Reactivity Flattening for a Soluble Boron-Free Small Modular Reactor

JinHa Park [a], JungKil Kang [a], ChangJoo Hah [a*]
[a]*KINGS, 658-91, Haemaji-Ro, Seosaeng-Myeon, Ulju-Gun, Ulsan, 45014, Korea*
[*]*Corresponding author: changhah@kings.ac.kr*

1. Introduction

Soluble boron in a reactor coolant is one of the most effective and reliable means of controlling excess reactivity of the reactor. On the contrary, the use of soluble boron causes side effects: corrosion of structural materials, less negative Moderator Temperature Coefficient (MTC), an increase in liquid radwaste, and the requirement of boron control and water purification systems like Chemical and Volume Control System. Therefore, removing soluble boron from the primary coolant system brings many benefits of simplifying the reactor operation and maintenance. Although a Soluble Boron-Free (SBF) operation has a lot of advantages, there are several barriers to overcome such as heavily bottom skewed axial power distribution due to the strong negative MTC, control rod design to secure the reactivity shutdown margin, and excess reactivity hold-down by using burnable absorbers and control rods, etc. For these reasons, there is no practical boron-free power operation in the world in spite of many studies on the SBF reactor [1, 2].

Burnable absorbers and control rods are the only available means, so far, to compensate excess reactivity for a SBF reactor. Frequent use of the control rods, however, can give a big burden to operators, and deep insertion of the control rods can cause fuel damage when Reactivity Initiated Accident (RIA) occurs like CEA ejection and bank withdrawal. Thus, it is very important to maintain excess reactivity as small and constant as possible in order to minimize movement of control rods through the entire cycle. Consequently, the optimization of burnable absorber rod is the one of the most important key factors for a SBF reactor core design.

The purpose of this study is to design a new conceptual burnable absorber to achieve flat reactivity from Beginning Of Cycle (BOC) to End Of Cycle (EOC). For these reasons, firstly, we carry out the investigation of the nuclear characteristics of the 17X17 WH (WestingHouse) type Fuel Assembly (FA) containing various burnable absorbers which have been widely used in PWR. Secondly, three kinds of new conceptual Burnable Poison (BP) rods are introduced and unit assembly analyses are carried out to find the best candidate for a SBF core. Lastly, core depletion calculations with the new conceptual burnable absorber rods are performed to verify the effect of the flat reactivity of the new burnable absorber.

2. Methods and Results

2.1 Core Description and Computational Methods

In this study, the optimization for burnable absorber pattern is demonstrated with 17x17 WH type FA which has twenty-four guide tubes for control rods and one central water hole for in-core instrumentation. BP rods are not loaded in the guide tubes, but placed at normal fuel rod location. The conceptual core rates 180 MWt whose active fuel height is 200 cm. The core consists of 37 fuel assemblies with slightly enriched UO_2 whose enrichment is 4.95 w/o.

CASMO-4E/CMS-LINK/SIMULATE-3 codes are used for an unit assembly and core analysis. The infinite multiplication factor and power distribution of the unit assembly are calculated using CASMO-4E code [3]. Cross section data from CASMO-4E are converted for SIMULATE-3 by CMS-LINK [4] which is a linking code. Core depletion calculations to obtain power peaking factor and core reactivity versus burnup are performed using the SIMULATE-3 [5] which is an advanced two-group nodal code.

2.2 Analysis on WABA and Gadolinia

The analyses for an unit assembly are carried out to investigate the nuclear characteristics of the 17X17 WH type fuel containing PYREX, WABA (Wet annular Burnable Absorber), Gadolinium Oxide (Gd_2O_3), Erbium Oxide (Er_2O_3), and IFBA (ZrB_2 Integral Fuel Burnable Absorber). The reactivities versus fuel burnup are represented in Figures 1 and 2 for WABA and Gadolinia, respectively.

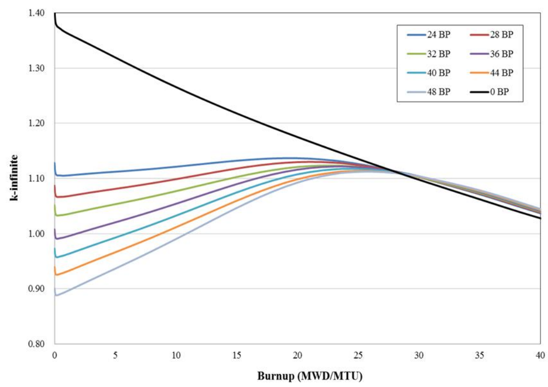


Fig. 1. Infinite Multiplication Factor of WABA vs. Burnup

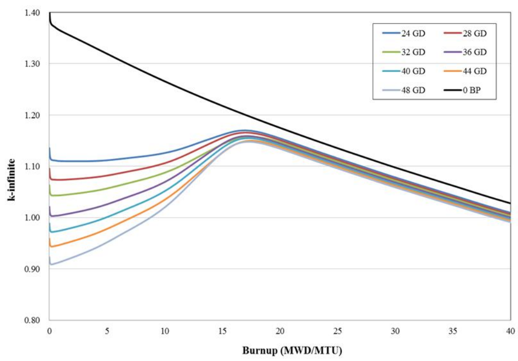


Fig. 2. Infinite Multiplication Factor of Gd vs. Burnup

For these analyses, 24 through 48 BPs are used, and the location of BP rods in a FA is determined by trial and error method to obtain lower nuclear peaking factor (Fxy).

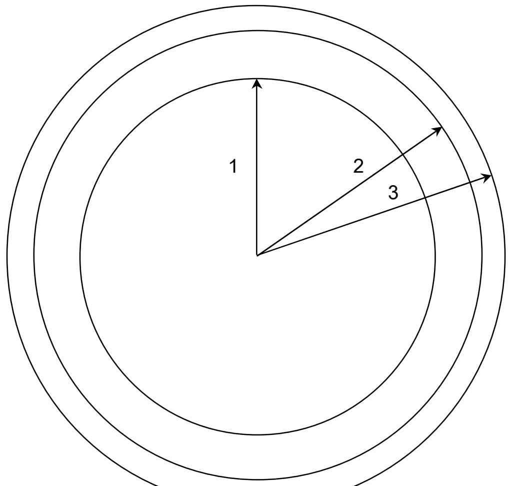
As shown in the figures, burnable absorber rods are depleted faster than UO_2 rods, so that they are fully burned out at the middle of cycle. It means that core reactivity increases until that time, so that excess reactivity can't be maintained flat with burnup.

2.3 A New Conceptual Design for Burnable Absorber Rod

In this study, three kinds of new burnable absorber rods are proposed. Flattening reactivity can be possible by combining the two factors: the thickness of absorber material and weight ratio of Al_2O_3 (Alumina), B_4C (Boron Carbide), and Gd_2O_3. All of the BP rods have good characteristics to make flat reactivity.

The first type of BP rod is shown in Figure 3. The absorber material of the first BP rod consists of B_4C and Al_2O_3, which are located in central region of the rod. It has single-layered structure. The second type of BP rod is shown in Figure 4, and it has double-layered burnable absorbers. The absorber material in inner layer is B_4C-Al_2O_3, while outer is Gd_2O_3-Al_2O_3. The purpose of double-layered structure is to maintain the same burnup rate for both burnable absorber and UO_2 rods, and to make more flat reactivity. The third type of BP rod is the same as the second type except the outer layer filled with B_4C-Al_2O_3. The inner and outer layers are filled with the same absorber materials.

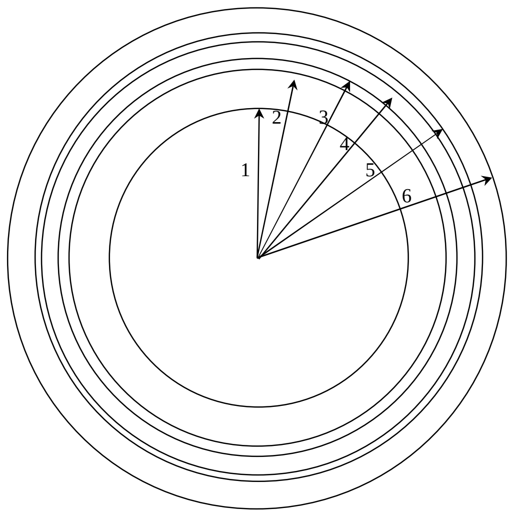
A number of unit assembly calculations were performed using the above burnable absorbers and the results are represented in Figures 5, 6, and 7, respectively. According to the Figure 5, it is found that the single-layered BP rod is less efficient in making reactivity flatten than other types of BP. As shown in the Figure 6, the reactivity of the second type of BP rod, double-layered with different absorber, decreases more rapidly than those of other types of BP due to the residual penalty of gadolinia. It results in significant reduction of cycle length. Figure 7 shows that the third



Region	Diameter (cm)	Material
0 - 1	D1*	B_4C/Al_2O_3
1 - 2	0.4316	Air
2 - 3	0.4760	Zr-4

* D1 has the range from 0.00 to 0.41

Fig. 3. Single Layer BP rod



Region	Diameter (cm)	Material
0 - 1	D1*	B_4C/Al_2O_3
1 - 2	0.3750	Air
2 - 3	0.3800	SS-304
3 - 4	D2**	Gd_2O_3/Al_2O_3 or B_4C/Al_2O_3
4 - 5	0.4316	Air
5 - 6	0.4760	Zr-4

* D1 has the range from 0.00 to 0.28

** D2 has the range from 0.38 to 0.43

Fig. 4. Double Layer BP rod

type of BP rod, double-layered with same absorber, has an advantage in both small residual penalty and flat reactivity. The third type of BP rod shows flat tendency in reactivity to higher burnup than other types of BP. This tendency is desirable in Loading Pattern (LP) determination because it is highly probable to produces flat reactivity curves up to the end of cycle. As a result of analysis, the double-layered BP rod with same absorber is the best candidate among the three for a SBF reactor.

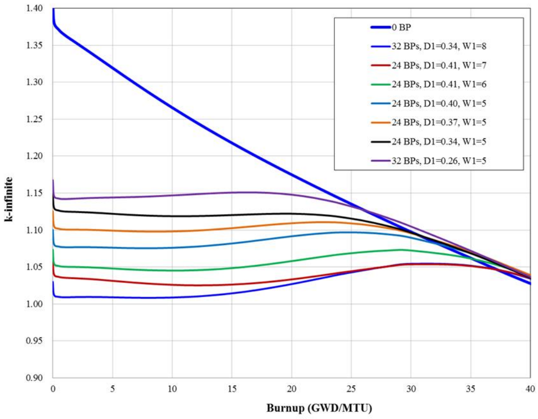


Fig. 5. Infinite Multiplication Factors of Single Layer BP (B_4C) vs. Burnup

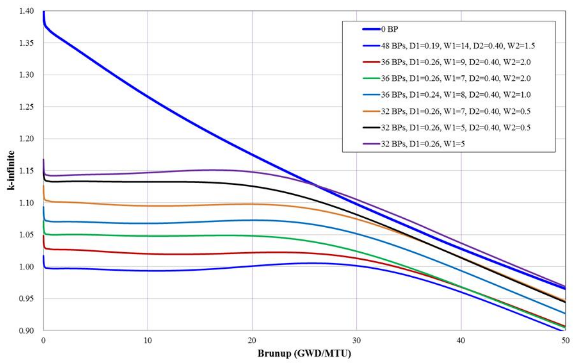


Fig. 6. Infinite Multiplication Factors of Double Layer BP (B_4C/Gd) vs. Burnup

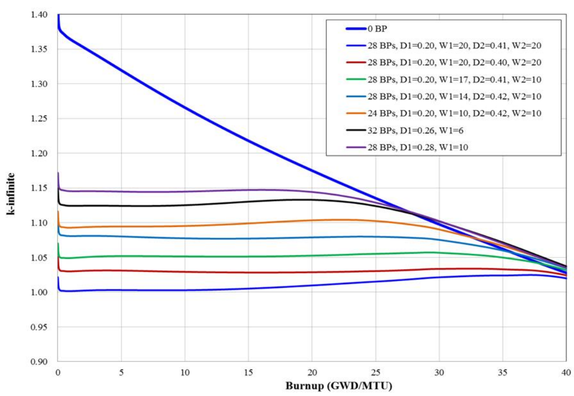


Fig. 7. Infinite Multiplication Factors of Double Layer BP (B_4C/B_4C) vs. Burnup

2.4 Core Analysis

In order to verify the effect of flat burned FA, a core depletion calculation loaded with and B_4C/B_4C double-layered BP rods was carried out. The loading pattern is shown in Figure 8, and the configuration of A0 is in Figure 9. The FA information is provided in Table 1.

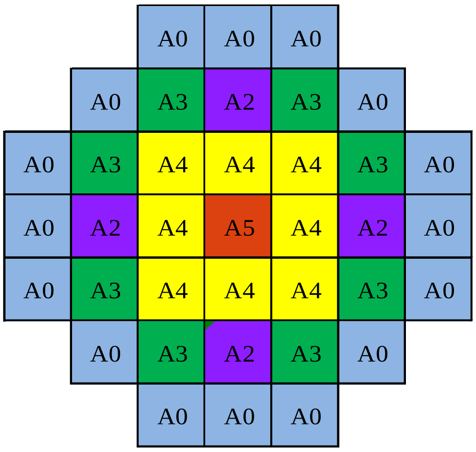


Fig. 8. Core Loading Pattern

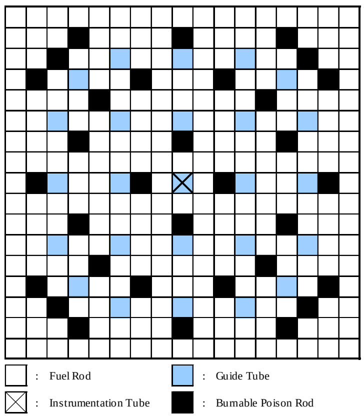


Fig. 9. Cross Sectional Drawing of 17x17 WH Type FA (A0)

Table 1. Summary of FA

FA Type	# of FA	# of BP	BP Type	D1* (cm)	W1** (w/o)	D2* (cm)	W2** (w/o)
A0	16	32	B_4C	0.24	5	-	-
A2	4	32	B_4C	0.28	5	-	-
A3	8	24	B_4C/B_4C	0.19	10	0.42	10
A4	8	36	B_4C	0.26	14	-	-
A5	1	28	B_4C/B_4C	0.24	10	0.41	10
Total	37	1148	-	-	-	-	-

* D1 and D2 indicate inner and outer layer diameters, respectively.

* W1 and W2 indicate weight ratio between B_4C and Al_2O_3 of inner and outer layer, respectively.

The reactivity curve versus burnup at HFP, ARO, Eq. Xenon is presented in Figure 10. As shown in Figure 10, the flatness of core reactivity with the double-layered BP rods was well maintained throughout whole cycle. A core loaded with the third type of BP assemblies shows the maximum excess reactivity of about 0.7 %Δρ compared with the core loaded with that of gadolinia BP assemblies, 4.0 %Δρ. The calculation result of radial power peaking factor is shown in Figure 11. The maximum Fxy with B_4C/B_4C double-layered BP rods is 1.54. It means core radial power distributions are also well flattened from BOC to EOC.

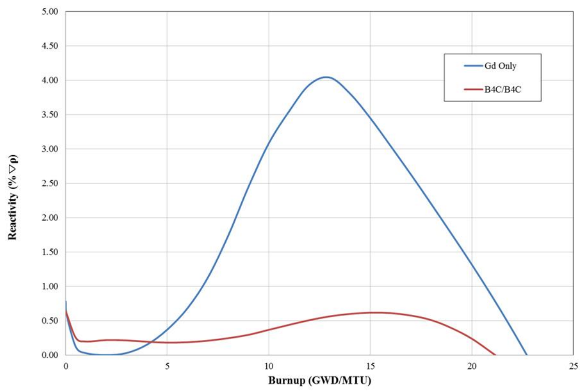


Fig. 10. Core Reactivity vs Burnup

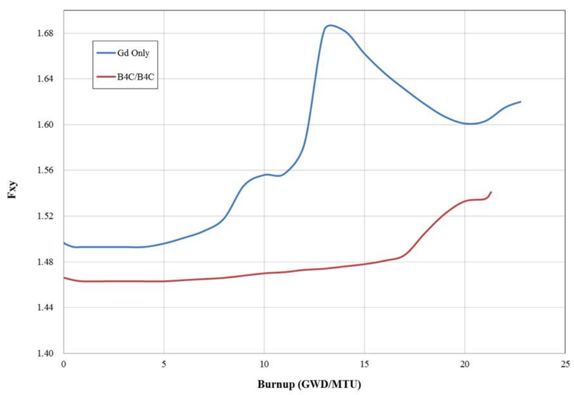


Fig. 11. Fxy vs Burnup

3. Conclusions

The design of burnable absorber is the one of the key factors for a SBF reactor since a certain number of burnable absorber rods should be used in order to minimize the control rod movement and to maintain the excess reactivity as small and constant as possible over the entire fuel cycle. In this study, it is found that double-layered BP rod with same absorber material, B_4C/B_4C, is the most efficient candidate of BP for a SBF reactor. This burnable absorber is flexible to cope with various reactivity shapes by adjusting the thickness of absorber material, weight ratio of Al_2O_3 and B_4C, and it can be used like a single-layered burnable absorber by replacing outer layer with air. The results of depletion calculation verify that core excess reactivity can be well controlled, and show that core radial power distributions are also well flattened over the entire core burnup.

REFERENCES

[1] Jong-Chae Kim, Myung-Hyun Kim, Nuclear Design Feasibility of the Soluble Boron Free PWR Core, Journal of the Korean Nuclear Society 30.4, August 1998.
[2] Soon Young KIM, Jong Kyung KIM, Conceptual Core Design of 130MWe Reactor of r Soluble Boron Free Operation Using a New Fuel Concept, Journal of the Korean Nuclear Society 31.4, August 1999.
[3] Studsvik Scandpower, Inc, CASMO-4E : Extended Capability CASMO-4 User's Manual, SSP-09/442-U Rev. 0, 2009.
[4] Studsvik Scandpower, Inc, CMS-LINK User's Manual, SSP-09/444-U Rev. 0, 2009.
[5] Studsvik Scandpower, Inc, SIMULATE-3: Advanced Three-Dimensional Two-Group Reactor Analysis Code User's Manual, SSP-09/447-U Rev. 0, 2009.