Preliminary Evaluation of Centrally Shielded Disk-Type Burnable Absorber in Three-Batch Soluble-Boron-Free APR1400 Reactor

Husam Khalefih, Xuan Ha Nguyen, and Yonghee Kim †
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea
Corresponding author: yongheekim@kaist.ac.kr

1. Introduction

APR1400 is a 1400 MWe pressurized water reactor that has been developed by KEPCO/KHNP to meet the new market demand for large-size nuclear power plants [1]. In this study, we investigate the applicability of the newly developed centrally shielded burnable absorber (CSBA) [2] in designing a soluble-boron-free (SBF) APR1400 reactor core with 3-batch fuel management.

CSBA is introduced to eliminate the soluble boron that is used to control the excess reactivity in the conventional PWRs since it poses a few detrimental issues such as the possible positive moderator temperature coefficient (MTC) at the beginning of cycle (BOC) at the hot zero power (HZP) condition in addition to the problems related to radioactive waste production and its effects on the cladding and other structural material [2]. It has been demonstrated that the CSBA can be very successfully utilized in designing an SBF small modular reactor [3]. Also, a very-low-boron APR1400 core was proposed with the CSBA application for 2-batch long-cycle fuel management [4].

Unlike the previous application of the CSBA to the APR1400 core, this study aims to achieve an SBF APR1400 core based on the popular three-batch fuel management scheme. As a result, the CSBA should be burned quite faster than in the 2-batch very-low-boron core to maintain a small excess reactivity over an 18-month cycle operation. To evaluate the feasibility of a CSBA-loaded SBF APR1400 with 3-batch fuel management, an equilibrium cycle is determined for an identical fuel loading and shuffling scheme. In this work, the equilibrium cycle is directly searched through repetitive simulations of cycle-wise depletions from an all-fresh core condition.

All the neutronic analyses including the burn-up calculations of the reactor core have been performed using the Monte Carlo SERPENT 2 code and the ENDF/B-VII.1 data library [5]

2. CSBA Design

The centrally shielded burnable absorber is designed to be placed at the central region of the fuel pellet to adjust the self-shielding of fast-depleting burnable absorber such as Gd. The gadolinia (Gd_2O_3) is a widely used BA in Light Water Reactors (LWRs) due to its well-proven characteristics and behavior in terms of the chemical and neutronic stability. Gd_2O_3 is usually admixed with UO_2 fuel due to its high compatibility with the ceramic fuel. In the commercial APR1400 design, a few fuel enrichments with Gd_2O_3 zoning is utilized to control the power profiles and reduce the power peaking in both axial and radial directions. [6]

Considering its high absorption cross-section, the self-shielding effect plays a very important role in determining the depletion rate of Gd_2O_3 and so the core reactivity changes. The integral BA can be loaded only in a fresh fuel assembly and will reside there for a few consecutive operational cycles depending on the fuel management. Therefore, self-shielding of BA shall be optimized so that the Gd_2O_3 should completely burn at the end of cycle (EOC) of the first residential cycle and the residual BA should be minimized in the following cycle. In this work, the popular 3-batch fuel management is considered to maximize fuel burnup. In a 3-batch core design, the BA should be relatively quickly burned to compensate for reactivity reduction due to the once- and twice-burned fuel assemblies in the core.

In the CSBA, self-shielding is controlled by adjusting the surface area to volume ratio of BA in the fuel pellet. Unlike the previous CSBA applications for one- or two-batch cores using ball-type CSBAs, a cylindrical CSBA is used in this work for a 3-batch APR1400 core since the BA should burn quite quickly.

For a given volume of BA, its self-shielding is enhanced by decreasing the surface area. Figure 1 shows the surface area as a function of the height-to-diameter ratio for a fixed volume of a cylinder. It is very clear that the self-shielding can be effectively controlled by adjusting the H/D ratio. In general, radius should be increased if a faster depletion is requested for a cylindrical CSBA.

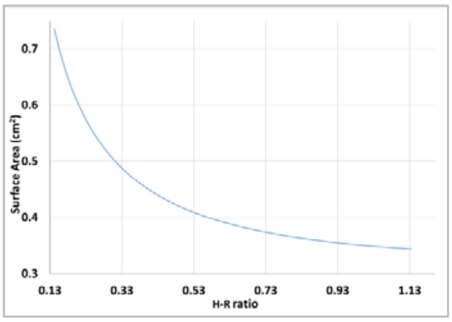

Fig.1. Surface area vs. height-to-diameter ratio for a cylinder of a fixed volume.

In order to devise proper CSBA designs for a 3-batch APR1400, various lattice analyses have been performed for the 16x16 FA using a single Uranium enrichment of 4.95 w/o. It was found that 4~10 disk-type CSBAs are requested in a single pellet to achieve a fast depletion rate for an SBF APR1400 using 3-batch fuel management. Figure 2 shows the fuel pellet encompassing 10 cylindrical CSBA disks inside. It is mentioned that the number of disks can be reduced to 4 by increasing its radius. CSBA disks are placed in equidistance from each other along the whole fuel rod. In this work, the density of CSBA is assumed to be 99% of the theoretical density of gadolinia.

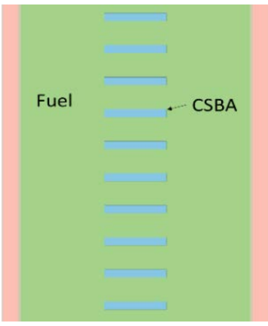

Fig. 2. Fuel pellet with 10 cylindrical CSBA disks.

To design an SBF ARP1400 core based on 3-batch fuel management with a fuel enrichment of 4.95 w/o, the CSBA-loaded fresh fuel assemblies should hold down a huge amount of excess reactivity and the BA should quickly burn to minimize the excess reactivity during a cycle and the residual BA should be minimized at EOC. FA optimization studies were first done with the Monte Carlo Serpent 2 to devise proper CSBA for the 3-batch APR1400 core and the results are summarized in Fig. 3, where the disk-type CSBA is compared with a ball-type one, too. One million histories, 250 active, and 100 inactive cycles were used in these lattice simulations to get uncertainty in the reactivity estimation of less than 10 pcm.

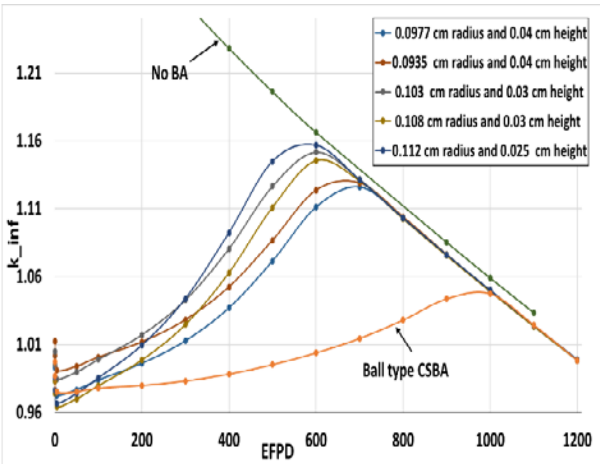

Fig. 3. Fuel assembly depletions with CSBA designs

As shown in Fig. 3, it is very clear that the ball-type CSBA depletes too slow to be used in the 3-batch core with a cycle length of ~500 EFPDs (Effective Full-Power Days). One can also note that the depletion rate of the disk-type CSBA is much faster due to the enlarged surface area and is strongly dependent on the H/D ratio of the CSBA design, and an appropriate depletion speed can be obtained when the H/D ratio is about 0.1824. Figure 3 also clearly indicates that small the residual BA, or penalty due to the BA, is noticeable in the SBF core even when the gadolina burned out rather completely. However, it should be noticed that the SBF core provides much more beneficial than the conventional as discussed previously in Refs. 3 and 4.

As a preliminary study, ten disks per pellet have been selected in the current study, but the total number of disks can also be reduced to minimize the manufacturing complexity and costs, which will be done in future works.

3. Full Core Model and Monte Carlo Analysis

The APR1400 core has been modeled using the Serpent 2 Monte Carlo code. The 3D Serpent model for APR1400 includes the baffle, reflector, and vessel. The APR1400 core consists of 241 16x16-fuel assemblies, and each fuel assembly contains five guide tubes that are used for control rod or in-core instrumentations [6]. Table 1 provides the major design parameters used in the Serpent model. In the current APR1400 core, a single fuel enrichment of 4.95 w/o is adopted to maximize the cycle length and density of the CSBA Gd_2O_2 is assumed 99% Theoretical Density (TD).

Table 1. Major design parameters of APR1400

Parameter	Value
Fuel pin height	381 cm
Pin pitch	1.28776 cm
Fuel pellet radius	0.40958 cm
Fuel enrichment	4.95 w/o
Fuel density	10.4668 g/cc
Clad inner/outer radius	0.4187/0.4760 cm
Clad material	Zircaloy-4
Cutback height	15 cm each
Cutback region enrichment	3.5 w/o
Zone I CSBA thickness	0.0219 cm
Zone I CSBA radius	0.12 cm
Zone II CSBA thickness	0.0109 cm
Zone II CSBA radius	0.12 cm
Number of CSBA/pellet	10
Gd_2O_3 density	7.332 g/cc

Fig. 4 shows the full core Serpent model, where the reactor core has been divided into nine regions axially. In the inactive top and bottom regions, a burnable absorber-free cutback region has been placed to obtain a reasonable axial power profile and minimize the residual BA inventory due to the low flux in the boundary layers. The fuel enrichment in the cutback region has also been reduced to 3.5 w/o, for the best utilization of nuclear material. For accurate modeling of the self-shielding, the fuel pellet and the CSBA disk are divided into two and three depletion zones in the radial direction, respectively. It is mentioned that the axial reflector regions are rather simplified in this study.

For an accurate estimation of burnup in each fuel assembly and to enhance the shuffling plan, each fuel assembly has been modeled separately, leading to a total number of depletion cells around 9400 in the whole core.

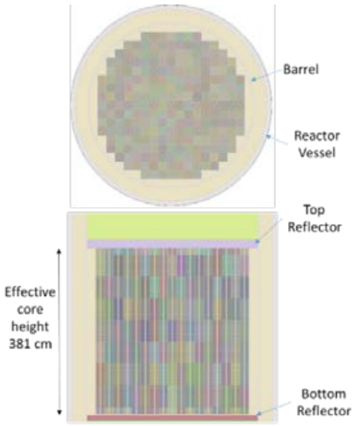

Fig.4. APR1400 core Serpent model

For a reasonable estimation of the k_{eff} values and power distribution with the Monte Carlo Serpent code, 500,000 neutron histories are used in each Monte Carlo cycle and 250 active cycles are considered with 100 inactive cycles in this preliminary work. Consequently, the standard deviation of the k_{eff} values are less than 10 pcm. For this kind of scoping analysis, a rather coarse time step of 100 EFPDs has been utilized, and the Xe equilibrium option has been considered to reduce the simulation time, in which an equilibrium Xe concentration is assumed from the BOC.

4. Results and Discussion

In this study, we investigated many loading patterns, to maximize fuel utilization and get the optimal fuel cycle length. The major requirement to reach an optimal loading pattern is to reduce the neutron leakage with acceptable power peaking, and the twice-burned fuel assemblies are largely placed in the peripheral region. In an SBF APR1400, such a loading pattern will result in a relatively large neutron leakage at the BOC due to the heavy loading of BA in the fresh fuel assemblies. Actually, the relatively high BOC leakage is favorable in that it reduces the excess reactivity in the early depletion period. During the depletion of the core, the radial neutron leakage gradually decreases and remains rather unchanged after the MOC (middle of cycle) condition.

For simplicity, we try to propose an SBF 3-batch fuel management scheme in the APR1400 without any zoning in terms of fuel enrichment. However, it is still necessary to utilize a different BA mass loading to make the power profile as flat as possible and reduce the residual BA in each successive cycle. Fig.5 shows the proposed loading pattern in a quarter core of APR1400. One can see that fresh fuel assemblies are scattered in the interior region, while many of the twice-burned fuel assemblies are placed on the peripheral regions facing the reflector. Due to the odd number of core fuel assemblies, the number of discharged fuel assemblies in two consecutive fuel cycles will not be the same, and then we will have two equilibrium cycles. To achieve a single equilibrium cycle, 81 fuel assemblies are discharged in each cycle and 81 fresh fuel assemblies are loaded, and the center fuel assembly is replaced each time by a fresh one. Taking into account the power profile and fuel utilization, a lower enrichment of 3.5 w/o is used for the particular center fuel assembly.

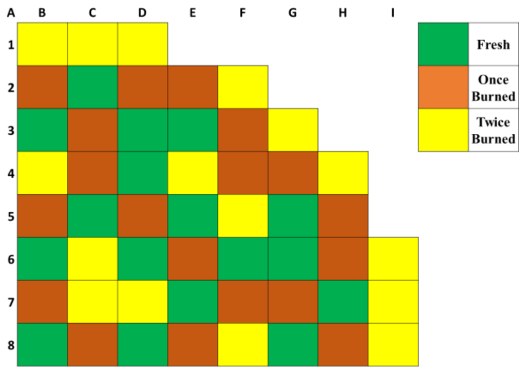

Fig.5. Loading pattern of the CSBA-loaded APR1400

To reduce the power peaking and flatten the radial power profile, two different zones are considered in terms of BA loading mass. Basically, more CSBA is loaded in the inner core region (zone I), while less BA is utilized in the low-power peripheral region (zone II) and the center FA to minimize the residual BA mass at EOC. Typically, 50% of the BA mass in zone I is used in zone II. The simulations showed that this combination of BA zoning is quite necessary to reduce the power peaking and minimize the residual BA. For the 3-batch fuel loading pattern in Fig. 5, fuel shuffling scheme was determined to achieve a reasonable power and burnup profiles in the whole core. And repetitive Serpent depletion analysis was performed to determine an equilibrium cycle for the SBF APR1400 core. Fig. 6 shows the reactivity evolution during the equilibrium cycle with a cycle length of 490 EFPDs.

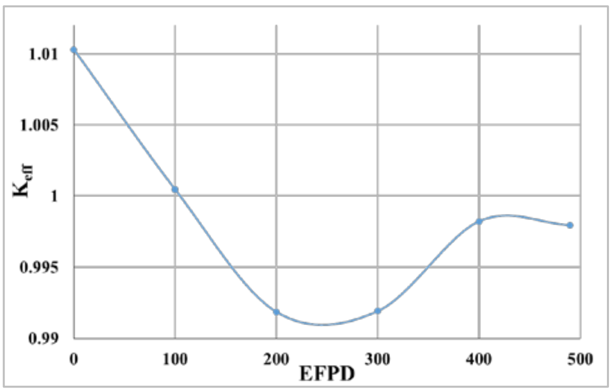

Fig.6. k_{eff} change during the equilibrium cycle

Fig. 6 shows the evolution of reactivity during the equiliburm cycle operation. It is clear that the excess reactivity at BOC is only about 1,000 pcm and the EOC excess is quite close to zero. However, the reactivity becomes negative in the middle of depletion, indicating that the CSBA design should be further modified and optimized to achieve a practical equilibrium core in an SBF APR1400 core. The reactivity behavior in Fig. 6 means that the depletion rate of CSBA is not high enough in the early depletion period of the equilibrium cycle.

Radial power profiles for the equilibrium core are provided in Fig. 7 for BOC, MOC, and EOC. The power peaking is 1.62, 1.48, and 1.35 at BOC, MOC, and EOC, respectively. The relatively low power peaking indicates that the current 3-batch loading pattern and fuel shuffling scheme are rather acceptable. It is expected that the power peaking values can be noticeably reduced by improving the CSBA design and the fuel management schemes for the 3-batch core.

1.2 1.2 1.5	1.3 1.1 1.2	1.3 1.2 1.4	1.4 1.1 1.1	1.2 0.9 0.9	1.1 1.2 1.3	1.0 1.1 1.0	0.4 0.5 0.4
1.4 1.1 1.2	1.1 0.8 0.8	1.1 0.9 0.9	1.3 1.2 1.5	1.4 1.2 1.1	1.3 1.2 1.2	1.0 1.3 1.2	0.4 0.5 0.4
1.4 1.2 1.4	1.2 0.9 1.0	1.3 1.2 1.5	1.4 1.2 1.3	1.2 1.3 1.6	1.0 1.3 1.5	0.8 1.0 0.9	0.3 0.4 0.3
1.6 1.1 1.1	1.5 1.3 1.5	1.6 1.2 1.3	1.2 1.2 1.5	0.9 0.9 0.9	0.9 1.3 1.3	0.6 0.7 0.6	
1.3 1.0 0.9	1.6 1.2 1.1	1.3 1.4 1.6	1.1 1.0 1.0	1.0 1.0 0.9	0.8 0.8 0.7	0.3 0.3 0.3	
1.2 1.3 1.3	1.4 1.3 1.1	1.1 1.3 1.4	1.0 1.3 1.3	0.8 0.8 0.6	0.3 0.4 0.3		
1.1 1.2 0.9	1.0 1.4 1.1	0.8 1.0 0.8	0.6 0.8 0.6	0.3 0.3 0.3			BoC MoC EoC
0.5 0.6 0.4	0.4 0.5 0.4	0.3 0.4 0.3					

Fig. 7. Radial power profile for the equilibrium cycle

Fig. 8 shows the axial power distributions at BOC, MOC, and EOC for the SBF equilibrium APR1400 core, and the axial power peaking is 1.23, 1.3, and 1.44, respectively. One observes that the BOC axial power is rather well balanced, while the MOC and EOC are relatively more skewed due to the CSBA depletion.

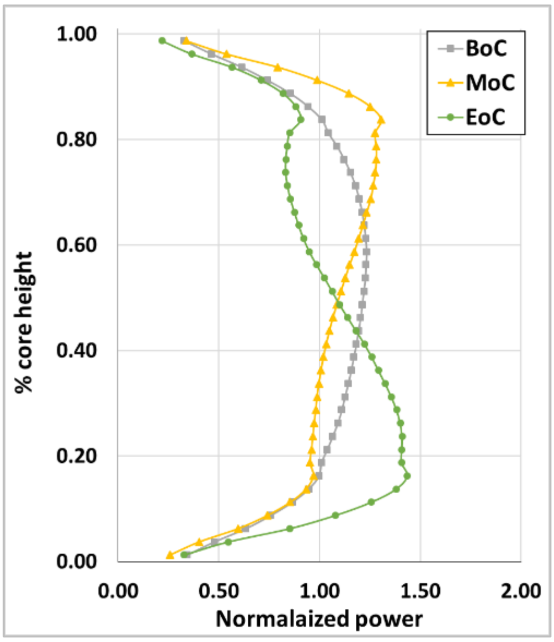

Fig. 8. Axial power profile for the equilibrium cycle

5. Conclusions and Future Works

A preliminary analysis has been performed to evaluate the feasibility of CSBA-based soluble-boron-free APR1400 core with 3-batch fuel management. The current study clearly demonstrates the potential advantage of using the CSBA to achieve a soluble-boron-free APR1400 reactor in view of the reactivity control and power shapes although the CSBA design should be modified for a realistic core design.

In order to design a more practical SBF APR1400 core, future works are necessary for optimization of the CSBA designs and fuel assembly loading pattern and associated 3-batch fuel shuffling to minimize the reactivity swing and the power peaking in the equilibrium core.

ACKNOWLEDGMENTS

This research was supported by the KUSTAR-KAIST Institute, KAIST, Korea and the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (NRF-2016R1A5A1013919).

REFERENCES

[1] IAEA Status report 83 – "Advanced Power Reactor 1400 MWe (APR1400)".

[2] Deshon, Jeff; Hussey, Dennis; Kendrick, Brian; McGurk, John; Secker, Jeff; Short, Michael, "Pressurized water reactor fuel crud and corrosion modeling, the journal of the Minerals", Metals & Materials Society, JOM, Vol. 63 (8), pp.64-72, August 2011.

[3] X. H. Nguyen, C. Kim, and Y. Kim, "An advanced core design for a soluble-boron-free small modular reactor ATOM with centrally-shielded burnable absorber", Nuclear Engineering and Technology, Vol. 51 (2), 2019, Pp. 369-376.

[4] M. Do, X. H. Nguyen, S. Jang, and Y. Kim, “Physics study for high-performance and very-low-boron APR1400 core with 24-month cycle length”, Nuclear Engineering and Technology, Vol. 52 (5), 2020, Pp. 869-877
[5] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta, and T. Kaltiaisenaho, "The Serpent Monte Carlo code: status, development and applications in 2013", Annals of Nuclear Energy, vol. 82, pp. 142-150, 2015.
[6] APR1400 Design Control Document Tier 2, APR1400-K-X-FS-14002-NP, REVISION 0, DECEMBER 2014