Application of the BigT Burnable Absorber to an OPR1000 Core for a Low Critical Boron Concentration

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1. Introduction

In PWRs, reducing the core operational dependency on soluble boron solves many of its associated economic and safety issues, such as the troublesome crud depositions and liquid radioactive waste accumulation, and more crucially the undesirable 'less negative' or even 'slightly positive' moderator temperature coefficient (MTC) at beginning of cycle (BOC). With a 'more negative' MTC at BOC, the core life and burnup can possibly be extended.

A new burnable absorber concept named "Burnable absorber-Integrated control rod Guide Thimble" (BigT) was recently proposed for the PWR core [1]. In this paper, the BigT absorber is loaded to an existing OPR1000 core, in place of the commercial gadolinia-bearing fuels (GBF) design. Preliminary lattice analyses of the BigT-loaded PLUS7 assemblies were first performed to characterize the BigT absorber against the conventional absorber technology. A 3-D BigT-loaded OPR1000 core analyses were performed next to assess technical feasibility of a lower boron OPR1000 core with the BigT absorbers. All neutronic calculations were completed using the continuous energy Monte Carlo SERPENT code [2] with ENDF/B-VII.0 library.

It should also be noted that this paper is a revision of the work previously published in the KNS Spring 2014 Meeting [3]. This paper updates a minor calculation error on the CBC calculation documented in Ref. 3.

2. Methods and Results

2.1 BigT: A New Burnable Absorber Concept

The BigT absorber requires slight modification to existing PWR fuel assembly in which outer or inner surfaces of the guide thimble is to be used for the burnable absorber material. Despite occupying the guide thimble, the BigT still allows insertion of control rods within the thimble. Furthermore, the BigT offers design flexibilities of the absorber geometries to enable applications for various operational specifications.

Fig. 1 depicts basic concept of the BigT-fAHR (fixed Azimuthal Heterogeneous Ring) with a B_4C absorber, while Table 1 tabulates parameters of the two BigT-fAHR designs simulated in this paper. One notes that since BigT-fAHR calls for expansion of inner surface of the guide thimble, size of the control rod (CR) should be smaller than conventional. Table 2 lists the new rod size required for the simulated BigT-fAHR designs, which were later used in subsequent lattice and core analyses.

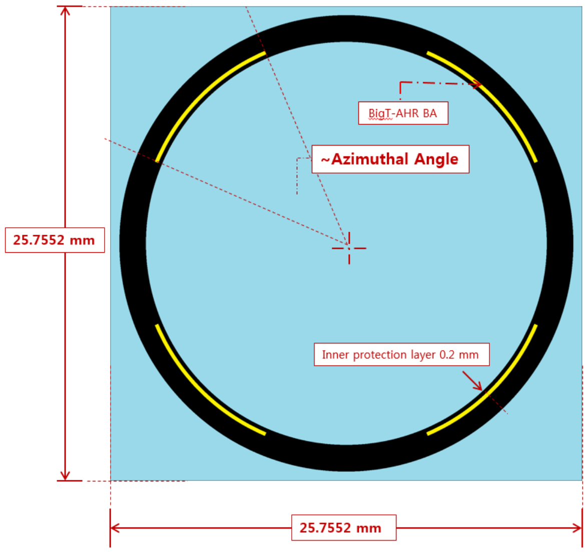

Fig. 1 BigT-fAHR for PLUS7 fuel assembly lattice

Table 1 Design Parameters of the BigT-fAHR Designs

Design Parameter	BigT-fAHR 1	BigT-fAHR 2
Azimuthal angle (°)	44	76
Thickness (cm)	0.0254	0.0231
Width (cm)	0.1375	0.2377

Table 2 Control Rod Parameters of PLUS7 Lattices

Parameter	Conventional Lattice	BigT-loaded Lattice
B_4C rod radius (cm)	0.93599	0.88967
Clad inner radius (cm)	0.94742	0.9011
Clad outer radius (cm)	1.03632	0.990

2.2 The BigT-Loaded PLUS7 Lattice Analyses

Single lattice depletion analyses were performed to characterize the BigT-fAHR listed in Table 1 against conventional gadolinium technologies. Figure 2 illustrates the PLUS7 assembly loaded with 4.5 w/o and 52 zones of 4.0 w/o fuels for a better local power peaking control. Meanwhile, Fig. 3 depicts reactivity depletion of the PLUS7 lattices loaded with the BigT-fAHR against the conventional GBF absorbers.

As shown in Fig. 3, initial reactivity hold-downs of the BigT-AHR are noticeably larger than those of the GBF designs. This additional suppression of excess reactivity at BOC can reduce CBC in the BigT-loaded core, which evidently is maximum at BOC. One notes inserting neutron absorbers around control rods, as it is in the BigT absorbers, would result in power shape distortion and control rod worth degradation.

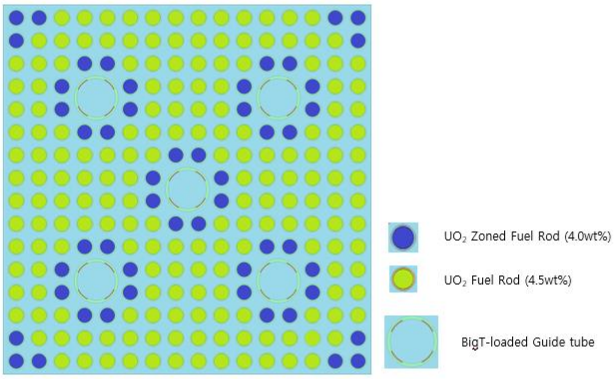

Fig. 2 Layout of the simulated BigT-loaded PLUS7 lattice.

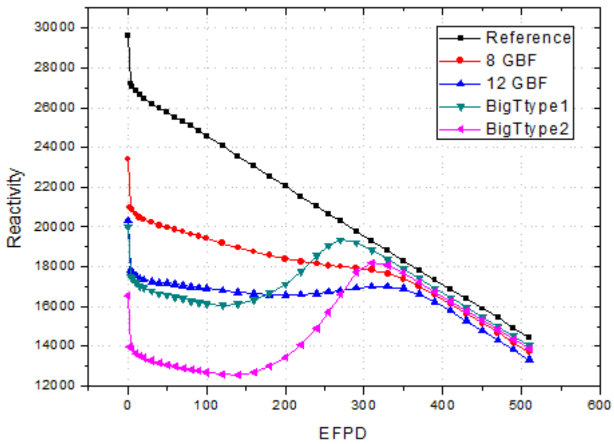

Fig. 3 Comparison of lattice reactivity change over burnup.

Table 3 tabulates power peaking factors of the BigT-loaded and the conventional GBF-loaded lattices. It is clear that the power peaking of the BigT-loaded lattice are lower than those of GBF-loaded fuel assembly.

Table 4 lists worth of natural B_4C control rods in the BigT-loaded assemblies against the no absorber lattice. Worth of the smaller control rod inserted in the BigT-loaded lattices are 10,739 pcm and 8,767 pcm, noticeably smaller than reference (17,284 pcm). These losses of control rod worth can, however, be easily recovered with enrichment of ^{10}B, if necessary [4].

Table 3 Power Peaking Factor of PLUS7 Lattices Loaded with Different Absorber Designs

Absorber Design	Power Peaking Factor		
	BOC	MOC	EOC
BigT-AHR 1	1.1020	1.0518	1.0547
BigT-AHR 2	1.1275	1.0443	1.0623
8 GBF	1.1037	1.10889	1.0737
12 GBF	1.1637	1.1079	1.0724

Table 4 Control Rod Worth of BigT-loaded PLUS7 Lattices

Lattice	Natural B_4C CR Worth [pcm]	
	0.936 cm Rod	0.890 cm Rod
BigT-fAHR 1	11,454	10,739
BigT-fAHR 2	9,318	8,767
Reference	17,284	-

2.3 The BigT-loaded OPR1000 Core Analyses

In this feasibility study of a low boron OPR1000 core, Hanbit Unit 3 Cycle 6 core [6] was selected as reference. Since 3-D whole core depletion requires very long computing time, the authors chose to simplify the reference core modeling as a quarter-symmetrical core with a single axial depletion zone. Figure 4 illustrates the simulated fuel loading and shuffling pattern for a 3-batch fuel management, which is consisted of 64 fresh, 64 once-burned and 49 twice-burned fuel assemblies. Of the 64 fresh assemblies, 24 were loaded with BigT-fAHR 1 in place of 8 GBF and another 24 with BigT-fAHR 2 in place of 12 GBF technology [5]. Equilibrium cycle of the simulated OPR1000 core was directly searched with repetitive Serpent depletions until convergence. Figure 5 shows reactivity depletion of equilibrium cores and its corresponding CBC (critical born concentration). Figure 6 meanwhile depicts the normalized assembly-wise power distributions of the BigT-loaded OPR1000 core at BOC, MOC and EOC.

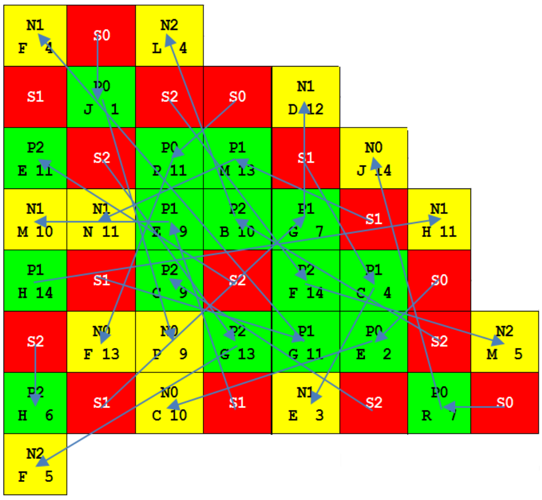

Fig. 4 Fuel loading and shuffling pattern of the BigT-loaded OPR1000 core (fresh=red, once-burned=green, twice-burned=yellow)

From Fig. 5, maximum CBC of the BigT-loaded OPR1000 at HFP (Hot Full Power) and equilibrium Xe condition was 1,364 pcm, lower than reference (1,475 ppm). Boron worth at BOC, HFP and equilibrium Xe condition was 7.36 pcm/ppm, slightly higher than typical (7.14 pcm/ppm) but still acceptable [6]. At EOC, core excess reactivity was 325 pcm, higher than typical (100 pcm).

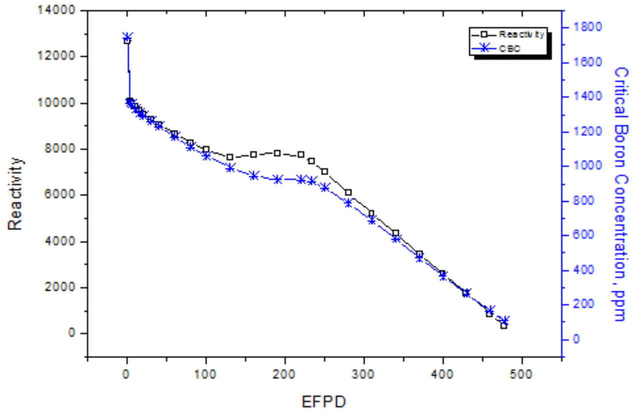

Fig. 5 Reactivity depletion of the equilibrium BigT-loaded OPR1000 core and its corresponding CBC.

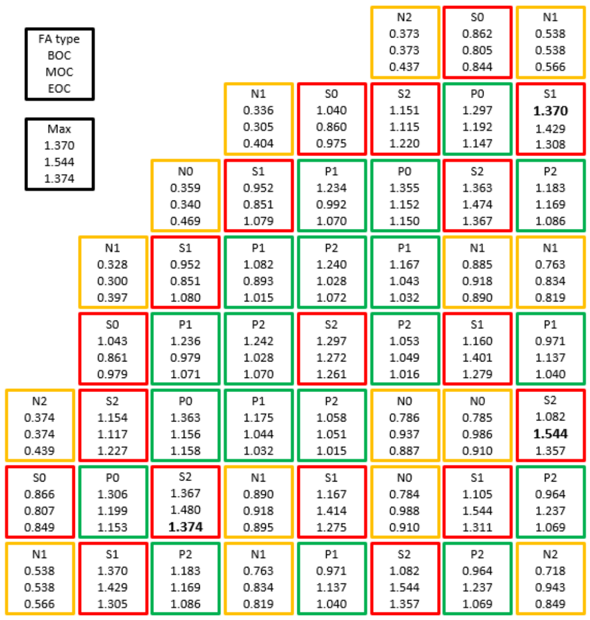

Fig. 6 Normalized assembly-wise power distribution of the BigT-loaded OPR1000 equilibrium core at different burnups.

Spatial power peaking factor, F_q, of the core was evaluated as follows [6]:

$$F_q = F_{xy} \times F_z \times PF(lattice) \quad (1)$$

For conservatism, maximum axial power peaking factor, F_z, is taken from reference (1.212 at BOC). The limiting spatial peaking factor, F_q, at full power was then 2.504 [5].

Table 5 lists important neutronic parameters of the equilibrium BigT-loaded OPR1000 core in comparison with reference at HFP equilibrium Xe condition.

It is worthwhile to note that the BigT-loaded OPR1000 core can be operated 8 EFPD longer than reference. This is mainly due to the removal of the GBF using a low-enriched U from the core. Interestingly, the control rod worth was calculated to be slightly smaller than the reference core, and surprisingly the N-1 worth of the BigT-loaded core is quite similar to the reference value. This is because the N-1 rod worth depends strongly on core power distribution and the burned fuel assemblies are not loaded with any BigTs. Spatial peaking factor F_q of the BigT-loaded core are also acceptable, albeit slightly higher than reference. Shutdown margin was 6,704 pcm, smaller than reference. Nevertheless, this shutdown margin is acceptable since it is still bigger than typical requirement (5,500 pcm) [6].

Table 5 Neutronic Parameters of the BigT-loaded OPR1000 Core against Reference at HFP, Equilibrium Xe condition

Item	Reference	BigT-Core
Cycle length [days]	470	478
Max. CBC [ppm]	1,475	1,364
Total CR worth [pcm]	15,836	13,490
N-1 CR worth [pcm]	9,100	9,315
Fq value	1.802 (BOC)	1.830 (BOC)
	1.686 (MOC)	1.954 (MOC)
	1.602 (EOC)	1.769 (EOC)
Shutdown Margin	7,700	6,704
MTC (HFP)	-12.8	-19.89
MTC (HZP)	+3.1	-4.30

MTC at BOC-HFP and equilibrium Xe condition of the BigT-loaded OPR1000 core was -19.89 pcm/K, clearly 'more negative' than reference (-12.8 pcm/K). MTC at HZP of the BigT-loaded OPR1000 core was about -4.3 pcm/K, again 'more negative' than reference (+3.1 pcm/K). In summary, the safety concern about 'less negative' or 'slight positive' MTC of a PWR core can be largely allayed with the application of BigT absorbers.

3. Conclusions

This paper presents a preliminary investigation of a low boron PWR core with the BigT absorbers. It is found that application of the BigT absorbers in a commercial OPR1000 core may reduce the maximum CBC by about 100 ppm, and thereby extending core cycle length by about 8 EFPDs. Power peaking factors of the BigT-loaded OPR1000 core are also acceptable, and can be further improved with optimized loading patterns. The BigT-loaded OPR1000 core also has acceptable shutdown margin, which can be easily enhanced with enriched boron, if necessary. More importantly, MTC of the BigT-loaded OPR1000 core at HFP and HZP conditions at BOC stay 'more negative' than reference. It is safely concluded that a low boron PWR core is technically feasible with the BigT absorbers.

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