Feasibility Assessment of Low Boric Acid SMR with Gadolinia Burnable Absorber

Jong Hoon Kim , Bum Hee Jo*, Jin Sun Kim, Gong Hoon Bae
KEPCO Nuclear Fuel, 242, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea
**Corresponding author: bhjo@knfc.co.kr*

1. Introduction

Internationally, various conceptual SMR have been proposed by nuclear institutions and universities. In Korea, discussions on the design of Small Modular Reactor(SMR)[1] have been actively progressing beyond conceptualization, towards the development of practical and efficient SMRs. This research presents two cases of low boric acid SMR core. One model is designed to maximize the cycle length, while the other aims to minimize the radial peaking factor. Both cases demonstrated sufficient core performance and safety compared to commercial reactors of the WH type.

2. Description

In this work, the typical design procedure for PWR core design is considered to Low boric acid SMR which has 520MWt. The fuel assembly calculations are designed with KARMA code which is a two-dimensional multi group transport theory code[2,3]. The core design and analysis are performed by using ASTRA code which is a 3D core depletion code[4].

2.1 Fuel assembly design

The reference fuel assembly is the typical WH 17×17 type used in typical commercial PWR. Thermal power of the core is 520MWt, with power density of 3.625 kW/ft, as shown in Table I. The number of guide tubes is 24, and the effective length of the core is 240cm. The burnable absorber utilized natural gadolinium oxide (Gd_2O_3) at a concentration of 10wt.% or less. The summarized data for each assembly type is shown in Table II.

Table I: Reactor design data

Thermal Power (MWt)	520
Fuel Rod Array	17×17
Power Density (kW/ft)	3.625
Number of Fuel assemblies (#)	69
Number of guide tubes	24
Core Effective Length (cm)	240
Fresh Fuel enrichment (wt.%)	< 4.95

2.2 Core design

The loading patterns were conducted for two cases, with each case involving a selection of two cycles. The selected loading pattern for cycle 1 through cycle 2 of Case 1 and Case 2 were shown in Fig. 1 and Fig. 2.

For the first cycle, the loading pattern was selected using only 3.64wt.% assemblies to control the initial excess reactivity.

For the second cycle, to ensure cycle length extension, a loading pattern with two batch using 4.95wt.% assemblies was selected. Case 2 was also configured with two batch loading patterns, similar to Case 1.

A24	A12	A16	A04	A02
A12	A12	A24	A08	A04
A16	A24	A16	A04	A02
A04	A08	A04	A02	
A02	A04	A02		

A24	C24	A02	C19	A02
C24	C24	A02	C14	A04
A02	A02	C24	C14	A04
C19	C14	C14	C12	
A02	A04	A04		

Fig. 1. The loading patterns of Cycle 1 and Cycle 2 of Case 1.

A24	A12	A16	A04	A02
A12	A11	A24	A08	A03
A16	A24	A16	A04	A01
A04	A08	A04	A01	
A02	A03	A01		

A24	A02	C20	A01	C01
A02	C20	A01	C16	A04
C20	A01	C20	C16	A03
A01	C16	C16	C01	
C01	A04	A03		

Fig. 2. The loading patterns of Cycle 1 and Cycle 2 of Case 2.

Both cases have similar first cycle core design. In the second loading pattern, Case 1 maximizes the cycle length by placing the C assemblies, which are fresh fuel assemblies, as close to the core center with a total of 4 assemblies placed on the periphery. Case 2, on the other hand, aims to maximize the radial peaking factor by dispersing the C assemblies as much as possible with a total of 8 assemblies placed on the periphery.

Table II: Summary of assembly type

Assembly Type	U^{235} Enrichment (wt.%)	No. of Fuel Rods per Assembly	No. of Gd Rods per Assembly	Gd Enrichment (wt.% Gd2O3)
A01	3.64/2.86	252	12	4
A02	3.64/2.49	252	12	6

A03	3.64/2.13	252	12	8
A04	3.64/1.77	252	12	10
A11	3.64/2.13	244	20	8
A12	3.64/1.77	244	20	10
A16	3.64/1.77	240	24	10
A24	3.64/1.77	232	32	10
C01	4.95/3.91	252	12	4
C12	4.95/2.42	244	20	10
C14	4.95/3.41	240	24	6
C16	4.95/2.42	240	24	10
C19	4.95/2.92	236	28	8
C20	4.95/2.42	236	28	10
C24	4.95/2.42	232	32	10

3. Results

3.1 EFPD and CBC comparison

The values comparing Effective Full Power Days (EFPD) and Critical Boron Concentration (CBC) for both cases are presented in Table III. Case 1, aimed at maximizing the cycle length, surpassed 800 EFPD for Cycle 1 and Cycle with the maximum CBC remaining below 800ppm. On the other hand, Case 2 exhibits EFPD below 800 for the Cycle 2, while the maximum CBC is observed to be above 800ppm.

Table III: The results of comparison of EFPD and CBC

Cycle		Cycle Length		Max CBC (ppm)
		Burnup (MWD/MTU)	EFPD	
Case 1	01	22101	880.2	771.4
	02	20776	827.4	743.2
Case 2	01	22426	893.7	830.2
	02	20016	797.5	843.8

The CBC comparison results according to Burnup is depicted in Fig. 3. The black line is the EOC in a typical commercial reactor. In the low boric acid SMR, due to the advantage of two batch, the cycle length is about 2,500MWD/MTU long.

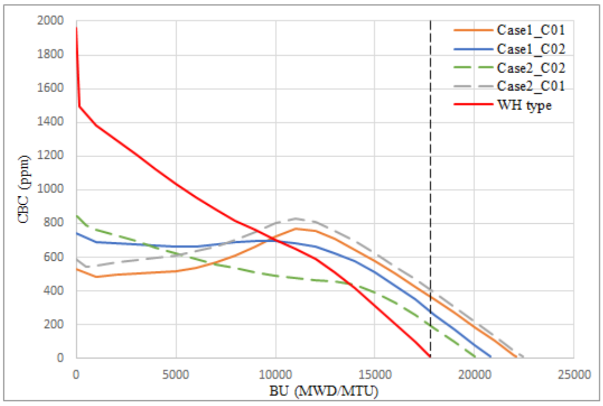

Fig. 3. The CBC comparison results according to Burnup with commercial reactor.

3.2 Peaking factors comparison between two cases

The comparison of power peaking factors is presented in Table IV. In the Cycle 1, both cases had Fxy below or equal 1.6. However, in the Cycle 2, only Case 2 remained below 1.6, while Case 1 reached 1.711. The maximum Fq for Case 1 in each cycle were 2.402 and 2.154. Case 2 had values of 2.314 and 1.928.

Both factors are influential on safety, with Fxy particularly closely tied to DNBR, significantly impacting reactor safety. Consequently, additional safety evaluation for both factors are planned for future assessment.

Table IV: The results of peaking factors

Cycle		Fxy	Fq
Case 1	01	1.575	2.402
	02	1.711	2.154
Case 2	01	1.55	2.314
	02	1.587	1.928

3.3 The comparison of MTC

The low boric acid SMR assemblies used in this study is similar to the commercial reactor WH type. To show validity, the research results were compared with the Moderator Temperature Coefficient (MTC) results according to Burnup in a typical commercial reactor. The comparison results are shown in Fig. 4, 5. The red line show the least negative MTC on WH reactor.

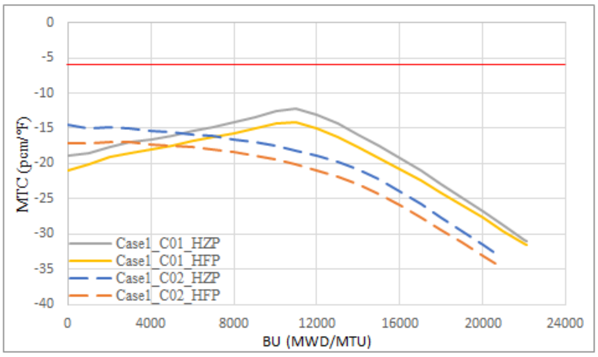

Fig. 4. The MTC comparison results according to Burnup with commercial reactor for Case 1

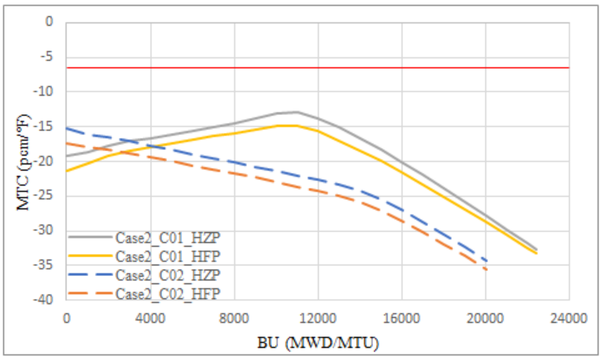

Fig. 5. The MTC comparison results according to Burnup with commercial reactor for Case 2

The least negative MTC for Case 1 is -12.2 pcm/°F and Case 2 is -13.0pcm/°F. The calculated MTC from this core satisfies the Unfavorable Exposure Time limit of -7pcm/°F applied in WH type commercial core [5].

Both cases of the proposed SMR exhibit a convex shape in the MOC in the first cycle, while showing a decreasing trend form the beginning of the cycle in the second cycle. This phenomenon is attributed to the presence of significant amounts of burnable absorbers at the beginning of the cycle. These values, being more than about -5pcm/°F lower than the least negative MTC of the typical commercial reactor, can be considered to have sufficient safety.

4. Conclusion

The feasibility of low boric acid SMR was evaluated in this study. In conclusion, for all cycles, Case 1 exhibited a cycle length of over 820 EFPD, while Case 2 had Fxy below 1.6. Additionally, both cases demonstrated high safety in terms of MTC. In order to supplement the feasibility of the low boric acid SMR core, future study will include calculation of additional safety evaluation and the possibility of flexible operation.

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