Reactor Core Design with High-content Gadolinia Burnable Absorbers in Soluble Boron-free i-SMR

Jeongmu Eun[a*], Hoseong Yoo[a], Gonghoon Bae[a], Jinsun Kim[a]
[a]KEPCO Nuclear Fuel, 242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea
[*]Corresponding author: jmeun@knfc.co.kr

***Keywords :** i-SMR, burnable absorber, soluble boron-free, high-content gadolinia

1. Introduction

The innovative-Small Modular Reactor (i-SMR) is characterized by a 24-month operational cycle and soluble boron-free (SBF) operation. Under SBF conditions, only control rods are used to control reactivity. However, typical Gd_2O_3 burnable absorbers (BAs) have a short burnout time, which can increase reliance on control rod insertion during operation. Therefore, typical Gd_2O_3 BAs are not suitable for i-SMR, and BAs with long burnout time are required for effective reactivity control under SBF operation. A previous study proposed a core design with enriched gadolinia BAs (Gd_2O_3 BAs enriched in ^{155}Gd and ^{157}Gd) [1].

In this study, we designed high-content gadolinium BAs with natural isotopic abundance (i.e., ^{155}Gd and ^{157}Gd are not enriched) for the i-SMR to enhance long-term reactivity control under SBF operation. To evaluate core characteristics with high-content gadolinium BA, loading patterns were determined from the initial core (1st cycle) to the equilibrium core (8th cycle).

2. Method and Results

2.1. Computational Method

The core design is implemented using the Kernel Analyzer by Ray-tracing Method for fuel Assembly (KARMA) [2, 3] and Advanced Static and Transient Reactor Analyzer (ASTRA) [4]. KARMA is a two-dimensional multi-group lattice transport code that performs assembly burnup calculations and generates two group cross sections. This code uses the subgroup method for resonance self-shielding effect and Method of Characteristics (MOC) as the transport solution method. ASTRA is a 3D core depletion code as a nuclear design code for the core design of PWRs. ASTRA has the neutronic solver based on the Semi Analytic Nodal Method (SANM) formulated with the Coarse-Mesh Finite Difference method (CMFD) [5, 6].

2.2. Fuel Assembly Design

As the gadolinia content increases, the thermal conductivity and melting point of the UO_2-Gd_2O_3 fuel mixture decrease [1], which may affect fuel performance and safety margins. Therefore, the ^{235}U enrichment was adjusted according to the gadolinium content.

Table I present the fuel assembly (FA) specifications of the initial core. Table II present the FA specifications of the equilibrium core. A3, A4, and H2 through H5 include both high Gd BA and Low Gd BA.

Table I: Fuel Assembly Specifications for Initial Core

Type	Fuel Rod	High Gd BA		Low Gd BA	
	^{235}U (w/o)	^{235}U / Gd (w/o)	No.	^{235}U / Gd (w/o)	No.
A1	4.0	1.0 / 13.0	16	-/-	-
A2	4.0	1.0 / 13.0	20	-/-	-
A3	4.0	0.5 / 18.0	20	2.2 / 2.0	4
A4	4.0	0.5 / 18.0	24	2.2 / 1.0	4

Table II: Fuel Assembly Specifications for Equilibrium Core

Type	Fuel Rod	High Gd BA		Low Gd BA	
	^{235}U (w/o)	^{235}U / Gd (w/o)	No.	^{235}U / Gd (w/o)	No.
H1	4.95	2.2 / 8.0	20	- / -	-
H2	4.95	1.5 / 13.0	20	2.2 / 6.0	8
H3	4.95	1.5 / 13.0	24	2.2 / 6.0	4
H4	4.95	1.5 / 13.0	20	2.2 / 6.0	12
H5	4.95	0.5 / 18.0	24	2.2 / 8.0	12

2.3. Reactor Core Design

The thermal power of the i-SMR is 520 MWth, and the core has 69 FAs. The active core height is 240 cm, with the upper 30 cm configured as a 2.2 w/o ^{235}U enrichment axial blanket region. The operating pressure was assumed to be 15.5 MPa, the overhaul period was set to 30 days. The control rods are composed of a regulating control rod group (R4, R3, R2, R1) and a emergency shutdown control rod group (SB). In this study, only the regulating control rod group was used. The regulating control rod overlap was 50% between each group.

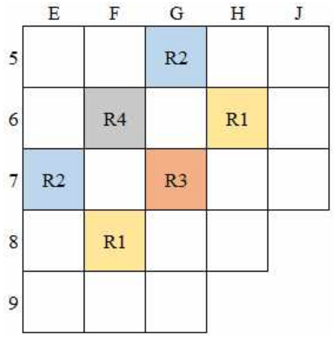
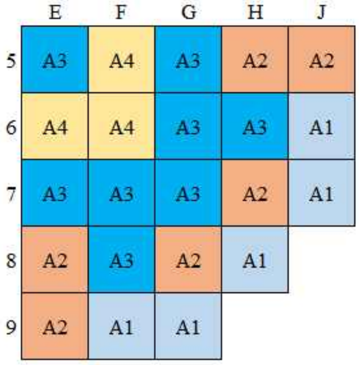


Fig. 1. Regulating Control Rod Pattern

The loading pattern was determined to satisfy the assumed design limits of $-0.3 < \text{ASI} < 0.3$, $\text{Fq} \leq 2.3$, and a cycle length ≥ 680 EFPD (effective full power day). The end-of-cycle (EOC) condition was assumed with control rod group R4 withdrawn to 70%.

Figure 2 through 4 present the loading pattern and the results of the initial core. The maximum ASI is 0.299, and the maximum Fq is 2.275. The cycle length of the initial core was 742.4 EFPD.



	E	F	G	H	J
5	A3	A4	A3	A2	A2
6	A4	A4	A3	A3	A1
7	A3	A3	A3	A2	A1
8	A2	A3	A2	A1	
9	A2	A1	A1		

Fig. 2. Initial core loading pattern

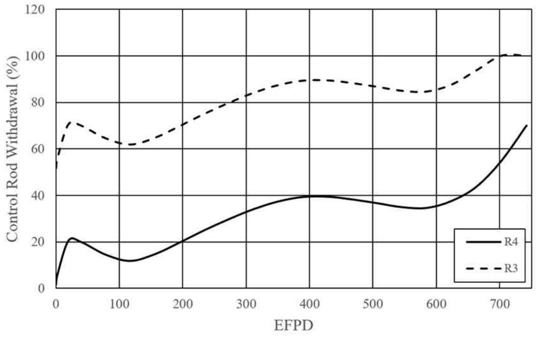


Fig. 3. Control rod position in 1st cycle

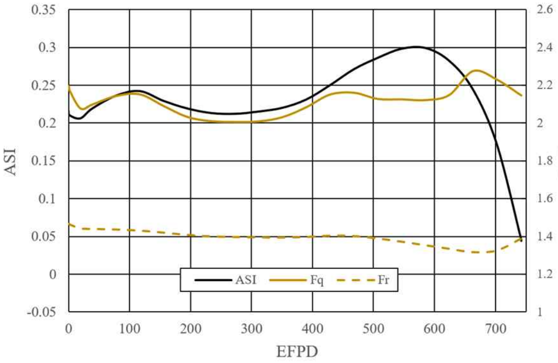
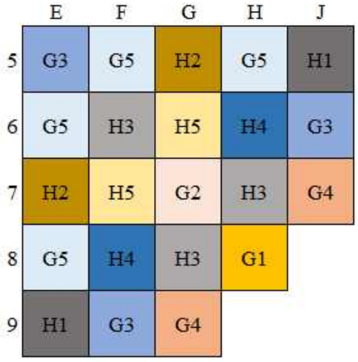


Fig. 4. ASI, Fq, and Fr in 1st cycle

Figure 5 through 7 present the loading pattern and the results of the equilibrium core. The G1 through G5 FAs have the same specifications as the H1 through H5 FAs. The maximum ASI is 0.231, and the maximum Fq is 2.272. The cycle length of the equilibrium core was 702.1 EFPD.



	E	F	G	H	J
5	G3	G5	H2	G5	H1
6	G5	H3	H5	H4	G3
7	H2	H5	G2	H3	G4
8	G5	H4	H3	G1	
9	H1	G3	G4		

Fig. 5. Equilibrium core loading pattern

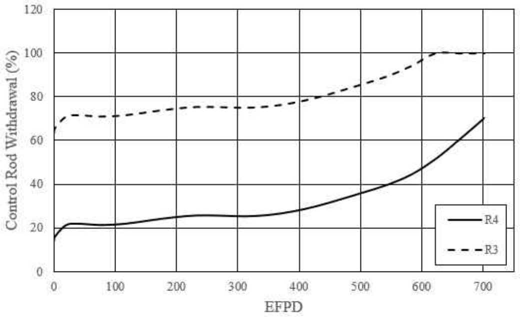


Fig. 6. Control rod position in 8th cycle

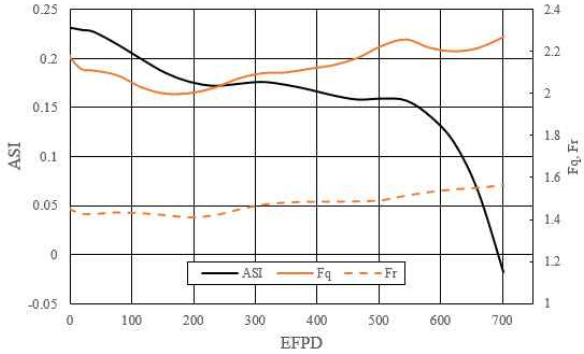


Fig. 7. ASI, Fq, and Fr in 8th cycle

It was confirmed that both cycles satisfied the specified design limits. These results indicate that the proposed high-content gadolinium BAs can provide sufficient long-term reactivity control to achieve the design targets, which is difficult to obtain with typical Gd_2O_3 BAs due to their short burnout time.

3. Conclusions

In this study, a high-content gadolinium BA design was proposed for a 24-month SBF operation in i-SMR. The objective was to enhance long-term reactivity control under SBF operation. From the initial core to the equilibrium core, loading patterns were determined based on assumed design limits of $\text{ASI} \leq 0.3$, $\text{Fq} \leq 2.3$, and cycle length ≥ 680 EFPD. The analysis confirmed that both cycles satisfied these criteria.

The use of high-content gadolinium BA effectively suppressed excess reactivity at the beginning of cycle (BOC) and contributed to extending the cycle length under SBF conditions. Although only the 24-month cycle and SBF operation were considered in this study, the results demonstrate the feasibility of high-content gadolinium BA for i-SMR.

Acknowledgement

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (MCEE) (No. RS-2023-00259032).

REFERENCES

[1] J. S. Kim et al., “Reactor core design with enriched gadolinia burnable absorbers for soluble Boron-Free operation in the innovative SMR”, Nuclear Engineering and Design, Vol. 428 (2024).
[2] K. S. Kim et al., “Transport Lattice Code KARMA 1.1,” Transactions of Korea Nuclear Society Autumn Meeting (2009).
[3] K. S. Kim et al., “Implementation of the Gamma Transport Calculation Module in KARMA 1.2”, Transactions of Korea Nuclear Society Spring Meeting (2011).
[4] T. Y. Han et al., “Verification of ASTRA Code with PWR MOX/UO2 Transient Benchmark Problem”, Transactions of Korea Nuclear Society Autumn Meeting (2010).
[5] J. I. Yoon and H. G. Joo, “Two-Level Coarse Mesh Finite Difference Formulation with Multigroup Source Expansion Nodal Kernels”, Journal of Nuclear Science and Technology, Vol. 45, p.668-682 (2008).
[6] H. G. Joo et al., “Multigroup pin power reconstruction with two-dimensional source expansion and corner flux discontinuity”, Annals of Nuclear Energy, Vol. 36, p.85~97 (2009).