Nuclear Science and Technology Symposium - NST2016
Helsinki, Finland, 2-3 November 2016

Reactivity Control of a Soluble-Boron-Free AP1000 Equilibrium Cycle

Mohd-Syukri Yahya, Yonghee Kim*
Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, 34141 Daejeon, South Korea.
syukri@kaist.ac.kr, yongheekim@kaist.ac.kr
*corresponding author

ABSTRACT

This paper describes the results of a preliminary design study to assess the neutronic feasibility of a commercial-sized PWR core which does not use soluble-boron for reactivity control. The study specifically investigates performance of BigT absorbers and IFBA rods as the main reactivity control system in a soluble-boron-free (SBF) AP1000 equilibrium cycle. The BigT absorbers are loaded batch-wise in this design. The analyses clearly demonstrate a promising SBF PWR design as burnup reactivity swing over the equilibrium cycle is reasonably small (~1,850 pcm). Fairly consistent albeit high radial power peaks (<2.0) are also obtained throughout the cycle. All calculations were completed using the Monte Carlo Serpent code with ENDF/B-VII.0 library.

1 INTRODUCTION

Elimination of soluble-boron reactivity control from PWRs offers a number of significant improvements. Firstly, it eliminates the risk of boric acid-induced corrosion of pressure vessels, bolting and other critical components as a result of primary system leaks. Secondly, it possibly simplifies the plant design, operation and maintenance. Thirdly, it potentially reduces radioactive waste volumes and water processing requirement. Fourthly, it maintains a consistently large negative moderator temperature coefficient (MTC) at all times.

It is generally accepted that the feasibility of an SBF PWR improves significantly as its core power (hence core size) is reduced [1]. In addition, safe cold shutdown is known to be very challenging without soluble-boron, even for a small-sized core [2]. Nonetheless, a new approach for an SBF PWR core was recently proposed [3]. This paper aims to extend the said investigation by optimizing performance of the BigT-loaded SBF AP1000 equilibrium core. AP1000 [4] was selected for it is the first Gen III+ reactor to receive the final design approval from USNRC. The equilibrium core was chosen since most of a reactor's lifetime is comprised of such cycles. All calculations were completed using the Monte Carlo Serpent [5] code with ENDF/B-VII.0 library.

2 ALTERNATIVE CONTROL

There is currently no successful large SBF PWR. This is mainly because commercial burnable absorber (BA) technologies are fairly limited and inflexible in terms of the core excess reactivity management. A novel BA concept named "Burnable absorber Integrated Guide Thimble" (BigT) was thus proposed, which by design possibly offers the much desired BA neutronic flexibilities needed to realize the SBF PWR operation.

2.1 BigT Absorber

Aptly named, the BigT absorber loads BA materials in spaces surrounding the standard PWR guide thimble. Figure 1 illustrates one such variant of the BigT concept, which is a ring embedded with azimuthally heterogeneous BAs. The BigT is conceptually replaceable and permits insertion of control rod in its thimble. More importantly, it is neutronically flexible since thickness and span of its BA (which dictate its spatial self-shielding and, thus, neutronic characteristics) can easily be adjusted per operational specifications. The BigT has previously been demonstrated to perform relatively well against commercial BA technologies, especially in terms of reactivity control, power management and control rod worth [3].

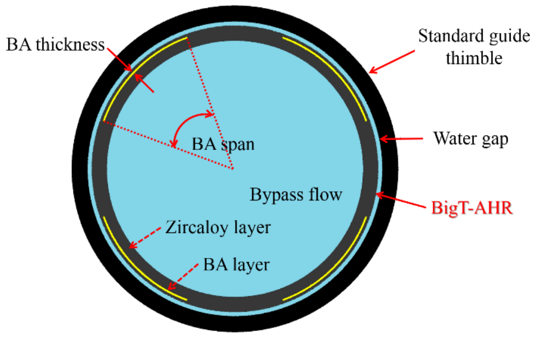

Figure 1: Design concept of the BigT absorber.

2.2 BigT- and IFBA-loaded Assembly

In this research, B_4C-based BigT is loaded into a 112 IFBA-rodded fuel assembly as shown in Figure 2. Boron content in the IFBA rod modelled in this work was set at 0.617 mg/cm.

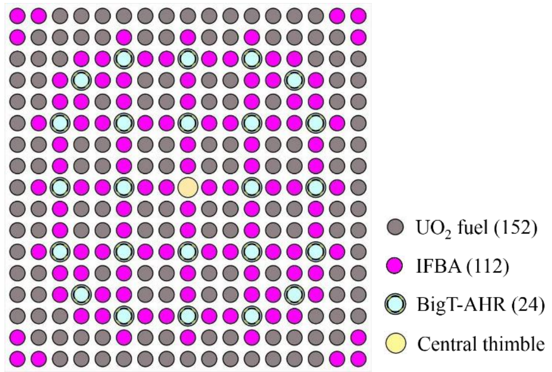

Figure 2: BigT- and IFBA-loaded fuel assembly.

Figure 3 shows depletion patterns of the BigT- and IFBA-loaded assemblies. It is clear that the BigTs increase BOC reactivity suppression in the 112 IFBA-rodded fuel assembly, from k-inf ~1.2 to ~1.1. This reactivity suppression can easily be enhanced by loading more B_4C in the BigT design. Furthermore, assembly depletion characteristics can also be modified by changing the B_4C thickness and span in the BigT absorbers.

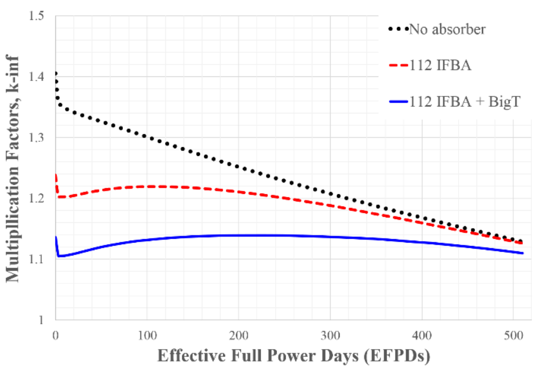

Figure 3: Burnup-dependent reactivity of the BigT- and IFBA-loaded fuel assembly.

3 SBF PWR CORE

Objective of this study is to define a conceptual equilibrium core design of an SBF PWR, which was based on Westinghouse's AP1000 [4]. Rated power of the reactor is 3,400 MWth. Fresh fuel assemblies are 4.95-w/o UO_2 of 95.5% theoretical density. A total of 157 fuel assemblies are loaded into the core as depicted in Figure 4. BigTs containing 0.25 mm thick and 30˚ wide B_4C pads are installed in the fresh and once-burned assemblies. Simulated cycle length is 490 EFPDs.

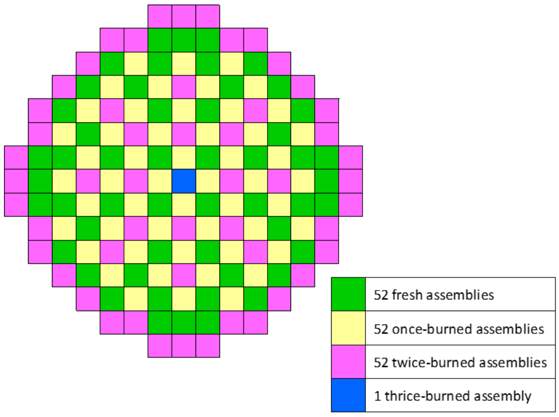

Figure 4: The model AP1000 equilibrium core.

3.1 Reactivity Control

Equilibrium cycle of the core was searched via repetitive depletion calculations until convergence as depicted in Figure 5. 500 active and 100 inactive cycles, with 1,000,000 particles per cycle, were simulated to assure sufficient convergence with standard deviations of the reactor eigenvalues about ±5 pcm. Six vertical stacks (including top and bottom BigT cutbacks) of core-averaged temperatures were modeled in this scoping study, with an assumption that there is no significant axial effect which would invalidate general conclusions of the simulations.

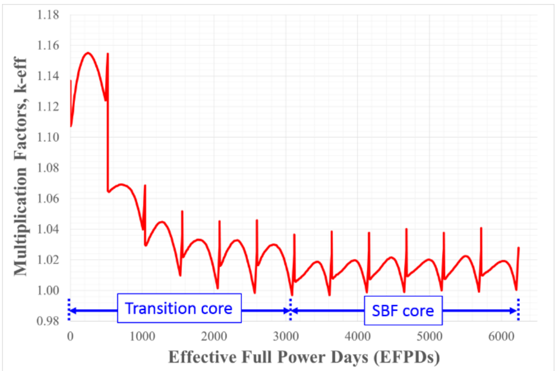

Figure 5: The search for the SBF AP1000 equilibrium cycle.

Figure 6 depicts the burnup-dependent core reactivity depletion pattern over the equilibrium cycle. Burnup reactivity swing (BRS) over the cycle is ~1,850 pcm. Though the targeted BRS for a successful SBF PWR is actually <1,000 pcm [1], this design is still quite promising.

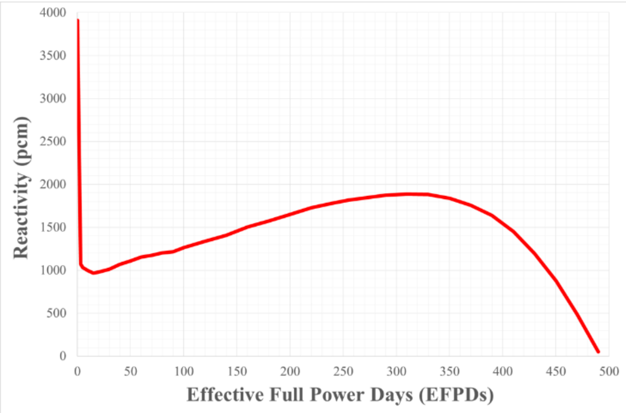

Figure 6. Reactivity depletion over equilibrium cycle of the SBF AP1000 core.

3.2 Power Distribution Management

Figure 7 shows normalized assembly power profile of the core at different burnup. The figure clearly illustrates a low leakage pattern as relatively low power loading occurs at the core periphery. This loading pattern is, albeit not optimized, quite practical. One also notes the assembly radial power peaks moves from the inner core (1.704) at BOC to the core sub-periphery at EOC (1.595).

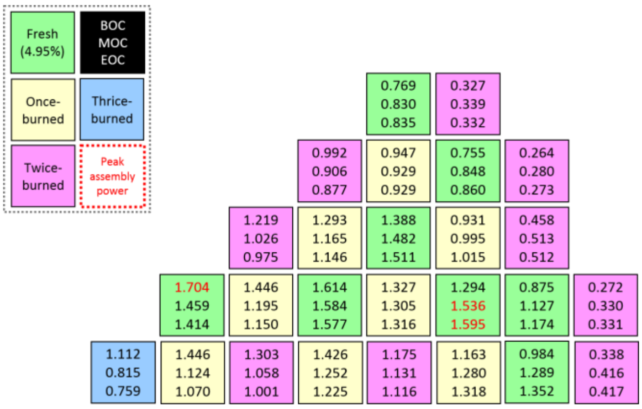

Figure 7. Normalized radial assembly power profile of 1/8th of the equilibrium SBF AP1000 core.

4 CONCLUSIONS

Removal of soluble-boron in a PWR offers many significant improvements, chiefly in the simplification of core design and operation, elimination of boric acid-induced corrosion and reduction of liquid radioactive waste volumes. This research aims to assess the neutronic feasibility of an SBF AP1000 equilibrium core with batch-wise BigT absorbers. The analyses imply a promising solution to the SBF PWR operation, as burnup reactivity swing over the equilibrium cycle is quite small (~1,850 pcm). Besides, fairly consistent albeit high radial power peaks are attained with the proposed design. This research is, however, far from complete. Further BigT optimization is needed, as well as quantifications of other core neutronic parameters, to fully assess technical feasibility of the design.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (20131610101850)

REFERENCES

[1] Electrical Power Research Institute, “Elimination of Soluble Boron for a New PWR Design”, EPRI NP-6536, 1989.

[2] J.J. Ingremeau, M. Cordiez, “Flexblue Core Design: Optimisation of Fuel Poisoning for a Soluble Boron Free Core with Full or Half Core Refuelling”, ICAPP, Nice, France, 2015.

[3] Mohd Syukri Yahya, “A New Approach for a High-Performance Soluble-Boron-Free PWR Core”, KAIST PhD Dissertation, 2016.

[4] Westinghouse Electric Corp., “Public version of AP1000 Design Control Document rev. 19”, APP-GW-GL-702, 2011.

[5] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta, T. Kaltiaisenaho. "The Serpent Monte Carlo code: Status, development and applications in 2013." Ann. Nucl. Energy, 82 (2015) 142-150.