Applicability Evaluation of Burnable Absorber Rods for the i-SMR

JangSoo Oh*, YongSik Yang
Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea
**jangsoo@kaeri.re.kr*

***Keywords :** i-SMR, HIGA, Burnable absorber, Gd_2O_3-Al_2O_3, Damage criteria

1. Introduction

The innovative small modular reactor (i-SMR) under development in Korea considers soluble boron-free (SBF) operation, load-following capability, and a 24-month operating cycle as key design requirements [1,2]. In particular, because SBF operation eliminates soluble boron from the reactor coolant, high-performance burnable absorber rods are required to control the initial excess reactivity [1,2].

Gadolinia (Gd_2O_3)-based absorber candidates considered for the i-SMR include high-content and enriched Gd_2O_3-UO_2 pellets and Highly Intensive Gadolinia Burnable Absorber (HIGA) pellets based on the Gd_2O_3-Al_2O_3 system [2,3]. Gd_2O_3-UO_2 pellets are based on the conventional gadolinia fuel concept, and the gadolinium (Gd) and Gd_2O_3 contents are key quality parameters associated with reactivity-control performance and conformance to manufacturing specifications. Therefore, the Gd_2O_3 content of the final product should be confirmed against the design requirement.

HIGA is a Gd_2O_3-Al_2O_3-based burnable absorber developed to achieve a high Gd loading while mitigating the hydration of the Gd_2O_3 phase [2,4]. A key material characteristic of HIGA is the formation of a stable $GdAlO_3$ phase through the reaction between Gd_2O_3 and Al_2O_3 during sintering. Accordingly, the applicability evaluation of HIGA pellets should consider the formation of the $GdAlO_3$ phase, the presence of unreacted residual Gd_2O_3, and hydration resistance. Thermophysical properties of the HIGA pellets should also be evaluated to support the assessment of HIGA pellet thermal behavior and its impact on cladding integrity [2,4].

Current light-water-reactor safety review guidelines classify fuel-system damage mechanisms according to normal operation and accident conditions but do not specify damage criteria specifically for HIGA burnable absorber rods [5]. Therefore, the applicability of existing fuel-rod damage criteria should be distinguished from additional review items arising from the material characteristics of HIGA. In this study, the Gd_2O_3 content evaluation of high-content Gd_2O_3-UO_2 pellets and the manufacturing integrity and thermophysical properties of HIGA pellets were reviewed, and the applicability of existing fuel rod damage criteria to HIGA burnable absorber rods was evaluated under normal operation and accident conditions.

2. Material Characteristics and Manufacturing Integrity

2.1. Gd_2O_3 content evaluation

For high-content Gd_2O_3-UO_2 pellets, the Gd and Gd_2O_3 contents are key manufacturing parameters because they are directly associated with the designed reactivity-control performance. The Gd_2O_3 content can be evaluated by measuring the Gd and U concentrations in dissolved pellet samples using inductively coupled plasma atomic emission spectrometry (ICP-AES) and converting the measured concentrations to the Gd_2O_3 content [6]. Because the oxygen-to-metal (O/M) ratio of Gd_2O_3-UO_2 pellets may vary depending on the fabrication conditions, the O/M ratio should be considered in determining the final Gd_2O_3 content, which is then compared with the design requirement and manufacturing specification [6,7].
ISO 16796 specifies an ICP-AES method for Gd_2O_3 contents ranging from 1 to 10 wt% [8]. Therefore, when this method is applied to high-content Gd_2O_3-UO_2 pellets containing more than 10 wt% Gd_2O_3, its applicability should be confirmed for the extended concentration range [6,8].

2.2. HIGA composition and phase stability

HIGA is based on the Gd_2O_3-Al_2O_3 system and is intended to achieve a high Gd loading while reducing the hydration susceptibility associated with the Gd_2O_3 phase. Accordingly, the HIGA composition should provide the required Gd content while allowing Gd_2O_3 to react with Al_2O_3 to form a stable $GdAlO_3$ phase.

As shown in Fig. 1, the Gd_2O_3-Al_2O_3 phase diagram includes an Al_2O_3-rich region in which $GdAlO_3$ and Al_2O_3 coexist [9]. The literature indicates that the addition of more than 50 mol% Al_2O_3 to Gd_2O_3 results in the formation of a perovskite $GdAlO_3$ phase, and a composition of 10–20 mol% Gd_2O_3 with the balance Al_2O_3 has been proposed for HIGA [2].

Within this range, a composition of 20 mol% Gd_2O_3 and 80 mol% Al_2O_3 was considered for the HIGA candidate in this study [4]. Based on these compositional and phase relationships, the manufacturing-integrity evaluation of HIGA should confirm the formation of the stable $GdAlO_3$ phase and the presence of unreacted

residual Gd_2O_3. Phase identification can be performed by X-ray diffraction, while microstructural and compositional analyses can be used to assess pellet uniformity.

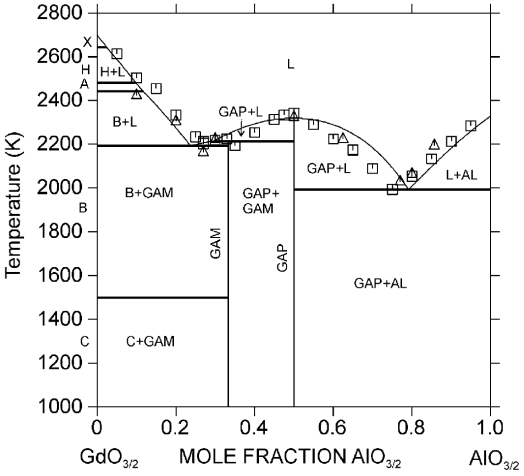


Fig. 1. Gd_2O_3-Al_2O_3 phase diagram [9].

2.3. Hydration and high-temperature steam resistance

The hydration resistance of HIGA is an important manufacturing-integrity consideration because unreacted residual Gd_2O_3, if present, may react with water. Candidate HIGA specimens exposed to pressurized water at 350 °C and 15.9 MPa for 15 days showed limited changes in mass and appearance, and no distinct hydration-induced phase change was identified by X-ray diffraction [4]. These results indicate that the Gd_2O_3-Al_2O_3 HIGA candidate maintained its macroscopic integrity and phase stability under the tested pressurized-water condition.

High-temperature steam resistance was also evaluated for metal-oxide-based gadolinia absorber candidates. After exposure to steam at 1200 °C for 20 h, the Gd_2O_3-Al_2O_3 specimen exhibited limited weight change, with no significant surface spallation or overall change in crystal structure [10]. These results support the phase and structural stability of the HIGA candidate under the evaluated hydration and high-temperature steam conditions.

3. Thermophysical Properties of HIGA

3.1. Effective heat capacity

The thermophysical properties of HIGA are required to evaluate heat transfer from the absorber pellet to the cladding and coolant. Because direct heat capacity data for HIGA pellets are limited, the effective heat capacity was estimated using literature data for $GdAlO_3$ and Al_2O_3. Assuming complete reaction of the initial composition of 20 mol% Gd_2O_3 and 80 mol% Al_2O_3, the final phase composition is approximately 40 mol% $GdAlO_3$ and 60 mol% Al_2O_3.

The effective heat capacity was estimated using a rule of mixtures in which the literature heat capacities of the $GdAlO_3$ and Al_2O_3 phases [9,11,12] were weighted according to their final phase mole fractions. As shown in Fig. 2, the effective molar heat capacity of HIGA was closer to that of Al_2O_3 because Al_2O_3 constitutes the larger mole fraction.

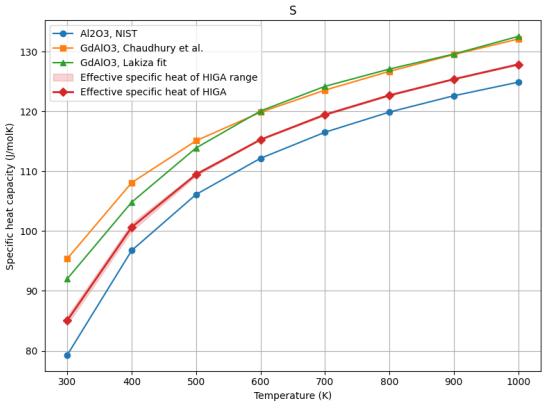


Fig. 2. Literature heat capacities of $GdAlO_3$ and Al_2O_3 and estimated effective heat capacity of HIGA.

3.2. Effective thermal diffusivity

Measured thermal diffusivity data are available for the HIGA candidate [4], whereas direct thermal conductivity data for the HIGA composite are limited. Accordingly, composite effective thermal conductivity models were evaluated using literature thermal conductivity data for the Al_2O_3 and $GdAlO_3$ phases [13–15]. Among the effective thermal conductivity models considered, the Bruggeman EMT was selected as a preliminary model because the volume fractions of $GdAlO_3$ and Al_2O_3 are comparable, making it difficult to define a specific matrix phase, while the model treats both phases symmetrically.

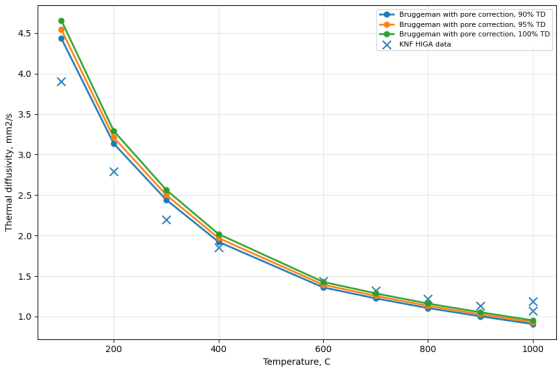


Fig. 3. Comparison of measured and Bruggeman-predicted thermal diffusivity of HIGA at different relative densities.

The effective thermal conductivity predicted by the Bruggeman EMT was converted to thermal diffusivity for relative densities of 90, 95, and 100% TD and compared with the measured HIGA data. As shown in Fig. 3, the predicted thermal diffusivity was higher than the measured values at lower temperatures, while the

difference decreased with increasing temperature. The discrepancy in the lower temperature range cannot be sufficiently explained by relative density alone and may arise from microstructural effects not accounted for in the model, such as interfacial thermal resistance, microcracks, and actual pore morphology. However, above approximately 400 °C, the calculated and measured values are relatively close, suggesting that the Bruggeman EMT can provide a preliminary estimate of HIGA thermal diffusivity in this temperature range.

4. Applicability of Existing Damage Criteria to HIGA Rods

4.1. Normal operation

Because current light water reactor safety review guidelines do not specify damage criteria specifically for HIGA rods, the applicability of existing fuel rod damage criteria was evaluated based on the damage mechanisms defined for normal operation and accident conditions [5].

Hydriding, cladding collapse, and cladding overheating under normal operation are primarily governed by cladding characteristics, coolant environment, and operating conditions rather than by the HIGA pellet material itself. Therefore, existing damage criteria can be applied when the cladding and operating conditions of HIGA rods are equivalent to those of conventional fuel rods or burnable absorber rods [5].

4.2. Accident conditions

Under accident conditions, criteria for fuel overheating and excessive fuel enthalpy or temperature rise are not directly applicable to HIGA because HIGA rods contain no fissile fuel. Therefore, the evaluation should focus on HIGA pellet temperature and its effects on cladding integrity [5]. For mechanical interaction between the pellet and cladding, the intent of the 1% uniform cladding strain criterion can be retained, with additional consideration of thermal expansion, irradiation swelling, volume change, and gap closure. Cladding rupture can be evaluated based on cladding temperature, stress, strain, and rod internal pressure, while existing criteria for mechanical failure can be applied under equivalent structural and loading conditions [4,5].

5. Conclusions

This study evaluated candidate burnable absorbers for the i-SMR. The Gd_2O_3 content was identified as a key evaluation item for high-content Gd_2O_3-UO_2 pellets, while $GdAlO_3$ phase formation, residual Gd_2O_3, hydration resistance, and thermophysical properties were identified as key evaluation items for HIGA pellets. For HIGA burnable absorber rods, existing fuel rod damage criteria can be applied under normal operation when equivalent cladding and operating conditions are demonstrated, whereas accident conditions require additional evaluation of the effects of HIGA pellet temperature and mechanical behavior on cladding integrity [4,5]. Accordingly, existing criteria can be retained when the governing damage mechanisms remain applicable, while the need for additional criteria should be considered if HIGA-specific material behavior introduces damage mechanisms not adequately addressed by the existing criteria. These results provide a technical basis for evaluating the applicability of HIGA burnable absorber rods to the i-SMR.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. RS-2025-02310358).

REFERENCES

[1] H. O. Kang, B. J. Lee, S. G. Lim, Light water SMR development status in Korea, Nucl. Eng. Des. 419 (2024) 112966.

[2] J. S. Kim, T. S. Jung, J. Yoon, Reactor core design with practical gadolinia burnable absorbers for soluble boron free operation in the innovative SMR, Nucl. Eng. Technol. 56 (2024) 3144–3154.

[3] J. S. Kim, G. Bae, J. Yoon, Reactor core design with enriched gadolinia burnable absorbers for soluble boron free operation in the innovative SMR, Nucl. Eng. Des. 428 (2024) 113557.

[4] Y. S. Na, S. W. Ha, C. R. Kim, M. J. Joo, K. Y. Lim, Y. H. Kim, Evaluation of properties of candidate burnable absorber for soluble boron free in the i-SMR, Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, 2025, pp. 1–3.

[5] Korea Institute of Nuclear Safety, 경수로형 원전 안전심사지침 개정 4 판, KINS/GE-N001, Daejeon, 2014.

[6] C. J. Park, P. S. Kang, C. J. Park, H. J. Kim, Determination method of Gd_2O_3 content in gadolinium fuel pellets by measurements of gadolinium and uranium elements, Transactions of the Korean Nuclear Society Autumn Meeting, Jeju, Korea, 2010, pp. 1–2.

[7] ASTM International, Standard test method for determination of uranium, oxygen to uranium, and oxygen to metal in sintered uranium dioxide and gadolinia-uranium dioxide pellets by atmospheric equilibration, ASTM C1430-18, ASTM International, 2018.

[8] International Organization for Standardization, Nuclear energy, Determination of Gd_2O_3 content in gadolinium fuel blends and gadolinium fuel pellets by atomic emission spectrometry using an inductively coupled plasma source, ISO 16796:2022, Geneva, 2022.

[9] S. Lakiza, O. Fabrichnaya, Ch. Wang, M. Zinkevich, F. Aldinger, Phase diagram of the ZrO_2-Gd_2O_3-Al_2O_3 system, J. Eur. Ceram. Soc. 26 (2006) 233~246.

[10] S. W. Ha, Y. S. Na, G. Y. Lim, M. J. Joo, C. R. Kim, Y. H. Kim, Evaluation of corrosion behavior of Gd_2O_3-MOX burnable absorber in a high-temperature steam, Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, 2025, pp. 1–3.

[11] S. Chaudhury, S. C. Parida, K. T. Pillai, K. D. Singh Mudher, High-temperature X-ray diffraction and specific heat

studies on $GdAlO_3$, $Gd_3Al_5O_{12}$ and $Gd_4Al_2O_9$, J. Solid State Chem. 180 (2007) 2393~2399.
[12] National Institute of Standards and Technology, Aluminium oxide, NIST Chemistry WebBook, Standard Reference Database No. 69.
[13] R. G. Munro, Evaluated material properties for a sintered alpha-alumina, J. Am. Ceram. Soc. 80 (1997) 1919~1928.
[14] M. McQuarrie, Thermal conductivity: VII, Analysis of variation of conductivity with temperature for Al_2O_3, BeO, and MgO, J. Am. Ceram. Soc. 37 (1954) 91~95.
[15] Z. Zhang, J. Sun, G. Liu, Y. Han, W. Liu, Y. Li, W. Wang, X. Liu, P. Zhang, W. Pan, C. Wan, High toughness and CMAS resistance of $REAlO_3/RE_2Zr_2O_7$ composites with eutectic composition for thermal barrier coatings, J. Adv. Ceram. 13 (2024) 800~809.