Applicability Evaluation of Enriched Gadolinium as a Burnable Absorber in Assembly Level for Boron-Free i-SMR core

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1. Introduction

Innovative-Small Modular Reactor (i-SMR) considers boron-free operation as one of its top requirements. The boron-free core must control excess reactivity with only control rods and burnable absorber (BA). In order to secure shutdown margin and to improve the control rod operation strategy at the same time, it is important to maximize the ability to control excessive reactivity using BA.

Gadolinia(Gd_2O_3) has a large absorption cross-section, therefore it is widely used to suppress excessive reactivity. The gadolinia depletes too rapidly, however, the residual poisoning effect at the end of the cycle is too small, which makes it difficult to control the infinite multiplication factor after the middle of cycle (after around 10 GWD/T). Also, it is difficult to control the power peaking factor because the internal power distribution of fuel assembly has severe fluctuation when the gadolinia pellets are depleted completely. To avoid the fast burnout, a higher content of gadolinia can be used in a burnable absorber. However, as the gadolinia content increases, the thermal conductivity and the melting point of its mixture (UO_2-Gd_2O_3) are reduced. As the result, currently, the gadolinia content in UO_2-Gd_2O_3 pellets is usually 2 ~ 8 wt% for commercial operation.

In this paper, the effect of enriching ^{155}Gd and ^{157}Gd isotopes that have large thermal neutron absorption cross-section were evaluated from the natural Gd (i.e., 30% ^{155,157}Gd) up to 99%. The results showed that, in terms of multiplication factor, enriching ^{155}Gd and ^{157}Gd isotopes has the effect of increasing the weight percent of Gadolinia in the BA pellet.

2. Methods and Results

2.1 Computational Methods

Assembly burnup calculations for two group cross section generation were calculated by KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly) [1] [2] which is a two-dimensional multi-group lattice transport code using 190 group and 47 group cross section library based on ENDF/B-VI.8. This code uses the subgroup method for resonance self-shielding effect and MOC (Method of Characteristics) as the transport solution mehtod. For simple verification, ASTRA code was used for 3D core calculation [7]. ASTRA code is a 3D core depletion code and developed by KEPCO NF (KEPCO Nuclear Fuel) as a nuclear design code for the core design of pressurized water reactors (PWRs) based on the reactor physics technologies. ASTRA has the neutronic solver based on the Semi Analytic Nodal Method (SANM) formulated with the Coarse-Mesh Finite Difference method (CMFD). [8,9]

2.2 Parameter and Geometry Data

The calculations were done with Westinghouse Electric Corporation(WEC) type 17x17 fuel assembly. Table I shows the input parameters such as fuel assembly geometry, thermal power, uranium enrichment, and number of gadolinia rods considered in this work.

Table I. i-SMR design and fuel assembly information

Parameter	Unit	Value
Reactor thermal power	MWt	540
Fuel assembly array		17x17
Fuel assembly height	cm	240
Number of fuel rods		264
Number of guide tubes		24
Fuel enrichment	wt%	4
Number of gadolinia rods	EA	20
Fuel rod		
Pellet outer diameter	inch	0.3225
Rod pitch	inch	0.4960
Cladding inner diameter	inch	0.3290
Cladding outer diameter	inch	0.3740
Guide tube inner diameter	inch	0.4420
Guide tube outer diameter	inch	0.4820
Cladding material		HANA

Fig. 1 shows the WEC type 17x17 fuel assembly configuration used in the work. The burnable absorber (UO_2-Gd_2O_3) rods are located in 20 pin positions for control of the excess reactivity. This geometry is used in all calculations. Only the Gd isotopic composition of UO_2-Gd_2O_3 pellets is changed in the calculation cases. The reflective boundary conditions are used for all the boundaries.

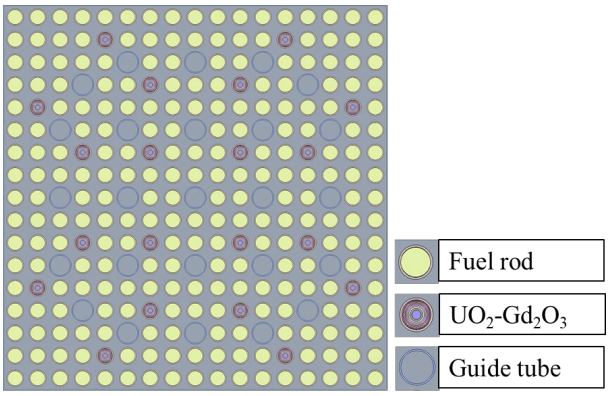

Fig. 1. 17x17 fuel assembly configuration(4.0% ^{235}U enrichment, 20 Gd_2O_3 BA rods)

2.3 Results of Natural Gadolinia

Fig. 2 compares the changes in infinite multiplication factor (k-inf) using natural isotopic ratio of gadolinium isotopes. The Gd_2O_3 content is varied from 2 wt% to 14 wt% with 4.0% ^{235}U enrichment in normal UO_2 pins. As the Gd_2O_3 content increases, the self-shielding effect reduced the effective absorption cross-section of burnable absorber [3]. The hold-down effect increases and k-inf value becomes more flatter as Gd_2O_3 content increases. In Fig. 2, the k-inf for 2 wt% Gd_2O_3 content case increased sharply from 1.15 to 1.25 and decreased after 6 GWD/MTU. On the other hand, the k-inf of 14 wt% Gd_2O_3 content stays around 1.06 until around 25 GWD/MTU.

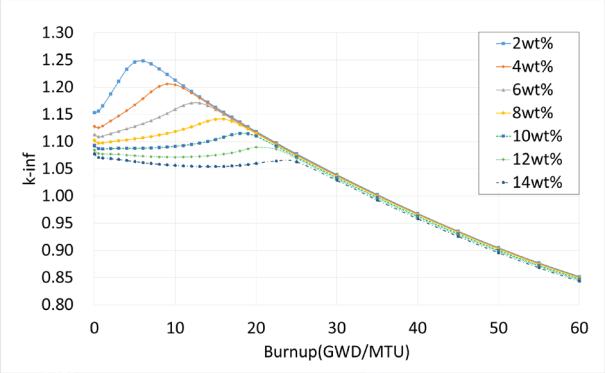

Fig. 2. Comparison of k-inf versus burnup (4.0% ^{235}U uranium enrichment, 20 BA rods) for various Gd_2O_3 contents

Table II summarizes the burnout points at which Gd is almost completely depleted, which shows that the burnout point of Gd_2O_3 significantly increases as the content of Gd_2O_3 (wt%). In order to achieve longer cycle length controlling the excess reactivity without soluble boron, it is necessary to use BA with a higher Gd_2O_3 content.

Currently, 2 ~ 8 wt% Gd_2O_3 contents are mainly used in commercial operation. To avoid the disadvantage of the high Gd_2O_3 content such as the effect of lower thermal conductivity and melting temperature, we searched for the assemblies giving a similar ability in controlling excess reactivity with consideration of high enriched Gd [4].

Table II. Burnout points of Gd_2O_3 depletion as a function of Gd_2O_3 content

Gd_2O_3 wt%	Burnup (MWD/MTU)
2	6,000
4	10,000
6	13,000
8	16,000
10	19,000
12	21,000
14	25,000

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Fig.3 shows the results of k-inf as a function of burnup considering the different isotope ratio of Gd including ^{155}Gd enriched only, ^{157}Gd enriched only, and ^{155,157}Gd enriched together. Since the ^{157}Gd has a larger neutron absorption cross section area compared to ^{155}Gd, the ^{157}Gd enriched only case showed that the k-inf is lower compared to the ^{155}Gd enriched only case at the beginning and reversed as it progresses to the second half. In the case of ^{157}Gd enriched only, a sharp rise of power occurs at around the burnout point. The proportional ratio of ^{155}Gd and ^{157}Gd simulated with red lines was used in this study since the dependency is negligible in terms of k-inf [5].

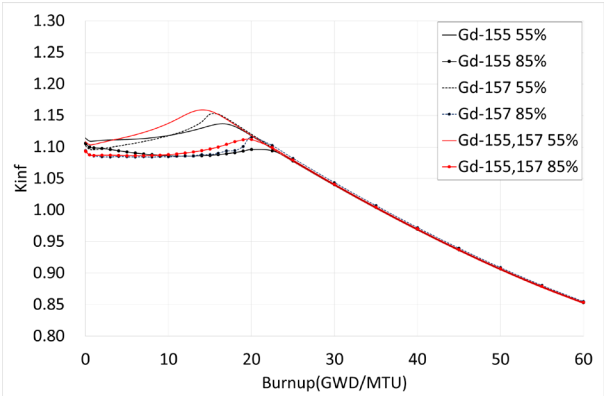

Fig. 3. Infinite neutron multiplication factor as a function of burnup considering the different isotope ratio of ^{155}Gd enriched only, ^{157}Gd enriched only, and ^{155,157}Gd enriched together (4.0% ^{235}U enrichment, 20 BA rods (4 wt% Gd_2O_3))

2.4 Results of Enriched Gadolinia

The enrichment of ^{155,157}Gd is varied up from 30% to 99% with an increase step of 5% while the content of Gd_2O_3 in UO_2-Gd_2O_3 is changed from 1 wt% to 10 wt% to show the effect of ^{155,157}Gd enrichment on the reactivity change. Fig. 4 shows the change in k-inf with various combinations of ^{155,157}Gd enrichments and Gd_2O_3 contents. The natural Gd case uses 12 wt% Gd_2O_3 content with the Gd burnout point of around 21.0 GWD/MTU, and the k-inf stay around 1.07 until the burnout point. The k-inf values of all the enriched cases stay around 1.07 until around 21.0 GWD/MTU.

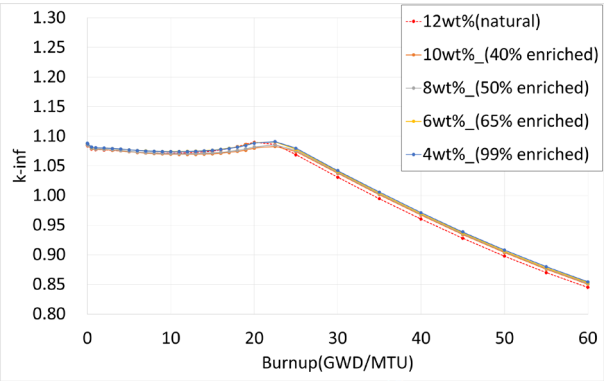

Fig. 4. Infinite neutron multiplication factor of burnup (4.0% ^{235}U enrichment, 20 BA rods)

Table III shows the abundances of the enriched and natural isotopes of Gd [6]. The enrichments for the cases considered here were assumed to be performed by maintaining the fixed ratio of ^{155}Gd and ^{157}Gd of the natural Gd.

We searched for assemblies with excess reactivity control effect such as 12 wt% natural Gd through the sensitivity evaluation of various cases. For stable excess reactivity control of the initial and reload cycle of boron free i-SMR, we need assemblies that have various excess reactivity. In Fig. 2, we can find that assemblies using 10 wt% ~ 14 wt% Gd show a long burnout point and flat excess reactivity. In Fig. 4, we can see that assemblies using high enriched ^{155,157}Gd have similar performance to that of high content Gd through the sensitivity evaluation of the enriched Gd.

Table III. Abundances of enriched Gd and natural Gd.

Isotope	Abundance (%)				
^{152}Gd	0.2	0.17	0.14	0.10	0.00
^{154}Gd	2.18	1.88	1.57	1.10	0.03
^{155}Gd	14.8	19.44	24.30	31.59	48.12
^{156}Gd	20.47	17.66	14.72	10.30	0.29
^{157}Gd	15.65	20.56	25.70	33.41	50.88
^{158}Gd	24.84	21.43	17.86	12.50	0.36
^{160}Gd	21.86	18.86	15.72	11.00	0.31
Sum ^{155,157}Gd	30.45 (nat.)	40	50	65	99

Fig. 5 shows the required Gd_2O_3 contents and enrichments of ^{155}Gd and ^{157}Gd to have the same burnout point as 12 wt% Gd_2O_3 with natural Gd. This figure shows that 10 wt% of Gd_2O_3 with the 40% enriched Gd is required to achieve the same performance of 12 wt% Gd_2O_3 with natural Gd. As the Gd content decreases, the same performance as 12 wt% Gd_2O_3 with natural Gd can be achieved with a higher ^{155,157}Gd enrichment. This graph can help the core designer to select the Gd enrichment of assembly for loading in the core. Since the uranium enrichment of UO_2-Gd_2O_3 decrease as the Gd_2O_3 content increase, it is possible to control the amount of uranium in the core and give an advantage to the cycle length.

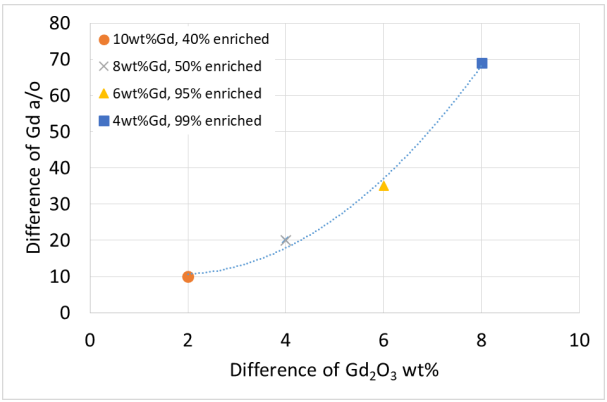

Fig. 5. Comparison of the enrichment difference between natural Gd and enriched Gd as a function of the difference in Gd_2O_3 (wt%) contents from 12 wt% Gd_2O_3 with natural Gd

Fig. 6 shows the required enrichment of ^{155,157}Gd as a function of the Gd depletion point for each Gd_2O_3 content. To increase the Gd depletion time to 20,000 MWD/MTU, the cases using 4 wt%, 6 wt%, 8 wt%, and 10 wt% Gd_2O_3 contents require 90%, 60%, 45%, and 35% ^{155,157}Gd enrichments, respectively.

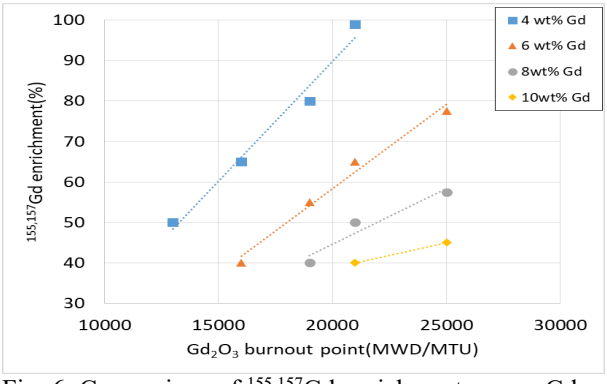

Fig. 6. Comparison of ^{155,157}Gd enrichment versus Gd bunrnout point versus Gd_2O_3 content (wt%)

It can be confirmed that the burnout point increase when the content of Gd_2O_3 increases or the concentration of Gd increases at the same content of Gd_2O_3. This graph can help determine whether to

increase the total amount of Gd_2O_3 content or increase the $^{155,157}Gd$ enrichments to change the cycle length of the core.

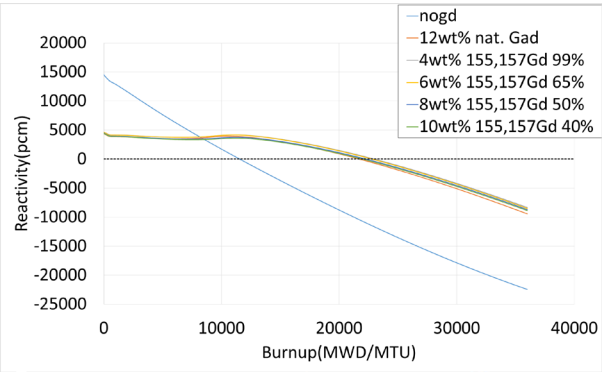

Fig. 7. The reactivity results of 3D core calculation using only one type assembly in the core as a function of burnup (69 Fuel assemblies)

To verify the results, we analyzed the 3D core calculation. The i-SMR core has a reactor power rate of 540 MWt. It consists of 69 fuel assemblies with only one BA rods type. Fig.7 shows that the results of a core composed of assemblies with 12 wt% natural Gd have the similar reactivity as that of a core with a low-content, high enriched Gd assemblies.

3. Summary and Conclusions

In the boron-free i-SMR core, the excess reactivity is controlled by control rods and BA rods. In order to achieve the longer cycle length under sufficiently controlled excess reactivity with only burnable absorbers, it is necessary to use higher Gd_2O_3 content, which leads to degradation of thermal conductivity. In this work, the use of enriched Gd in $^{155,157}Gd$ in the i-SMR core was suggested to achieve longer Gd burnout point, and its application was analyzed with fuel assembly depletion calculations. From the results of the analysis, it was found that the long burnout point of Gd comparable to those of high Gd_2O_3 contents can be achieved with high Gd enrichments with low Gd_2O_3 contents. It can help the core designer to select the Gd enrichment of assembly in the core for the cycle length prediction. It can be also found that the burnout point increase when the content of Gd_2O_3 increases or the concentration of Gd increases at the same content. It can help determine whether to increase the total amount of Gd_2O_3 contents or increase the $^{155,157}Gd$ enrichments to change the cycle length of the core.

However, the feasibility of using enriched Gd as BA should be analyzed through the future core-level caculation.

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