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Implementation of Low Boron Core for APR1400 Initial Cycle

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1. Introduction

Low boron capability of a nuclear power plant has been of interest recently since there have been several attempts to export APR1400 to European regions and European Utility Requirement (EUR) has a specification of the low boron capability. Low boron capability of a nuclear power plant is rather a qualitative specification requiring the nuclear power plant to be shut down by control rods alone at any time of a plant cycle according to EUR. The reduction of soluble boron is beneficial since it gives the reduction of the corrosive effects in the plant system and improves plant safety giving more negative MTC. Thus, it is necessary to reduce the amount of soluble boron for the criticality to achieve the low boron capability. However, the reduction of soluble boron has its own set of specific challenges that must be overcome.

There are two methods to enable the reduction of soluble boron without modifying plant system significantly. One is to use enriched boron as a soluble absorber and the other is the extended usage of burnable absorbers. When using the enriched boron, the CBC is decreased in proportion to the boron content. So, it has some advantages such as reduction of the corrosive effects and simplification of CVCS. But there is no advantage in plant safety. In Reference 1, a low boron core was implemented using the extended BA usage (multiple combination of various types of burnable absorbers) for an OPR1000 plant and safety parameters were evaluated. In Reference 2, a systematic approach using two kinds of gadolinia content to reduce soluble boron was suggested and applied to APR1400 initial core. However, the approach used assembly-wise reactivity preservation based on the fine adjustment of the fuel rod enrichment against the reference loading pattern, which is not practical in terms of fuel fabrication. The goal of this study is to investigate the loading pattern to achieve the soluble boron reduction for Shin-Kori Unit 5 APR1400 initial core using the low and high content gadolinia burnable absorbers with standard fuel rod enrichment and to verify the feasibility of low boron core with conventional gadolinia burnable absorbers only.

For this study, KARMA [3] has been employed to solve 2-D Transport equation, and ASTRA is used for full core analysis.

2. Low boron core design optimization

2.1 Systematic core design method

A systematic core design method [2] was developed to determine Gd-bearing fuel assembly having two types of Gd rods, low content Gd (low-Gd) rod and high content Gd (high-Gd) rod. In this method, the ratio of the number of low-Gd rod to the number of high-Gd rod, fuel enrichment and total number of Gd rod in an assembly are the decision variables. The objective function is the amount of reduction of boron concentration, which is a function of k-infinite of an assembly. The constraints required to satisfy the objective function are to maintain core average enrichment invariable which guarantees no change in cycle length, physically realizable ratio factor of low-Gd to high-Gd rod, the number of new Gd-bearing fuel assembly and total weight of gadolinia. Based on this approach, the initial loading pattern is developed for the reference loading pattern of APR1400 Cycle 1 minimizing the assembly-wise reactivity difference compared to the original assembly in terms of the infinite multiplication factor at the beginning of the cycle .

2.2 Fuel assembly optimization

There are various options to place Gd rods within a fuel assembly. Thus, rules are necessary to find the appropriate locations. First, Gd rods should be located around guide tubes since these locations rich in thermal neutrons and locating the Gd rods near the guide tube helps to flat power distribution. Second, Gd rods should not be located close to each other for the flat burnup distribution. The selection of Gd rod pattern affects the form factors and core peaking factors in the end. Thus, it is necessary to find the optimal pattern for the various numbers of Gd rods in an assembly. Optimization of Gd rod pattern is performed with geometrical weighting method to reduce the peaking factor in an assembly for various numbers of Gd rods [4]. Fig.1 shows the optimized assembly configurations with two types of Gd rods.

Since the number of fuel rod enrichments are restricted in practical standpoint of fabrication, it was not possible to preserve the assembly-wise reactivity for a low boron core to result in the increase of fuel rod enrichments compared to original loading pattern of APR1400 Cycle 1 to maintain the cycle length. Gadolinia contents in burnable absorber rods are 2 w/o and 8 w/o, with 2.7 w/o and 2.2 w/o U-235 enrichment, respectively. Two types of Gd-content is based on the reasoning that high-Gd rods show great self-shielding effects to give relatively reduced hold-down capability, while low-Gd rods show great hold-down power but depletes up rapidly. These two types of Gd rods in the same assembly complement each other to give moderate hold-down power lasting enough through the cycle. The numbers of Gd rods per assembly for low boron core are 4, 20 or 24. While all the assemblies with burnable absorbers in Ref. 2 contained both low-Gd and high-Gd rods, it was found that assemblies with single Gd content are required in this approach to control the core peaking factor. It has been judged that the assembly power changes caused by the relative reactivity change compared to the original loading pattern result in a significant increase in the core peaking factor. Therefore, new types of the assemblies were introduced, namely D0, E0, F0 and H0 to control the peak. Assemblies containing Gd rods for the low boron core are shown in Table 1.

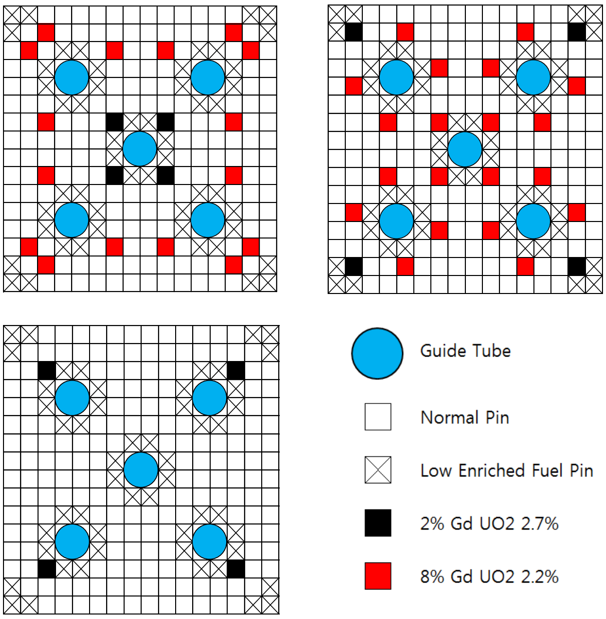

Fig . 1. Assembly Configurations

Table 1. Gd-bearing Fuel Assembly Data

Assembly Type	w/o U-235	Fuel Rods	Gd Rods	w/o Gd_2O_3
B1	3.20 2.70	164 52	4 16	2 8
B2	3.20 2.70	116 100	4 16	2 8
B3	3.20 2.70	160 52	4 20	2 8
C1	3.65 3.20	164 52	4 16	2 8
D0	3.20 2.70	180 52	4	2
E0	3.65 3.20	180 52	4	2
F0	3.20 2.70	164 52	20	8
H0	3.20 2.70	160 52	24	8

2.3 Loading pattern

The loading pattern for a low boron core design of APR1400 Cycle 1 has been developed using the assembly types of Section 2.2 according to the following criteria. The representative criteria & recommendations for APR1400 are as follows; Fxy ≤ 1.531, $MTC_{hfp,NoXe}$ ≤ 0 pcm/°F, shutdown margin (SDM) > 5.5 %Δρ. The loading pattern developed which satisfies general design criteria, is given in Fig. 2. Since H0 contains the strongest absorber, it is located in the inner side of the core to control the peak and maintain the soluble boron hold-down capability. 4 low-Gd rods assemblies such as D0, E0 is located in the periphery to control the peak until 2000 MTD/MTU unlike the original loading pattern which does not allow any gadolinia rods in the periphery assemblies.

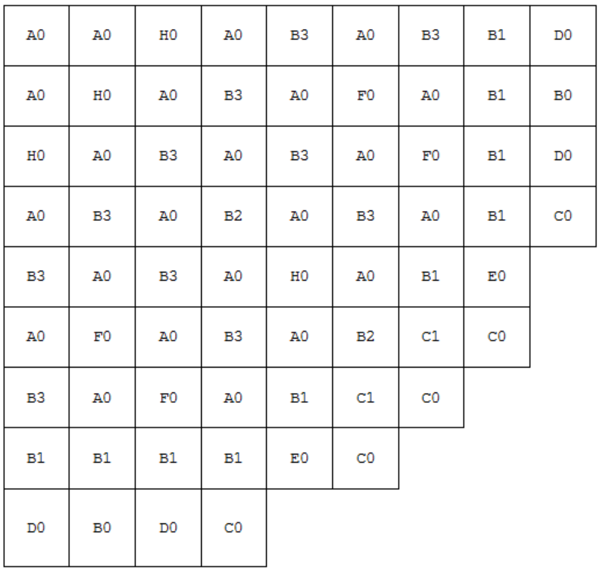

Fig. 2. Cycle 1 loading pattern for low boron core

3. Results

As shown in Table 2 and Fig. 3, the low boron core design has been achieved for APR1400 Cycle 1. The number of burnable absorbers are increased from 1680 (8w/o Gd) to 2592 (2160 (8 w/o Gd) + 432 (2 w/o Gd)). The core average enrichment is kept almost same. The amount of critical boron concentration (CBC) was reduced by 45.4% at BOC. More negative MTC was achieved which enhance plant safety. Especially, maximum best estimate MTC at HFP was reduced to less than -8 pcm/°F compared to the -4.7 pcm/°F of original loading pattern. The reduction of BE MTC would help greatly to relieve the consequence of anticipated transient without scram (ATWS) accident. Although the type of plant is different, in the NRC report, Westinghouse guarantees that RCS pressure does not exceed the 3200 psig when maximum MTC is less than -8 pcm/°F [5]. For the MTCs lower than this value, the core power increase could be effectively controlled by the moderator temperature feedback during ATWS.

Also, the minimum SDM of low boron core was improved compared to the reference case. The maximum plane-wise pin peaking factor is reduced significantly throughout cycle except at BOC as shown in Fig 4. It is almost similar to the reference case. The maximum core peaking factor is increased slightly but acceptable as shown in Fig. 4. Cycle length is reduced about 3 EFPDs which degrades the fuel cycle economy, however, cycle length could be adjusted by the slight increase in enrichment of all assemblies. The axial power shape behavior is compared in Fig. 5. Fig. 5 indicates that the degree of axial power shape change is distinctly different compared to the reference core. This fluctuation of axial power shape is due to the decreased MTC to result in more bottom skewed power shape at the beginning of cycle and this bottom shifted power shape results in more top skewed power shape in return due to reactivity balance effect caused by fuel depletion. However, the ASI remains within the limiting condition specified for plant operation.

It was possible to achieve low boron core sacrificing fuel cycle economy a little bit enhancing plant safety significantly. Also it was found that the low boron core might impose kind of operational difficulty. Generally, It is not necessary to add soluble boron during the steady-state operation for the conventional PWR as shown in typical boron letdown curve [7]. But, boration is necessary for the low boron core since the CBC continues to increase until 8000 MTD/MTU which is mainly caused by the fast burning of 2 w/o gd rods.

Table 2. Comparison of core parameters for APR1400 Cycle 1

	Low boron core	Reference core	Unit
CBC at BOC	433.7	794.9	ppm
Least negative $MTC_{hfp,NoXe}$	-3.096	-1.542	pcm/°F
Maximum best estimate $MTC_{hfp,EqXe}$	-8.062	-4.677	pcm/°F
Maximum pin peaking factor	1.438	1.435	-
Effective Full Power Day	470.1	473.5	EFPD
Minimum SDM at BOC	6.749	6.482	%Δρ
Minimum SDM at EOC	7.687	7.655	%Δρ

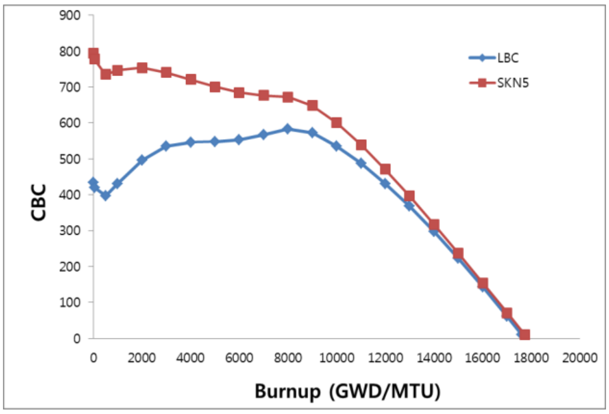

Fig . 3. CBC vs Burnup

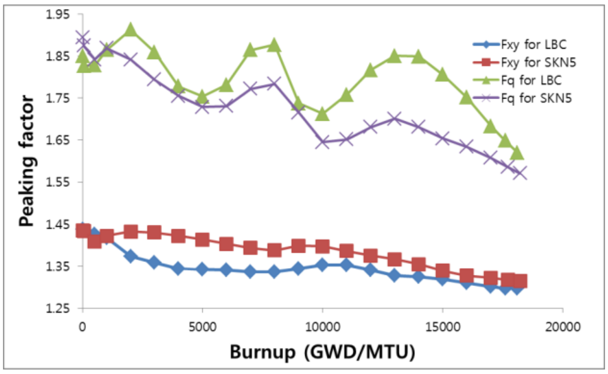

Fig. 4. Fxy, Fq comparison

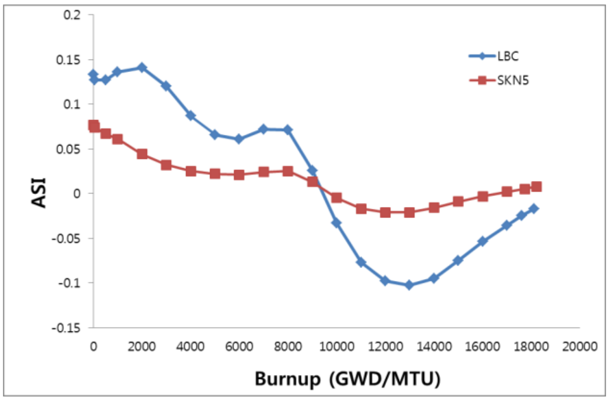

Fig. 5. ASI comparison

4. Conclusions

It was possible to achieve the low boron core for APR1400 Cycle 1 using extended usage of two types of gadolinia burnable absorbers sacrificing fuel cycle economy a little bit while enhancing plant safety significantly. Gd rod patterns within an assembly were optimized through geometrical weighting and loading pattern was developed based on these patterns. The amount of soluble boron reduction achieved is 45.4%. The improvement in plant safety is significant resulting in the reduction of least negative best-estimate MTC by about 4 pcm/°F. Also shutdown margin is increased slightly for low boron core. However, the behavior of axial power shape turns out to be undesirable showing a relatively large fluctuation caused by the more negative MTC.

It was found that the low boron core might impose kind of operational difficulty. It is usually not necessary to add soluble boron during the steady-state operation for the conventional PWR. But, boration is necessary for the low boron core. The efforts to maintain steady soluble boron will be attempted in the future study. Also the adjustment of axial BA placement to give a slight offset toward the bottom of the fuel will be performed in the next study. It is expected this will give more stable axial power behavior through depletion.

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