

Performance analysis of B₄C-Al₂O₃ burnable absorber for SMR

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1. Introduction

Recently, the Republic of Korea has been actively developing the Innovative Small Modular Reactor (i-SMR) based on pressurized water reactor (PWR) technology [1]. The i-SMR aims for enhanced safety, economic viability, and flexibility as its primary design objectives, integrating core features such as soluble boron-free (SBF) operation, improved thermal margins for fuel, and long-cycle operation exceeding 24 months [1].

The transition to SBF operation presents the challenge of controlling initial excess reactivity [1]. While conventional commercial PWRs utilize boron or gadolinium-based absorbers, these materials struggle to meet the long-term reactivity suppression requirements demanded by the 24-month cycle and SBF environment of SMRs [1]. Specifically, although Gadolinia (Gd₂O₃) possesses excellent absorption capacity, concerns exist regarding its low thermal conductivity and the potential for mechanical integrity degradation due to phase transformations at high temperatures [1]. On the other hand, while boron (B) offers stable depletion characteristics, it has been noted that helium (He) gas generated during the depletion process increases the rod internal pressure [1].

In response to these challenges, this study focuses on a B₄C-Al₂O₃ composite, which disperses boron carbide (B₄C)—noted for its superior neutron absorption—within a chemically stable alumina (Al₂O₃) matrix with excellent thermal properties [2][3]. This research evaluates the feasibility of applying the B₄C-Al₂O₃ burnable absorber by analyzing its neutronic and thermal behavior in a soluble boron-free core.

2. Gas release modeling

2.1 He production

In order to evaluate the helium (He) release behavior in B₄C, it is first necessary to quantitatively determine the amount of He produced within the material. He is generated via the ¹⁰B(n, α)Li reaction in B₄C, which is calculated from the relationship in Eq. (1)[4].

$$\dot{R} = [^{10}\text{B}] \cdot \sigma \cdot \phi \quad (1)$$

where

\dot{R} = the reaction rate (reactions/cm³·sec)

[¹⁰B] = the concentration of the ¹⁰B isotope (cm²)

σ = the absorption cross section for the ¹⁰B isotope (cm²)

ϕ = the neutron flux (neutrons/cm²·sec)

2.2 He diffusion coefficient

Due to the absence of experimental data for the He diffusion coefficient within B₄C-Al₂O₃, it was assumed in this study that the He release behavior is governed by the diffusion mechanism within B₄C grains. The diffusion coefficient of He is defined as expressed in Eq. (2)[4]

$$D = 1.4 \times 10^{-6} \exp\left(\frac{-29000}{RT}\right) \quad (2)$$

2.3 He release

The amount of helium (He) released from B₄C plays a critical role in determining the rod internal pressure. The correlation between He release and irradiation temperature is presented as Eq. (3), which was derived based on experimental data from thermal reactor irradiations conducted at Oak Ridge National Laboratory (ORNL)[4].

$$\% \text{He release} = e^{(C-1.8D)} e^{-Q/RT} \quad (3)$$

where

C = constant, 6.69 for pellets

D = fractional density, 0.73

Q = activation energy content, 3,600 cal/mole

R = gas constant, 1.98 cal/mole · K

T = pellet temperature, K

2.4 Thermal conductivity of B₄C-Al₂O₃

An effective thermal conductivity model was employed to calculate the internal temperature of the B₄C-Al₂O₃ burnable absorber rod. Due to the absence of experimental thermal conductivity data specifically for the B₄C-Al₂O₃ composite, the effective thermal conductivity was derived through the volume-weighted Rule of Mixture (ROM) based on the thermal conductivity values for B₄C [5] and Al₂O₃ [6] reported in existing literature

3. Evaluation of B₄C-Al₂O₃ behavior

3.1 Assembly configuration

DeCART2D-MASTER depletion analysis was conducted across Cycles 1 to 7 using SMR core data. Based on the analysis, the fuel assembly exhibiting the maximum burnup was selected as the final target for evaluation. The configuration of the selected assembly is illustrated in (Fig. 1), with a total axial length of 240 cm. To enhance computational efficiency, a 1/8 symmetry was assumed for the core analysis, and the behavior of the four B₄C-Al₂O₃ rods located within this symmetric region was considered representative of the characteristics of the entire assembly.

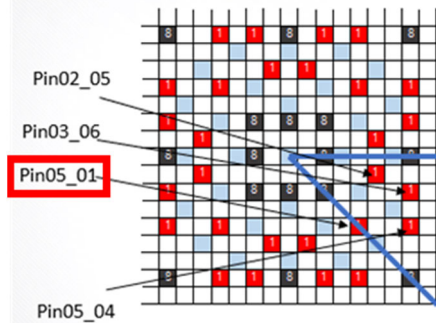


Fig. 1. Assembly containing B₄C-Al₂O₃ burnable absorber rods

Table 1 Material composition of B₄C-Al₂O₃ burnable absorber rod

Isotope	Density (g/cm ³)
B-10	6.61319E-02
B-11	2.92677E-01
C-12	9.84615E-02
C-13	1.19760E-03
O-16	1.54725E+00
Al-27	1.74003E+00
Total	3.74575E+00

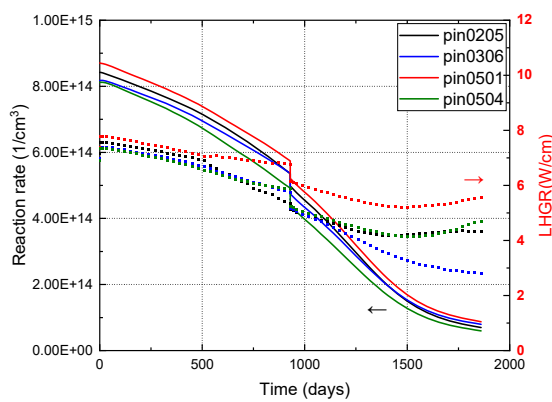


Fig. 2. Reaction rates and power levels according to the position of the burnable absorber rods

3.2 Performance Assessment

The performance evaluation of the B₄C-Al₂O₃ burnable absorber was conducted using power and reaction rate data from the Pin05_01 location, which exhibits the highest linear power, to ensure a conservative assessment. The behavioral evaluation was performed using the FRAPCON code[7], into which the models of the relevant composite were integrated.

A diffusion equation was applied for the analysis of the He release behavior induced by neutron reactions. It was assumed that He gas is generated within the interior of the B₄C-Al₂O₃ pellet grains and diffuses toward the grain boundaries. To simulate this process, the Massih model, a well-established fission gas diffusion model, was utilized. The release amount was calculated based on the assumption that He reaching the grain boundaries is immediately released to the exterior.

The variation in the centerline temperature of the B₄C-Al₂O₃ rod according to the depletion time is shown in (Fig. 3). As a result of the analysis, the centerline temperature at the peak power location was calculated to be in the range of approximately 320–350 °C. Subsequently, a behavior was confirmed where the centerline temperature gradually decreases along with the reduction in power.

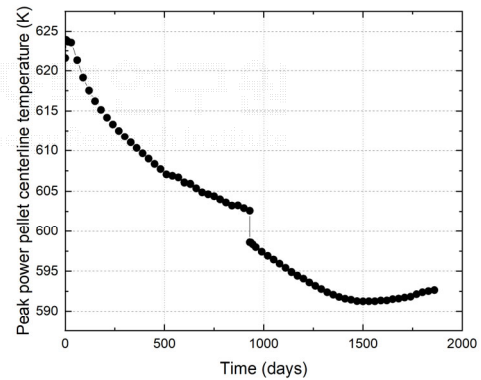


Fig. 3. Centerline temperature of B₄C-Al₂O₃ burnable absorber rods over time at peak power

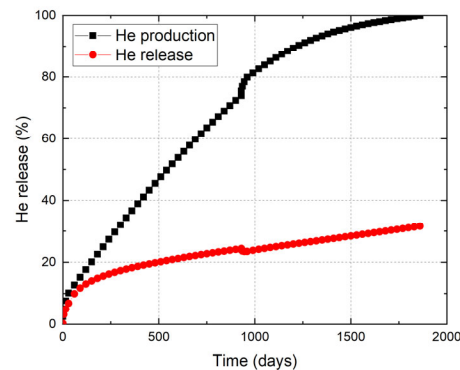


Fig. 4. He production and gap release in B₄C-Al₂O₃ burnable absorber

As illustrated in (Fig. 4), the amount of He released from the $B_4C-Al_2O_3$ pellet into the gap under SMR core conditions was calculated to be approximately 30% of the total production. This relatively low release fraction is attributed to the low peak temperature of the burnable absorber rod, which is approximately 350 °C. At this temperature range, the diffusion coefficient of He within the grains remains low, thereby limiting the release of gas into the rod gap.

The resulting rod internal pressure of the $B_4C-Al_2O_3$ burnable absorber, calculated by considering this He release behavior, is shown in (Fig. 5). Consequently, due to the low operating temperature and the resulting restricted He release, the increase in internal pressure for the $B_4C-Al_2O_3$ rod was calculated to be approximately 10% relative to the initial pressure.

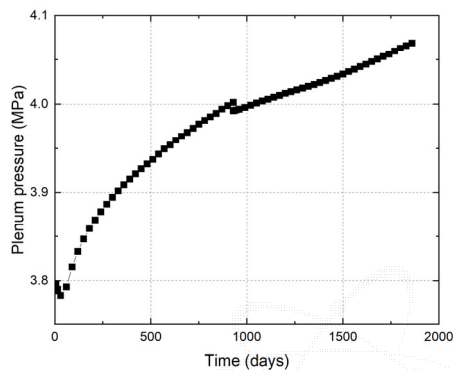


Fig. 5. Internal pressure variation in $B_4C-Al_2O_3$ burnable absorber rods

4. Conclusions

In this study, the thermal behavior and neutronic characteristics of $B_4C-Al_2O_3$ burnable absorber rods were evaluated by simulating the SMR core. The analysis results confirmed that the rod centerline temperature at the peak linear power location (Pin05_01) was maintained at a remarkably low level of approximately 320–350 °C. This low-temperature behavior served as a primary mechanism for suppressing the helium (He) release into the gap to approximately 30% relative to the cumulative production by maintaining a low diffusion coefficient of He within the pellet. As a result, the increase rate of the rod internal pressure was limited to approximately 10% compared to the initial pressure. This demonstrates that the $B_4C-Al_2O_3$ composite possesses sufficient mechanical integrity and thermal stability for long-term reactivity control in SMR cores. Since the analytical results of this study rely on existing literature models due to the absence of experimental data, further experiments on the irradiation behavior and helium release characteristics of $B_4C-Al_2O_3$ are necessary to validate the models and address analytical uncertainties.

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REFERENCES

- [1] J. S. Kim, T. S. Jung, and J. Yoon, Reactor core design with practical gadolinia burnable absorbers for soluble boron-free operation in the innovative SMR, Nuclear Engineering and Technology, Vol. 56, pp. 3144-3154, 2024.
- [2] B. Muth and C. J. Hah, Application of B_4C/Al_2O_3 burnable absorber rod to control excess reactivity of SMR, Transactions of the Korean Nuclear Society Autumn Meeting, 2016.
- [3] American Nuclear Society, Westinghouse PWR burnable absorber evolution and usage, Doc. No. 11269.
- [4] F. J. Homan, Performance Modeling of Neutron Absorbers, Nuclear Technology, Vol. 16, pp. 216-225, 1972.
- [5] Touloukian, Y. S. Thermophysical properties of high temperature solid materials: Vol. 5. No oxides and their solutions and mixtures, including miscellaneous ceramic materials. Macmillan Company, New York, 1967.
- [6] NIST, "NIST Property Data Summaries for Advanced Materials: Sintered Alumina (Al_2O_3)," NIST Standard Reference Database 150, 2002.
- [7] K. J. Geelhood, W. G. Luscher, P. A. Raynaud, and I. E. Porter, FRAPCON-4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup, PNNL-19418, Vol. 1 Rev. 2.