Feasibility of LEU+ Fuel Loading Patterns in the i-SMR with HIGA and Erbia Burnable Absorbers

Jinsun Kim [a, b], Jooil. Yoon [b*]
[a]*KEPCO Nuclear Fuel, 242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea*
[b] *KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Korea*
[*]*Corresponding author: jiyoon@kings.ac.kr*

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1. Introduction

Efforts are underway to achieve soluble-boron-free operation and a 24-month fuel cycle in the innovative small modular reactor (i-SMR). However, realizing this cycle length using conventional low enriched uranium (LEU, ≤5 wt.% U-235) fuel requires a core design incorporating 36 fresh fuel assemblies and a two-batch loading scheme. This is problematic as the resulting low burnup and short fuel cycles lead to more frequent refueling, higher operational costs, and increased spent nuclear fuel generation. These factors collectively reduce the fuel cycle efficiency of the i-SMR.

To extend the fuel cycle of the i-SMR, fuel assemblies with enrichment levels above 5 wt.% are required instead of the currently used LEU (≤5 wt.% U-235) fuel. Such fuels are classified as high-assay low enriched uranium (5–19.75 wt.%) fuels. This study evaluates the feasibility of using LEU+ (5–10 wt.% U-235) fuel to achieve soluble-boron-free operation in the i-SMR and enhance its economic viability. Currently, fuels produced by most manufacturing facilities worldwide are limited to an enrichment level of up to 5.0 wt.%. However, some facilities are being upgraded to support the production of LEU+ fuel and promote extended fuel cycles based on ongoing research [1].

In general, improving fuel cycle efficiency leads to increased discharge burnup of fuel assemblies, potentially surpassing the current regulatory limit of 62 GWD/MTU in an equilibrium core [2]. However, in South Korea, the Korea Institute of Nuclear Safety imposes an even stricter limit, capping the maximum allowable rod-averaged discharge burnup at 60 GWD/MTU [3]. Addressing this constraint requires advancements in fuel cladding performance. A key area of research in this context is the development of accident-tolerant fuel (ATF) cladding, which involves modifying cladding materials to boost their resistance to accidents [4].

This study evaluates the feasibility of integrating ATF cladding and LEU+ fuel in a soluble-boron-free i-SMR core. Additionally, it assesses the effectiveness of high-integrity gadolinium aluminate (HIGA) and Erbia (Er_2O_3–UO_2) burnable absorbers, developed in previous studies, in effectively controlling the excess reactivity of LEU+ fuel within the core [7],[8]

2. Methods and Results

2.1 Computational Method

The core design is implemented using the Kernel Analyzer by Ray-tracing Method for fuel Assembly (KARMA) and SNU Pin Homogenized Innovative Neutronics Core Simulator (SPHINCS) codes. Among these, the KARMA code generates two-dimensional multi-group cross-sections, which are then used as input for SPHINCS. Using a pin-by-pin calculation method, SPHINCS performs whole-core neutronics simulations, allowing for a detailed analysis of neutron flux distribution and reactivity effects [5][6].

2.2 Parameter and Geometry Data

Table I. Parameters of the 17 × 17 fuel assembly

Parameter	Unit	Value
Fuel assembly array		17 × 17
Fuel assembly height	cm	240
Number of fuel rods		264
Number of guide tubes		24
Instrument center		1
Reactor thermal power	MWt	520
Fuel enrichment	wt%	6.0
Number of HIGA rods	EA	16
Number of ERBIA rods (Er_2O_3–UO_2)	EA	248
Fuel rod		
Pellet's outer diameter	inch	0.3225
Rod pitch	inch	0.4960
Cladding's inner diameter	inch	0.3290
Cladding's outer diameter	inch	0.3740
Guide tube's inner diameter	inch	0.4420
Guide tube's outer diameter	inch	0.4820
Cladding material		HANA

Fig. 1 illustrates the 17 × 17 fuel assembly configuration used in this study. To enable soluble-boron-free operation of the i-SMR with LEU+ fuel (6.0

wt.% U-235), 16 HIGA rods are incorporated to control excess reactivity. Except for the HIGA rods, all fuel rods are doped with 0.5–2.0 wt.% Er_2O_3 into UO_2. The HIGA rods contain 20.0 mol.% Gd_2O_3 in a Gd_2O_3–Al_2O_3 composite form.

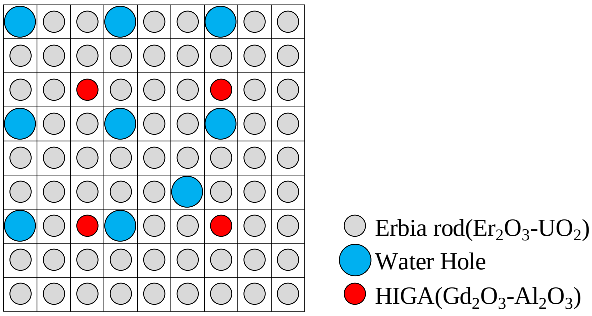

Fig. 1 One-quarter cross-sectional view of the 17 × 17 fuel assembly, showing Er_2O_3–UO_2 fuel rods and HIGA (Gd_2O_3–Al_2O_3) burnable absorber rods.

Fig. 2 illustrates the variation in k-inf values as a function of burnup for different HIGA rod counts. Notably, increasing the number of HIGA rods improves excess reactivity control for LEU+ fuel. However, decreasing the number of fuel rods increases the linear power density (kilowatts per foot), which lowers the safety margin. Considering this trade-off, 16 HIGA rods are selected for this study.

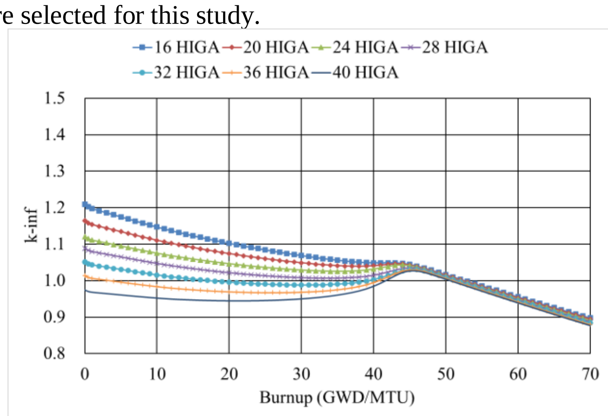

Fig. 2 k-inf variation with burnup for different HIGA rod configurations

Fig. 3 depicts the locations of the regulating bank (RB), shutdown bank (SB), and top-mounted in-core instrumentation (TI). Notably, the TI technology used in the i-SMR requires the removal of 16 control rods, which poses a challenge for soluble-boron-free SMRs, where control rod worth is pivotal. To ensure long-term insertion capability, the RB is designed using Al–In–Cd. Additionally, to compensate for the reduced rod worth, the SB is enriched with more than 80% B-10.

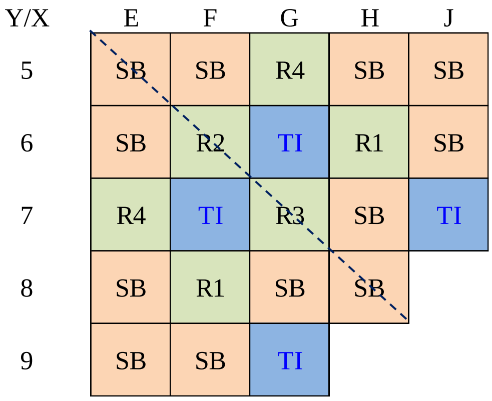

Fig. 3 Arrangement of RBs (R1–R4), SBs, and TIs in the 1/4 core configuration.

Fig. 4 presents the first-cycle burnup results for LEU+ fuel with Erbia and HIGA rods. Under the all rod-out (ARO) condition, the maximum excess core reactivity is approximately 2500 pcm, with a cycle length of approximately 1400 EFPD. These results confirm the feasibility of soluble-boron-free control rod operation in the reactor. The control rod positions required to maintain core criticality throughout the cycle are illustrated in Fig. 5, where excess reactivity is controlled by inserting control rods up to R4: 100%, R3: 64%, and R2: 14%, with the RB interval arbitrarily set at 50%. Under rodded depletion conditions, the cycle length increases to 1430 EFPD, with a maximum pin burnup of 47,128 MWD/MTU. In comparison, the first-cycle i-SMR using conventional LEU (4.0 wt.% U-235) fuel achieves a shorter cycle length of 840 EFPD and a lower maximum pin burnup of 26,421 MWD/MTU [7].

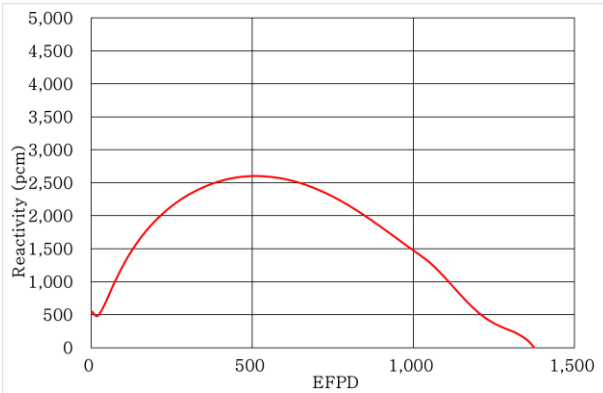

Fig. 4 Reactivity trend of the first-cycle i-SMR core with LEU+ fuel under ARO conditions

Given that the first-cycle core is primarily composed of fresh fuel, the peaking factor remains relatively unchanged, as presented in Fig. 6. However, heavy reliance on the RB for excess reactivity control causes the axial shape index (ASI) to shift downward to approximately 0.3, leading to a localized increase in the

Fq value. The Fq value remains stable thereafter but rises again near the end of the cycle as control rods are withdrawn, causing the ASI to shift upward. For a soluble-boron-free SMR, defining the end of a cycle requires an approach similar to that adopted in commercial pressurized water reactors, where the remaining boron concentration is substituted by an equivalent rod worth to ensure safe core shutdown.

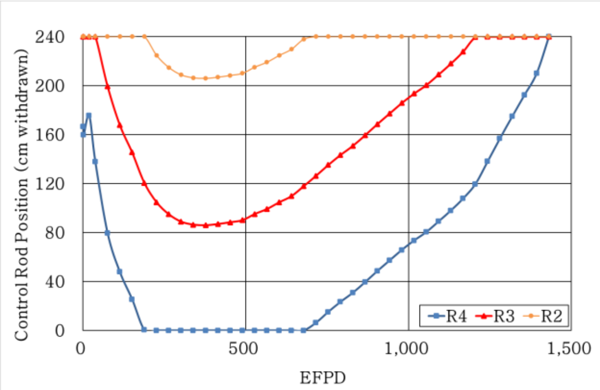

Fig. 5 Control rod withdrawal positions as a function of EFPD in cycle 1

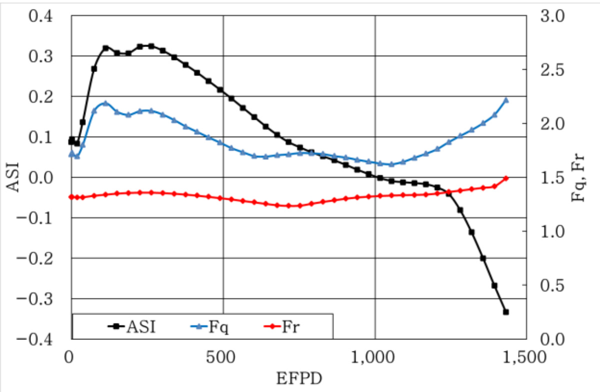

Fig. 6 ASI, Fq, and Fr variations as a function of EFPD in cycle 1

3. Conclusions

The primary objective of using LEU+ fuel is to improve nuclear fuel economy. To evaluate the feasibility of this fuel, we design the first-cycle core of the boron-free i-SMR with 6.0 wt.% U-235 fuel.

Compared to previous research findings, our results confirm that increasing U-235 enrichment extends the fuel cycle. However, given that the i-SMR design aims for boron-free operation, prior assessments of burnable absorbers capable of effectively managing the resulting excess reactivity are essential.

In this study, lattice calculations and first-cycle core analysis are performed using Erbia (Er2O3–UO2) absorbers instead of the previously used HIGA absorbers. The results confirm both the feasibility and validity of using LEU+ fuel.

Future research should include sensitivity analyses on U-235 enrichment variations in LEU+ fuel. Additionally, to further improve fuel economy, studies on burnable absorber design and loading pattern optimization considering ATF should be conducted, with particular emphasis on burnup and maximum pin burnup evaluations.

REFERENCES

[1] L. Carlson, J. Miller, Z. Wu, "Implications of HALEU fuel on the design of SMRs and micro-reactors," Nucl. Eng. Des. 389 (2022) 111648.
[2] K.J. Geelhood, "Fuel performance considerations and data needs for burnup above 62 GWd/MTU," PNNL-29368, Pacific Northwest National Laboratory (2019).
[3] Y. Inagaki, T. Iwasaki, S. Sato, T. Ohe, K. Kato, S. Torikai, Y. Niibori, S. Nagasaki, K. Kitayama, "Fuel safety criteria in NEA member countries, compilation of responses received from member countries," J. Nucl. Sci. Technol., 46 (2009) 677-689.
[4] M. Alrwashdeh, S.A. Alameri, "Preliminary neutronic analysis of alternative cladding materials for APR-1400 fuel assembly," Nucl. Eng. Des., 384 (2021) 111486.
[5] K.-S. Kim, S.G. Hong, J.Y. Cho, J.S. Son., “Transport lattice code KARMA 1.1," Transactions of Korea Nuclear Society Autumn Meeting (2009).
[6] H. Hong, J. Yoon, "Solution of OECD/NEA PWR MOX/UO2 benchmark with a high-performance pin-by-pin core calculation code," Nucl. Eng. Technol., 56 (2024) 3654-3667.
[7] J.S. Kim, T.S. Jung, J. Yoon, "Reactor core design with practical gadolinia burnable absorbers for soluble boron-free operation in the innovative SMR," Nucl. Eng. Technol., 56 (2024) 3144-3154.
[8] Husam Khalefih, T.S Oh, Y.S Jeong, Y.H. Kim, “LEU+ loaded APR1400 using accident tolerant fuel cladding for 24-month two-batch fuel management scheme,” Nucl. Eng. Technol., 55(2023), 2578-2590.