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A Novel Burnable Absorber for Small Modular Reactors: Gadolinium (III) Nitride Coating

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1. Introduction

Recently, small modular reactors (SMRs) have attracted significant interest due to their potential for safety, flexibility in deployment, and low-carbon energy. Current SMRs are usually based on the technologies of pressurized water reactors (PWRs). However, soluble boron used in PWRs has safety issues, such as generic safety issue 22 related with inadvertent boron dilution. Other problems such as more positive or less negative moderator temperature coefficient (MTC), and crud-induced power shift (CIPS) could also be problematic. Thus, soluble boron-free (SBF) reactors have been proposed and widely accepted for SMRs.[1]

SBF reactors, however, heavily rely on the control rods and burnable absorbers (BAs) to control excess reactivity. The traditional BAs have some limitations in usage for SBF reactors, which has led to some researches for new BAs such as CsBA, DiBA, and CIMBA [1, 2].

In this paper, we introduce a new burnable absorber that utilizes a gadolinium (III) Nitride coating burnable absorber (GdN BA). The purpose of this study is to determine the optimal thickness and combination of the GdN coating, and to compare its effectiveness with existing burnable absorbers.

2. Computer Code and BA Model

The UO_2 fuel pellet having the GdN BA coating layer that we suggested is illustrated in Fig. 1. GdN is well-known for its high absorption cross-section and high melting point (approximately 3170 K), making it an excellent candidate for a coating material [3]. GdN BA has a similar structure to IFBA. But unlike IFBA, the coating layer of GdN cuts the outside of the fuel pellet and replaces the pellet with the GdN instead. If the thickness of GdN BA is sufficiently thick, it can also be applied by processing it into a ring shape and joining it with a fuel pellet.

To study the nuclear properties of the GdN BA, we used a 17x17 Westinghouse fuel assembly (FA), consisting of 289 rods, with 25 instrumental and guide tubes and 264 fuel rods. To compare the performances with the traditional gadolinia, the number of BA pins was set to 16 for gadolinia and GdN, and 132 for IFBA.

We assumed that the fuel assembly used in this work would be used later, in PWR-based SMR of 180 MWt and 200 cm high active core. The number of FAs is 37, which gives ~92.1W/cm average linear heat generation rate and average assembly power per unit height (cm) of 24.3 kW/cm. Boron concentration was set to 500 ppm.

The density of UO_2 pellet was assumed to be 10.220 g/cm^3, which is 95% of the theoretical density of UO2 at 900 K (10.76 g/cm^3). For the gadolinia BA rod, gadolinia was mixed with natural uranium (0.711% enrichment), and the density was determined using the following formula based on the weight percentage of gadolinia, where the theoretical density of UO2 (i.e., 10.96 g/cm^3), and theoretical one of gadolinia (i.e., 7.66 g/cm^3) were used [4].

$$\rho = \frac{10.22}{10.96} \times (10.96 - 0.033\text{wt}\ \%\ \text{Gd})[\text{g/cm}^3] \qquad (1)$$

For the GdN coating, we used 8.645 g/cm^3 density, which is 95% of the theoretical density at room temperature. For traditional IFBA, the density was assumed to be 6.085 g/cm^3, and natural boron was used. For Zircaloy, we used a density of 6.55 g/cm^3 at 600 K. The physical properties and calculational conditions are summarized in Table 1.

Calculations were performed using DeCART2D, a code developed by the Korea Atomic Energy Research Institute (KAERI) that uses two-dimensional ray tracing and the method of characteristics (MOC) to solve the multi-group transport equation. For the cross-section calculation, we used 47 neutron groups and 18 gamma groups cross-sections processed from the ENDF/B-VII.1 library [5]. Radial zone was set as three for fuel, and one for coating, gap and cladding.

Table I. Geometry and compositions of reference fuel assembly and fuel pellets.

Geometry of fuel assembly	
Full core power (MWt)	180 MWt
Assembly power per unit height	24.3 kW/cm
Fuel cladding outer radius	0.4750 cm
Fuel pins spacing	1.2600 cm
Boron concentration	500 ppm
Fuel pellet radius	0.4096 cm
Number of BA pins	16 (GdN, gadolinia) 132 (IFBA)
UO_2 fuel pins	
Fuel pellet density	10.220 g/cm^3
U-235 enrichment	4.95 wt.%
GdN BA fuel pins	
Fuel pellet radius	0.3976 cm
GdN coating thickness	0.0120 cm
GdN coating density	8.645 g/cm^3
Gadolinia BA fuel pins	
Fuel pellet density	9.974 g/cm^3
U-235 enrichment	0.711 wt.%
Gadolinia enrichment	8.00 wt.%
IFBA fuel pins	
ZrB2 thickness	0.004 cm
ZrB2 density	6.085 g/cm^3

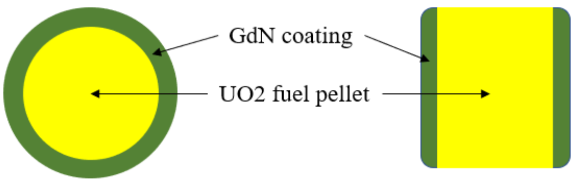

Fig. 1. Radial and axial configurations of fuel pellet with GdN BA

3. Results and discussions

Fig. 2 shows the effect of the thickness of the GdN BA on the evolution of multiplication factor as depletion. The results indicate that an increase in the thickness of the GdN coating leads to a decrease in the multiplication factor and an increase in the depletion time of gadolinium. Due to the self-shielding effect of gadolinium, the multiplication factor at the beginning of the cycle (BOC) does not decrease proportionally with the GdN thickness. Fig. 3 compares the evolutions of the power peaking factor of the fuel pin-wise power distribution. As expected, the initial power peaking factor is higher for the thicker GdN coating.

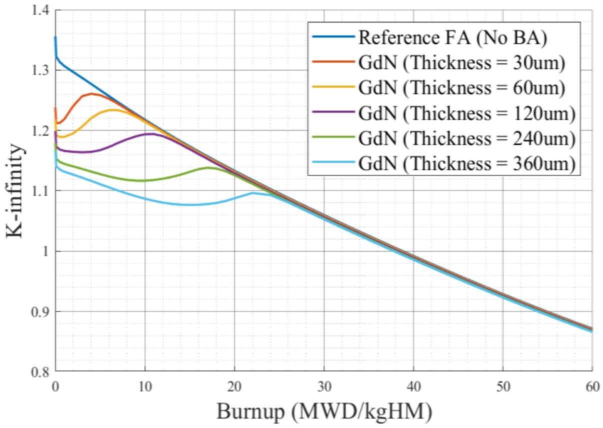

Fig. 2. Comparison of the multiplication factor by coating thickness of GdN BA

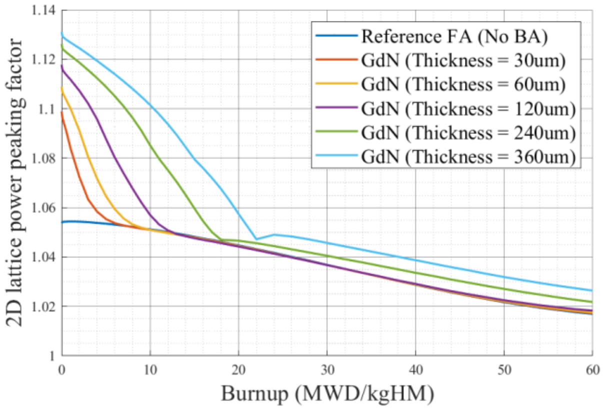

Fig. 3. Comparison of the 2D lattice power peaking factor by coating thickness of GdN BA

Next, the effect of the number of GdN BA pins is analyzed. Fig. 4 compares the changes of the infinite multiplication factor for different numbers of GdN BA pins for a fixed GdN BA coating of 120 µm. The result shows that an increase in the number of GdN BA pins leads to a decrease in the multiplication factor, but there was no significant difference in the depletion time of GdN.

As the GdN coating thickness or the number of GdN BA pins increases, the cycle length gradually decreases. For a thickness of 360 µm, the decrease in cycle length was approximately 1 MWD/kgHM. which is similar to the result obtained with 32 GdN BA pins of 120 µm thick GdN coating.

Fig. 5 compares the changes of the infinite multiplication factors for several combinations of GdN BA pins, having different GdN coating thicknesses. From Fig. 5, it is shown that a very effective reduction of excess reactivity can be achieved with a well selected combination (e.g., 8 GdN BA pins with 180 µm thick coating in conjunction with 16 GdN BA pins with 360 µm thick coating).

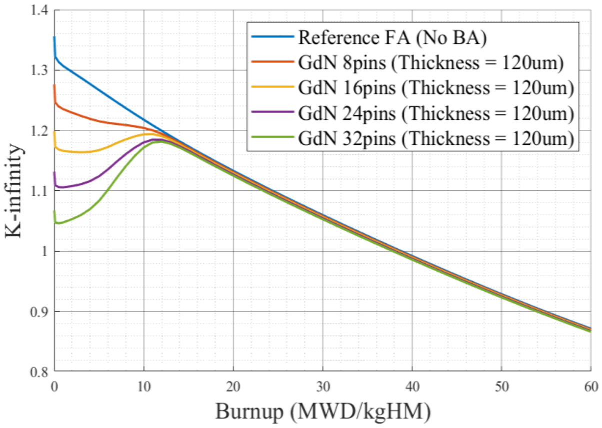

Fig. 4. Comparison of the multiplication factor by the number of pins of GdN BA

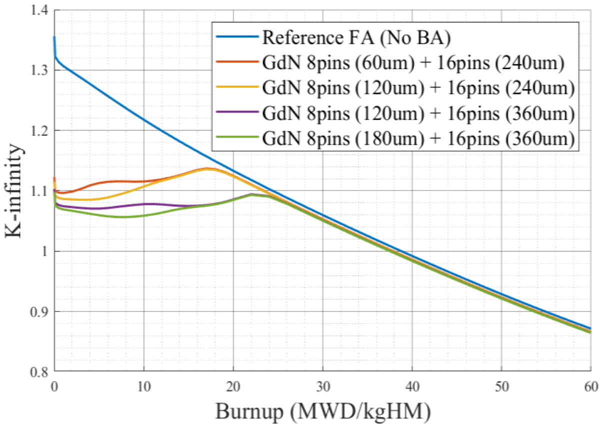

Fig. 5. Comparison of the multiplication factor by combination of different coating thickness of GdN BA.

In this work, the use of GdN coating on the gadolinia or Erbia BA pellets was also suggested to increase the effectiveness of the BA. Fig. 6 compares the changes of the multiplication factor for this concept in which GdN coating is added to the traditional gadolinia BA pellets. Gad wt.% in the figure refers to the content of gadolinia in weight percentage, in the Gd_2O_3-UO_2 fuel pellet. From this figure, it is shown that for both gadolinia 4wt.% and 8wt.%, the additional GdN coating results in lower excess reactivity and longer depletion time than their corresponding cases, without GdN coating. Also, it is noted that the cycle length was almost the same for the cases with or without GdN coating for different Gd contents.

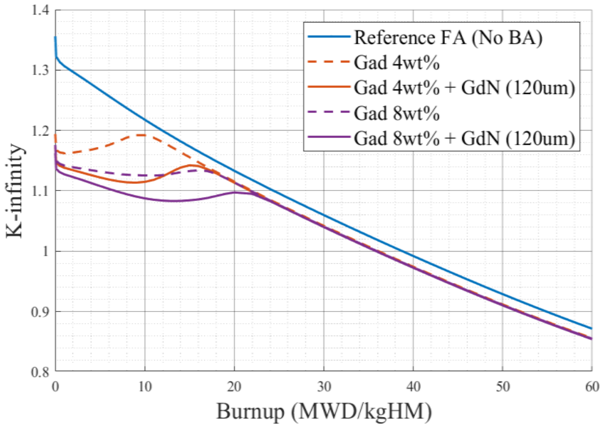

Fig. 6. Comparison of the multiplication factor of GdN in conjunction with the traditional gadolinia

Next, we compared the performance of GdN BA with traditional gadolinia BA and IFBA. Fig. 7 compares the changes of infinite multiplication factors of IFBA, and the conventional gadolinia with new GdN BAs. This figure shows that the GdN BA of 360µm thick coating and Gd BA (8wt% Gd2O3) coated by 120µm thick GdN layer give the most favorable changes of the infinite multiplication factor. For cycle length, due to natural uranium fuel pellets, gadolinia BA had the shortest cycle length roughly 36 MWD/kgHM, followed by 38 MWD/kgHM of GdN BA. Reference FA and IFBA showed the same cycle length of 39 MWD/kgHM. This result suggests that GdN BA was the most effective BA in reducing excess reactivity in the reactor, without degrading cycle length, among candidates considered in this work.

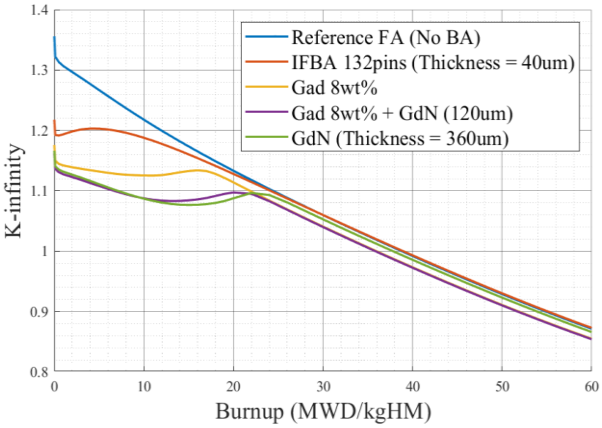

Fig. 7. Comparison of the multiplication factor of traditional BAs and GdN BA

The power peaking factors in the fuel pin-wise power distribution of each BAs are compared in Fig. 8. The peaking factors was the highest for the conventional gadolinia BA, followed by Gad + GdN BA and GdN BA. GdN showed a similar tendency to gadolinia, while IFBA showed lower peaking factor than reference FA. From this analysis, it can be concluded that the GdN BA has slightly lower or similar power peaking factor over the depletion time. However, this large power peaking can be resolved by adjusting the BA positions.

Finally, the moderator temperature coefficients (MTC) are compared in Fig. 9. This figure shows that new GdN-based BA concepts have similar MTC values to the conventional Gd BA.

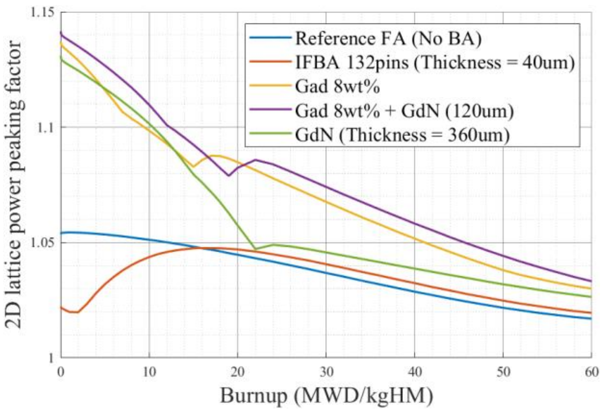

Fig 8. Comparison of the 2D power peaking factor of traditional BAs and GdN BA

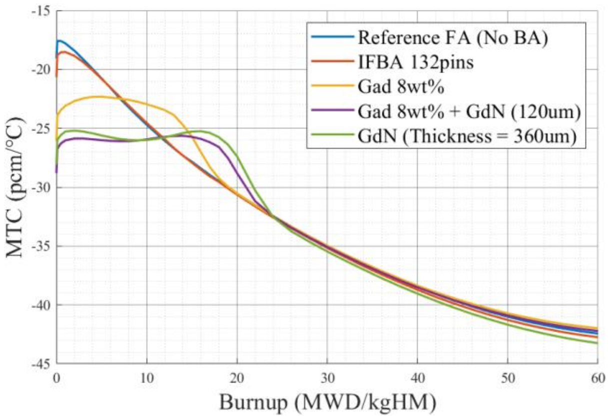

Fig. 9. Comparison of the moderator temperature coefficient of traditional BAs and GdN BA

4. Conclusions

In this work, we suggested BA concepts in which the GdN coatings are applied on the UO_2 or Gd_2O_3-UO_2 pellets. Additionally, we considered a various combination of the GdN BAs having different coating thicknesses. From the fuel assembly depletion analyses, it was shown that the new GdN BA exhibits a very favorable reduction of excess reactivity with only small reduction in cycle length compared to the conventional gadolinia. Also, the application of GdN coating on the conventional Gd_2O_3-UO_2 pellet showed more favorable reduction of excess reactivity than the conventional Gd_2O_3-UO_2 pellet for the same Gd content and number of BA pins. Therefore, it can be concluded that the GdN BA is a good candidate of the BA options for boron-free operation. Furthermore, GdN BA possesses better thermal properties than the conventional Gd BA and has no issues on gas release for IFBA. Based on these findings, we are planning to design a SMR that can operate without soluble boron, utilizing GdN BA.

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