Effect of U-235 Enrichment on Depletion Characteristics of Gadolinia Burnable Absorber

YuGwon Jo[a*] and Jae-Yong Lim[a]
[a]Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 34057
[*]*Corresponding author: yugwonjo@kaeri.re.kr*

1. Introduction

The goal of accident tolerance fuel (ATF) technology in light water reactor (LWRs) is to enhance the safety by improving the oxidation resistance not only in the accident condition but also during the normal operation, which is expected to extend the licensed burnup limit to 65-68 GWd/tU or even higher 75 GWd/tU. Since the ATF technology such as zircaloy cladding coated with chromium or stainless steel reduces the neutron economy, the nuclear industry aspires to increase the licensed limit of U-235 enrichment beyond 5 wt%.

In this circumstance, the commercial LWR operators and fuel vendors in United States launched the low-enriched uranium plus (LEU+) project [1-4] to increase the maximum U-235 enrichment up to 10 wt% which is expected to meet the regulator requirements without involving significant design changes in entire stages of nuclear fuel cycle including enrichment, fabrication, transportation, irradiation, and storage. The LEU+ project aims to improve the economy of commercial LWRs by enhancing capacity factor through the high burnup long-cycle operation and reducing the amount of spent fuel per energy produced. Furthermore, it is also preferred in the small modular reactors (SMRs) to overcome the high neutron leakage characteristics.

This paper presents a preliminary investigation of neutronics of LEU+ in the aspect of the depletion characteristics of the gadolinia burnable absorber (GAD) since the excess reactivity control of LEU+ can be important for the high-burnup core design. The lattice depletion calculations were performed by DeCART2D code [5] developed by Korea Atomic Energy Research Institute (KAERI). The numerical results show that higher enrichment hardens the neutron spectrum and reduces the thermal neutron capture reactions by Gd-155 and Gd-157. As a result, the depletion of the GAD becomes slower, providing a means to control high burnup excess reactivity around 30 GWd/tU.

2. Neutronics Analysis of LEU+

2.1. Spectral Analysis without GAD

In a standard 17x17 fuel assembly design, the multi-group lattice transport calculations were performed by the DeCART2D code to analyze the spectral effect with various U-235 enrichments at the beginning of life (BOL) condition, where, the DeCART2D uses 47-group library based on ENDF/B-VII.1 [6]. Figure 1 shows the spectrum hardening effect of higher U-235 enrichment, which is explained by the relatively enhanced neutron absorption by U-235 especially in intermediate and thermal energy range, compared to U-238 (see Figure 2).

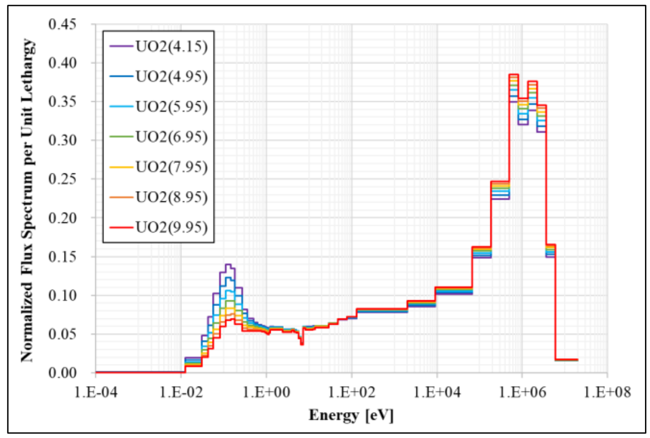

Figure 1. Normalized neutron flux spectra per unit lethargy for various U-235 enrichments in a standard 17x17 fuel assembly without burnable absorber.

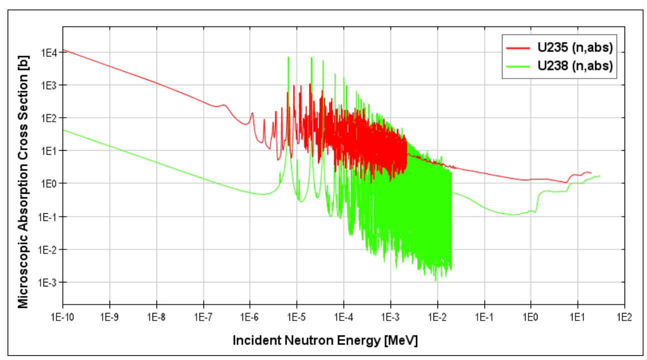

Figure 2. Comparisons of microscopic absorption cross sections of U-235 and U-238 (ENDF/B-VII.1).

2.2. Depletion Analysis with GAD

Table I shows three test cases for the lattice depletion calculations. Case 1 represents a conventional fuel assembly consisting of 245 normal fuel pins with 4.15 wt% and 24 GAD pins, where the GAD content is 10 wt% of gadolinia and 2.2 wt% of U-235, where the GAD with 10 wt% of gadolinia has the irradiation experience in the LWR [7]. Case 2 represents a fuel assembly consisting of LEU+ normal fuels with 7.0 wt% and 44 GAD pins. The number of GAD pins in Case 2 was determined to obtain an equivalent k-inf to that of Case 1, where the GAD contents are the same. In Case 3, the U-235 enrichment of the normal fuel is same as the Case 1 but the number of GAD pin is taken from Case 2.

Table I. Test cases for depletion analysis

Case id	Case Name	Normal Fuel Enrich. [wt%]	No. of GAD Pins	k-inf
Case 1	UO2(4.15)-GADx24	4.15	24	1.04406
Case 2	UO2(7.00)-GADx44	7.00	44	1.04079
Case 3	UO2(4.15)-GADx44	4.15	44	0.88134

Figure 3 compares the k-inf curves for three test cases, while Figure 4 compares the odd gadolinium isotopic density as the burnup proceeds. In Cases 1 and 3, the GAD is burn out around 18 GWd/tU, while it is further extended around 28 GWd/tU in Case 2. It is observed that regardless of the number of GAD pins, higher U-235 enrichment leads to the slower depletion of the GAD. It is noted that the loss of uranium loading in Cases 2 and 3 is less than 1% compared to Case 1.

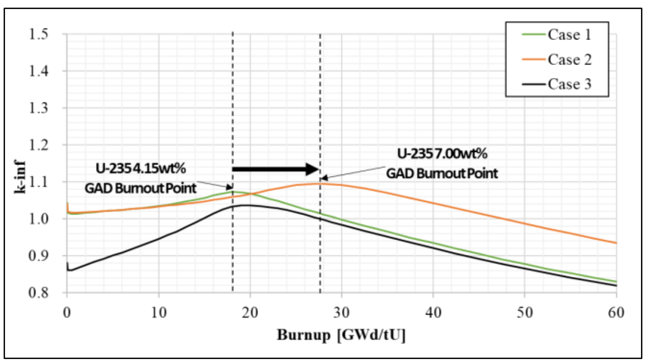

Figure 3. Comparisons of k-inf vs. burnup for three test cases.

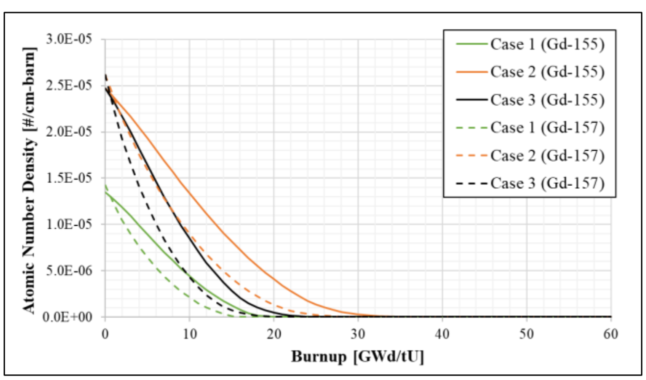

Figure 4. Comparisons of odd gadolinium isotopic density vs. burnup for three test cases; solid line indicates Gd-155 and dashed line indicates Gd-157.

The aforementioned behavior can be explained by the spectrum hardening effect resulting from higher U-235 enrichment, as discussed in section 2.1. Table II shows the spectral index, which is the fast-to-thermal flux ratio, and the thermal group microscopic capture cross sections of Gd-155 and Gd-157 for three test cases at the BOL condition. The higher spectral index indicates a lower thermal flux level for a given power density. The spectrum hardening effect also reduces the thermal group capture cross section, as shown in Figure 5. Both the lower thermal flux level and the reduced thermal group capture cross section resulting from the spectrum hardening lead to the slower depletion of the GAD.

Table II. Spectral index and thermal group microscopic capture cross sections of Gd-155 and Gd-157 for three test cases at BOL condition

Case id	Case Name	Spectral Index(F/T)	Thermal miXS* [b]	
			Gd-155	Gd-157
Case 1	UO2(4.15)-GADx24	6.385	322	1,349
Case 2	UO2(7.00)-GADx44	9.189	302	1,244
Case 3	UO2(4.15)-GADx44	6.906	322	1,349

*The energy boundary between thermal and fast groups is 1.825 eV.

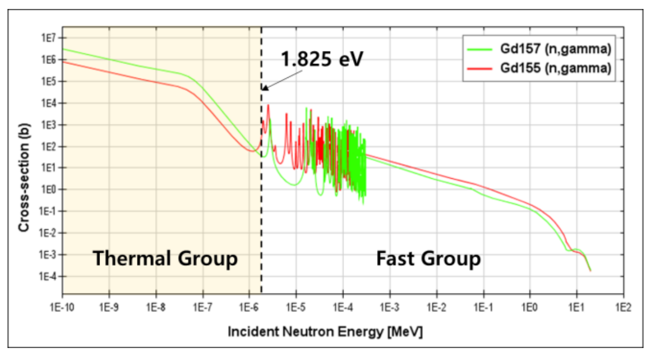

Figure 5. Microscopic capture cross sections of Gd-155 and Gd-157 (ENDF/B-VII.1).

3. Summary and Conclusion

This study demonstrated the capability of the conventional gadolinia burnable absorber (GAD) with 10 wt% of gadolinia to control the high-burnup excess reactivity of LEU+ fuel. Due to the spectrum hardening effect of higher U-235 enrichment, the depletion speed of the GAD is effectively reduced and the GAD becomes more efficient for high-burnup reactivity control in the LEU+ fuel.

Acknowledgement

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