Assessment of Radiation Stability in Gd_2O_3-MOx Burnable Absorber for i-SMR

Yunsong Jung *, Dong Seok Kim, Jae Ho Yang, Dong-Joo Kim, Ji-Hae Yoon, Ji Hwan Lee, Hyeon Jin Kim
LWR Fuel Technology Research Division, Korea Atomic Energy Research Institute
**Corresponding author: ysjung33@kaeri.re.kr*

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1. Introduction

Burnable absorbers (BAs) are essential components in nuclear reactor design, primarily utilized to manage initial excess reactivity and optimize power distribution throughout the fuel cycle. By providing negative reactivity that gradually decreases as the BA material depletes alongside the fissile fuel, BAs enable extended cycle lengths and enhance safety margins. With the recent development of the innovative Small Modular Reactor (i-SMR), there is an increasing demand for advanced BA materials capable of maintaining structural integrity and performance under higher burnup and more rigorous reactor environments [1]. To address these requirements, the High-intensity dispersed Gadolinium-oxide burnable Absorber (HIGA) is currently under development [2]. HIGA is characterized by its high Gd_2O_3 content and is designed to utilize various oxide additives to enhance its overall stability.

The long-term performance of HIGA under irradiation, however, should be evaluated. Irradiation-induced displacement damage and the accumulation of defects can significantly alter the material's properties and lead to structural degradation. The irradiation response of these specific phases, particularly regarding their resistance to displacement damage and susceptibility to gas-induced swelling, remains a critical factor in determining the overall performance of the absorber.

In this study, ion irradiation tests were performed on Gd_2O_3-MO_x and reference Gd_2O_3 samples to simulate the irradiation effect. The primary objective is to evaluate the irradiation stability of HIGA materials by characterizing their microstructure evolution. These findings provide a fundamental understanding of the irradiation effects on HIGA materials, offering essential data for the optimization of next-generation burnable absorbers.

2. Experimental

2.1 Ion irradiation

The radiation damage and ion distribution profiles were calculated using the Stopping and Range of Ions in Matter-2013 (SRIM-2013) code with quick Kinchin-Pease (Quick K-P) mode. To simulate displacement damage levels of 0.1, 1, and 10 displacement per atom (dpa) in Gd_2O_3, the corresponding Ar ion fluences were determined to be 1.2×10^{14}, 1.2×10^{15}, and 1.2×10^{16} ions/cm^2, respectively.

Three HIGA candidate materials (Gd_2O_3-Al_2O_3, Gd_2O_3-TiO_2, Gd_2O_3-ZrO_2) and reference materials Gd_2O_3 were polished with diamond suspension down to 1 μm prior to irradiation. The ion irradiation was conducted at KAERI heavy-ion irradiation facility (KAHIF) using 6.87 MeV Ar ions at a constant temperature of 450 °C.

2.2 Characterization

Cross-sectional specimen of irradiated were prepared via focused ion beam (FIB, Helios Nanolab 450 F1, FEI). The microstructural evolution and radiation-induced defects were investigated using transmission electron microscopy (TEM, Talos F200X G2, Thermo Fisher).

3. Results

3.1 SRIM simulation

Figure 1 illustrates the depth distribution of radiation damage (in dpa) for Gd_2O_3, candidate additives (Al_2O_3, TiO_2, ZrO_2), and corresponding secondary phases ($GdAlO_3$, $Gd_2Ti_2O_7$, $Gd_2Zr_2O_7$) calculated by SRIM. The peak damage depth and the maximum dpa value vary significantly depending on atomic density and atomic composition of target material. The reference material, Gd_2O_3, shows the highest peak damage of approximately 10 dpa at a depth of ~2.7 μm. In contrast, the secondary phases found and their metal oxides in HIGA materials exhibit lower peak damage levels, ranging from 6 to 8 dpa. The peak damage locations for these secondary phases are situated at shallower depths, ranging from 2.1 to 2.5 μm, compared to the peak position observed in Gd_2O_3. All secondary phases in the three types of HIGA pellets exhibited lower radiation damage compared to Gd_2O_3, which is attributed to their lower average atomic mass and higher displacement threshold energy (E_d) values relative to Gd_2O_3.

The Ar ion concentration profiles as a function of depth are illustrated in figure 2, which reveals significantly higher peak concentrations in Al_2O_3 and TiO_2, compared to Gd_2O_3. The elevated Ar concentrations are a direct consequence of their lower atomic densities, suggesting these phases may be more susceptible to radiation-induced swelling via bubble nucleation compared to the their secondary phases and Gd_2O_3.

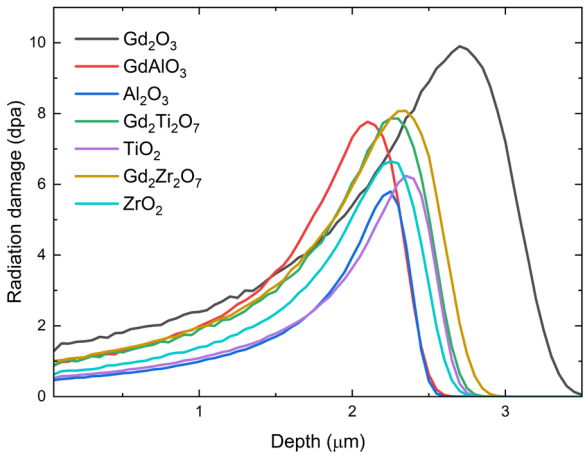

Fig. 1. Displacement damage for Gd_2O_3 and HIGA materials under 6.87 MeV Ar ion irradiation.

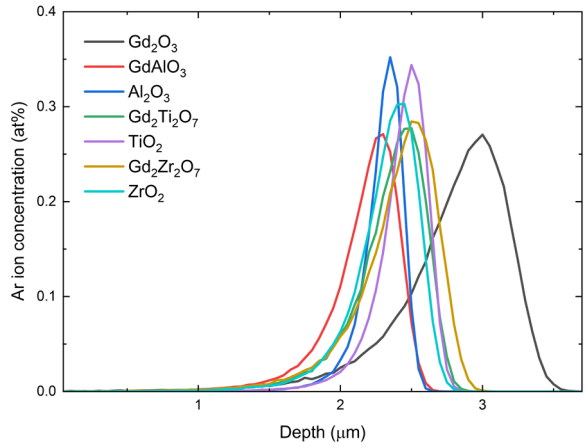

Fig. 2. Displacement damage for Gd_2O_3 and HIGA materials under 6.87 MeV Ar ion irradiation.

3.2 TEM analysis

Nanoscale characterization of the irradiated samples was conducted to evaluate the radiation-induced defects and phase stability of the HIGA secondary phases. No significant microstructural evolution was observed across the irradiated specimens, indicating the high phase stability of these complex oxides under the specified conditions. Notably, two gas bubbles with a diameter of ~ 20 nm were observed in the Al_2O_3 phases. This observation is consistent with the SRIM simulation results in Fig. 2, which predicted a higher local Ar ion concentration in Al_2O_3 region thereby increasing the driving force for bubble nucleation compared to other secondary phases and Gd_2O_3.

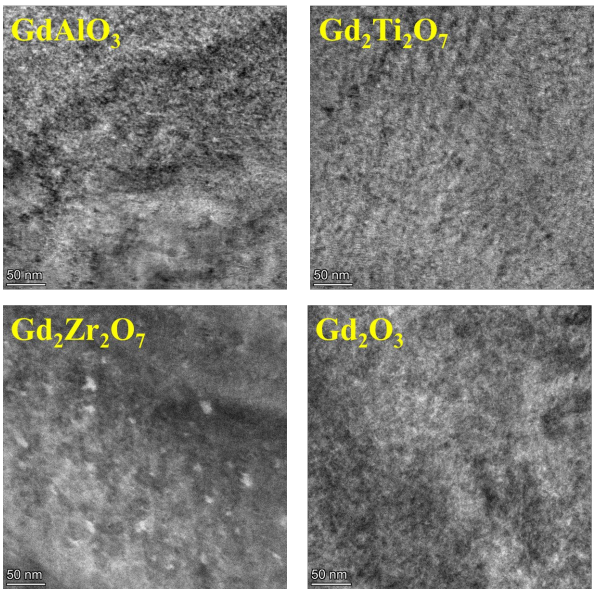

Fig. 3. Microstructure of HIGA and Gd_2O_3 after Ar ion irradiation

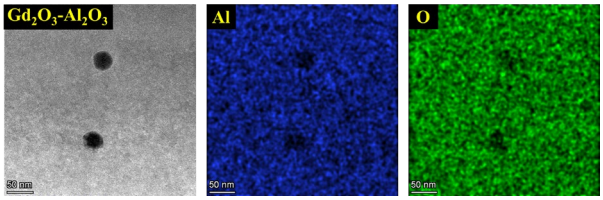

Fig. 4. Irradiation-induced bubbles observed in Al_2O_3

3. Conclusions

The irradiation resistance and microstructural stability of Gd_2O_3-based burnable absorbers for i-SMR applications were evaluated through 6.87 MeV Ar ion irradiation. The secondary phases observed in HIGA materials, such as $GdAlO_3$, $Gd_2Ti_2O_7$, and $Gd_2Zr_2O_7$, showed lower peak displacement damage compared to the Gd_2O_3. The Ar ion concentration profiles indicated that Al_2O_3 and TiO_2 phases showed higher peak Ar concentrations at shallower depths. Nanoscale characterization through TEM confirmed that the secondary phases remain structurally stable and the presence of irradiation-induced bubbles in the Al_2O_3 phase. Additional TEM analysis and ion irradiation tests were performed to further validate the long-term performance and microstructural integrity of these candidate materials.

ACKNOWLEDGEMENT

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REFERENCES

[1] Jin Sun Kim, Tae Sik Jung, and Jooil Yoon, Reactor core design with practical gadolinia burnable absorbers for soluble boron-free operation in the innovative SMR, Nuclear Engineering and Technology, Vol.56, p. 3144, 2024.
[2] Sungwoo Ha, Yeonsoo Na, Gwangyeong Lim, Minjae Joo, Chaerin Kim, Yoon ho Kim, Evaluation of Corrosion Behavior of Gd_2O_3-MO_X Burnable Absorber in a High-Temperature Steam, Transactions of the Korean Nuclear Society Autumn Meeting, Oct. 30-31, 2025, Changwon, Korea.