Preliminary Investigation of the Soluble Boron Free AP1000 Core with the BigT Burnable Absorber

Mohd-Syukri Yahya[a], Yonghee Kim[a]*, and HyeongHeon Kim[b]
[a]*Department of Nuclear & Quantum Engineering, KAIST, Daejeon, Republic of Korea*
[b]*KEPCO Engineering & Construction Company (KEPCO E&C), Daejeon, Republic of Korea*
**Corresponding author: yongheekim@kaist.ac.kr*

1. Introduction

A soluble boron-free (SBF) Pressurized Water Reactor (PWR) has been pursued for a long time since it can simplify the nuclear power plant design, improve corrosion resistance of the structural materials, and drastically reduce the liquid radioactive waste. The pursuit of an SBF PWR is unfortunately still fruitless due to the challenging difficulties in managing the excess reactivity in the SBF core with current commercial technologies, without sacrificing safety and performances of the core. Quite recently, however, a new burnable absorber concept for PWR was proposed [1-2]. The new PWR absorber design, named "Burnable absorber-Integrated control rod Guide Thimble" (BigT), is conceptually-replaceable and flexible such that various loading patterns and core management objectives, including that of an SBF PWR, can sufficiently be met. It is upon this motivation that this paper was prepared. In this paper, the BigT burnable absorber (BA) is applied to an AP1000 core for a preliminary evaluation of a BigT-loaded SBF AP1000 core [3]. All neutronic analyses were performed using Monte Carlo Serpent code with ENDF/B-VII.0 library [4].

2. The BigT Design Concept

This work mainly focuses on BigT-AHR (Azimuthally-Heterogeneous Ring) design illustrated in Figure 1, which also depicts how 24 of the BigT-AHRs are loaded into the 17x17 AP1000 fuel assembly lattice.

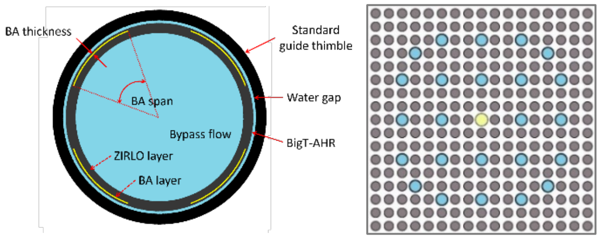


Fig. 1. (left) BigT-AHR absorber and (right) BigT-loaded 17x17 AP1000 fuel assembly lattice.

The BigT-AHR is in essence a separate ring component with an embedded azimuthally-heterogeneous BA layer, loaded in a standard guide thimble. Azimuthal length and thickness of the BA layer dictates its self-shielding behavior and eventual lattice reactivity management. In contrast to other thimble-occupying PWR BA concepts, the BigT still allows insertion of control rods into the guide thimble. Size of the control rod should, however, be made a little smaller, thereby significantly reducing its worth. Nevertheless, it has been shown in Ref. 1 and 2 that this loss of control rod worth can easily be recovered by replacing the Ag-In-Cd with a natural, or if necessary enriched, B_4C control rod.

3. Description of the Model AP1000 Core

A model AP1000 core is considered in this preliminary investigation of an SBF PWR design. A 3-batch fuel management consisting of 52 fresh, 52 once-burned, 52 twice-burned and 1 once-used center fuel assemblies, as shown in Figure 2, was assumed. A simple low-leakage in-out loading pattern was simulated with a cycle length of 490 efpds (effective full power days). Uranium enrichments of the fresh and once-used center assemblies were 5.0% and 2.75% respectively.

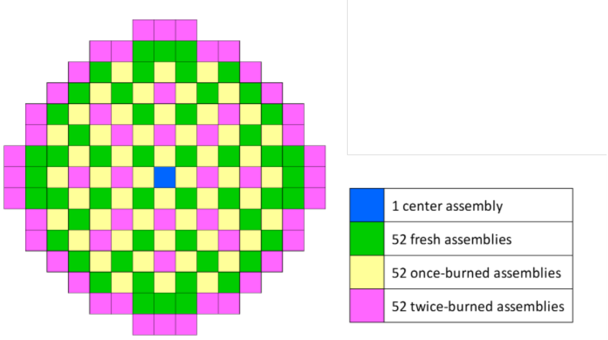


Fig. 2. Loading pattern of the simulated BigT-loaded AP1000 core.

Table 1 tabulates the BigT-AHR designs for the respective fuel assemblies to account for their different isotopic compositions. B_4C absorbers were used for all fuel assemblies. Single-lattice reactivity depletions of the three-batch fuel management are depicted in Figure 3, which clearly illustrates the reactivity control strategy for the SBF core: burnup reactivity swing in each batch should properly be minimized.

It should also be noted that the batch-wise power densities depicted in Fig. 3 are uneven to account for the imbalanced power sharing of the fuel batches in the actual core; i.e. fresh and once-burned assemblies have generally higher power densities than that of the twice-burned assemblies due to higher fissile compositions and fewer fission products. These loading factors disparity significantly affect performances of the BigT designs.

Table I. BigT-AHR designs for the SBF AP1000 Core

Fresh Assembly	**Once-Burned Assembly**	**Twice-Burned Assembly**	**Center Assembly**
B_4C absorber, thick 0.16 mm, span 45°	B_4C absorber, thick 0.28 mm, span 25°	B4C absorber, thick 0.02 mm, span 88°	B_4C absorber, thick 0.40 mm, span 18°
Loading factor = 1.33	Loading factor = 1.12	Loading factor = 0.54	Loading factor = 1.28

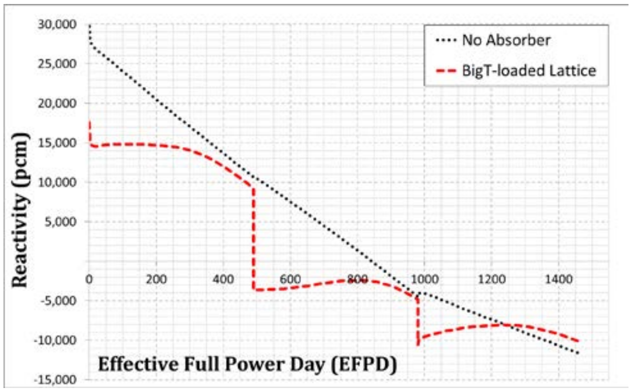


Fig. 3. Batch-wise lattice reactivity control via the BigT-AHR absorbers in a 3-batch fuel management.

4. Preliminary Core Analysis

An equilibrium cycle of the AP1000 core was directly searched through repetitive Serpent depletion calculations until convergence. Due to the limited memory size of the computer used in this work, average isotopic composition was used for each fuel batch. Figure 4 shows reactivity change of two equilibrium AP1000 cores while Figure 5 depicts the normalized assembly-wise power profile of AP1000 BigT set 2. The Big sets 1 and 2 are only different in that the AP1000 BigT set 2 was loaded with 10% more B_4C in the fresh fuel batch. Figure 4 clearly indicates the burnup reactivity swing over the cycle of AP1000 BigT set 2 is only ~2,400 pcm, while EOC core reactivity is slightly positive (+40 pcm).

For a successful design of an SBF core, the burnup reactivity swing should be small, e.g. < 1,000 pcm. In this regard, the BigT-based AP1000 core is quite promising. It is clear that the reactivity swing of AP1000 BigT set 1 (3,000 pcm) can be reduced with loading a bit more BA in the fresh assemblies as in the AP1000 BigT set 2 (2,400 pcm). Future optimization shall be pursued in this direction to further minimize the burnup reactivity swing; i.e. balancing BA load in the 3-batch fuel management. It should also be noted that the small upward swing in mid-cycle of the BigT set 2 could be traced to the similarly noticeable upward swing in the once- and twice-burned assemblies depicted in Figure 3. This upward swing can be easily flattened with an optimized BigT BA angle for the BigT designs. The design optimization is, however, quite complicated due to the power sharing disparity of the fuel batches. Coupled with the low-leakage loading pattern adopted, removal of BA from twice-burned assemblies will increase their average power density. This will in turn slightly enhance core leakage, thereby reducing core reactivity. Bigger BA loading in twice-burned assemblies will, conversely, reduce neutron leakage, resulting in higher core reactivity should the residual reactivity is sufficiently small. One the other hand, loading more BAs in fresh assemblies will reduce its power sharing, altering performance of the corresponding BigT. Similar but weaker impact will be observed for once-burned assemblies. All these possibly complicate optimization of the SBF AP1000 core.

The radial power distribution shown in Figure 5 also suggests that the neutron leakage is quite small and the power peaking is rather high. This high power peaking should also be accounted for in future optimizations. Cycle length can also be shortened to increase the EOC reactivity, if necessary.

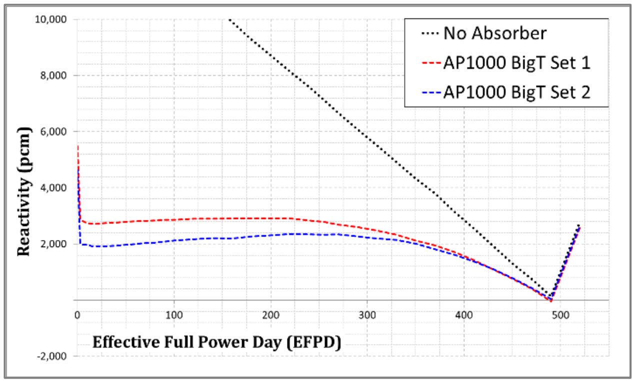
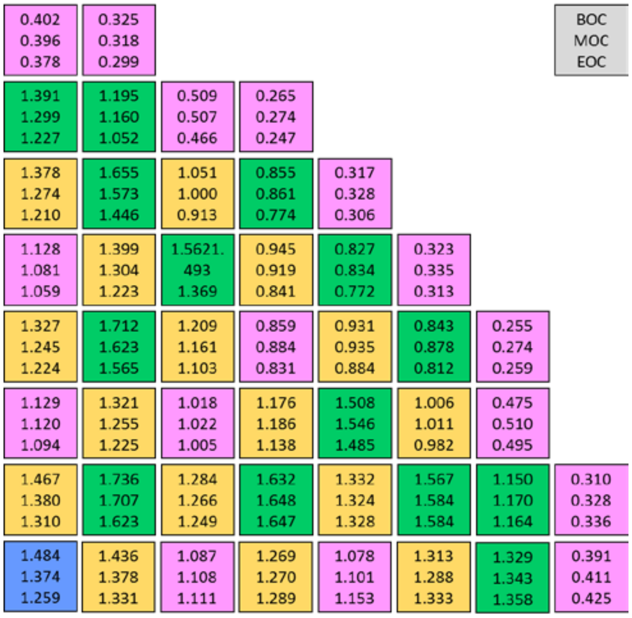


Fig. 4. Reactivity change during the equilibrium cycle.



0.402 0.396 0.378	0.325 0.318 0.299						BOC MOC EOC
1.391 1.299 1.227	1.195 1.160 1.052	0.509 0.507 0.466	0.265 0.274 0.247				
1.378 1.274 1.210	1.655 1.573 1.446	1.051 1.000 0.913	0.855 0.861 0.774	0.317 0.328 0.306			
1.128 1.081 1.059	1.399 1.304 1.223	1.5621. 493 1.369	0.945 0.919 0.841	0.827 0.834 0.772	0.323 0.335 0.313		
1.327 1.245 1.224	1.712 1.623 1.565	1.209 1.161 1.103	0.859 0.884 0.831	0.931 0.935 0.884	0.843 0.878 0.812	0.255 0.274 0.259	
1.129 1.120 1.094	1.321 1.255 1.225	1.018 1.022 1.005	1.176 1.186 1.138	1.508 1.546 1.485	1.006 1.011 0.982	0.475 0.510 0.495	
1.467 1.380 1.310	1.736 1.707 1.623	1.284 1.266 1.249	1.632 1.648 1.647	1.332 1.324 1.328	1.567 1.584 1.584	1.150 1.170 1.164	0.310 0.328 0.336
1.484 1.374 1.259	1.436 1.378 1.331	1.087 1.108 1.111	1.269 1.270 1.289	1.078 1.101 1.153	1.313 1.288 1.333	1.329 1.343 1.358	0.391 0.411 0.425

Fig. 5. Assembly power distribution at equilibrium cycle of AP1000 BigT Set 2 core.

5. Conclusions and Future Works

The paper investigates potential application of the BigT absorbers in an SBF AP1000 core. Preliminary core analyses imply a promising solution to realizing a soluble boron-free (SBF) PWR with the BigT absorbers. It was demonstrated that the burnup reactivity swing in the 3-batch core can be about 2,400 pcm for 490 efpds by using the BigT absorbers only. Further refinements on the BigT designs and core loading pattern are required to optimize the SBF AP1000 core. Important neutronic parameters such as rod worth and shutdown margin will have to be evaluated in future works.

REFERENCES

[1] M.S. Yahya, Y. Kim, C.K. Chung, “A Novel Burnable Absorber Concept for PWR: BigT (Burnable Absorber-Integrated Guide Thimble)”, Transaction of the Korean Nuclear Society Spring Meeting, Korea (2014).

[2] M.S. Yahya, H.Y. Yu, Y. Kim, “A Burnable Absorber-Integrated Guide Thimble for PWR”, Transaction of the American Nuclear Society vol. 110, USA (2014).

[3] Westinghouse AP1000 Design Control Document Rev. 19, Westinghouse Electric, USA (2011).

[4] J. Leppänen, Serpent – A Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code, VTT Technical Research Centre of Finland, Finland (2012).