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A Preliminary SMR Core Design using LEU+ Fuels with Gadolinium-Nitride Coating Burnable Absorber

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1. Introduction

Recent global efforts towards low-carbon initiatives have led to active research into Small Modular Reactors (SMRs). SMRs has the advantages of more flexible installation and maintenance, and lower initial investment costs compared to traditional large-scale nuclear power plants. However, the weakness of SMRs such as short cycle lengths and low burnup due to its smaller core size has remained a significant obstacle in achieving overall economic efficiency.

In this study, we propose the use of Low Enriched Uranium Plus (LEU+) fuel, which possesses a higher enrichment level, to overcome these issues, in a PWR-based SMR core. Utilizing higher-enriched fuel (< 10wt%) is an effective strategy for extending cycle lengths and increasing burnup and also greatly enhances the operational efficiency [1]. Also, high burnup fuels reduce the spent fuel generation per electricity production. However, the advanced fuels which can sustain the high burnup without violation of their integrity should be considered with LEU+. So, the current uranium oxide fuel is not suitable for LEU+ due to its limit in burnup. In this work, we adopted accident tolerant fuel having chromium coating on cladding [2]. Chromium coating was designed to improve the durability of fuel rod, ensuring stable performance even in high burnup environments (< 75MWd/kg).

On the other hand, as the uranium enrichment in the fuel rods has risen, the excess reactivity has also increased. Previous research has shown that GdN-CBA has good capability for controlling reactivity [3]. In this work, we used the GdN-CBA to effectively control the excess reactivity.

2. Computer Code and Modeling

2.1 Burnable Absorber(BA)

The GdN-CBA burnable absorber used in this work is explained in **Fig. 1** and **Table I**. The GdN coats the GdN on the fuel pellet from the outside to the inside. That is to say, the fuel pellet radius including GdN coating is the same as the ones of the normal fuel pins having no GdN-CBA. Also, the GdN coat is featured by its high thermal conductivity and no issue on gas generation as in ZrB_2 coating of IFBA.

2.2 Computer Code

The core design and analysis consists of two steps, assembly burnup calculations and core burnup calculations, which were performed using DeCART2D and MATER, respectively. Both codes were developed by Korea Atomic Energy Research Institute (KAERI). DeCART2D is 2D fuel assembly and core calculation code using MOC for solving transport equation and sub-group method for resonance self-shielding [4]. In DeCART2D, homogeneous cross-sections are generated and these cross-sections are then used for core calculations in MASTER [5]. The cross-section data in DeCART2D were obtained from the ENDF/B VII.1 library.

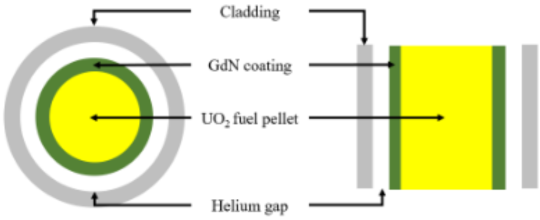

Fig. 1. Radial and axial configurations of fuel pellet with GdN BA

Table I. Specification of GdN-CBA rods

GdN BA fuel pin	
Feul pellet radius	0.3796 cm or 0.3596 cm
GdN coating thickness	0.0300 cm or 0.0500 cm
Outer radius of cladding	0.4750 cm
GdN coating density	8.645 g/cm

3. Design Analysis and Results

3.*1 Fuel Assembly(FA)*

Fig. 1 shows the GdN-CBA rod design, where a GdN layer is coated on the UO_2 fuel pellet. The GdN-CBA has a structure like IFBA but is applied by removing part of the outer UO_2 layer. GdN-CBA is a good candidate for burnable absorber material because it has high thermal neutron absorption cross-section, high melting point, and thermal conductivity. In our previous work, it was shown that GdN-CBA can have smaller residual penalty on the cycle length reduction than the conventional gadolinia burnable absorber [3]. **Table I** summarizes two types of GdN-CBA having two different dimensions.

Table II represents the design parameters of fuel assemblies. The FA design followed the Westinghouse method, with the exception of chromium coating on the cladding tube outside of the fuel rod, which was applied considering the burnup limit. The thickness of the chromium coating is 30 µm [2].

During the FA calculations, it was observed that GdN-CBA exhibits favorable behavior in high uranium enrichment. In **Fig. 2,** it can be observed that as uranium enrichment increases, the burnup time at which GdN is burnt out is delayed even with the same thickness of GdN, and the reactivity swing decreases. The reasons for these phenomena can be found in the code calculation process. During DeCART2D calculations, the power remains constant, indicating that the fission rate is fixed. This suggests that the neutron spectrum is harder for the higher uranium enrichment case than the lower one, which leads to the lower depletion rate of GdN. Thanks to this phenomenon, as shown in **Fig. 3** and **Table III**, Fuel Assemblies (FAs) utilizing high-enriched uranium showed lower reactivity swing with small GdN thickness variations, resulting in relatively flat profiles of reactivity compared to FAs with lower-enriched uranium. The delayed burnup of GdN also led to no significant increase in thickness of GdN coating. Two types of thicknesses, 0.0300 cm and 0.0500 cm, were employed, with different uranium enrichments of 3.2, 3.9, 5.4, 6.8, and 7.95 wt% over different types of FAs.

Table II. Design parameter of fuel assemblies

Design parameter of fuel assemblies	
Fuel rod array square	17 x 17
FA pitch (cm)	21.5
Fuel pin pitch (cm)	1.26
Number of instrument / guide tube	25
Number of fuel rod	264
Fuel pellet density (g/cm^3)	10.212~10.217
U-235 enrichment (wt%)	3.2 ~ 7.95
Fuel pellet radius (cm)	0.4096
Fuel cladding inner radius (cm)	0.4178
Fuel cladding outer radius (cm)	0.4750
Cladding material	Zircaloy-4
Fuel Cr coating inner radius (cm)	0.4750
Fuel Cr coating outer radius (cm)	0.4780
Coating material	Cr

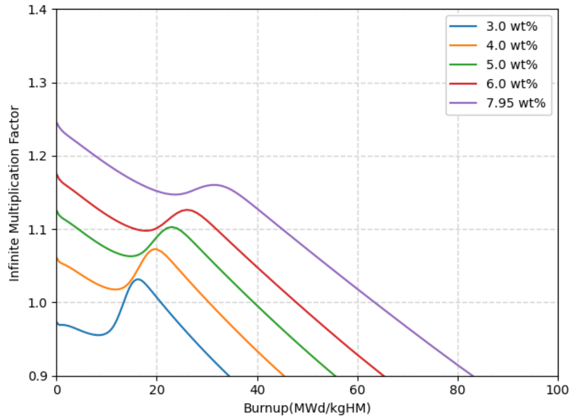

Fig. 2. Comparison of the k_{inf} changes over burnup for different uranium enrichments.

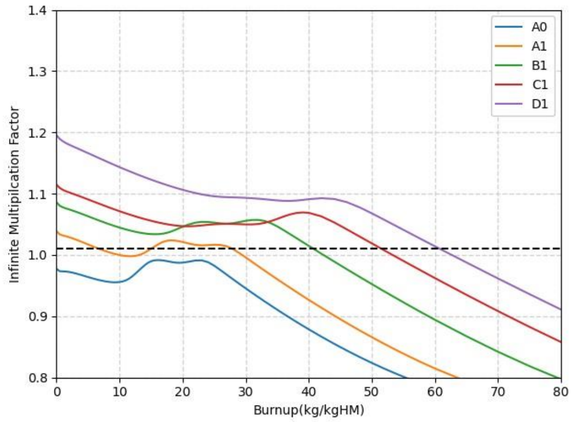

Fig. 3. Comparison of k_{inf} with respect to FAs

Table III. Design parameters of fuel assemblies

Type	A0	A1	B1	C1	C2
Enrichment (wt%)	3.2	3.9	5.4	6.8	7.95
BA coating thickness (cm) / Number of BA in FA	0.03/12 0.05/8	0.03/12 0.05/8	0.03/12 0.05/12	0.03/8 0.05/20	0.03/12 0.05/12
Total # of BA in FA	20	20	24	28	24

3.2 Core

LEU+ fuel uses a higher uranium enrichment than the conventional one, leading to increased reactivity, which requires an effective control. Therefore, BA becomes important because of increased reactivity. High boron concentration without effective control of reactivity can induce a positive MTC and increase liquid waste production. However, an excessive usage on BAs may negatively impact cycle lengths or result in the pin power peaking factors. **Table IV** summarizes the design parameters and targets of the core. The core generates 180MWth thermal power and is 200cm tall. The core consists of 37 fuel assemblies and it adopted a lower linear power density (92.13 W/cm). SS304 is adopted as reflector. In this work, a 3-batch fuel management strategy was employed to increase fuel burnup and to control excess reactivity, coupled with GdN-CBA. **Fig. 4** compares core loading patterns for the first and equilibrium cycles. In the equilibrium cycle core, the C1, C2, and A1 type assemblies are used and the C1 and C2 type fuel assemblies are irradiated for three cycles before discharge, while the A1 type ones are utilized for only one cycle before being discharged. Their enrichments are 8 wt%, 6.8 wt%, and 3.2 wt%, respectively. To bridge the transition from cycles 1 and 2 to the equilibrium cycle, the A2 and B1 type assemblies were introduced. These A2 and B1 type assemblies with 3.2 wt% and 5.6 wt% uranium enrichments, respectively are irradiated for one and two cycles, respectively. This core was designed to closely approach the burnup limit by the equilibrium cycle. In particular, the every cycle core was designed to have similar cycle length such that the pin-wise burnup does not exceed the burnup limit (i.e., 75 MWd/kg) at earlier cycles.

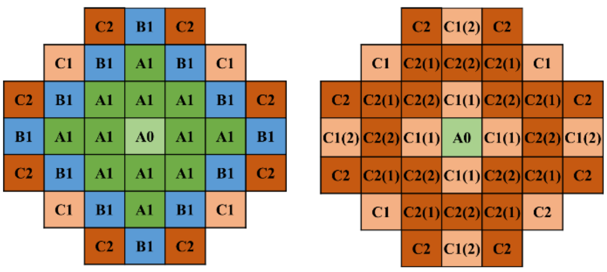

Fig. 4. Figurations of cycle 1 and equilibrium cycle core

Table IV. Design parameters and target of core design

Parameters	Values
Full core power	180 MWth
Active core height	200 cm
Equivalent core diameter	150.5 cm
Average linear power density	92.13 W/cm
Fuel management scheme	3 batchs
Number of FAs in core	37
Maximum CBC over cycle	1400 ppm
Minimum cycle length	1000 EFPD
Maximum Fxy / Fxyz	2.0 / 2.5
AO range	-0.3<AO<0.3

3.3 Core Analysis Results

The important goal of the LEU+ core design in this study was to avoid a positive MTC by limiting excessive boron concentration and to maximize burn up within its limit, using the GdN-CBA burnable absorber rods.

Table V summarizes the main results of the first and equilibrium cycle core design analysis. The maximum CBC (Critical Boron Concentration) for the first and equilibrium cycle cores are 893 and 1315 ppm. The MTC and FTC values are negative for both cycle cores Also, the 2D power peaking factors are lower than 1.5 and the 3D power peaking factors are lower than 2.5, and in the case of the equilibrium cycle, it was maintained below 2.08. The axial offset also meets the design criteria.

Table V. Result of the core parameter 1 cycle and equilibrium cycle

Cycle		1	Equilibrium
Maximum CBC (ppm)		893	1315
Maximum F_{xy}		1.46	1.50
Maximum F_{xyz}		2.08	1.88
Maximum axial offset in absolute value		0.091	0.039
MTC (pcm/℃)	HFP (BOC / EOC)	-40.73/-63.04	-37.68/-69.51
	HZP (BOC / EOC)	-26.63/-39.71	-22.68/-46.24

Fig. 5 compares the changes of CBC over cycles. As shown in this figure, CBCs are lower than 1360 ppm for all the cycles and the cycle lengths are not much different over the cycles.

Table VI shows the discharge burnups of the A0, C1, and C2 fuel assemblies in the equilibrium cycle core. This table shows that all of the rod-wise discharge burnups do not exceed the rod averaged burnup limit. The core average discharge burnup is about 58 MWd/kg.

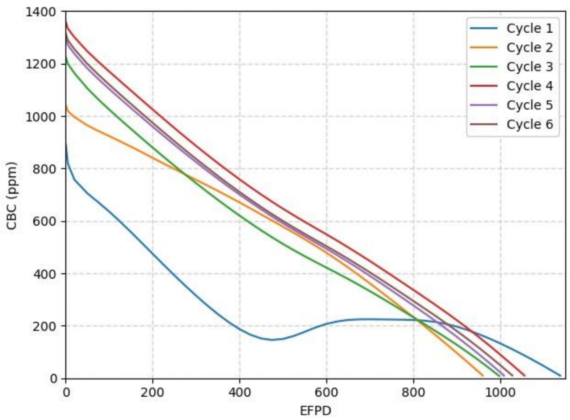

Fig. 5. Change of CBC over EFPD for cycle 1~6

Table VI. Average FA discharge burnup and maximum rod average burnup in the equilibrium cycle core

FA types	A0	C1	C2
Average FA burnup (MWd/kgHM)	21.8	56.6	63.2
Maximum rod average burnup(MWd/kgHM)	24.10	65.64	72.02

4. CONCLUSION

In this work, a PWR-based SMR core loaded with LEU+ fuels of Cr coated cladding was designed using the GdN-CBA burnable absorber to improve cycle length and burnup, and neutronically analyzed. The core used SS304 as the reflector. In the equilibrium cycle, the core was loaded with 6.8 and 7.95% uranium enrichment fuel assemblies except for one fuel assembly having 3.2% uranium enrichment fuels. In particular, the core employed only two different thickness of GdN coating for simplification in manufacturing GdN-CBA rods.

From the analysis, it was shown that the core has cycle lengths longer than 960 EFPD, reasonably low power peaking factors, negative reactivity coefficients (i.e, MTC and FTC), and high fuel assembly discharge burnup of 58 MWd/kg. The maximum fuel pin burnup is less than 75 MWd/kg which is considered as burnup limit. The maximum CBC is less than 1360 ppm over all the cycles.

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