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A Conceptual SMR Core Design Utilizing LEU+ Fuel and IFBA for Higher Discharge Burnup

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1. Introduction

Due to the increasing electricity demand from AI and data centers, energy demand has emerged as a critical global challenge. In response, active research into Small Modular Reactors (SMRs) technology is underway as a potential solution which has its advantage in flexible installation, easier maintenance, and lower initial investment costs. However, the small core size may increase neutron leakage, which in turn reduces cycle length and discharge burnup.

This study introduces Low Enriched Uranium Plus (LEU+) fuel enriched between 5-10 wt% and utilizes fuels with enrichment maintained below 7 wt% into a PWR-based SMR core. This approach is aimed at increasing its discharge burnup, accompanied by extended cycle length. To support this change, we adopt the Accident-Tolerant Fuel (ATF) by utilizing chromium coated cladding, which enhances fuel rod integrity.

Previous studies have employed Integral Fuel Burnable Absorber (IFBA) in combination with other burnable absorbers [1]. However, this paper exclusively utilizes IFBA to achieve the established design criteria and notably higher discharge burnup compared to SMRs with 3-5 wt% enrichment.

This study outlined conceptual framework and discussed the anticipated benefits of using LEU+ fuel with IFBA for extended cycle length and higher discharge burnup in a 180 MWt SMR comprised of 37 fuel assemblies.

2. Computational Code and Methodology

The core design and analysis were conducted in the conventional two-step approach which consists of 2D fuel assembly (FA) calculations and 3D nodal diffusion calculation using the DeCART2D and MASTER codes respectively.

DeCART2D employs the method of characteristics (MOC) to solve the neutron transport equation and utilizes a sub-group method for resonance self-shielding. In this process, it generates homogenized cross sections based on data from the ENDF/B VII.1 library [2]. These homogenized cross sections after functionalization are then transferred to the MASTER code for comprehensive full-core analysis [3].

3. Core Design and Analysis Result

3.1 Fuel Rod

As shown in **Fig. 1**, this study adopts a IFBA as a burnable absorber (BA), where a thin coating of 10 µm thickness of ZrB_2 is uniformly applied to the outer radius of UO_2 pellets. To control the higher excess reactivity in LEU+, the ^{10}B isotope within the IFBA is enriched to 50 atomic percent (at%). 30 µm thickness of Cr coating is applied to the outer radius of cladding to maintain its structural integrity at increased cycle length and burnup.

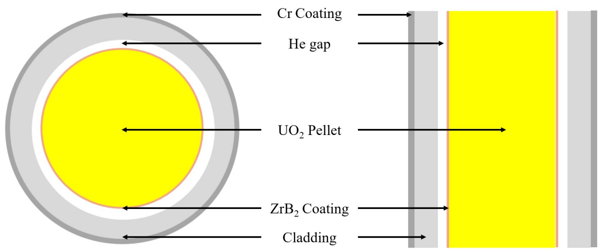

Fig. 1 Radial and axial configurations of IFBA rod

3.2 Fuel Assembly

In this work, we considered 17x17 Westinghouse type fuel assembly with parameters shown in **Table I**. Since the FA calculations are conducted using DeCART2D which solves the transport equation by MOC, it is necessary to adjust the ray spacing and azimuthal angle considering the thin coating of IFBA and Cr. As shown in **Table II**, by setting the reference case as 0.001 cm ray spacing and 64 azimuthal angles, a sensitivity analysis was performed. The results indicated that while adjustments in the azimuthal angle produced only minor differences, those in the ray spacing resulted in significant variations. Therefore, to ensure that the difference remains within 100 pcm of the reference value, a ray spacing of 0.001 cm and an azimuthal angle of 8 were ultimately adopted.

The advantage of IFBA is that it helps to maintain a uniform power peaking factor within the FAs. Moreover, ZrB_2 exhibits minimal residual effects, indicating that once IFBA is fully depleted, the fuel depletion behavior is almost identical to that of fuel without BA. However, the IFBA rods could show a notable reactivity swing from BOC until their complete depletion, owing to their higher depletion rate relative to other BAs. As shown in **Fig. 2**, the reactivity swing becomes more moderate with increasing uranium enrichment. This behavior can be explained by the spectrum hardening and thermal flux level decrease resulted from the use of high uranium enrichment, which would reduce boron worth in ZrB_2 of IFBA [4]. By using this phenomenon, this study has designed the FA to control the high excess reactivity of LEU+ while mitigating the associated reactivity swing as shown in **Table III** and **Fig. 3**

Table I. Fuel assembly parameters

Fuel assembly parameters	
Fuel array	17 x 17
Number of fuel pins	264
FA pitch	1.26 cm
Number of instrument / guide tube	25
Fuel pellet density	10.22 g/cm^3
ZrB_2 density	6.085 g/cm^3
U-235 enrichment	2.8 ~ 6.95 wt%
B-10 enrichment	50 at%
Cladding material	Zircaloy-4
Coating material	Cr
Fuel pellet radius	0.4096 cm
ZrB_2 cladding inner radius	0.4096 cm
ZrB_2 cladding outer radius	0.4106 cm
Fuel cladding inner radius	0.4178 cm
Fuel cladding outer radius	0.4750 cm
Cr coating inner radius	0.4750 cm
Cr coating outer radius	0.4780 cm

Table II. Sensitivity analysis of k_{inf} [pcm] by ray spacing and azimuthal angle

Ray spacing [cm]	Azimuthal angle			
	8	16	32	64
0.02	-313	-344	-318	-331
0.01	-246	-246	-211	-226
0.005	-122	-155	-128	-143
0.001	+26	-11	+13	Ref.

Table III. Used fuel assembly type

Type	A1	B1	C1	C2
Enrichment (wt%)	2.8	4.5	6.5	6.95
Number of BA rods	44	44	100	120

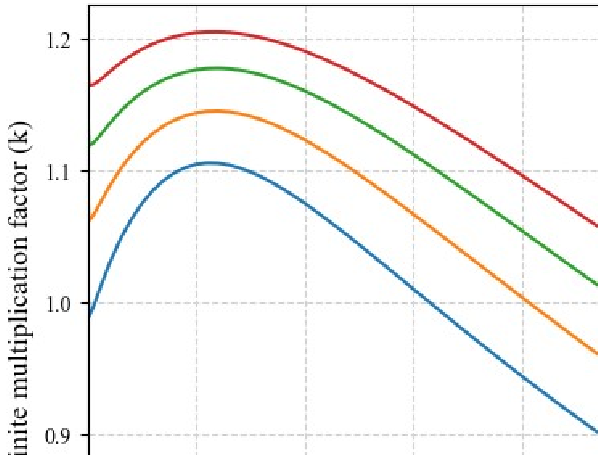

Fig. 2 Comparison of k_{inf} for the different uranium enrichments.

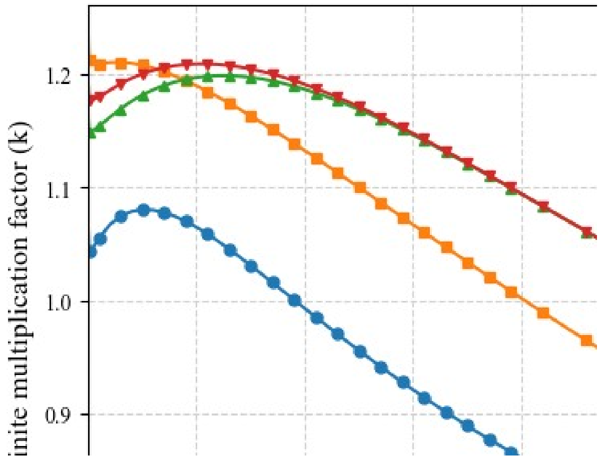

Fig. 3 Comparison of k_{inf} with respect to FAs

3.3 Core

Compared to the conventional PWR reactors, use of LEU+ fuels significantly increases the excess reactivity which should be effectively controlled. IFBA strongly suppresses the initial reactivity and leaves virtually no residual effect, allowing us to use many BA rods. **Table IV** summarizes the core design and its target parameters. The core produces 180 MWt with an active core height of 200 cm, uses SS304 as the reflector, and is comprised of 37 fuel assemblies. The average linear power density is 92.1 W/cm. A three-batch fuel management strategy has been adopted in this work.

As shown in **Fig. 4** and **Fig. 5**, the core employs Type A, B, and C FAs. Type B assemblies are only used for the first two cycles to optimize the initial power distribution and peaking factors whereas Type A and Type C assemblies are loaded for the entire cycle. During equilibrium cycles, Type A FAs with the lowest enrichment are positioned at the core center and reloaded every cycle. Type C FAs remain in the core for three operational cycles before being discharged.

Table IV. Design parameters and targets of core design

Core parameters	
Core thermal output	180 MWt
Active core height	200 cm
Average Linear power density	92.1 W/cm
Equivalent core diameter	150.5 cm
Number of FA	37
Fuel management	3 batch
Core target values	
Cycle length	1000 EFPD
Maximum CBC over cycle	1600 PPM
Peaking factor	1.7 (2D) / 2.8 (3D)
Axial offset	-0.3 < AO < 0.3

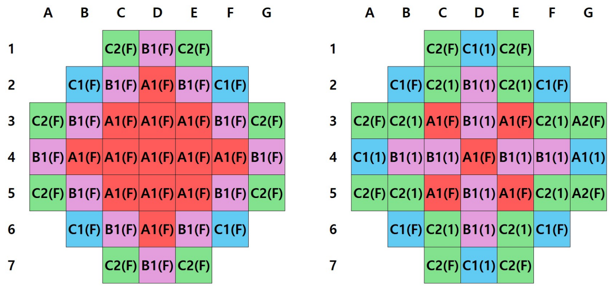

Fig. 4 Figurations of Cycle 1 and Cycle 2 core

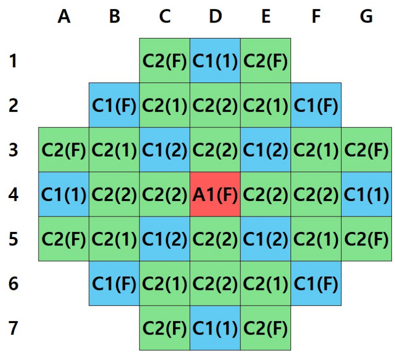

Fig. 5 Figuration of equilibrium cycle core

3.4 Result

The important objective of this study was to satisfy the core target values, especially about the CBC constraints to obtain a negative MTC. **Table V** summarizes the results of these parameters for the whole cycle. **Fig. 6** and **Fig. 7** illustrate the change of CBC to EFPD for each cycle, with the maximum CBC reaching 1595 ppm, and all cycles have reached a cycle length of longer than 1000 EFPDs. Furthermore, **Table VI** shows the discharge burnup for each FA and the core average discharge burnup during the equilibrium cycle. The core average discharge burnup was about 57 MWd/kgHM.

Table V. Core analysis result

Cycle			Cycle 1~3	Equilibrium
Maximum CBC (ppm)			1471.94	1595.22
Maximum F_{xy}			1.6146	1.4706
Maximum F_{xyz}			2.0677	1.8329
Maximum axial offset in absolute value			0.0193	0.0190
MTC (pcm/°C)	HFP	BOC	-31.03	-37.60
		EOC	-73.20	-82.00
	HZP	BOC	-16.90	-20.99
		EOC	-50.35	-58.57

Table VI. Discharge burnup

FA types	A1	C1	C2
Average FA burnup (Mwd/kgHM)	20.548	55.95	61.61
Core average discharge burnup (Mwd/kgHM)	56.71		

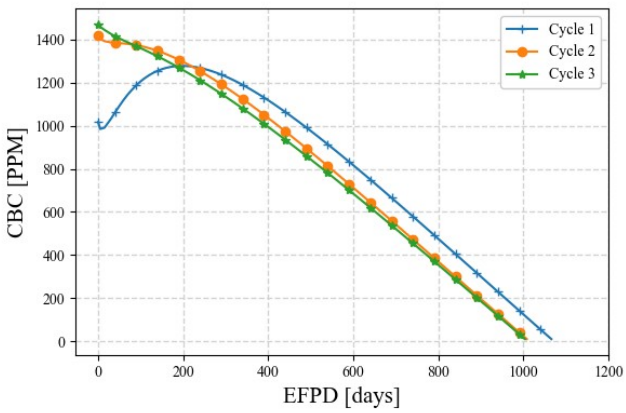

Fig. 6 Change of CBC over EFPD for cycle 1 ~ 3

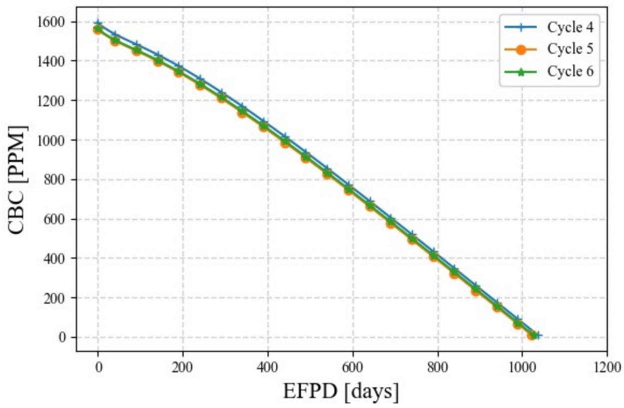

Fig. 7 Change of CBC over EFPD for cycle 4 ~ 6

4. Conclusion

In this study, a PWR-based SMR core design was developed using LEU+ fueled fuel assemblies with IFBA rods to achieve extended cycle length and high discharge burnup. The LEU+ fuel rods used 30 μm chromium coating on their pellets to maintain fuel integrity under the extended cycle operation and SS304 was used as the core reflector to reduce neutron leakage. To simplify manufacturing, the ^{10}B enrichment in the IFBA was fixed at 50 at%, and reactivity control was achieved by adjusting the number of IFBA rods from 44 to 120. Uranium enrichment was set at 2.8 wt% for the core center in the equilibrium cycle, with additional uranium enrichments of 6.5 wt% and 6.95 wt%. The calculation results indicated that all the cycles have cycle lengths longer than 1000 EFPDs and the maximum CBCs lower than 1600 ppm. Also, the core design met all the targets on low peaking factors, negative MTC, and axial offset as shown in **Table V**. In comparison with the BANDI-60S reference model which employs conventional LEU fuel and 52 fuel assemblies, achieving the average discharge burnup of 35 MWd/kgHM while the core developed in this study achieves average discharge burnup of 57 MWd/kgHM [5].

Acknowledgement

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