaking, and power distribution. However, the strong coupling between the physics and design options (fuel enrichment, amount of moderating material, locations of moderating material, amount of BP) and high sensitivity coefficients suggest the need for comprehensive multi-variable optimization study to determine the effectiveness of BP strategies in fast-spectrum SMR.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (grant no. 20214000000410) and the National Research Foundation of Korea Grant funded by the Korean Government (NRF-2021M2D1A1019061).

REFERENCES

[1] T.D.C Nguyen, M.F. Khandaq, E. Jeong, J. Choe, D. Lee, and D.A. Fynan, MicroURANUS: CORE Design for Long-Cycle Lead-Bismuth-Cooled Fast Reactor for Marine Application, International Journal of Energy Research, Vol.45(8), p.12426-12448, 2021.

[2] H. Lee, W. Kim, P. Zhang, M. Lemaire, A. Khassenov, J. Yu, Y. Jo, J. Park, and D. Lee, MCS-A Monte Carlo Particle Transport Code for Large-Scale Power Reactor Analysis, Annals of Nuclear Energy, Vol.139,107276, 2020.

[3] M.F. Khandaq, T.D.C Nguyen, E. Jeong, J. Choe, D.A. Fynan, and D. Lee, Conceptual Design of Onverted Core Lead Bismuth Eutectic Fast Reactor for Marine Applications, Proceedins of International Conference on Physics of Reactors (PHYSOR) 2022, p.598-605, 2022.