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Physical Studies of Burnable Absorbers in Hexagonal Fuel Assembly

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Abstract

We present the result of physical studies for three integral-type burnable absorbers of gadolinia, erbia and IFBA, in the hexagonal fuel assembly. The analysis of nuclear characteristics for gadolinia and IFBA cases shows that the spectrum hardening of hexagonal fuel assembly compared to rectangular one leads to smaller reactivity hold-down worth(RHW) and less change of MTC in the negative direction per insertion of one burnable absorber rod. Erbia case, on the other hand, exhibits reversed trend in RHW and MTC due to the enhanced absorption of large resonance of Erbium at 0.5 eV. It turns out to be that Erbia performs best in terms of minimizing the peak pin power and maintaining as more negative MTC as practically attainable during the entire operational phase, and IFBA provides the least residual reactivity penalty at EOC. Therefore, we take Erbium as the suitable burnable absorber and provide optimal designs of 60, 120, 180, 240 and 300 erbia-shimmed hexagonal fuel assemblies with regard to minimizing the peak pin power.

1. Introduction

Small and medium size reactors with integral configuration of major primary components are being actively developed in many countries for non-electric applications. The design concepts of these reactors vary depending on the purpose of application. Since the middle of 1994, the Korea Atomic Energy Research Institute(KAERI) has been putting efforts to develop various elemental technologies to be incorporated into an advanced integral PWR concept[1,2], SMART(System integrated Modular Advanced ReacTor) with an output power in the range of 100 MWe to 600 MWe. Advanced technologies such as intrinsic and passive safety features are incorporated in establishing the design concepts so as to achieve inherent safety, enhanced operational flexibility and good economy. In keeping with these goals, the design considerations of SMART core include the following main features; low power density, soluble boron free operation, extended fuel cycle and improved fuel utilization, etc..

The reactor core is currently being designed with the fuel design based on existing KOFA(Korean Optimized Fuel Assembly) which is in 17x17 rectangular rod array. In parallel, we are evaluating the merits of hexagonal lattice reactor core design as an option in order to take benefits from the use of hexagonal lattice fuel assembly due to its favorable characteristics[3]. Hexagonal lattice is naturally more compact than rectangular lattice, and thus results in more hardened neutron spectrum. This in turn makes conversion ratio higher and moderator temperature coefficient(MTC) more negative. In addition, hexagonal lattice fuel assembly shows smaller excess reactivity at the beginning of cycle(BOC) and more latent decrease of reactivity with burnup. These characteristics are all advantageous to the core design requirements, especially soluble boron free operation and improved fuel utilization. However, because of spectrum hardening, we can also predict the reduction of absorption effect in a tight lattice hexagonal fuel assembly. This reduced poison effect is disadvantageous to the core design which requires significant amount of burnable poisons and control rods to suppress and control the core excess reactivity without using soluble boron. Therefore one of the most important and difficult tasks for successful core design based on hexagonal fuel assembly becomes how to make optimum use of burnable poisons.

In this paper, we have performed a sensitivity study in order to analyze the nuclear characteristics from the use of different burnable absorbers, such as Gadolinium, Erbium and IFBA, in the hexagonal fuel assembly and searched the most appropriate absorber for the design requirements of SMART core. The nuclear analyses was done by using HELIOS[4] code which is a neutron and gamma transport code for lattice in general two-dimensional geometry.

2. Design of Hexagonal Fuel Assembly

The more tight a fuel lattice is, the more hardened the neutron spectrum becomes, resulting in higher conversion ratio and more negative MTC, which suggest that the use of tight lattice fuel assembly would be potentially beneficial to the design considerations of the SMART core. We have designed a tight lattice hexagonal fuel assembly having 360 fuel rods and 36 guide tubes and 1 instrument tube. Since the reactor core design with tight lattice hexagonal fuel assembly is an alternative to the one with rectangular 17x17 KOFA, the same fuel rod and assembly volume as for KOFA was maintained in the hexagonal fuel assembly. The moderator to fuel volume ratio($=V_m/V_f$) of hexagonal fuel assembly is reduced to 1.13 compared to 2.05 of KOFA. Consequently, the infinite multiplication factor of hexagonal fuel assembly becomes smaller at BOC than that of KOFA due to spectrum hardening, but greater beyond 40,000 MWD/MT due to enhanced conversion ratio.

3. Burnable Absorbers in Hexagonal Fuel Assembly

3.1. Performance Requirements

In order to have the most desirable burnable absorber design for SMART core concept, the following performance requirements for BP-shimmed fuel assembly have been established. Firstly, the reactivity hold-down worth(RHW) of burnable absorbers should be sufficient enough to suppress core excess reactivity throughout the cycle without the help of soluble boron control. Secondly, inherent safety and operational flexibility dictates the design of BP-shimmed fuel assembly having as more negative MTC as practically attainable during the entire operational phase and the capability to effectively control the peak pin power. Thirdly, the residual poison effect should be minimal at the end of cycle(EOC) so that no appreciable penalty is incurred in the cycle length.

With respect to those requirements, we performed physical studies for three integral-type burnable absorbers of gadolinia, erbia and IFBA, which included comparison of RHW, MTC and relative peak pin power as functions of absorber concentration and the number of BP rods. Gadolinia and erbia are assumed to be homogeneously mixed with urania so that the amount of absorber can be controlled by concentration. On the other hand, IFBA is in the form ZrB_2 coated on the outer surface of fuel rod and thus the amount can be controlled by the thickness of coating.

3.2. Analysis of Nuclear Characteristics

The characteristics of RHW and MTC are shown in Figure 1 as functions of the number of BPs and concentration. Use of IFBA offers the best capability to extend the range of RHW. However, since the required RHW could be achieved to a great extent by increasing the number of absorber rods for integral-type burnable absorber, all three burnable absorbers considered in this study are judged to possess a potential to meet the required RHW by a proper design of shimmed assembly. Given the same RHW, erbia case results in the most negative MTC, the magnitude of which only depends on the number of BPs. The MTC of gadolinia or IFBA shimmed fuel assembly becomes proportionally more negative at BOC with absorber concentration and the number of BP rods, but the difference caused by the concentration and the number disappears quickly with burnup. Erbia case shows the similar trend as the other two burnable absorbers, but the difference due to the number of BPs is still maintained to some extent until the burnout point of Erbium.

For the relative peak pin power, KOFA bearing gadolinia rods exhibits a jump in the peak pin power near the Gadolinium burnout point, while that of hexagonal fuel assembly decreases monotonously as illustrated in Figure 2. The monotonous decrease of peak pin power in gadolinia-shimmed hexagonal fuel assemblies provides an additional advantage in the core design in a way that the peak pin power constraint can be easily met at BOC. The higher absolute value of peak pin power in gadolinia bearing assemblies means, however, that gadolinia is not competitive with the other two absorbers in terms of peaking control. Figure 2 demonstrates erbia shimmed fuel assembly has more flexibility in minimizing peak pin power by using higher concentration of absorber as well as by optimizing the distribution of absorber rods.

The burnout point of Gadolinium depends on only concentration, implying that more gadolinia rods with lower concentration would be a better way to reduce the residual poison effect at EOC than less gadolinia rods with higher concentration. In both IFBA and erbia cases, the burnout point is not dependent on either the concentration or the number of BP rods. Since Erbium has a large resonance absorption at 0.5 eV, spectrum hardening in a tight lattice fuel assembly enhances absorption of Erbium and, therefore, burnout of Erbium occurs earlier than that of non-tight lattice fuel assembly like KOFA. For the same RHW at BOC, IFBA provides the least residual reactivity penalty at EOC.

The effect upon insertion of one burnable absorber rod at BOC is summarized in Table 1. Loading of gadolinia or IFBA into hexagonal fuel assembly leads to smaller reactivity hold-down worth(RHW) and less change of MTC in the negative direction compared to rectangular one. Erbium case, on the other hand, exhibits reversed trend in RHW and MTC due to the enhanced absorption of large Erbium resonance at 0.5 eV.

3.3. Optimal Design of Erbia-Shimmed Assembly

Since erbia shimmed fuel assembly can yield more negative MTC until the burnout point than that of other absorbers and have good capability to control the peak pin power, we have chosen Erbium as the burnable absorber for the SMART core concept. The concentration and the number of erbia rods determine the magnitude of initial reactivity hold-down and MTC. But the minimum peak pin power strongly depends on the distribution of erbia rods within the assembly. We used 2 w/o Erbium and designed optimal 60, 120, 180, 240 and 300 erbia-shimmed hexagonal FAs with regard to minimizing the peak pin power. The design layout of 180 erbia-shimmed hexagonal assembly is illustrated in Figure 3 as an example. The evolution of peak pin power for optimal erbia-shimmed fuel assemblies is shown in Figure 4.

4. Conclusion

We are convinced that a tight lattice hexagonal fuel assembly would provide advantageous nuclear characteristics to the design requirements of SMART core, especially from the viewpoint of achieving inherent safety, enhanced operational flexibility and better fuel utilization. The result of physical studies for three integral-type burnable absorbers of gadolinia, erbia and IFBA in the hexagonal fuel assembly shows that erbia performs best in terms of minimizing the peak pin power and maintaining as more negative MTC as practically attainable during the entire operational phase, and IFBA provides the least residual reactivity penalty at EOC. Therefore, we take Erbium as the burnable absorber for SMART core concept and present the designs of optimal erbia-shimmed hexagonal fuel assemblies having minimum peak pin power.

5. References

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Table 1. Reactivity hold-down worth(RHW) and MTC at BOC per insertion of one burnable absorber rod

BP	RHW at BOC per insertion of one BP rod (% $\Delta\rho$)			MTC at BOC per insertion of one BP rod (pcm)		
	KOFA	hexagonal FA	change (%)^a	KOFA	hexagonal FA	change (%)^a
Gadolinium	0.903	0.711	- 21	-0.692	-0.353	- 49
Erbium	0.054	0.111	+ 106	-0.094	-0.127	+ 35
IFBA	0.160	0.139	- 13	-0.068	-0.033	- 52

a = 100 x (hexagonal FA - KOFA)/KOFA

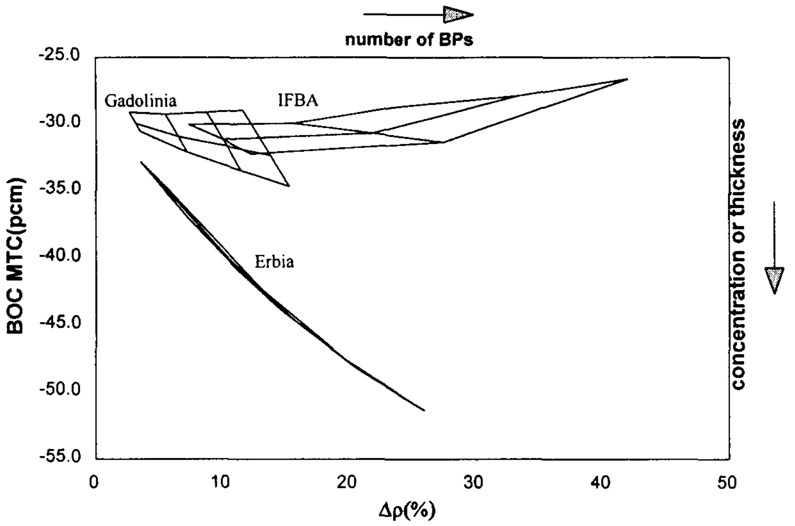
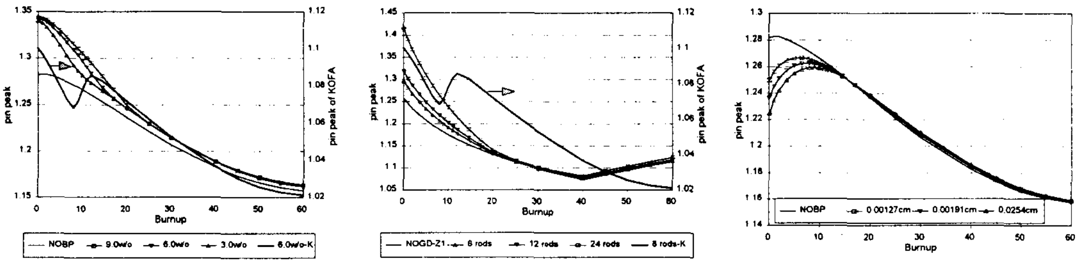
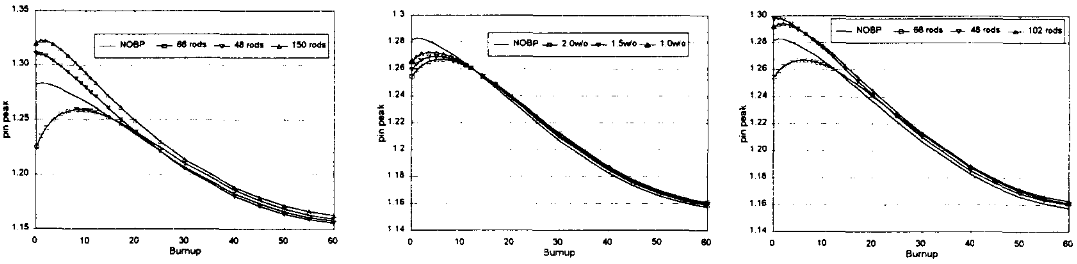


Figure 1. RHW and MTC as functions of the number of BPs and concentration



(a) for concentration of Gd_2O_3 (b) for the number of Gd rods (c) for thickness of IFBA



(d) for the number of IFBAs (e) for concnetration of Er_2O_3 (f) for the number of Er rods

Figure 2. Relative peak pin power for different burnable absorbers (note: K means KOFA)

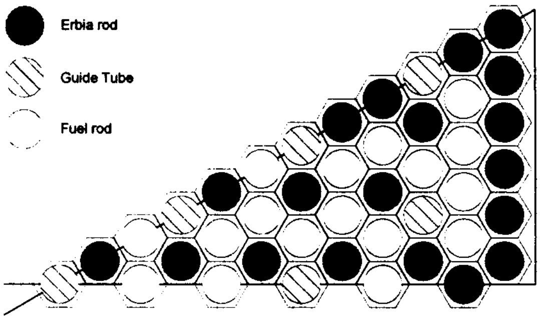


Figure 3. Configuration of optimal 180 erbia-shimmed fuel assembly

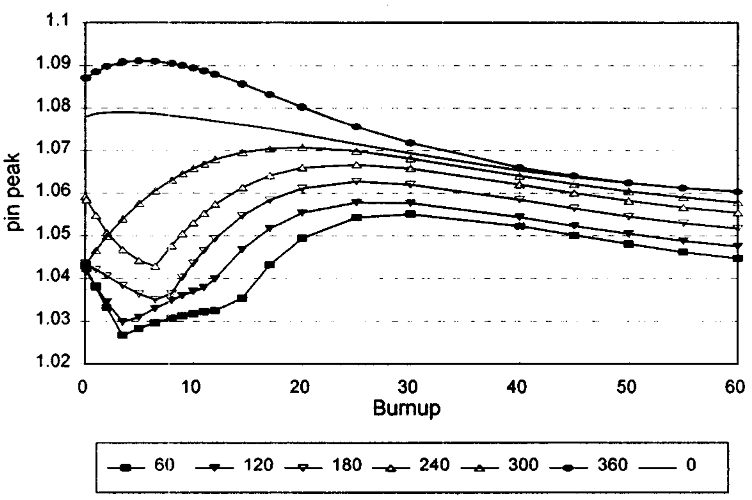


Figure 4. Peak pin powers of optimal erbia-shimmed fuel assemblies