Combination of Burnable Poison Pins for 24 months Cycle PWR Reload Core

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1. Introduction

Nowadays many researches have been conducted to design a Pressurized Water Reactor (PWR) core with longer cycle operation, in order to reduce the outage cost as well as production of spent fuels. For such PWR core design, the need for higher number of burnable poison (BP) pins to be loaded in the core is necessary with the purpose of hold-down the increase of initial excess reactivity, which is due to required high fuel enrichment. Also, the change in local pin power peaking and moderator temperature coefficient (MTC) should be within a design limitation [1].

Different types of separate and integral BP pins have been developed showing a very good performance. Nevertheless, each type of BP has weak points with favorable characteristics. In this paper, combinational location of two types of BP pins in a single assembly were tested. Benefits of combinational BP concept are expected by compensating weak points of each other when more BP pins were added in order to increase absorption.

The purpose of this feasibility study is to invent a new combinational BP concept for 24 month cycle PWR cores; the selected reference reload cores are Hanul unit-3 loaded with 16x16 Combustion Engineering (CE) type fuel assemblies and the other is Kori unit-4 loaded with 17x17 Westinghouse (WH) type fuel assemblies. Feasibility of application is measured by design parameters; cycle length, power peaking factor and MTC.

2. Reference Design for 24 Month Cycle PWR

2.1 Design Tools

The design tool that has been used in this study is DeCART2D-MASTER code system that is developed by Korea Atomic Energy Research Institute (KAERI). This system is a traditional two-step procedure which is used for NPP design analysis. DeCART2D is a lattice code which uses Method of Characteristic (MOC) in order to solve the transport equation. This code generates the Homogenized Group Constant (HGC) files, which can be used later on in MASTER code, by performing assembly depletion calculation. MASTER code solves two group nodal diffusion equations, and used for Core calculation [2,3].

2.2 Design of the Equilibrium Reload Core

Initially, two PWR equilibrium cycle reload cores with 18 month cycle length were designed as reference cores. Equilibrium cycle cores were searched for cycles 12 through 14 in case of Hanul Unit-3 (CE type) and cycles 22 through 24 for Kori Unit-4 (WH type). Table I shows the results as the reference core design parameters.

Table I: Reference Core Design Parameters

Design Parameter	Hanul Unit-3	Kori Unit-4
Thermal Power (MWth)	2815	2900
The number of Assembly	177	157
Active Core Height (cm)	381	365.76
Pressure (MPa)	15.514	15.513
Core Average Moderator Temp. (°C)	311.9	310.2
The number of fuel rod per assembly	236	264
The number of Guide Tube	4	24
The number of Instrumentation tube	1	1
Assembly Pitch (cm)	20.7772	21.5040
Cell Pitch (cm)	1.285	1.260
Fuel Diameter (cm)	0.8192	0.8192
Cladding material	ZIRLO	ZIRLO
Cladding I.D. (cm)	0.8357	0.8357
Cladding O.D. (cm)	0.95	0.95
Guide Tube material	ZIRLO	ZIRLO
Guide Tube I.D. (cm)	2.286	1.008
Guide Tube O.D. (cm)	2.4892	1.224

Design modification was done from 18 month cycle reference core to 24 month extended cycle cores. Many options can be applied for this purpose. Increase of fuel enrichment, fuel pellet size change, increase of physical density, or increase of conversion ratio by adjusting fuel to moderator ratio can be potential candidates. In this study, a simple and easy method, i.e. increase of fuel enrichment was chosen because the use of BP is the main theme of this study.

A primary test for 24 month extended cycle core with many different BP choices was done as the first step of study. Only fuel enrichment was increased into 6.59w/o, and all other core design parameters are remained same as reference cores. Table II shows the results (radial peaking factor (F_R), MTC and cycle length) from three different BP choices; Gadolinia (Gad), Erbia (Er) and Integral Fuel Burnable Absorber (IFBA). Even though three options satisfy most of design requirements, Er has the lowest values of F_R and the most negative values of MTC amongst themselves. On the other hand, IFBA assures the longest fuel cycle length. Er and IFBA pins should be loaded at many pin locations in an assembly due to their low thermal absorption cross-section. On the other hand, due to high thermal absorption cross-section of Gad, a small number of them can hold-down the initial excess reactivity efficiently. This advantage of Gad can make the core management and optimization easier than the use of other BP types. Therefore, there is a need to find the optimum BP combination.

Table II: Results of 24 Month Cycle Core Design

	Gad	Er	IFBA
F_R at BOC	1.6354	1.4741	1.5663
at MOC	1.5417	1.4917	1.5671
at EOC	1.5247	1.4643	1.4359
Max. F_R	1.6354	1.4962	1.6147
MTC (pcm/C°)			
at HZP BOC	-1.87	-11.54	-2.19
at HFP BOC	-18.85	-32.59	-16.96
at HFP EOC	-77.89	-84.25	-78.66
Cycle Length (EFPD)	677.77	715.33	742.32

3. Conceptual Design of Combinational BP Loading

The primary goal of BP utilization is to reduce the initial excess reactivity and additionally to control local pin power peaking. As is well known, finding the optimum BP pin loading is not a simple work. The number of possible combinational options of BP location inside of the fuel assembly is quite large; by using different types of BP (Gad, Er, IFBA, Wet Annular Burnable Absorber (WABA), etc.), by combining different set of BP, by locating one and the other. As an example of that, a fuel assembly loaded with 96 Er can be redesigned by combinational BP with 16 Er pins and 20 WABA pins. However, location of secondary BP pins, which are Er pins, can make many different designs with different results.

Classification of all possible combination of 4 BP choices (Gad, Er, IFBA, WABA) was taken as the first step of investigation. As can be guessed, possible design concepts are too many (more than thousands). Thus, selection of secondary BP is classified based on the primary BP selection. The combinations of BP pins are selected in order to compensate the weak points of primary BP by the secondary BP. Power peaking factor is variant sensitively depending on the selected location. Therefore, the location of secondary BP is fixed to the higher power peaking positions. Gad and WABA, due to their high thermal absorption cross-section, can cause high power peaking factor. For this reason, Er and IFBA pins were selected as secondary BP of Gad and WABA pins. On the other hand, since Er and IFBA pins do not have the ability to control the excess reactivity in an efficient way. Therefore, their secondary BP pins were selected to be Gad and WABA pins. Finally, the number of total probable options is 36. Among these options, as listed in Table III, 4 options were selected as the best candidate options. Fig. 1 shows an example of ¼ fuel assembly with combinational BP pins arrangement. Worth mentioning, detail design specification is not shown in this paper.

Table III: Candidate Optimum Options

Option	Primary BP	Secondary BP
Option A	Erbia	WABA
Option B	IFBA	WABA
Option C	WABA	Erbia
Option D	WABA	IFBA

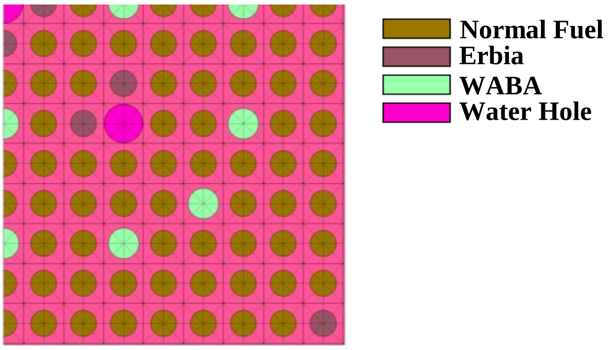


Fig. 1. Example of combinational BP pin arrangement (¼ WH fuel assembly, Er main + WABA Secondary).

4. Assembly Calculation of Combinational BP Pins

Assembly calculation results of successful combinations are shown in the following figures. Some of Er pins were replaced with WABA pins as secondary BP in order to overcome its low thermal absorption cross-section. As WABA pins are loaded, the initial excess reactivity is decreased as shown in Fig 2. Also, this option shows a good performance in peaking factor control and MTC as shown in Fig. 3 and 4 respectively.

5. Core Calculation of Combinational BP Pins

For core calculation, the Er was considered as primary BP pins and WABA as secondary BP pins, due to their good performance as shown in assembly calculation. In this paper, only Kori Unit-4 results are shown, although core calculation for both core designs (Hanul Unit-3 and Kori Unit-4) was done. In this section, two cores (Er+WABA and Er) were compared with each other.

Firstly, the cycle length was set as 525 EFPD, 615 EFPD and 685 EFPD for cycle 22~24 respectively. In order to achieve these cycles length, the fuel enrichment was increased as 5.7w/o, 5.9w/o and 6.8w/o for cycle 22~24 respectively. Assembly types and their details for Er and Er+WABA cores are shown in Table IV and Table V respectively. Fig. 5 shows the fuel assemblies loading pattern for same cores.

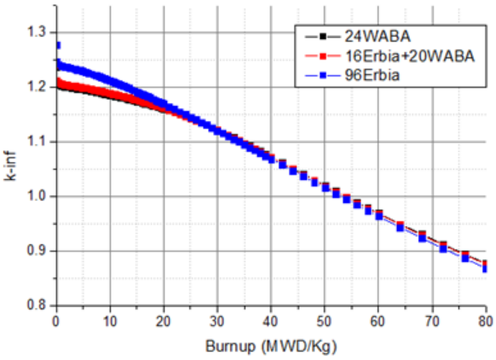


Fig. 2. Comparison of excess reactivity.

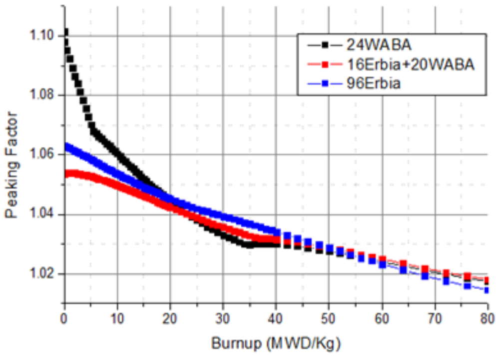


Fig. 3. Comparison of radial peaking factor.

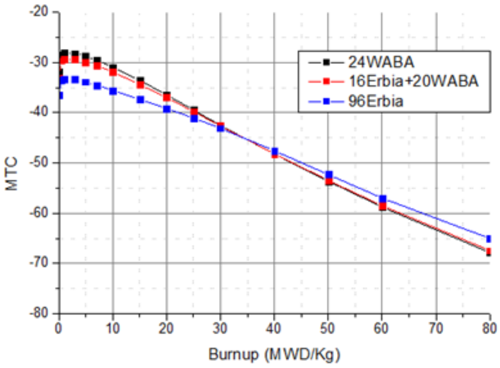


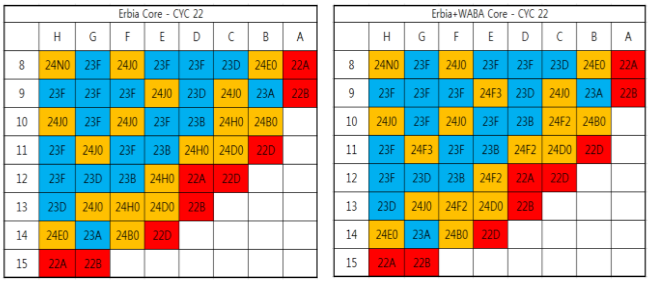
Fig. 4. Comparison of MTC.

Table IV: Assembly Type Details for Er Core

Er Core	Assembly Type	No. of Assembly	No. of Er	No. of WABA
CYC-22	24B0	8	16	0
	24D0	8	48	0
	24E0	4	64	0
	24H0	16	112	0
	24J0	28	144	0
	24N0	1	0	0
CYC-23	25D0	16	48	0
	25F0	8	80	0
	25H0	16	112	0
	25J0	28	144	0
	25N0	1	0	0
CYC-24	26E0	8	64	0
	26F0	8	80	0
	26G0	8	96	0
	26J0	40	144	0
	26N0	1	0	0

Table V: Assembly Type Details for Er+WABA Core

	Assembly Type	No. of Assembly	No. of Er	No. of WABA
CYC-22	24B0	8	16	0
	24D0	8	48	0
	24E0	4	64	0
	24J0	20	144	0
	24F2	16	80	8
	24F3	8	80	12
	24N0	1	0	0
CYC-23	25D0	4	48	0
	25F0	8	80	0
	25J0	20	144	0
	25B1	8	16	4
	25F2	16	48	8
	25F3	8	48	12
	25N0	1	0	0
CYC-24	26E0	8	64	0
	26G0	8	80	0
	26J0	20	144	0
	26B3	8	16	12
	26F3	8	80	12
	26N0	1	0	0



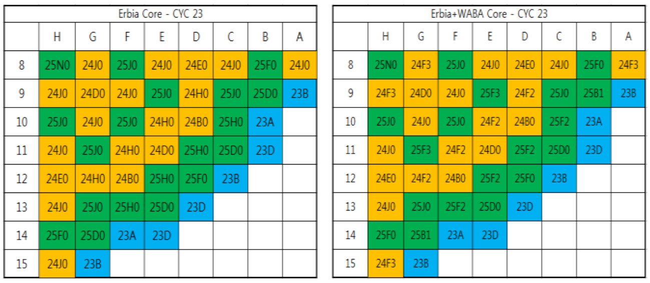
Erbia Core - CYC 22

	H	G	F	E	D	C	B	A
8	24N0	23F	24J0	23F	23F	23D	24E0	22A
9	23F	23F	23F	24J0	23D	24J0	23A	22B
10	24J0	23F	24J0	23F	23B	24H0	24B0	
11	23F	24J0	23F	23B	24H0	24D0	22D	
12	23F	23D	23B	24H0	22A	22D		
13	23D	24J0	24H0	24D0	22B			
14	24E0	23A	24B0	22D				
15	22A	22B						

Erbia+WABA Core - CYC 22

	H	G	F	E	D	C	B	A
8	24N0	23F	24J0	23F	23F	23D	24E0	22A
9	23F	23F	23F	24F3	23D	24J0	23A	22B
10	24J0	23F	24J0	23F	23B	24F2	24B0	
11	23F	24F3	23F	23B	24F2	24D0	22D	
12	23F	23D	23B	24F2	22A	22D		
13	23D	24J0	24F2	24D0	22B			
14	24E0	23A	24B0	22D				
15	22A	22B						

A. Erbia Core – CYC 22 B. Erbia+WABA Core – CYC 22



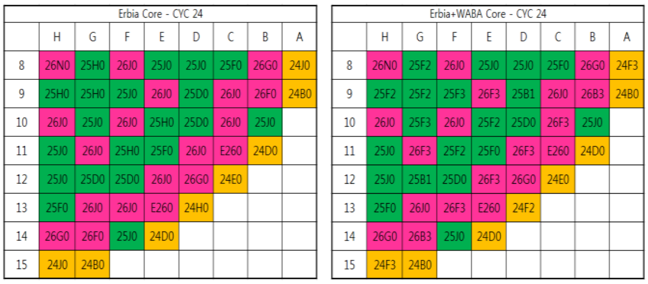
Erbia Core - CYC 23

	H	G	F	E	D	C	B	A
8	25N0	24J0	25J0	24J0	24E0	24J0	25F0	24J0
9	24J0	24D0	24J0	25J0	24H0	25J0	25D0	23B
10	25J0	24J0	25J0	24H0	24B0	25H0	23A	
11	24J0	25J0	24H0	24D0	25H0	25D0	23D	
12	24E0	24H0	24B0	25H0	25F0	23B		
13	24J0	25J0	25H0	25D0	23D			
14	25F0	25D0	23A	23D				
15	24J0	23B						

Erbia+WABA Core - CYC 23

	H	G	F	E	D	C	B	A
8	25N0	24F3	25J0	24J0	24E0	24J0	25F0	24F3
9	24F3	24D0	24J0	25F3	24F2	25J0	25B1	23B
10	25J0	24J0	25J0	24F2	24B0	25F2	23A	
11	24J0	25F3	24F2	24D0	25F2	25D0	23D	
12	24E0	24F2	24B0	25F2	25F0	23B		
13	24J0	25J0	25F2	25D0	23D			
14	25F0	25B1	23A	23D				
15	24F3	23B						

A. Erbia Core – CYC 23 B. Erbia+WABA Core – CYC23



Erbia Core - CYC 24

	H	G	F	E	D	C	B	A
8	26N0	25H0	26J0	25J0	25J0	25F0	26G0	24J0
9	25H0	25H0	25J0	26J0	25D0	26J0	26F0	24B0
10	26J0	25J0	26J0	25H0	25D0	26J0	25J0	
11	25J0	26J0	25H0	25F0	26J0	E260	24D0	
12	25J0	25D0	25D0	26J0	26G0	24E0		
13	25F0	26J0	26J0	E260	24H0			
14	26G0	26F0	25J0	24D0				
15	24J0	24B0						

Erbia+WABA Core - CYC 24

	H	G	F	E	D	C	B	A
8	26N0	25F2	26J0	25J0	25J0	25F0	26G0	24F3
9	25F2	25F2	25F3	26F3	25B1	26J0	26B3	24B0
10	26J0	25F3	26J0	25F2	25D0	26F3	25J0	
11	25J0	26F3	25F2	25F0	26F3	E260	24D0	
12	25J0	25B1	25D0	26F3	26G0	24E0		
13	25F0	26J0	26F3	E260	24F2			
14	26G0	26B3	25J0	24D0				
15	24F3	24B0						

A. Erbia Core – CYC 24 B. Erbia+WABA Core – CYC24

Fig. 5. Fuel Assemblies Loading Pattern for Erbia core and Erbia+WABA Core.

Radial peaking factors and MTC for Er core and Er+WABA core are shown in the following figures. As can be seen from Fig. 6, Er+WABA core at Beginning Of Cycle (BOC) and Middle Of Cycle (MOC) has lower radial peaking factor compared with Er core for all cycles (22~24). On the other hand, as shown in Fig. 7, Er+WABA core has slightly higher MTC values than Er core. However, this difference is negligible. The discussed results show that WABA pins work very well with Er pins in order to reduce the radial peaking factor notably; at the same time keep MTC values as negative as only Er pins were used.

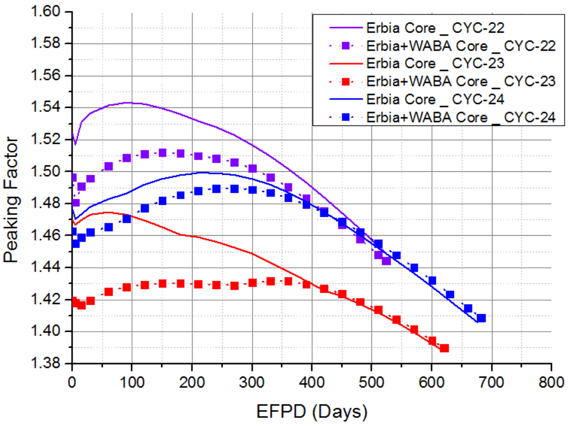


Fig. 6. Radial Peaking Factor for core calculation.

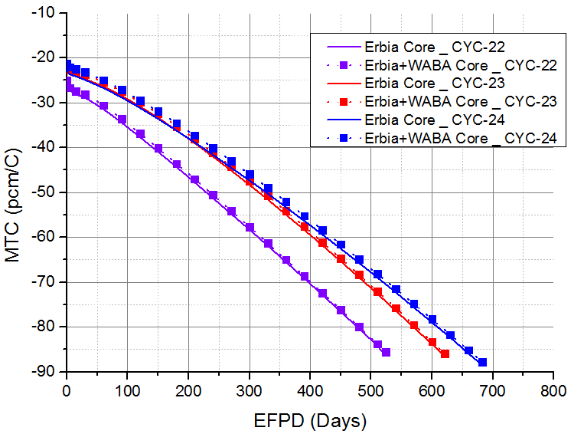


Fig. 7. MTC for core calculation.

6. Conclusions

In the present paper, assembly and core calculations were performed for combinational BP concept. The results clearly showed that the use of two carefully selected BP types can overcome the disadvantages of single BP pins.

REFERENCES

[1] Jeffery A. Brown, Ho Q. Lam, "Hybrid IFBA Gad Assembly Designs for Long PWR Cycles," 2017 Water Reactor Fuel Performance Meeting, Ramada Plaza Jeju, Jeju Island, Korea, Sep. 10-14, (2017).

[2] B.O. Cho, H.G. Joo, J.Y. Cho, J.S. Song, S.Q. Zee, "MASTER-3.0: Multi-purpose Analyzer for Static and Transient Effects of Reactors," KAERI/TR-2061/2002, Korea Atomic Energy Research Institute (2002).

[3] J.Y. Cho, J.C. Lee, K.H. Lee, S.Y. Park, H.J. Park, H.Y. Kim, K.Y. Kim, H.J. Jung, J.S. Song, S.Q. Zee, C.K. Jo, H.C. Lee, "DeCART2D v1.0 User's Manual," KAERI/TR-5116/2013, Korea Atomic Energy Research Institute, (2013).

[4] A. Abdelghafar Galahom, "Investigation of different burnable absorbers effects on the neutronic characteristics of PWR assembly," Annals of Nuclear Energy, 94, 22 (2016).

[5] J.C.Wagner and C.V.Parks, "Parametric Study of the Burnable poison Rods for PWR Burnup Credit," NUREG/CR-6761/ORNL/TM-2000/373, Oak Ridge National Laboratory, (2002).