Investigation of Unified IFBA-GAD Fuel Assembly Design for Soluble Boron Free Reactivity Control

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Contents

Research Background

❖ Soluble-Boron-Free (SBF) Reactor

Conventional pressurized water reactors (PWRs)

can **control the excess reactivity** via

1) the control rods,

2) the burnable absorbers,

and 3) the soluble boron,

where the soluble boron is commonly used for the uniform reactivity control.

In the case of **SBF**, **the soluble boron is not used** to control the excess reactivity.

Therefore, SBF's reactivity control system must be able to **precisely control the reactivity** to fill the role of the soluble boron.

Research Background

❖ Soluble-Boron-Free (SBF) Reactor

Advantages of **the soluble-boron-free (SBF) reactor**;

1) the elimination of the boron-dilution accident,

2) the simplification of the chemical volume control system (CVCS),

3) the extension of the lifetime of main component in the primary loop,

and 4) the removal of Axial Offset Anormaly (AOA).

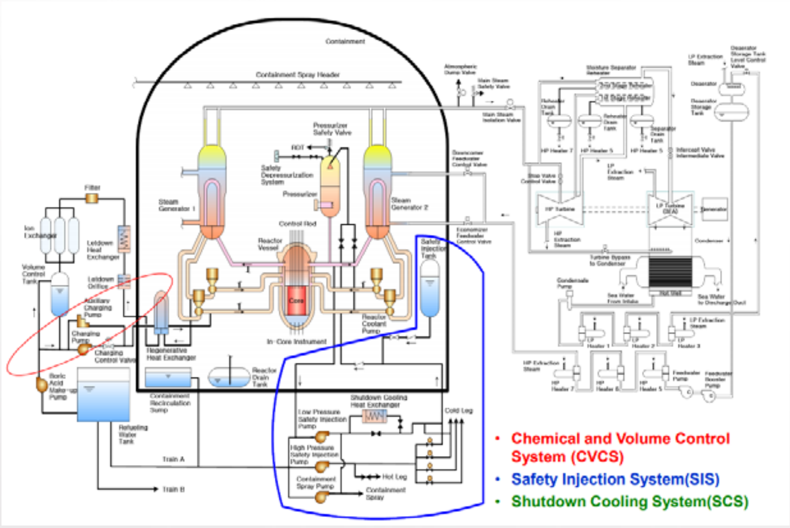


Figure 1. Description of the reactor safety system

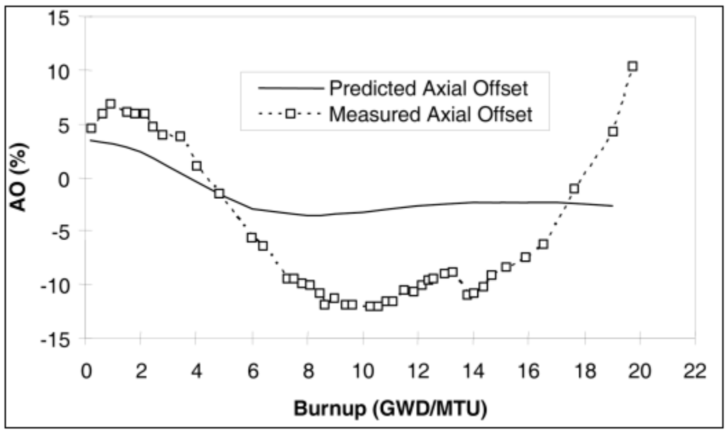


Figure 2. Example of Axial Offset Anomaly (AOA) – Westinghouse Plant

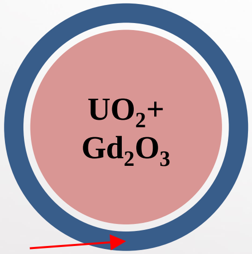
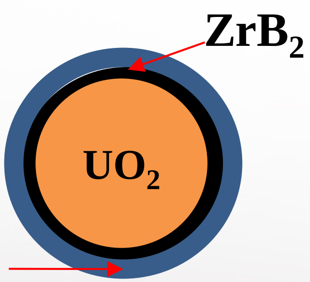
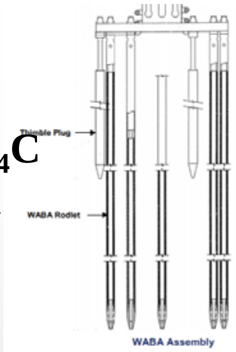
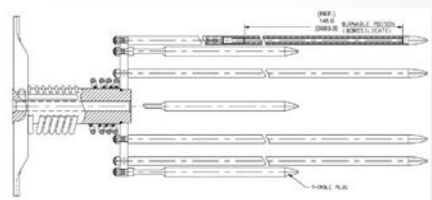
EPRI, "PWR Axial Offset Anomaly (AOA) Guidelines, Revision 1", 1008102, Final Report, June 2004

❖ Burnable Absorber Design

To overcome these problems, **new burnable absorber designs** such as R-BA and CSBA were proposed **to reduce the initial excess reactivity and the burnup reactivity swing** by utilizing the spatial self-shielding effect for the burnable absorber.

A new burnable absorber named as **unified IFBA-GAD (UIG)** is proposed which combines the two commercialized and proven burnable absorber designs.

Table I. Commercialized burnable absorbers

GAD	IFBA	WABA	Pyrex
• Fuel Thermal Conductivity ↓ • Amount of UO_2 ↓	• Internal Rod Pressure ↑	• Number of Rod Cluster Control Assembly ↓	• Number of Rod Cluster Control Assembly ↓
 **Cladding**	 **Cladding**	**Al_2O_3+B_4C (alumina -boron carbide)** 	 **B_2O_3+SiO_2 (borosilicate glass)**

NFCM-0016, Nuclear Fuel Wet Annular Burnable Absorber (WABA) Assembly, May 2017
ML11171A500, Westinghouse AP1000 Design Control Document Rev. 19, June 21, 2011

Unified IFBA-GAD Fuel Assembly Design

❖ 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.

UIG's expected advantages
- The UIG **suppresses both the initial excess reactivity and the maximum excess reactivity** by adjusting the ^{10}B enrichment in ZrB_2.
- **The spatial self-shielding of the gadolinia** by the IFBA coating allows for longer control over excess reactivity.

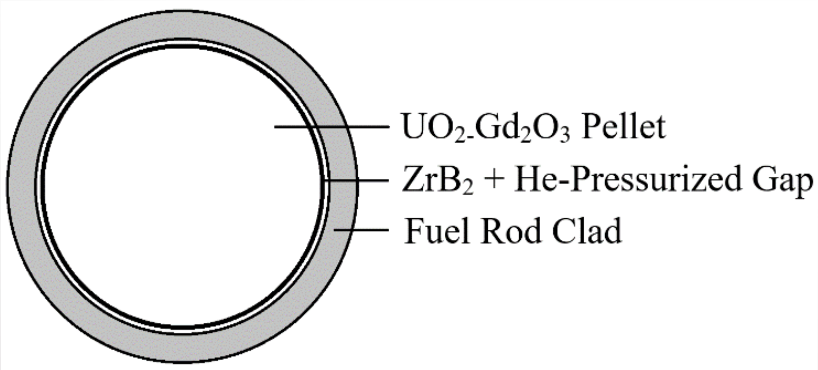


Figure 3. Cross-sectional view of UIG fuel rod

Table II. 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

❖ Fuel Assembly Design

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.

Table III. 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

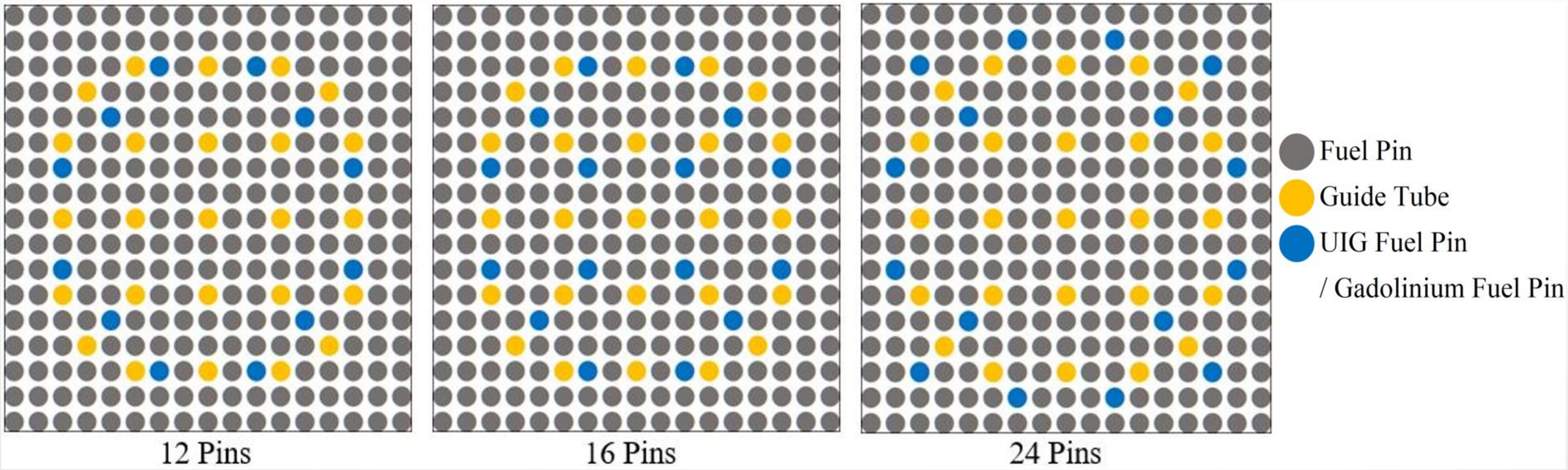


Figure 4. Arrangement of rods in fuel assembly

Numerical Results

❖ Sensitivity Analysis in Ray Tracing Parameter

The results were calculated by the lattice physics code STREAM.

MOC variables include ray spacing, azimuthal angles, and polar angles.

Due to the thin layer of IFBA, the ray spacing of the method of characteristics (MOC) to solve the neutron transport equation should be **sufficiently small**.

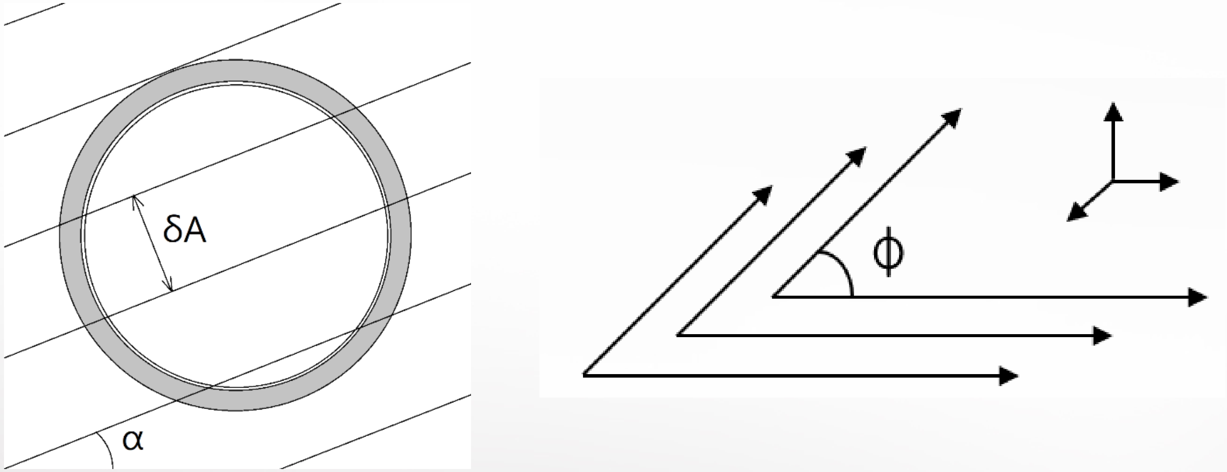


Figure 5. The representation of MOC characteristic lines

Numerical Results

❖ Sensitivity Analysis in Ray Tracing Parameter

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 IV. 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%.

❖ Comparison Between GAD and UIG Burnable Absorber

Test conditions for the GAD and UIG cases were selected as Table IV for the equivalent critical burnup condition.

Table V. 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

Table VI. 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.

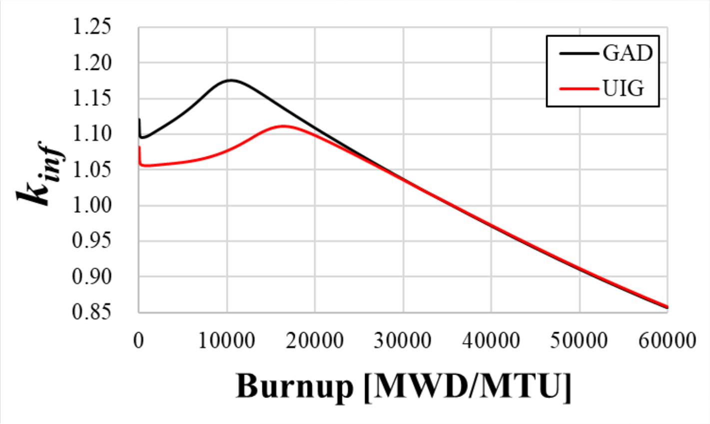


Figure 6. Comparison of k_{inf} for GAD and UIG

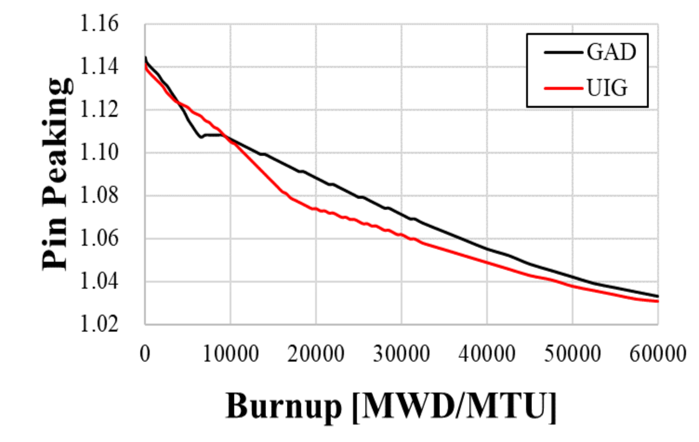


Figure 7. Comparison of pin peaking of GAD and UIG

Numerical Results

❖ Sensitivity Analysis of UIG

Critical burnup, peaking factor, and k_{inf} of UIG were investigated.

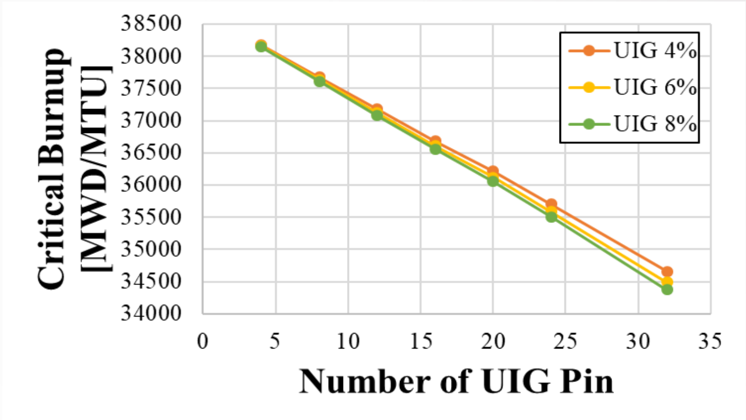


Figure 8. Critical burnup (where k_{inf} = 1.0) according to gadolinium enrichment

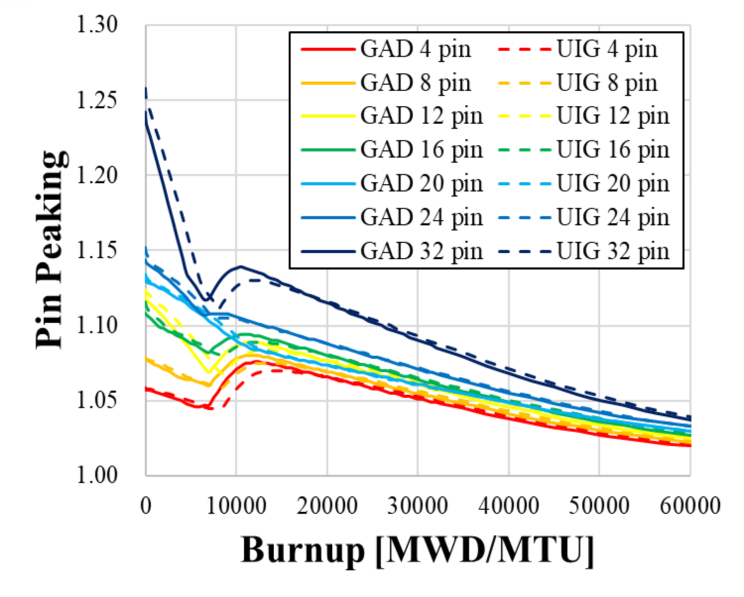


Figure 9. Comparison of pin peaking of GAD and UIG; the gadolinium enrichments in UIG and GAD pins are 4%, and the ^{10}B enrichment in ZrB_2 of UIG is 50%.

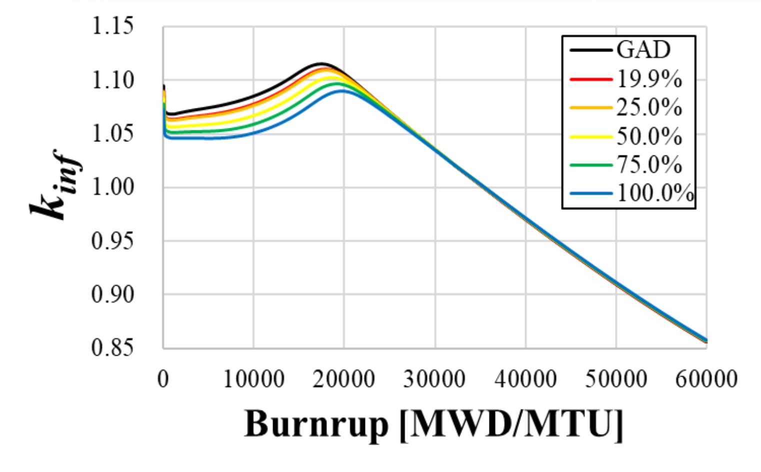


Figure 10. k_{inf} vs. burnup of GAD and UIG for various ^{10}B enrichment in ZrB_2; the gadolinium enrichment is 8%, and the number of pins is 24.

Numerical Results

❖ Sensitivity Analysis of UIG

- The higher ^{10}B enrichment induces the stronger spatial self-shielding of the gadolinia, which leads to the smaller burnup reactivity swing.

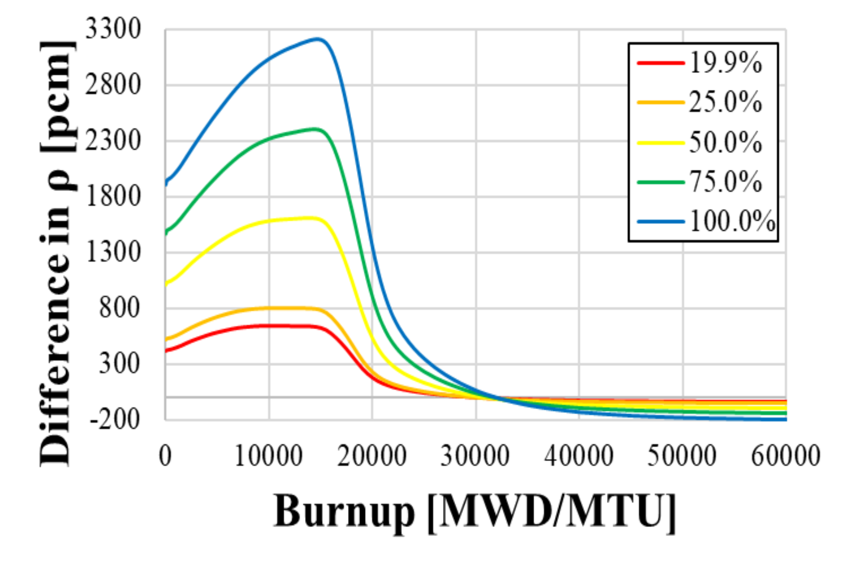


Figure 11. Reactivity difference between GAD and UIG (GAD - UIG) vs. burnup according to the ^{10}B enrichment in ZrB_2; the gadolinium enrichment is 8%, and the number of pins is 24.

Table VII. 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.

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 and mitigates the weakness of the IFBA.

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**.

As a further study, the proposed UIG burnable absorber design can be applied to the soluble-boron-free **SMR core design**.

References

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6. E.D. Walker, “Modeling integral fuel burnable absorbers using the method of characteristics,” Ms. Thesis, The University of Tennessee, (2014).

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