Investigation of Unified IFBA-GAD Burnable Absorber for Soluble Boron Free Reactivity Control

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1. Introduction

The conventional pressurized water reactors (PWRs) can control the excess reactivity via the control rods, the burnable absorbers, and the soluble boron, where the soluble boron is commonly used for the uniform reactivity control. Recently, the design concept for the soluble-boron-free (SBF) reactor has been vastly investigated due to the several advantages; 1) the elimination of the boron-dilution accident, 2) the simplification of the chemical volume control system (CVCS), and 3) the extension of the lifetime of main component in the primary loop. For that purpose, new burnable absorber designs such as R-BA [1] and CSBA [2] were proposed to reduce the initial excess reactivity and the maximum excess reactivity by utilizing the spatial self-shielding effect for the burnable absorber.

This paper proposes a new burnable absorber named as unified IFBA-GAD (UIG) which combines the two commercialized and proven burnable absorber designs; the integral burnable absorber (IFBA) [3] and the gadolinium burnable absorber (GAD). The numerical results show the improved performances of the new burnable absorber in terms of the initial excess reactivity and the maximum excess reactivity by the lattice physics code STREAM [4].

2. Unified IFBA-GAD (UIG) Burnable Absorber Design

2.1. Fuel Rod Design

The UIG fuel rod is the gadolinia fuel rod (UO_2-Gd_2O_3) coated with a thin layer of ZrB_2. Compared to the GAD, the UIG suppresses both the initial excess reactivity and the maximum excess reactivity by adjusting the ^{10}B enrichment in ZrB_2. The UIG also takes advantage of the spatial self-shielding of the gadolinia by the IFBA coating.

The design specifications of UIG fuel rods are shown in Table I, and Figure 1 shows the cross-sectional view of the UIG fuel rod. The stack height density was calculated by referring to the IAEA Report [5].

Table I. Design specifications of UIG fuel rod.

Pellet diameter, cm		0.8192
Clad material		ZIRLO
Clad ID, cm		0.8375
Clad OD, cm		0.9500
^{235}U wt.%	Normal fuel	4.95
	Gadolinia fuel	1.80
Stack height density, g/cm^3	UO_2	10.264
	UO_2-Gd_2O_3 4.0%	10.141
	UO_2-Gd_2O_3 6.0%	10.079
	UO_2-Gd_2O_3 8.0%	10.017
ZrB_2 thickness, μm		10.0
ZrB_2 density, g/cm^3		6.08
^{10}B at% in ZrB_2, %		19.9(natural), 25, 50, 75, and 100

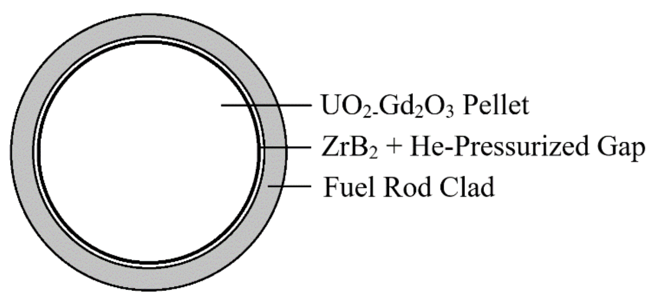

Figure 1. Cross-sectional view of UIG fuel rod

2.2. Fuel Assembly Design

The specifications of the UIG fuel assembly design are shown in Table II. The number of the UIG fuel rods, the concentration of Gd_2O_3 in the UIG, and the enrichment of ^{10}B in ZrB_2 were varied for the sensitivity analysis. Figure 2 shows the configurations of the UIG fuel rods in a fuel assembly for 12 pins, 16 pins, and 24 pins.

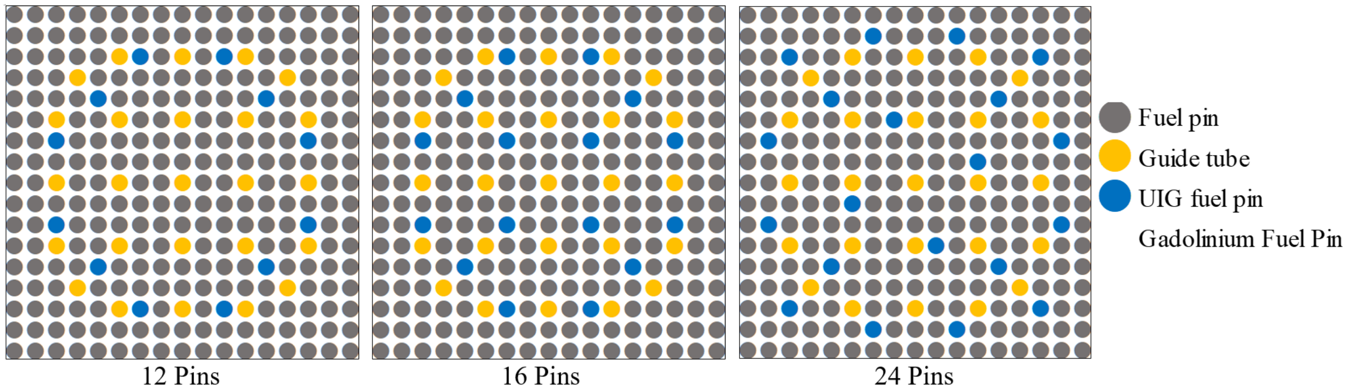

Figure 2. Arrangement of rods in fuel assembly

Table II. Design specifications of the UIG fuel assembly.

Fuel rod array square	17 x 17
Fuel rod pitch, cm	1.25984
No. of UIG fuel pins	4, 8, 12, 16, 20, 24, and 32

3. Numerical Results

3.1. Sensitivity Analysis in Ray Tracing Parameters for UIG Fuel Assembly Modeling

Due to the thin layer of IFBA of the UIG fuel assembly, the ray tracing parameters of the method of characteristics (MOC) can significantly affect the lattice calculation results [6]. The finer divisions of the ray spacing and the larger number of azimuthal angle divisions leads to the higher accuracy, while the simulation becomes time-consuming. To determine the optimized ray tracing parameters, the sensitivity analysis at the beginning of cycle (BOC) condition of the UIG fuel assembly was performed with various ray spacing and the azimuthal angles, where the number of the polar angles was fixed to 6. Table III shows that the differences of k_{inf}'s are less than 62 pcm. The subsequent MOC calculations were calculated with a ray spacing 0.05cm, 48 azimuthal angles, and 6 polar angles.

Table III. Differences in k_{inf} [pcm] for various ray tracing parameters in UIG fuel assembly*.

Ray spacing, cm	Azimuthal angle divisions				
	48	64	80	96	128
0.05	62	15	-8	6	-8
0.01	55	43	25	16	4
0.005	52	32	21	16	0
0.001	50	34	20	14	Ref.

*The number of UIG pins is 20, the gadolinium enrichment of UIG pin is 4%, the thickness of ZrB_2 is 10 μm, and ^{10}B enrichment in ZrB_2 is 50%.

3.2. Comparison Between GAD and UIG Burnable Absorber

To show the performance of the UIG burnable absorber, the k_{inf} and the pin peaking are compared to those of the conventional GAD for several test conditions. In that purpose, test conditions for the GAD and UIG cases were selected as Table IV for the equivalent critical burnup condition.

Table IV. Test conditions of GAD and UIG for equivalent critical burnup.

Burnable absorber	Critical burnup, GWD/MTU	UIG or GAD fuel pins	Gd_2O_3 wt.% in fuel	^{10}B at% in ZrB_2
GAD	35.63	24	4	N/A
UIG	35.64	24	6	100

Figure 3 and Figure 4 compare the k_{inf} and the pin peaking between the GAD and the UIG cases, respectively. Table V summarizes the reactivity comparison between these two cases. At the equivalent critical burnup condition, the UIG reduces the initial excess reactivity, the peak excess reactivity, and the reactivity upswing compared to the GAD, while the pin peaking of the GAD and UIG are almost similar. These results can be explained by the delayed depletion of UO_2-Gd_2O_3 by the spatial self-shielding of the ^{10}B in ZrB_2 coating.

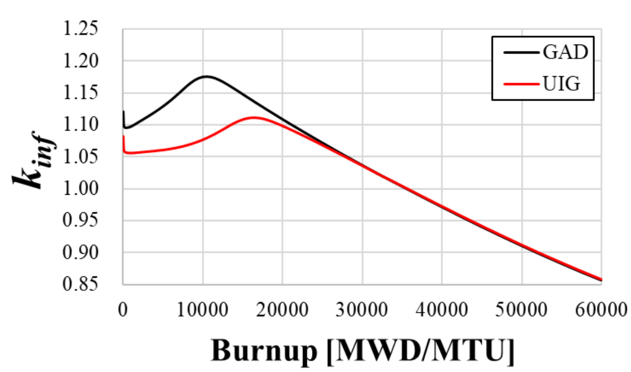

Figure 3. Comparison of k_{inf} for GAD and UIG

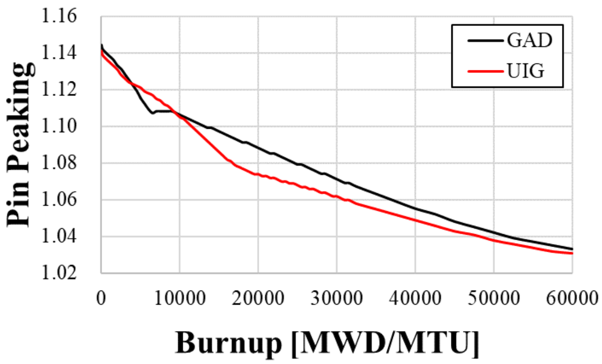

Figure 4. Comparison of pin peaking of GAD and UIG

Table V. Summary of reactivity comparisons between GAD and UIG.

Unit, pcm	GAD	UIG	Difference
Initial excess reactivity	10,787	7,554	3,233
Maximum excess reactivity	14,954	9,990	4,964
Reactivity upswing*	6,051	4,402	1,650

*Reactivity upswing = maximum excess reactivity – excess reactivity at 100 MWD/MTU.

3.3. Sensitivity Analysis of UIG

Figure 5 shows the critical burnup according to the number of the UIG fuel pins and the gadolinium enrichments. Changes due to the gadolinium enrichment was insignificant, and there was almost no change according to the ^{10}B enrichment in ZrB_2. Thus, the fuel cycle length would change significantly only by the number of UIG pins in one fuel assembly.

Figure 6 compares the pin peaking of the UIG and those of the GAD pins. In the case of 32 pins, the maximum pin peaking of the UIG is noticeably higher than that of the GAD. In other cases, however, the pin peaking of the UIG becomes similar or even lower.

Figure 7 shows the k_{inf} vs. burnup of the UIG for the various ^{10}B enrichments in ZrB_2, while Figure 8 shows the reactivity difference between the GAD and the UIG (GAD-UIG). Table VI summarizes the reactivity comparison between GAD and UIG according to the ^{10}B enrichment in ZrB_2. It is shown that the higher ^{10}B enrichment reduces the initial excess reactivity and the maximum excess reactivity, while the change in reactivity upswing was insignificant.

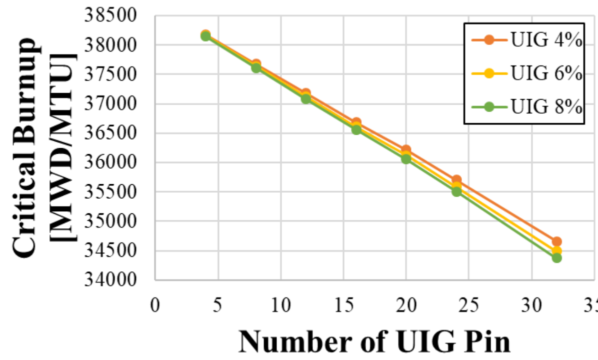

Figure 5. Critical burnup (where k_{inf} = 1.0) according to gadolinium enrichment

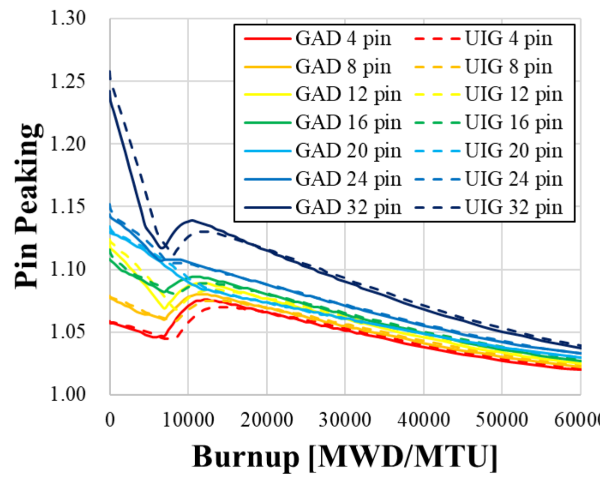

Figure 6. Comparison of pin peaking of GAD and UIG*

*The gadolinium enrichments in UIG and GAD pins are 4%, and the ^{10}B enrichment in ZrB_2 of UIG is 50%.

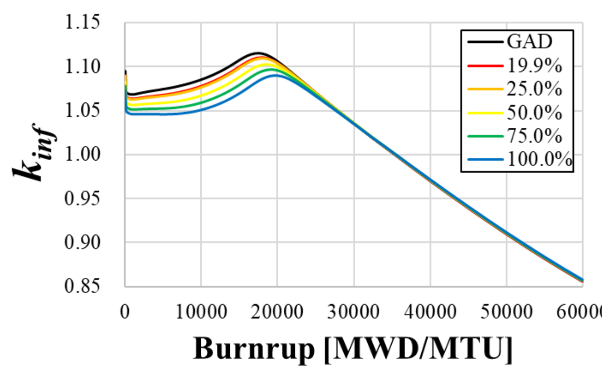

Figure 7. k_{inf} vs. burnup of GAD and UIG for various ^{10}B enrichment in ZrB_2*

*The gadolinium enrichment is 8%, and the number of pins is 24.

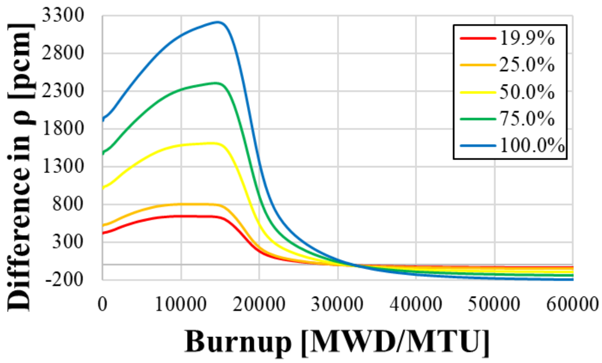

Figure 8. Reactivity difference between GAD and UIG (GAD - UIG) vs. burnup according to the ^{10}B enrichment in ZrB_2*

*The gadolinium enrichment is 8%, and the number of pins is 24.

Table VI. Summary of reactivity comparisons between GAD and UIG for various ^{10}B enrichment in ZrB_2*.

	^{10}B at% in ZrB_2	GAD, pcm	UIG, pcm	Difference, pcm
Initial excess reactivity	19.9	8,700	8,283	417
	25.0		8,179	521
	50.0		7,692	1,008
	75.0		7,231	1,469
	100.0		6,794	1,906
Maximum excess reactivity	19.9	10,377	9,964	413
	25.0		9,860	517
	50.0		9,337	1,040
	75.0		8,812	1,565
	100.0		8,285	2,092
Reactivity upswing	19.9	3,622	3,633	-11
	25.0		3,636	-14
	50.0		3,610	12
	75.0		3,554	68
	100.0		3,474	148

*The gadolinium enrichment is 8%, and the number of pins is 24.

4. Summary and Conclusions

The unified IFBA-GAD (UIG) burnable absorber was proposed based on the combination of the two commercialized burnable absorber. It takes advantage of the spatial self-shielding of the gadolinia by the ZrB_2 coating. The numerical results show that the UIG suppresses both the initial excess reactivity and the maximum excess reactivity compared to those of the normal GAD, while the increase of the pin peaking is marginal. The ^{10}B enrichment in ZrB_2 can be adjusted to finely control excess reactivity.

The weakness of the IFBA that is the increase of the internal rod pressure by (n, α) reaction of ^{10}B is expected to be mitigated by the reduced UO_2 loading in the fuel rod, which leads to the smaller amounts of the fission gas. Thus, as a further study, it would be worthwhile to perform the fuel performance analysis for the UIG fuel rod to calculate the internal rod pressure and fuel centerline temperature. Furthermore, the proposed UIG burnable absorber design can be applied to the soluble-boron-free SMR core design.

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References

[1] J. Choe, et al., "New Burnable absorber for long-cycle low boron operation of PWRs," Ann. Nucl. Energy, 88, 272-279 (2016).
[2] X.H. Nguyen, et al., "An advanced core design for soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber," Nucl. Eng. Tech., 51, 369-376 (2019).
[3] R.L. Simmons, et al., "Integral fuel burnable absorbers with ZrB2 in Pressurized Water Reactors," Nuclear Technology, 80(3), 343-348 (1988).
[4] Choi S, et al., "Resonance self-shielding methodology of new neutron transport code STREAM," J. Nucl. Sci. Technol. 52(9), 113-1150 (2015).
[5] International Atomic Energy Agency (IAEA), "Characteristics and Use of Urania-Gadolinia Fuels," IAEA-TECDOC-844, IAEA, Vienna (1996).
[6] E.D. Walker, "Modeling integral fuel burnable absorbers using the method of characteristics," Ms. Thesis, The University of Tennessee, (2014).