An Optimization Study of Fuel Assembly Designs with GdN-CBA Rods for Boron-Free Operation

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***Keywords**: Boron-Free Operation, GdN-CBA, Lattice Optimization

1. Introduction

Small Modular Reactors (SMRs) have received attention for their flexible deployment and inherent safety. Such flexibility and inherent safety come from novel design, including removal of chemical volume control system (CVCS) and soluble boron free (SBF) operation. However, SBF operation may have potential concerns, such as excessive use of control rods and burnable absorbers, which can lead to undesirable effects on the reactor performance.

To solve this concern, recently, new type of burnable absorbers (i.e., DiBA, CsBA and CIMBA) that utilizes self-shielding effect of gadolinium, have been studied [1][2]. Our previous research also explored the use of Gadolinium Nitride Coating Burnable Absorber (GdN-CBA) as a burnable absorber (BA) in SMR fuel assembly design [3]. The results showed that combining GdN-CBAs of different GdN coating thicknesses exhibited better performance than traditional gadolinia in controlling excess reactivity. Excessive utilization of GdN may adversely impact neutron economics, leading to reduced burnup and reactor cycle length. Additionally, when GdN is used in conjunction with SBF operation, it induces a highly negative moderator temperature coefficient (MTC). Such negative MTC can result in increased axial offset and the insertion of more positive reactivity in case of moderator temperature decrease, particularly during reactor shutdown or steam system piping failure situations. [4].

This paper conducts further the study of GdN-CBA to addresses these concerns. We will investigate the ideal pitch-to-diameter (P/D) ratios [5] and the optimal combination of thicknesses for GdN-CBA. The objective is to achieve an optimal fuel assembly design that minimizes the negative effects on highly negative MTC and neutron economics, while maximizing the reactor performance and safety.

2. Methodologies

The computational method and fuel assembly geometry are similar to those of our previous study [3]. The UO_2 fuel pellet with GdN-CBA is illustrated in Fig. 1. and geometry parameters are specified in Table I.

To analyze the impact of the Pitch-to-Diameter (P/D) ratio on the fuel assembly's excess reactivity, adjustments to the P/D ratio were considered. This could be achieved either by altering the pin pitch or the size of the fuel pellets. However, modifying the size of the fuel pellets might deliver negative effect on the cycle length. Therefore, we decided to focus on adjusting the pin pitch. The pin pitch was varied from 1.2 cm to 1.8 cm in increments of 0.02 cm. In addition, we aimed to get detailed nuclear characteristics from different thicknesses of the GdN-CBA. All the calculations were performed through DeCART2D, a code developed by the Korea Atomic Energy Research Institute (KAERI) [6]. For the cross-section, we applied 47-group for neutron and 18-group for gamma calculation, processed from the ENDF/B-VII.1 library. The pellet regions were divided into 3 sub-regions in UO_2 pellets and 8 sub-regions in GdN coating of GdN-CBA rods in order to reduce the calculation error due to the high neutron absorption cross section and self-shielding effect of Gadolinium. Furthermore, 0.005 cm of ray spacing, 12 azimuthal angles, and 4 polar angles were used for MOC calculations.

Table I. Geometries and parameters of fuel assemblies

Geometry of fuel assembly	
Assembly power (W/cm)	24.3 kW/cm
Fuel cladding outer radius	0.4750 cm
Pin to pin pitch	1.26 cm (reference) 1.32 cm (optimal)
Boron concentration	500 ppm
UO_2 fuel pins	
Fuel pellet radius	0.4096 cm
Fuel pellet density	10.220 g/cm^3
U-235 enrichment	4.95 wt.%
GdN-CBA fuel pins	
Fuel pellet radius	0.4096 cm ~ 0.3196 cm
U-235 enrichment	4.95 wt.%
GdN-CBA thickness	0.08 cm ~ 0.96 cm
GdN-CBA density	8.645 g/cm^3

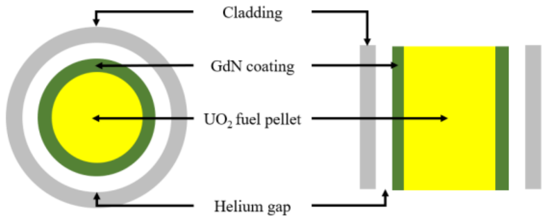

Fig. 1. Radial and axial configurations of GdN-CBA coated fuel pellet.

3. Analysis and Results

3.1. Optimizing P/D ratio

First, we explored the changes in excess reactivity and cycle length relative to the pin pitch of the fuel assembly, without considering GdN-CBA similar to the KAIST's study [4]. As displayed in Fig. 2, the infinite multiplication factor (k_∞) varied with the pin pitch. The pin pitch where maximum k_∞ occurs, was 1.7 cm under the boron-free condition, and gradually decreased as the boron concentration increased. Fig. 3 shows the cycle length (burnup where k_∞ reaches 1.01) of the fuel assembly with respect to the pin pitch. Under the boron-free condition, the cycle length showed a maximum value of 43.7 MWD/kgU for 1.36 cm pin pitch. However, in 500 ppm boron concentration, the cycle length was about 37.4 MWD/kgU and the pin pitch was 1.3 cm.

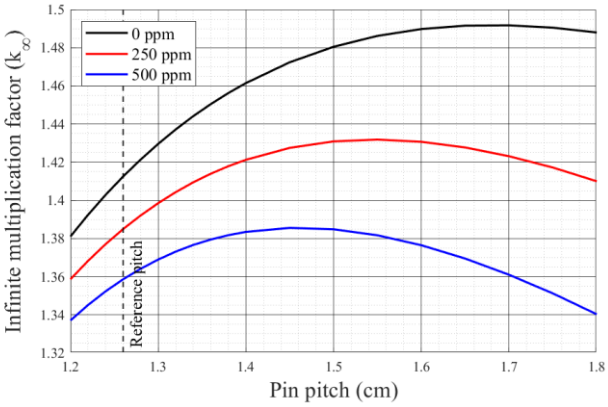

Fig. 2. Changes in the infinite multiplication factor at BOC as a function of pin pitch

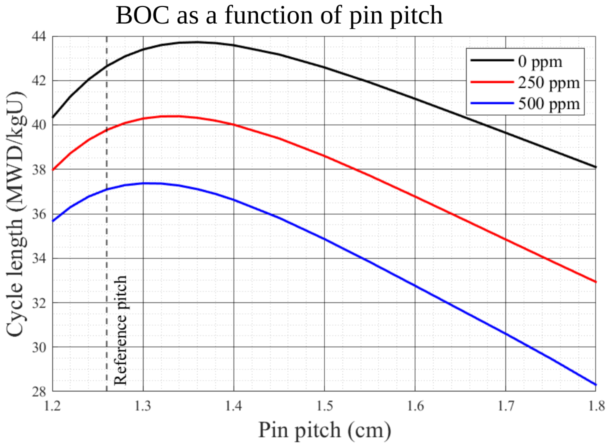

Fig. 3. Changes in the fuel assembly cycle length as a function of pin pitch

Next, we examined the changes in moderator temperature coefficient (MTC) and doppler temperature coefficient (DTC) at the beginning of the cycle (BOC), middle of the cycle (MOC, 20 MWD/kgU), and end of the cycle (EOC, 40 MWD/kgU) with respect to the pin pitch. Fig. 4 shows the MTC and Fig. 5 shows the DTC as a function of the pin pitch. MTC exceeded 3 pcm/°C when the pin pitch was 1.7 cm or more at BOC and MOC, and 1.6 cm at EOC. DTC was negative for all cases. Nevertheless, DTC became less negative as the pin pitch increased.

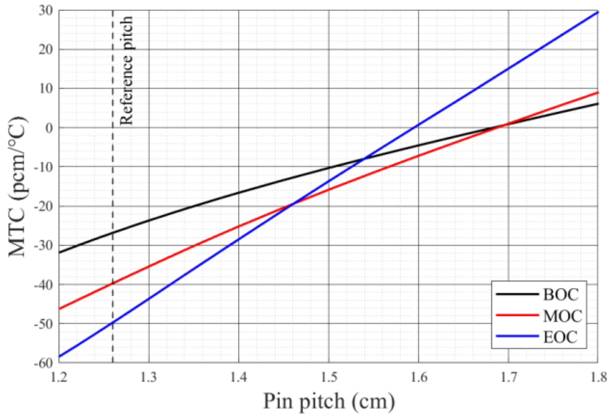

Fig. 4. MTC values at 0 ppm boron concentration, as a function of the pin pitch

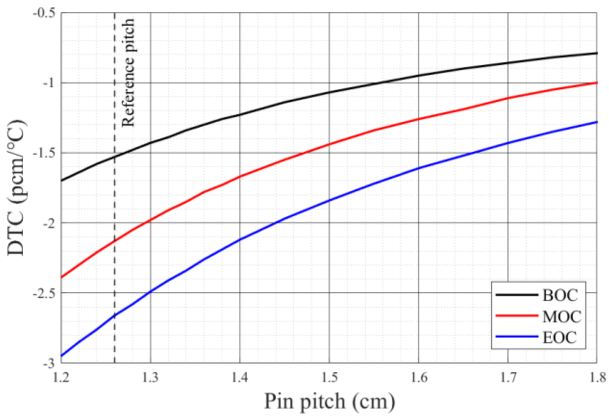

Fig. 5. DTC values at 0 ppm boron concentration, as a function of the pin pitch

Considering the cycle length and MTC, the optimal pin pitch was estimated to be in between 1.3 cm and 1.35 cm. If the pin pitch was longer than this, it had a negative impact from the perspective of cycle length, and the MTC and DTC became less negative, which could adversely affect inherent safety [6]. Thus, we adopted the pin pitch of 1.32 cm for the rest of the computational simulations.

3.2. Minima-maxima-mixing (MMM) strategy

Next, we explored a more detailed characteristics of GdN-CBA to identify an optimal combination of thicknesses. In order to figure out the burnout point of Gd relative to the thickness of the GdN-CBA, we assumed a fuel assembly as shown in Fig. 6, utilizing 28 GdN-CBAs. The evolutions of k_∞ as burnup for the various GdN thicknesses are compared in Fig. 7.

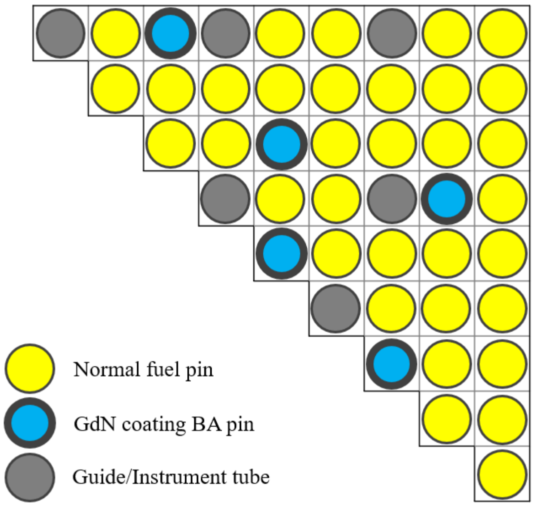

Fig. 6. Configuration of the fuel assembly used to search optimal GdN-CBA combination.

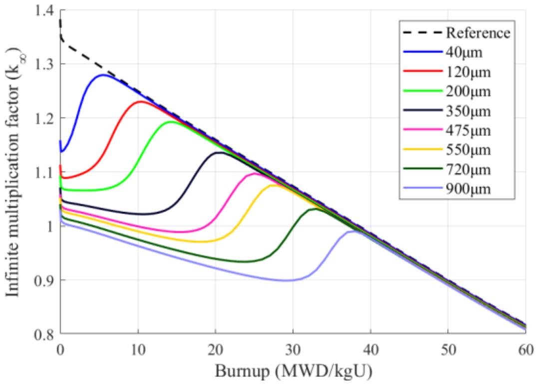

Fig. 7. Evolutions of the infinite multiplication factor of the fuel assembly with respect to GdN-CBA thickness.

From the computational simulations, it was found that as the thickness of GdN-CBA increases, the gadolinium burnout point is delayed. In particular, the local minimum in the excess reactivity appeared just before gadolinium burnout, and as burnup proceeds, the local maximum appeared. After that point, the fuel assemblies with GdN-CBA rods exhibited similar characteristics to the reference fuel assembly without GdN-CBA.

Fig. 8 shows the burnup points at which the local minimum and maximum of excess reactivity occur, depending on the thickness of the GdN-CBA. By connecting the two graphs horizontally, it is possible to find a combination of GdN-CBA thicknesses where the burnup of minimum and maximum reactivity coincides. By repeatedly performing this, the minimum and maximum reactivity overlap continuously throughout the cycle, thus reducing reactivity fluctuation. We named this strategy as Minima-Maxima-Mixing (MMM). For example, as shown in Fig. 8, vertical and horizontal lines can be drawn based on 25 MWD/kgU burnup, which allows us to find points where these lines intersect (i.e., the thickness of GdN-CBA). From this, we can ascertain that the optimal combination of thicknesses, which minimize the fluctuation of excess reactivity during the 25 MWD/kgU burnup, is approximately 700 μm, 475 μm, and 240 μm.

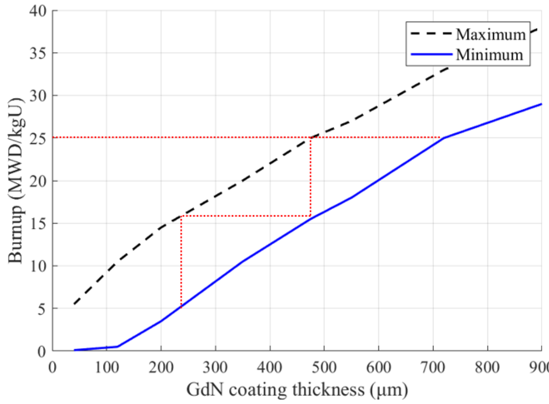

Fig. 8. The burnup point where local maximum and minimum reactivity occurs as a function of GdN-CBA thickness

3.3. Optimized fuel assemblies

Lastly, we designed fuel assemblies for soluble boron free (SBF) SMR, by utilizing the optimized pin pitch and the Minima-Maxima-Mixing (MMM) strategy. Computational simulations were performed assuming a boron-free condition. The selected two configurations of the fuel assembly are illustrated in Fig. 9. Actually, Type A and B assemblies are designed to have low and high reactivities, and so they could be loaded in the inner and outer regions of a core, respectively. Both fuel assemblies have a pin pitch of 1.32 cm. The thicknesses and number of the GdN Burnable Absorber (BA) pins are shown in Table II.

Table II. The number of GdN-CBA pins used for each type of fuel assembly.

	900 μm	700 μm	430 μm	260 μm	120 μm	80 μm
Type A	8	8	4	8	0	4
Type B	0	0	8	8	4	4

The results of the computational simulations are presented in Fig. 10 and Fig. 11. The Type A fuel assembly maintained an infinite multiplication factor of about 1.05 until reaching approximately 40 MWD/kgU, while the Type B fuel one maintained a level of around 1.12 until 25 MWD/kgU. For both type A and B fuel assemblies, pin pitch of 1.32 cm exhibited longer cycle length and higher infinite multiplication factor than the original fuel assembly designs with 1.26 cm pin pitch. The fluctuation of the multiplication factor throughout the entire cycle - the difference between the local minimum and maximum of multiplication factor - was less than 0.02 Δk throughout the entire cycle length, thus the issue of reactivity fluctuation was alleviated. The MTC values are maintained negative, without exceeding -45 pcm/°C, thereby resolving the issue of a highly negative MTC compared to the corresponding assemblies having 1.26 cm pin pitch. Therefore, the optimized fuel assemblies could be able to alleviate excessively negative MTC.

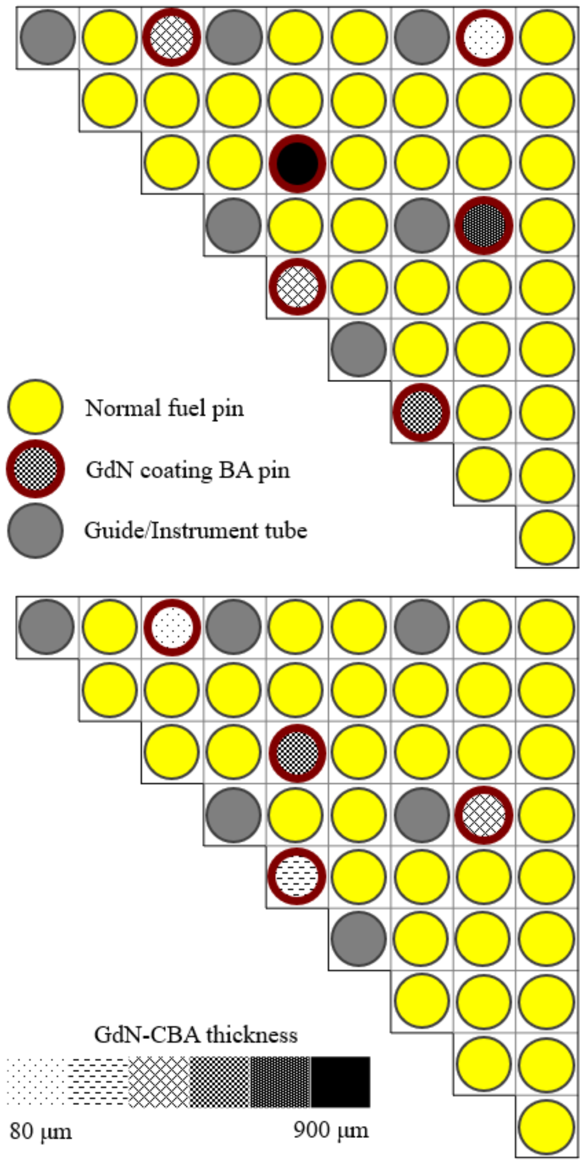

Fig. 9. Configurations of the type A (top) and type B (bottom) fuel assembly designs

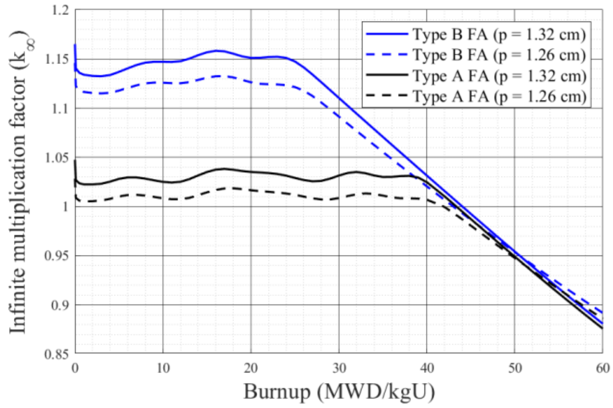

Fig. 10. The revolution of the infinite multiplication factor of Type A and B fuel assemblies

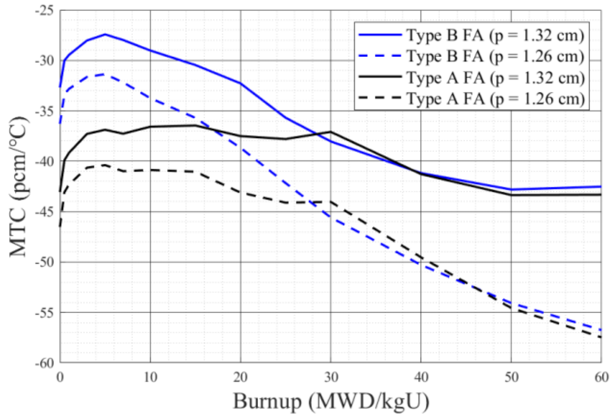

Fig. 11. The revolution of the MTC of Type A and B fuel assemblies

4. Conclusion

In this study, the fuel assembly design using GdN-CBA was optimized by fine-tuning the pitch-to-diameter (P/D) ratio and thickness combinations for GdN-CBA. The optimal pin pitch was identified as 1.32 cm, and thickness combination was determined via Minima-Maxima-Mixing (MMM) strategy. The optimal pin pitch increased fuel cycle length and made MTC less negative relatively to the original design. The MMM strategy successfully mitigated reactivity fluctuations. The optimized fuel assembly exhibited promising results, maintaining an acceptable infinite multiplication factor, and mitigating issues associated with highly negative MTC. These findings highlight the potential of our approach to effectively improve the safety and performance of SMRs operating under soluble boron-free conditions.

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