Burnable Poison Strategies for Extra-Long Cycle Small PWR

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1. Introduction

In the near future some of advanced Light Water Reactors (LWRs) including Small Modular Reactor will utilize High-Assay Low Enriched Uranium (HALEU) fuel. HALEU fuel is a UO_2 fuel with U^{235} enrichment > 5 w/o and < 20 w/o. This higher enrichment can improve the reactor performance and make it smaller. Also, allows the reactor to achieve higher burnup level with longer operation cycle length with less frequent refueling [1]. However, higher fuel enrichment means larger numbers of BP rods are required to hold-down the higher excess reactivity. This causes a great challenge to operate the system within the design limitations without any violation by using the conventional BP [2-4]. However, by enriched the absorber isotopes and combine two conventional BP types that are complementary to each other can overcome the weakness of holding-down the high excess reactivity and high power peaking.

In this paper, a preliminary investigation was conducted in order to check the feasibility of extra-long cycle SMR core. DeCART-2D code was used as a design tool to obtain the results of assembly calculation [5]. Letdown curve (k-infinite), power peaking and Moderator Temperature Coefficient (MTC) were analyzed.

2. Fuel Assembly Design

Fig. 1 shows the fuel assembly design used in this study, which is 17x17 Westinghouse (WH) type. Also, Table I shows the design parameters of the fuel assembly under study. In addition, the conventional BP types that were used here are Wet Annular Burnable Absorber (WABA), Gadolinia (Gad), Erbia, Integral Fuel Burnable Absorber (IFBA) and Solid Boron Rod (SBR). The utilization of HALEU fuel with 9.95 w/o enrichment is to achieve long cycle length.

3. Research Methodology

In this research the advantages of HALEU fuel with enrichment level of 9.95 w/o were considered in order to increase the operation cycle length of SMR core significantly. Moreover, in order to operate this kind of design within the design limitations, some requirements should be taken in account to choose suitable BP types. Such as the ability to reduce the initial excess reactivity to the desired level; maintain the k-infinite letdown curve to be as flat as possible; and keeping the effect of remaining absorber isotopes on the excess reactivity as low as possible [6].

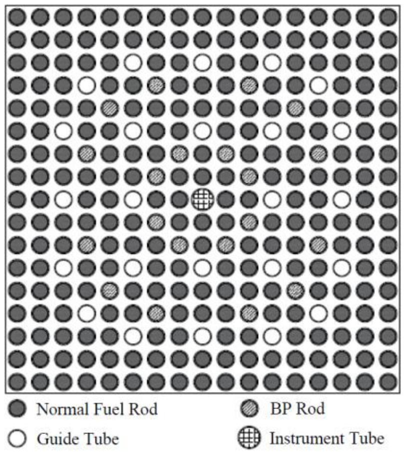

Fig. 1. Standard WH fuel assembly type.

Table I: WH Fuel Assembly Design Parameters

Design Parameter	
Fuel Rod Array	17×17
Number of Fuel Rods	264
Active Fuel Length (cm)	200
Number of Guide Tube (GT)	24
Number of Instrumentation tube	1
Fuel Assembly Pitch (cm)	21.5040
Cell Pitch (cm)	1.260
Fuel Diameter (cm)	0.8192
Cladding material	ZIRLO
Cladding I.D. (cm)	0.8357
Cladding O.D. (cm)	0.95
Guide Tube material	ZIRLO
GT I.D. (cm)	1.008
GT O.D. (cm)	1.224

The first step in this study was to check whether the conventional BP designs can fulfill the above requirements or not. 60 pins of Gad with 8 w/o of gadolinium, 24 pins of WABA with natural boron, 24 pins of SBR with natural boron, 196 pins of IFBA with natural boron and 228 pins of Erbia were used in different cases as shown in Fig. 2. This figure clearly shows that none of the conventional BP types can keep the k-infinite letdown curve as flat line. However, among all BP cases, SBR case shows promising behavior to be suitable for an extra-long cycle core due to slower BP depletion. Also, WABA case can show similar behavior when the B^{10} enrichment is increased. Therefore, SBR and WABA cases were chosen to be modified for further investigation. The next step is to determine the lowest required value of k-infinite. Actually, it depends on the design requirements. For example, in our case the lowest k-infinite value was set as 1.03 after taken in account the 3% as a margin for any negative reactivity. In order to achieve this value the SBR case was modified by increasing the B^{10} enrichment to 30 w/o and name the new case as Solid Boron Rod 2 (SBR2). Similarly, the WABA case was modified by increasing the B^{10} enrichment to 90 w/o and by increasing the thickness of Al_2O_3-B_4C tube from 0.0508 cm into 0.0635 cm then name it as Wet Annular Burnable Absorber 2 (WABA2). As shown in Fig. 3 the excess reactivity throughout the burnup is reduced remarkably from WABA case and SBR case to WABA2 case and SBR2 case respectively. The k-infinite letdown curve of the latter cases reduces gradually until 40 MWD/kgHM and then became almost flat around the value of 1.03 until the End OF Cycle (EOC). This behavior is due to the self-shielding effect which causes the absorbent material to slowly deplete. Even though these two cases have k-infinite letdown curve reasonably flat from 40 MWD/kgHM until the EOC, it is still very high before 40 MWD/kgHM. The simplest idea to reduce the excess reactivity at the Beginning Of Cycle (BOC) is by combining these two cases by one of the BP types that have strong effect at the BOC with very weak effect at the EOC. As someone can guess, the best options for this role are IFBA and Gad due to their faster rate depletion among other conventional BP types [7]. Therefore, by combining WABA2 and SBR2 with either IFBA or Gad, the k-infinite letdown curve can be maintained as flat as possible. IFBA or Gad pins are added one by one in the location of fuel pins that have the highest local power peaking factor until the initial value of k-infinite become little bit higher than 1.03. It should be noted that by changing the lowest required value of k-infinite and following these steps the k-infinite letdown curve can be made as flat as possible around any value.

4. New Combination Method

In this paper a new combination method is introduced. In this method two different conventional BP with different properties are used together at different location in the same fuel assembly. One of these BP has slow depletion rate and the other one has fast depletion rate. By using this combination method the excess reactivity can be controlled throughout the cycle operation length. Also, the k-infinite letdown curve can be made as flat line. Furthermore, the soluble boron concentration can be significantly reduced.

In this study four cases are studied (WABA2+IFBA, WABA2+Gad, SBR2+IFBA and SBR2+Gad) as shown in Fig. 4.

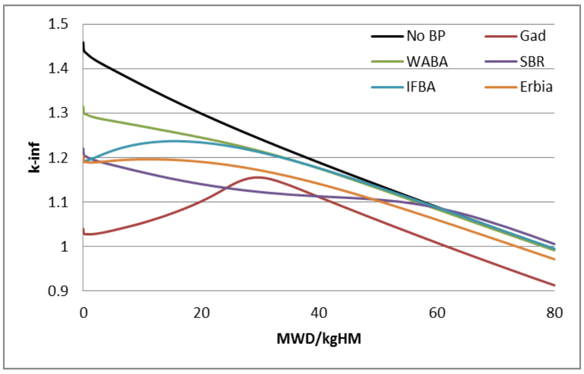

Fig. 2. Comparison of conventional BP types effect on excess reactivity.

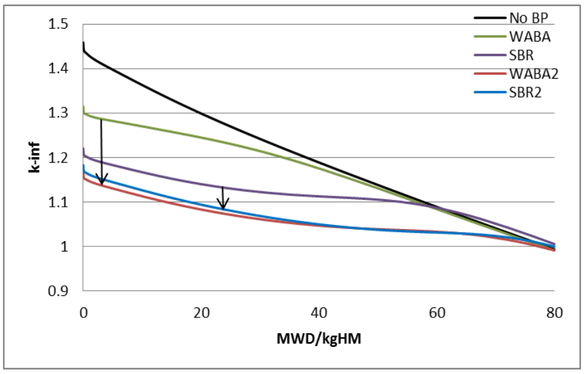

Fig. 3. Comparison of excess reactivity for WABA, SBR, WABA2 and SBR2 cases.

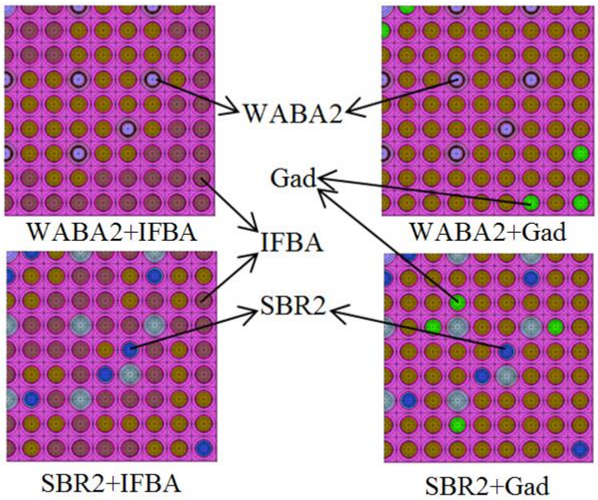

Fig. 4. ¼ WH fuel assembly with different BP pins loading (WABA2+IFBA, WABA2+Gad, SBR2+IFBA & SBR2+Gad).

5. Results and Discussions

The k-infinite versus burnup of No BP, WABA2, WABA2+IFBA and WABA2+Gad cases are shown in Fig. 5. The initial excess reactivity is reduced from 31,436 pcm as in No BP case to 14,224 pcm as in

WABA2 case. This reduction is about more than half after adding 24 pins of WABA2. The effect of IFBA and Gad is clearly shown by reducing the initial excess reactivity even more than WABA2 case to reach about 4,461 pcm for WABA2+IFBA case and 6,746 pcm for WABA2+Gad case. The k-infinite value of WABA2+IFBA case is little bit increased to the maximum value of about 1.05548 at 16.5 MWD/kgHM. Then it decreases very slowly until it matches the value of WABA2 case at 46 MWD/kgHM. After that these both cases reach the EOC, where the lowest value of k-infinite set as 1.03, at 64 MWD/kgHM. This value of burnup is equal to 3,744 EFPD (Effective Full Power Days). On the other hand, WABA2+Gad case is started with k-infinite value little bit higher than the initial k-infinite of WABA2+IFBA case. Then it decreases with a small value at the BOC, before it becomes almost flat line until the EOC. This case does not match with WABA2 case at any point rather it keeps a small difference with WABA2 case until the EOC. WABA2+Gad case reaches the EOC at 46 MWD/kgHM which is equal to 2,678 EFPD.

Similarly, Fig. 6 illustrates the k-infinite versus burnup of No BP, SBR2, SBR2+IFBA and SBR2+Gad cases. In these cases the initial excess reactivity is reduced to 15,463 pcm for SBR2 case and 7,008 pcm and 4,343 pcm for SBR2+Gad and SBR2+IFBA cases respectively. Also, the k-infinite value of SBR2+IFBA case is increased little bit to the maximum value of about 1.061345 at 17.5 MWD/kgHM. After that it decreases very slowly until it matches the value of SBR2 case at 48 MWD/kgHM, before they continue with similar values until the EOC at 64 MWD/kgHM. Unlike WABA2+IFBA case, here 64 MWD/kgHM is equal to 3,403 EFPD which is shorter operation cycle length. This is due to the fact that SBR is replacing the entire fuel rod. SBR2+Gad case has similar behavior to WABA2+Gad case. However, its operation cycle length is shorter with the value is equal to 2,327 EFPD at 44 MWD/kgHM. It is clearly that WABA2+Gad and SBR2+Gad cases have operation cycle lengths are far shorter than WABA2+IFBA and SBR2+IFBA cases, due to low fuel enrichment in Gad pins. On the other hand, the operation cycle length of SBR2+IFBA case has a little bit shorter period than WABA2+IFBA case. However, the latter two cases can be used in the same reactor core, as WABA2+IFBA case can be only used in the fuel assemblies that have no control rods.

Fig. 7 shows the radial power peaking factor (FRP) versus burnup of No BP, WABA2, WABA2+IFBA and WABA2+Gad cases. The effect of IFBA is clearly shown as a significant reduction of the value of FRP at the BOC when comparing WABA2 with WABA2+IFBA. Then around the burnup of 35 MWD/kgHM both cases start to behave almost the same until the EOC. On the other hand, Gad changes the behavior of FRP curve differently. At the BOC the FRP curve of WABA2+Gad case is reducing little bit than WABA2 case, before to start to increase at 20 MWD/kgHM to reach 1.1389 at 35 MWD/kgHM which is the highest value among all cases at this burnup level. Then start to decrease dramatically before to increase little bit at the EOC.

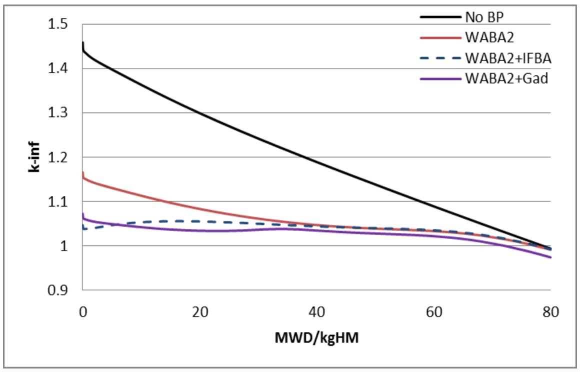

Fig. 5. Comparison of excess reactivity for WABA2, WABA2+IFBA and WABA2+Gad cases.

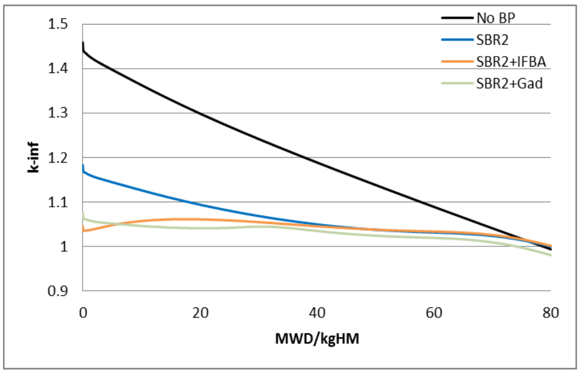

Fig. 6. Comparison of excess reactivity for SBR2, SBR2+IFBA and SBR2+Gad cases.

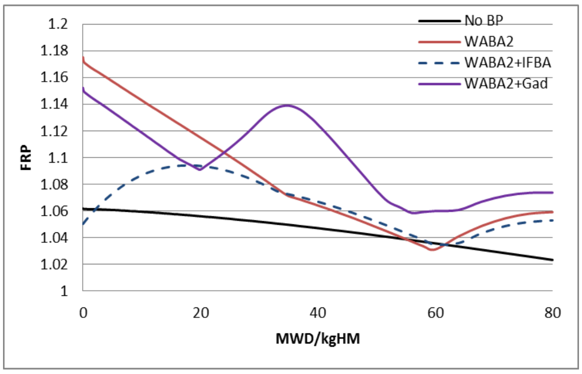

Fig. 7. Comparison of radial power peaking factor for WABA2, WABA2+IFBA and WABA2+Gad cases.

Fig. 8 demonstrates the FRP versus burnup of No BP, SBR2, SBR2+IFBA and SBR2+Gad cases. The latter case has the highest FRP curve among all other cases. On the other hand, at the BOC SBR2+IFBA case has the lowest FRP among all cases, before to match with the FRP of SBR2 case at 32 MWD/kgHM. Then both of them start to behave almost the same until the EOC. Noteworthy, the FRP of SBR2+IFBA case at the EOC, which is equivalent to 64 MWD/kgHM, is 1.102. This value is much lower than the value of 1.1349 at the End Of Life (EOL).

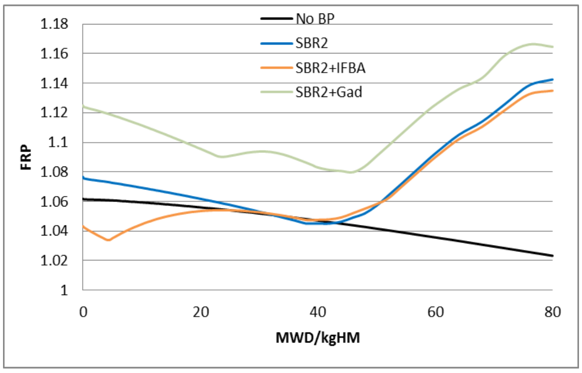

Fig. 8. Comparison of radial power peaking factor for SBR2, SBR2+IFBA and SBR2+Gad cases.

Fig. 9 and Fig. 10 show the MTC versus burnup of No BP, WABA2, WABA2+IFBA, WABA2+Gad, SBR2, SBR2+IFBA and SBR2+Gad cases respectively. When WABA2 and SBR2 are combined with IFBA or Gad, the MTC value is become less negative at BOC. For example the highest MTC value at BOC for WABA2+IFBA case, WABA2+Gad case and WABA2 case are -35.57 pcm/°C, -39.24 pcm/°C and -41.57 pcm/°C respectively. On the other hand, the highest MTC value at BOC for SBR2+IFBA, SBR2+Gad and SBR2 cases are -33.94 pcm/°C, -37.51 pcm/°C and -39.88 pcm/°C respectively. These differences are reducing step by step until they reach about 40 MWD/kgHM, where WABA2+IFBA case, WABA2+Gad case and SBR2+IFBA case, SBR2+Gad case become almost the same value of WABA2 case and SBR2 case respectively. Then they continue with the same behavior until the EOC.

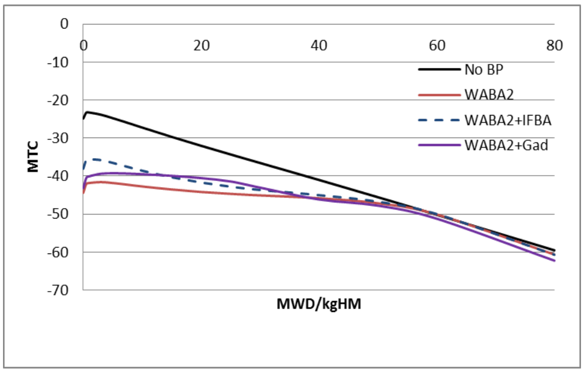

Fig. 9. Comparison of MTC for WABA2, WABA2+IFBA and WABA2+Gad cases.

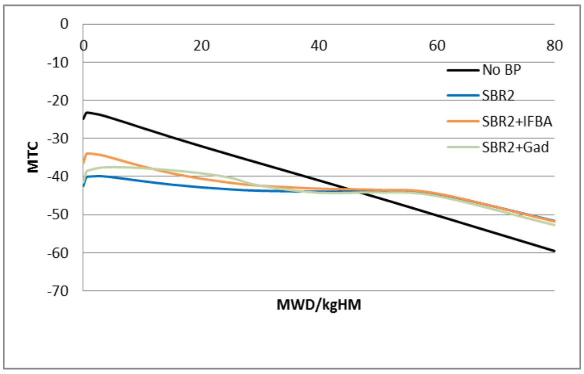

Fig. 10. Comparison of MTC for SBR2, SBR2+IFBA and SBR2+Gad cases.

6. Conclusions

In this paper a preliminary study was conducted to check the feasibility of SMR core with extra-long operation cycle length by using HALEU fuel with enrichment of 9.95 w/o and combination BP method to control the high excess reactivity.

Different assembly calculations were performed by DeCART2D code. The obtained results were compared with each other in terms of k-infinity, radial power peaking factor and MTC.

The results of this investigation showed that all conventional BP designs are not good enough to make k-infinite letdown curve of HALEU fuel flat in straight line. However, combination of BP designs showed advantage in holding-down the excess reactivity for HALEU fuel and maintaining the k-infinite letdown curve almost straight and flat throughout the longer burnup. Among them the cases that used IFBA as a complementary BP (i.e. WABA2+IFBA and SBR2+IFBA) showed better performance in terms of the ability of holding-down the initial excess reactivity which was about 86% for both cases. Also, they could maintain the k-infinite letdown curve as flat as possible with longer cycle length. Moreover, they give reasonably values of radial power peaking factor and MTC.

These two cases should be used together in the same core design as WABA can only be used with the fuel assemblies that do not have control rods.

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