Feasibility Study of a Two-Batch Soluble-Boron-Free APR-1400 Reactor

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1. Introduction

Advanced Power Reactor (APR1400) is a conventional Pressurized Water Reactor (PWR) that was designed and built by KEPCO-KHNP, its rated thermal power is 3983 MW [1]. The soluble Boron is utilized as a mean of reactivity control, conventionally the Boron-10 is used as a burnable absorber to compensate for the excess reactivity from the Beginning of Cycle (BOC), by controlling the concentration of the boron in the core, the criticality can be maintained all through the operation cycle. Traditionally the soluble boron is considered as an effective way for reactivity control since no action by Control Rods (CR) is needed. This way the CRs can be fully withdrawn so the axial power peaking will be reasonable. Besides, the local power peaking is adequately maintained as a result of coolant density distribution with axial temperature [2].

Nevertheless, there are many disadvantages related to the usage of the soluble boron, such as the possible positive Moderator Temperature Coefficient (MTC) at Beginning of Cycle (BOC) Hot Full Power (HFP) condition, which is a great safety concern for both, reactor designers, and regulatory bodies. Another operational concern related to the usage of soluble boron is material corrosion and degradation, there have been many recent studies on the effect of soluble boron on the cladding and other structure materials, which in turn is considered as a major safety-related problem [3].

There are other operational issues related to the soluble boron such as the huge amount of liquid radiowaste generation, as a result of boron (B-10) interaction with neutrons Tritium (H-3) is generated, another major source of tritium is Lithium-neutron interaction, LiOH is added to the coolant to compensate the pH number decrease due to boric acid injection. tritium is considered a serious radiation hazard, and a substantial source of worker's radiation exposure, especially during the refueling process, as a result of a 1,000 Mwth PWR operation 80% of the tritium generation comes from boron and lithium irradiation [4].

In this study, the applicability and feasibility of a two-batch Soluble Boron Free (SBF) APR1400 reactor will be investigated using an innovative new type of 3D Burnable Absorbers (BA) so-called Centrally-Shielded Burnable Absorber (CSBA), and Burnable Absorber Integrated Guide Thimble (BigT) [5][6]. In the CSBA, a solid neutron absorber is placed at the center of the fuel pellet, this way the burnable absorber will be integrated with the nuclear fuel, and it will be introduced into the reactor core with the fresh fuel assemblies in each cycle. The location of the burnable absorber in the center of the fuel pellet provides a local neutron shield due to the large effect of nuclear fuel self-shielding, this way the rate of burnable absorber depletion can be effectively controlled. On the other hand, APR1400 has 5 large guide thimbles in each fuel assemblies that are used for Control Rod (CR) insertion and instrumentation, these holes will be utilized for the BigT, another type of BA material will be coated at the inner surface of these guide thimbles. A combination of these two methods supposed to provide a favorable reactivity control throughout the cycle with a minimum reactivity penalty as will be described later on.

It worth mentioning that all of the neutronic analyses and simulations were done using Monte Carlo code, SERPENT 2, assessed with the nuclear data library ENDF/B-VII.1. [7]

2. CSBA and BigT design

When designing a burnable absorber device a few stuff shall be taken into consideration, first the material of the burnable absorber that shall be used, in the typical PWR’s the Gadolinium (Gd) is widely used by admixing it with the fuel material in different concentrations for the same purpose, which is excess reactivity control and to reduce the amount of soluble boron needed. So that, a large amount of data is available on that particular material, making it the best candidate burnable absorber.

Secondly, it should be on the perception that this burnable absorber will be loaded only with the fresh fuel assemblies at the BOC, so that the rate of burnable absorber depletion shall be optimized such that it shall remain active all over the operation cycle, for that a fine adjustment of the surface area of the CSBA shall be considered.

In this study, a SBF APR1400 using ball shape CSBA will be designed. A previous study was done on a very low concentration soluble boron APR1400 using the spherical shape CSBA, but reaching a completely SBF APR1400 reactor is an even challenging task that requires a more fixable design [8]. And here comes the importance of introducing the BigT as a secondary burnable absorber, for the simplicity of fuel manufacturing procedure, a single ball CSBA will be utilized in our SBF APR1400 fuel design. Figure 1 shows the CSBA configuration inside a single fuel pellet. The CSBA ball center will be placed at the centerline of each fuel pellet in the middle.

The Gadolinium oxide (Gd_3O_2) will be used as BA material for the CSBA since it is located at the center of the fuel pellet where the maximum fuel temperature exists, a ceramic material with high melting temperature is preferable to prevent any meltdown, which will affect the geometry of the absorber, and then the reactivity in the core might be changed.

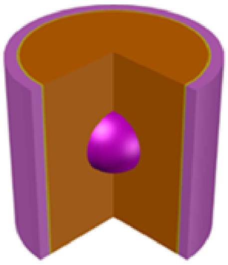

Figure 1 CSBA configuration.

The Boron Carbide (B_4C) will be utilized as BA in the BigT design, as a result of (B-10,n) interaction, tritium and helium are produced, and these isotopes have a negligible absorption cross-section which in turn helps in reducing the reactivity penalty at the EOC.

On the other hand, the absorption cross-section of Gd-156, Gd-158, and Gd-160 is still noticeable and some other high absorption cross-section isotopes such as Eu and Sm might be produced as a result of neutron interactions. Figure 2 shows the BigT configuration, to minimize the BigT thickness, 90 % enriched B-10 will be utilized instead of the natural B_4C, while the depletion rate of the B-10 can be controlled by adjusting the span angle, for a faster depletion rate a bigger span angle shall be used to increase the surface area.

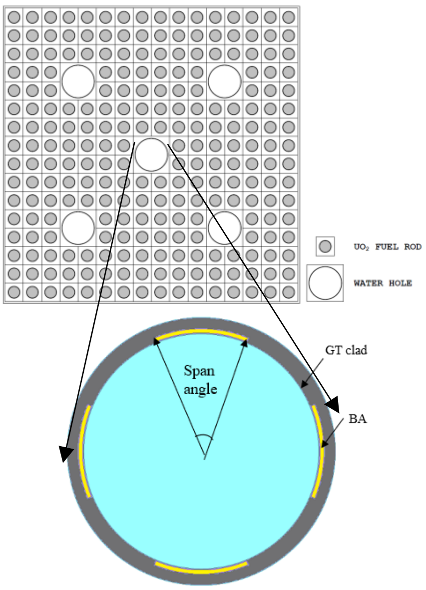

Figure 2 APR1400 fuel assembly configuration and the schematic diagram for the BigT that will be loaded into the 16x16 APR1400 fuel assembly.

Since the self-shielding of a one-ball CSBA is very high, a monotonically decreasing reactivity is observed in one ball CSBA only, while in the case of BigT, since it is located at the GT region in which the neutron flux is highly thermalized, the initial reactivity will be much lower and the depletion rate is higher. Figure 3 shows the effect of each BA loading on the reactivity from the lattice calculations. From figure 3 it can be concluded that a fast depletion rate of the BigT is needed to minimize the BA residuals at the EOC and to reduce the reactivity penalty as a result of the slow depletion for the CSBA, which in turn can be obtained by controlling the span angle.

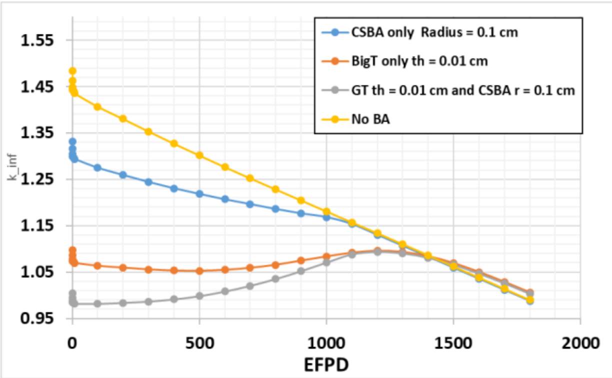

Figure 3 The effect of CSBA and BigT loading on the reactivity.

Figure 4 shows the effect of angle selection on the depletion rate from the lattice calculations. It can be noticed that the larger the span angle the faster the depletion rate so that to obtain the desired depletion rate an isotropic BA loading in the GT will be used by selecting 90 degrees as span angle.

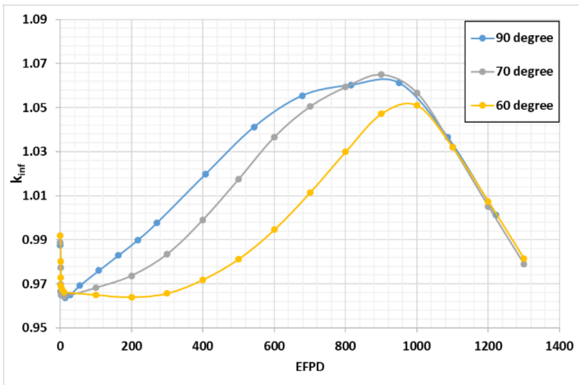

Figure 4 The effect of span angle on the depletion rate of the BigT for the same initial reactivity.

3. Full core Model

To estimate the actual core behavior, a full APR-1400 core has been modeled using SERPENT 2 code. The model includes 241, 16x16-type fuel assemblies, a top and bottom cutback regions of 14 cm thickness will be placed in each fuel pin to minimize the axial power peaking, 3.5 w/o enrichment will be used in the cutback region.

To increase the cycle length the water radial reflector has been replaced by Stainless Steel heavy reflector. Table 1 summarizes the parameters used for serpent simulations, for accurate estimation of the output, one million histories were used with 250 active cycles and 100 inactive. Figure 5 shows the full core model used in the calculations, the nuclear fuel management plan was introduced as well.

To minimize the dependency on the control rods for reactivity control a 1,000 pcm is set as a targeted reactivity swing, to achieve this target a large amount of BA shall be introduced into the core, but it should be guaranteed that almost all of the BA will be depleted by the EOC to minimize the reactivity penalty.

Table 1 Design parameters.

Parameter	Value
Thermal Power (MW_{th})	3983
Number of fuel assemblies	241
Pins per assembly	236
Fuel type (Enrichment w/°)	UO_2 (4.95)
Active core height (cm)	381
Cutback thickness (cm)	14
Cycle length (EFPD)	630
Moderator/Fuel temp (K°)	575/900
Gd_2O_3/B_4C density (g/cc)	7.035/2.27

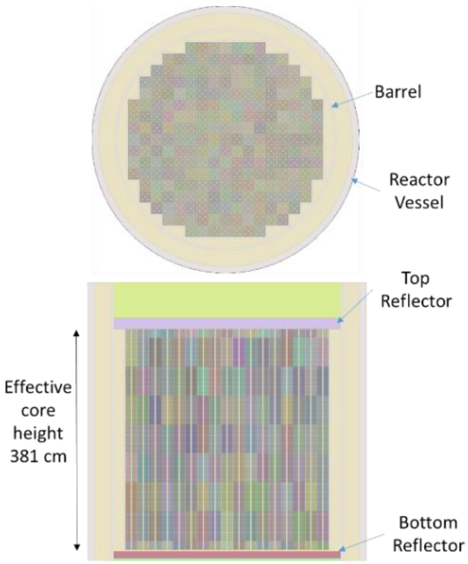

Figure 5 APR1400 full core model.

In typical PWRs, different fuel enrichment and, complicated loading pattern of fuel assemblies is used to reduce the power peaking in the reactor core and flatten the radial power profile, in this study, a simpler fuel assemblies' configuration will be used, particularly a uniform fuel enrichment of 4.95 w/o will be used. In that case, the power peaking at the core central FAs will be higher than that in the peripheral ones, so that the depletion rate of the Gd and B-10 will be varying within the reactor core, to flatten the power profile and guarantee a uniform BA depletion rate, different zoning in terms of BA loading is introduced.

The reactor core was divided into 4 zones radially, the first zone contains the maximum BA loading and it will be assigned to zone 1, while a smaller amount of BA (smaller CSBA radius and BigT thickness) will be used in zone 2, and even smaller amount if zone 3. Figure 6 shows the fuel assemblies loading pattern and shuffling scheme, with the BA volume reduction zones 2, and 3 about zone 1.

To achieve a single equilibrium cycle, the central FA (A9) will be treated separately, it will be replaced every cycle with a fresh one, for effective utilization of the nuclear material, a 3.5 w/o enrichment will be used in this region and the BA dimensions in zone 3 will be used for that FA.

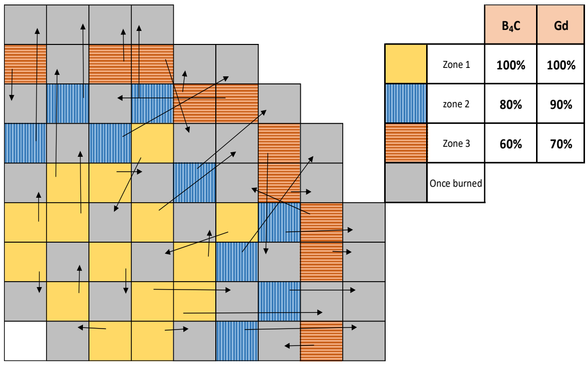

Figure 6 Designed Load pattern and shuffling scheme.

Due to BA loading in the GT region, the intra-assembly power peaking will be high, the existence of BigT will result in a higher power for the outermost fuel pins in the assembly, and even higher power for the corner fuel pins as a result of the intra-assembly gap, so the zoning is required again inside the assembly to minimize the local power peaking. Figure 7 shows the adopted intra-assembly zoning scheme, in which a bigger radius CSBA ball will be placed in the outermost fuel pins and an even bigger one for the 3 corner pins. Table 2 summarizes the BA dimensions used in the SBF APR1400.

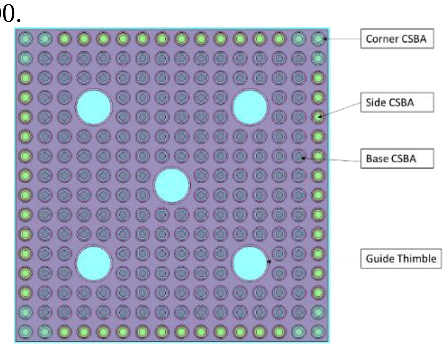

Figure 7 Intra - assembly zoning for the 16X16 SBF APR1400 fuel assembly.

Table 1 BA design in each radial region.

Zone #	B_4C	Gd	Base CSBA radius (cm)	Side CSBA radius (cm)	Corner CSBA radius (cm)	BigT thickness (cm)	Span angle
1	100%	100%	0.1300	0.1454	0.1700	0.0050	90.0
2	80%	90%	0.1255	0.1404	0.1641	0.0040	90.0
3	60%	70%	0.1154	0.1291	0.1509	0.0030	90.0

4. Results and Discussion

Figure 8 shows the reactivity behavior at the equilibrium cycle for a SBF APR1400, it was noticed that the equilibrium cycle is oscillating between two states, in odd and even cycles, and that's mainly due to the heavily loaded core with BA, and the weak self-shielding for the BA material in the BigT, since the axial power starts with cosine shape that makes the BA depletion at the center of the core faster than the top and bottom parts, and since the BA is depleting faster in that region, which will increase the neutron population in that region, that situation will increase the power further, as a result, the fuel will be more depleted in the central region compared to both ends, then in the next cycle the power peaking will be shifted forming a saddle shape, such a power distribution oscillation will cause a reactivity variation.

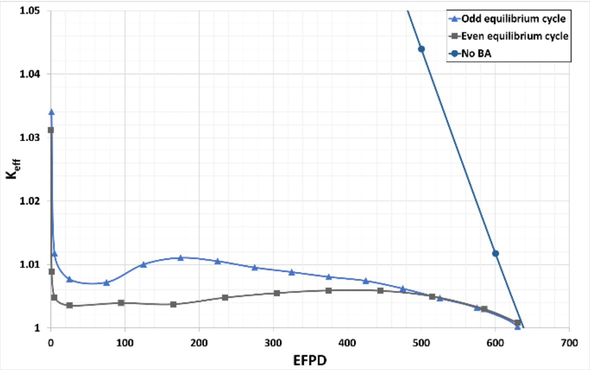

Figure 8 Burnup-dependent k_{eff} for a SBF APR1400 core.

Figure 9 shows the axial power comparison between odd and even equilibrium cycles with an Axial Offset Anomaly (AOA) equal to 1.05%, -5.02%, and 0.64% for the even cycles and 9.57%, -0.28%, and -0.5% for odd cycles BOC, MOC, and EOC axial power profile receptively.

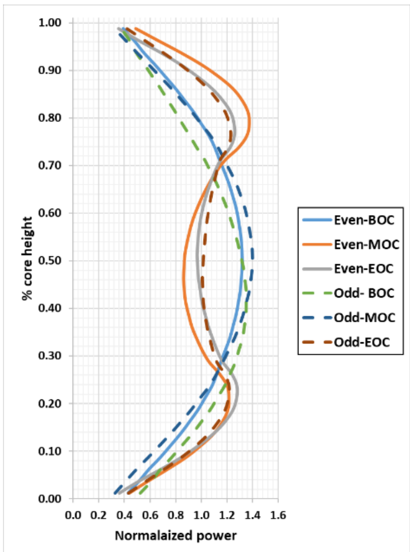

Figure 9 Odd and even equilibrium cycles axial power profile.

The radial power profile is not affected by the axial power oscillation, Figure 10 shows the radial power distribution in which the maximum power peaking is 1.4,1.49, and 1.57 at BOC, MOC, and EOC respectively.

The average discharge burnup is found to be 45.4 GWD/MTU, while the maximum discharge BU is 54.53 GWD/MTU, meanwhile the minimum discharge BU is 39.44 GWD/MTU except for the center FA.

It worth mentioning that the reactivity penalty in the SBF APR1400 as a result of CSBA introduction is very small, comparing to no BA case a shorter cycle length less than 10 EFPDs was found given that Gadolinia is also added to the APR1400 reactor, so it can be assumed that the effect on the reactor operation economy is very small.

0.75	0.74	0.68	0.49					
0.58	0.58	0.58	0.47					
0.42	0.42	0.46	0.40					
1.17	1.09	1.07	0.90	0.70	0.47			
1.07	0.92	1.06	0.97	0.67	0.46			
0.86	0.70	0.95	0.95	0.60	0.40			
1.27	1.21	1.21	1.05	1.05	0.89	0.54		BOC
1.05	1.22	1.09	1.15	1.10	0.88	0.50		MOC
0.86	1.11	0.96	1.21	1.07	0.82	0.43		EOC
1.13	1.11	1.08	1.06	1.23	1.12	0.90	0.50	
1.25	1.11	1.22	1.15	1.04	0.94	0.88	0.46	
1.27	1.04	1.35	1.28	0.90	0.77	0.83	0.40	
0.95	0.92	0.96	1.06	1.19	1.24	1.08	0.74	
1.08	1.11	1.11	1.03	1.19	1.05	1.11	0.68	
1.18	1.44	1.39	1.01	1.19	0.90	1.08	0.61	
0.81	0.85	0.93	1.00	1.08	1.10	1.09	0.96	0.54
1.07	1.07	0.98	1.10	1.05	1.18	1.18	1.00	0.49
1.54	1.49	1.08	1.28	1.03	1.29	1.22	0.95	0.40
0.82	0.86	0.89	0.94	0.99	1.14	1.28	1.15	0.75
1.12	1.07	1.10	1.00	1.16	1.27	1.16	1.13	0.61
1.48	1.19	1.39	1.09	1.41	1.36	0.96	0.95	0.46
0.85	0.84	0.87	0.88	0.98	1.19	1.30	1.19	0.82
1.15	1.19	1.11	1.12	1.18	1.18	1.31	0.99	0.62
1.17	1.42	1.21	1.50	1.45	1.05	1.10	0.69	0.42
0.79	0.86	0.84	0.86	1.03	1.24	1.40	1.30	0.85
1.26	1.18	1.17	1.14	1.16	1.36	1.15	1.17	0.64
1.32	1.18	1.51	1.57	1.19	1.27	0.85	0.85	0.41

Figure 10 Radial power profile.

5. Conclusion

An SBF APR1400 reactor core was designed with a reactivity swing around 1,000 pcm, At the same time a challenge in obtaining a single equilibrium cycle was found, a detailed study on optimizing the amount of BA loading, especially, B-10 should be carried out to minimize the oscillation effect. A reasonable power peaking was obtained in both axial and radial directions, while the discharge BU was within the acceptable limits.

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