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Optimal Ring Type Burnable Absorber Fuel Assembly Design for Long-cycle Soluble Boron-free SMPWR

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1. Introduction

This paper suggests the optimal ring type burnable absorber (R-BA) fuel assembly design for a long-cycle soluble boron-free Small Modular Pressurized Water Reactor (SMPWR). The main design feature of target model is a long cycle operation without refueling. For this point, the ability of suppressed excess reactivity and possession of plenty amounts of fuel are set up as the criteria for BA sensitivity study.

The ability of controlling the excess reactivity depends on the amount of absorber material, layout of BA pin in the fuel assembly, and types of BA. There are three types of commercial burnable absorbers: gadolinia, Integral Fuel Burnable Absorber (IFBA) and Wet Annular Burnable Absorber (WABA). In detail, those three types of BA have the following advantages and disadvantages. Firstly, gadolinia has high absorption cross section and is cheaper commercially. On the other hand, it has a low thermal conductivity (~ 8 w/o Gd_2O_3, < ^{235}U 2 w/o). Secondly, IFBA can control the pin power peak efficiently. The disadvantages are increment of rod internal pressure by helium gas and occurrence of the abnormal axial offset by fragment of ZrB_2. Lastly, WABA has a high performance to absorb the neutrons and disadvantage to take the place of some control rods. The newly suggested burnable absorber type, R-BA is coated outside of cladding [1][2]. Therefore, it gives similar advantage with IFBA without considering the helium gas release and gadolinium thermal conductivity [1][2]. For those reasons, this paper suggests the R-BA type and presents the optimization progress of three sensitivity studies: R-BA materials, R-BA thickness and pin layout in fuel assembly.

In addition, the assembly calculation is performed with a neutron transport analysis code STREAM [3]. STREAM is developed by the Computational Reactor physics and Experiment laboratory (CORE) of Ulsan National Institute of Science and Technology (UNIST).

2. Sensitivity study of burnable absorber Material

In this section, the five materials, B4C, Cd, Sm, Gd and Er, of Table I are used for sensitivity study of BA material [4][5]. During the sensitivity study, residual reactivity and burnable absorber burnout point are set up the main criteria.

The 17X17 Westinghouse type assembly is used with 4.90 w/o enriched UO_2 fuels and 21.3 W/g power density is utilized for fuel assembly depletion calculation. The Fig. 1. presents the calculation results of five burnable absorber materials from 0 to 31.95 MWd/kg (=1,500 EFPD). The end point of burnup range is same as target cycle length of soluble boron-free SMPWR. In the figure, the five different calculation results which have similar initial k_{eff} are selected and number of burnable absorber pins are presented in the legend. Sm and Er have large residual reactivity at the end point, 31.95 WMd/kg. The Cd has burnout point less than half of target cycle length as 15.98 MWd/kg. According to the criteria of residual reactivity and BA burnout point, gadolinium and B_4C are suitable for the long-cycle operation SMPWR.

Table I: Burnable absorber material specification

BP materials	B4C	Cd	Sm	Gd	Er
Main absorbing nuclides	^{10}B	^{113}Cd	^{149}Sm	^{155}Gd, ^{157}Gd	^{167}Er
Main absorber content (w/o)	90.00	12.22	13.82	14.80, 15.65	22.95
Density(g/cm^3)	1.76	8.65	7.52	7.90	9.07

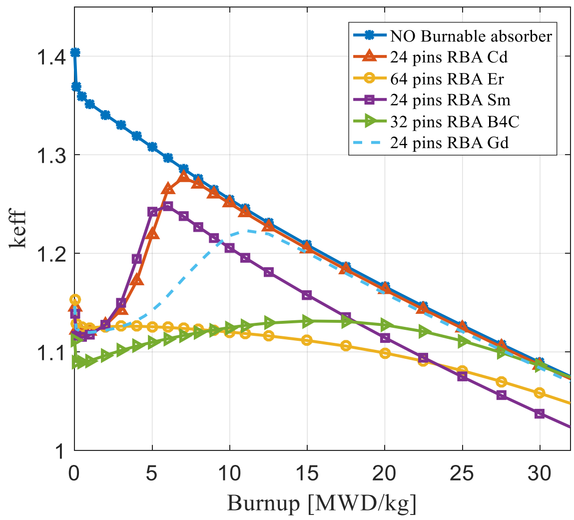

Fig. 1. Depletion characteristics of absorber materials in R-BA

3. Sensitivity study of R-BA thickness

In this section, WABA and R-BA are utilized for sensitivity study. Fig. 2 and Table II present the ring type burnable absorber (R-BA) geometry. The region between 0 and 1 is UO_2 fuel, 1 to 2 is air gap, 2 to 3 is cladding material, 3 to 4 is gadolinium R-BA and 4 to 5 is CrAl coating. The R-BA is coated outside of cladding and this is difference from IFBA. The CrAl coating is used to improve the structural integrity.

In addition, sensitivity studies are performed with four criteria: maximum reactivity, power peaking factor, residual reactivity at the target cycle length and burnout point of BA materials.

3.1. Design parameter of Fuel Assembly

The sensitivity study is performed with Fig. 3 and Table III fuel assembly specifications. The 17X17 Westinghouse type assembly with 4.95 w/o enriched UO_2 and 21.3 W/g power density are used. In the Fig. 3, pin 1 is normal UO_2 fuel pin, 2 is instrument tube, 4 is fuel pin with R-BA and 5 is WABA pin with 80 w/o enriched Al_2O_3/B_4C. Pin 3 is guide tube of normal FA while it is not shown here. Additionally, the power peaking factor criterion is set as 1.3.

3.2. Gadolinium R-BA thickness sensitivity study results

In the sensitivity study, the WABA geometry is fixed and only gadolinium R-BA thickness is changed from 0 cm to 0.040 cm. Fig. 4, Fig. 5 and Table IV present the gadolinium R-BA thickness sensitivity results. The Fig. 4 shows that the CASE05 has the greatest influence to control the excess reactivity. CASE05 has the greatest burnout point as 30 MWd/kg. According to the Table IV, the burnout point of CASE03, CASE04 and CASE05 have greater burnout point than half of target cycle length, whereas CASE01 and CASE02 do not. Additionally, the Fig. 4 and Fig. 5 show the burnout point of BA is associated with the maximum reactivity position and maximum pin power peak. CASE02 has 12,489 pcm greater maximum reactivity than CASE05 at the k_{eff} peak point.

The Table IV presents the residual reactivity is increased, as the gadolinium thickness is increased at the target cycle length, 31.95 MWd/kg. CASE05 has greatest residual reactivity as 2,722 pcm. This value is 2,413 pcm greater than CASE01, 1,922 pcm greater than CASE02 and 1,425 pcm greater than CASE04. The second greater thickness case, CASE04 has the 988 pcm greater residual reactivity than CASE01, 497 pcm greater than CASE02 and 218 pcm greater than CASE03. Those differences between other cases and CASE04 are at least 437 pcm smaller than the difference between CASE04 and CASE05.

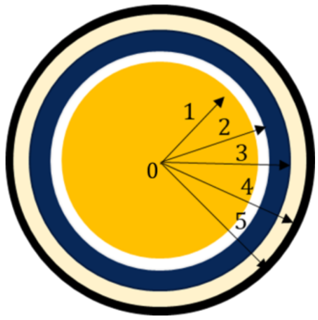

Fig. 2. R-BA Geometry

Table II: R-BA Geometry

Region	Material
0 – 1	UO_2
1 – 2	AIR
2 – 3	Zircaloy
3 – 4	Gadolinium R-BA
4 – 5	CrAl

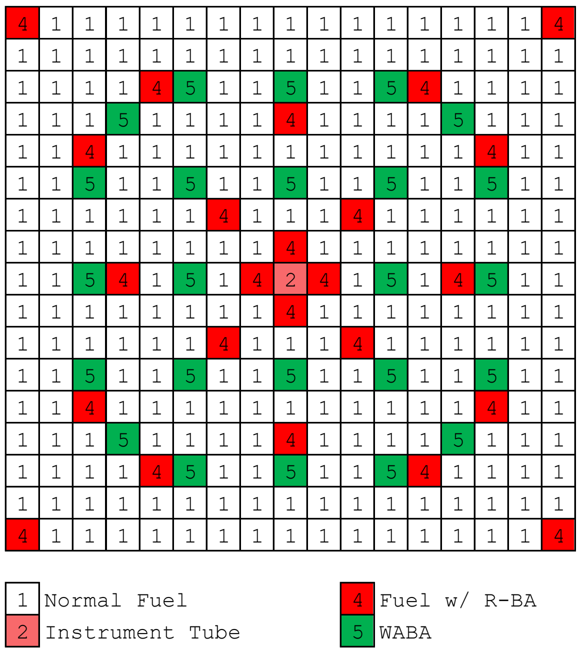

Fig. 3. Fuel Assembly Geometry with R-BA

Table III: specification of fuel assembly

Parameter	Value
Fuel Assembly Type	17X17 Westinghouse
Fuel pin pitch	1.26 cm
Fuel radius	0.4095 cm
CrAl coating thickness	0.0050 cm
Fuel enrichment	4.95 w/o ^{235}U

UO2 density	10.412 g/cc
Power density	21.3 W/g
WABA material	80 w/o ^{10}B Al_2O_3/B_4C
Fuel Temperature	850 K
Moderator Temperature	583 K

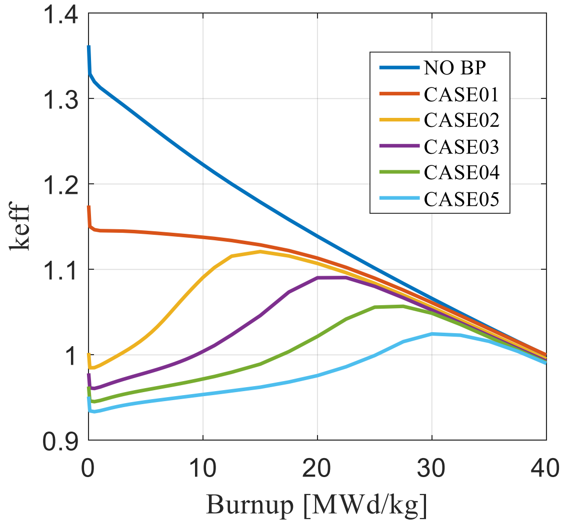

Fig. 4 Gadolinium R-BA Assembly sensitivity study multiplication factor results

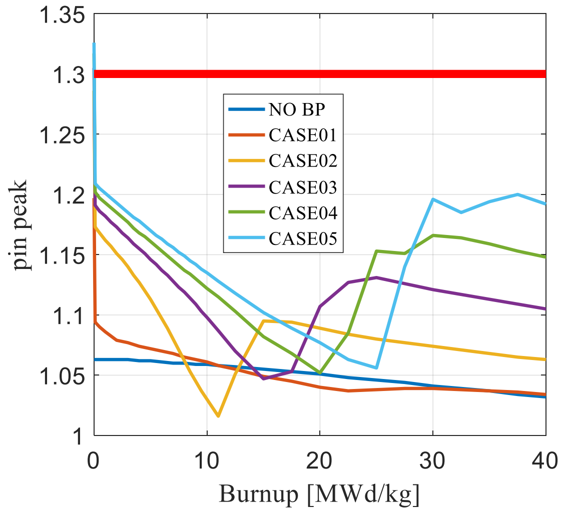

Fig. 5. Gadolinium R-BA Assembly sensitivity study maximum pin power results

Table IV: Gadolinium R-BA thickness sensitivity results

Assembly Name	R-BA Thickness [cm]	Burnout point [MWd/kg]	Maximum reactivity [pcm]	Residual reactivity [pcm]
NO BP	-	-	26,600	Reference
CASE01	0	-	14,883	309
CASE02	0.010	15	10,786	800
CASE03	0.020	22.5	8,294	1,079
CASE04	0.030	27.5	5,379	1,297
CASE05	0.040	30	2,394	2,722

4. Sensitivity study of Assembly layout with R-BA

The layout of fuel assembly with R-BA pins effects on the power distribution and core three-dimensional (3D) power peaking factor. The six assembly patterns shown in Fig. 6 are used for sensitivity study to decrease the maximum pin power. Fuel assembly depletion calculation is performed with Table III conditions. The 4.95 w/o enriched UO_2 and 21.3 W/g power density are used. In addition, 0.030 cm thickness R-BA is used.

Fig. 7, Fig. 8 and Table V present the sensitivity results. The Fig. 7 presents that the multiplication factor is greatly influenced by BA layout at beginning of cycle (BOC). The "position 5" has lowest multiplication factor as 1.01607. On the other hand, the burnout point is less affected by layout. According to the Table V, the range of burnout point is 25.5 MWd/kg to 26 MWd/kg. The 26 MWd/kg burnout point cases are "Origin" and "Position 5". The 25.5 MWd/kg burnout point cases are "Position 1", "Position 2", "Position 3" and "Position 4". The difference between two burnout points is smaller than gadolinium R-BA thickness sensitivity results.

The point of residual reactivity at the target cycle length, 31.95 MWd/kg, "Origin" and "Position 3" cases have the first and second smallest values compared with other 4 cases as 1,219 pcm and 1,210 pcm.

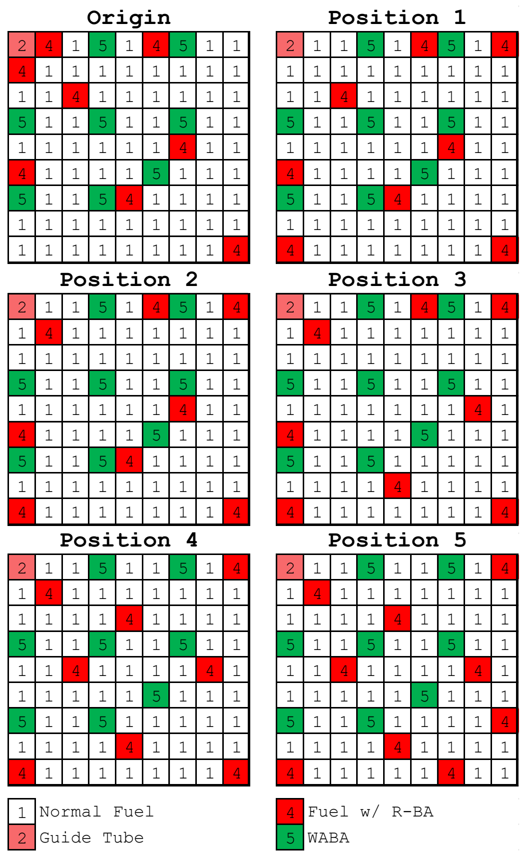

Fig. 6. One – fourth sensitivity study fuel assembly layout

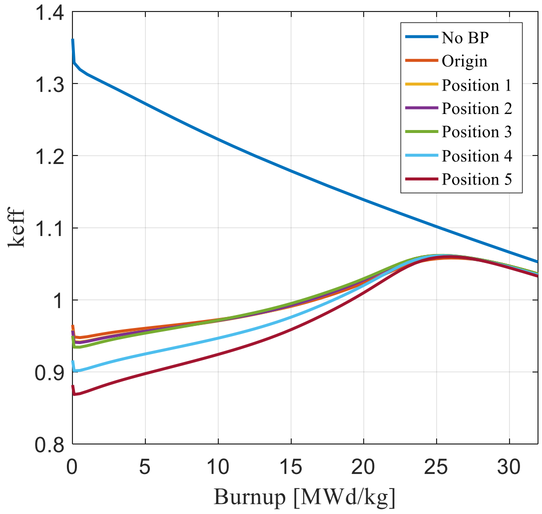

Fig. 7. Multiplication factor with gadolinium R-BA pin pattern sensitivity study

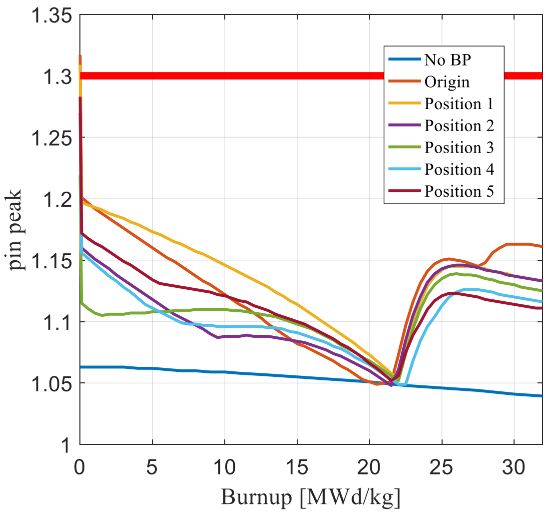

Fig. 8. Power peaking factor with gadolinium R-BA pin pattern sensitivity study

Table V: Gd R-BA pin pattern sensitivity results

Assembly Name	max pin power peak	Burnout point	k_{eff} at 1500 EFPD	Residual reactivity [pcm]
NO BP	1.063	-	1.04933	Reference
Origin	1.201	26	1.03608	1,219
Position 1	1.197	25.5	1.03594	1,232
Position 2	1.160	25.5	1.03604	1,222
Position 3	1.139	25.5	1.03617	1,210
Position 4	1.156	25.5	1.03453	1,364
Position 5	1.172	26	1.03287	1,518

5. Conclusion

This paper suggests the optimal ring type fuel assembly design with R-BA. The target core model is long-cycle soluble boron-free SMPWR. The ability of suppressed excess reactivity and possession of plenty amounts of fuel are set up as the criteria for BA sensitivity study. This paper suggests the R-BA type for long-cycle operation and presents the optimization progress of three sensitivity studies: R-BA materials, R-BA thickness and pin layout in fuel assembly.

According to the criteria of residual reactivity and BA burnout point, gadolinium and B_4C are suitable for the target cycle length, 31.95 MWd/kg. The sensitivity analysis of R-BA thickness shows that, CASE01 and CASE02 have too high maximum reactivities of 14,883 pcm and 10,786 pcm at burnout point; CASE05 has big reactivity penalty of 2,722 pcm at the target cycle burnup; while CASE03 and CASE04 with R-BA thickness of 0.020 cm and 0.030 cm are most suitable for long-cycle operation. In addition, to reduce the maximum pin power, "Origin" and "position 3" layouts are suitable.

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