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Study on the suitability of burnable absorber material with excess reactivity control for boric acid-free operation in i-SMR

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1. Introduction

The i-SMR, which has adopted boric acid-free operation, requires a new type of combustible absorber design required for controlling excess reactivity as it uses coolant that is not diluted with boric acid [1]. Currently, the development of a new type of absorber and the production of a prototype, which began in 2023, are under development with the goal of TRL 6 level.

In the case of developing accident-tolerant fuel (ATF), the goal is to rapidly apply it to existing commercial nuclear power plants, and without making significant changes to the form or material of existing nuclear fuel, only a design impact assessment in the field of core design and safety analysis is performed, and development can proceed as in existing cases, focusing on improving material (thermomechanical) performance, manufacturability, and economic feasibility [2]. However, the development of burnable absorber rods for i-SMR requires a new type of nuclear fuel assembly component suitable for the newly designed environment of boric acid-free operation [3]. This means that a formal nuclear fuel development phase must be completed, which is expected to take at least 20 years [4]. However, efforts are underway to meet the development and commercialization schedule required by the i-SMR development project by applying proven technology. In other words, this is a method of quickly entering the commercialization development stage of TRL 7 or higher by selecting materials that have been commercialized or have a development history, conducting a suitability assessment and design optimization, and then screening the final candidates at a specific point in time.

The materials currently under development in the burnable absorber development project include transition metal oxide-diluted Gd_2O_3 and high-content Gd_2O_3 added UO_2 types. Various out-of-pile performance evaluations and improvement designs are currently being conducted for the candidates, and in-pile test combustion is being prepared soon.

In this study, we will describe the results of the evaluation of existing and new types of neutron absorbing materials that were initially conducted to select a burnable absorber rod material suitable for i-SMR.

2. Burnable absorber (BA) materials

Figure 1 shows the candidate burnable absorber materials that have been considered since the initial i-SMR project in 2021.

First, there is the form in which Al_2O_3-B_4C pellet known as WABA is loaded into the zirconium cladding. In this material, neutrons are absorbed by the $^{10}B(n,\alpha)^{7}Li$ reaction. The second material is high-content Gd_2O_3-doped UO_2. This material is a concept that expands the design range from the range of 8 wt.% Gd_2O_3 added to existing commercially used UO_2 to a maximum of 17 wt.%. The third is a form in which Gd_2O_3 is diluted with various transition metal oxides. Both high-content Gd_2O_3-doped UO_2 and diluted Gd_2O_3 absorb neutrons by the $^{155,157}Gd(n,\gamma)$ reaction.

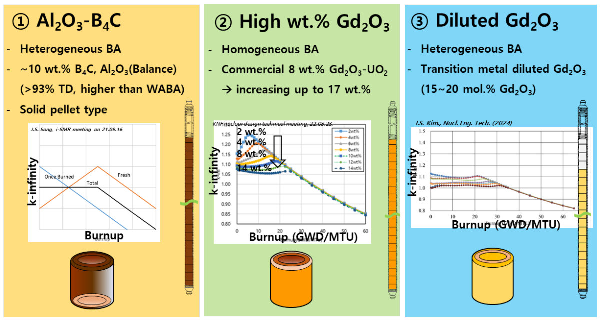

Fig. 1. Burnable absorber materials evaluated as component for fuel assembly for i-SMR.

3. Critical behavior characteristics of BA

The results of evaluating the three candidates in terms of manufacturability are as follows. First, the Al_2O_3-B_4C material has abundant design experience as it was designed by KNF in the form of WABA and was delivered to KHNP in the early 2000s at the Hanul and Hanbit nuclear power plants. Of course, the product was delivered directly to KHNP by WEC, but since it is a product that WEC has been using up to now, it is expected that there will be no problem in supply and demand. In the case of UO_2 with high Gd_2O_3 content, mass production is possible using KNF commercial facilities, but a inhomogeneous mixing region can be existed in its matrix due to the increased amount of Gd_2O_3 added by an additional 9 wt.%. To overcome this problem, the development of a mixing ability improvement technology that can be applied to large-scale production is currently underway. In the case of diluted Gd_2O_3, there is no problem in manufacturability as mass production is possible by applying a general fine ceramic process. However, when Gd_2O_3 is diluted below a certain level, it has a multi-phase matrix due to irreversible phase transformation during sintering process, which is a characteristic of rare-earth-oxide (hereinafter referred to as REO) [5]. That is, at room temperature, it has a cubic structure (C-type), and in the 1700°C region where sintering takes place, it transforms into a monoclinic structure (B-type, above 1250°C). However, it is difficult for the phase transformation to B-type to occur 100% during sintering, and even when the temperature drops to room temperature after sintering is complete, the phase does not return to C-type again [6].

Dimensional stability is also an important evaluation item. Since burnable absorber performs an essential function directly related to safety by suppressing fission reaction, it must maintain its structural shape stably within the reactor during the designed life cycle. GTRF is considered the case of the highest fuel rod failure [7], which can cause water-logging in rods. In the case of WABA, volume reduction due to its dissolution does not occur due to coolant infiltration [8]. In the case of high-content Gd_2O_3 added UO_2 that produces heat, steam fills the inside of the rod in the early stage of failure, and then flooding by coolant occurs, but as is already known, there is no significant volume change [9]. Figure 2 shows the result of thermodynamical evaluation for UO_2 in steam atmosphere.

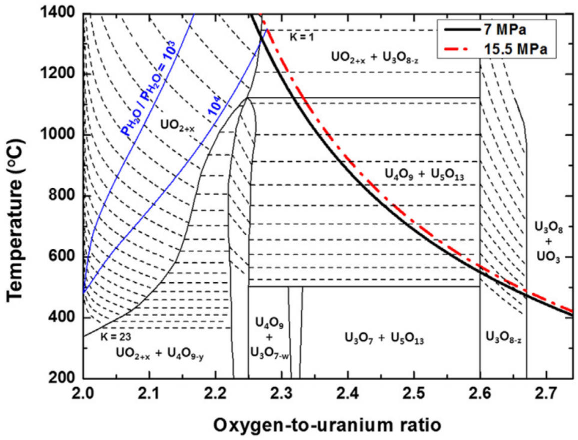

Fig. 2. Equilibrium PO_2 with O/U at PH_2O/PH_2 = 10^3, 10^4 with superimposed p-C-T diagram. The trends of the equilibrium PO_2 under pure steam are similar at the pressures of 7 MPa and 15.5 MPa [9].

In the case of diluted Gd_2O_3, if Gd_2O_3 is not diluted beyond a certain content, it maintains one of the REO characteristics, high basicity characteristic [10], so it becomes powdered due to volume expansion due to hydration phenomenon (see chemical formula below) due to water logging.

$$Gd_2O_3 + 3H_2 \rightarrow 2Gd(OH)_3$$

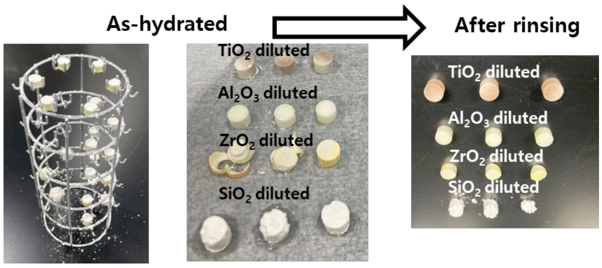

Fig. 3. Result of water-logging test under PWR-simulated pressure and coolant environment using autoclave.

Figure 3 shows the result of water-logging experiment for oxide-diluted Gd_2O_3 pellets using autoclave simulating PWR coolant environment and 50 mol. % TiO_2, Al_2O_3, ZrO_2-diluted Gd_2O_3 were found to maintain its integrity after autoclave experiment.

In the case of in-pile behavior, alpha particle(^4He) production caused by the n-alpha reaction for Al_2O_3+B_4C which may raise the possibility that the rod internal pressure design limit can be exceeded [11]. In the case of high-content Gd_2O_3, pores or cracks can be formed in the matrix due to the presence of macro Gd_2O_3-UO_2 interdiffusion layers in heterogeneous mixtures that can be accelerated in a high-temperature neutron environment [12]. Therefore, even distribution of Gd_2O_3 in the UO_2 matrix is required from the manufacturing stage. Finally, in the case of transition oxide-diluted Gd_2O_3, structural collapse may occur in a neutron environment caused by irreversible phase transformation, which is a REO characteristic. That is, the phase transformation from B-type (monoclinic structure, 8.352 g/cm^3) to C-type (cubic structure, 7.618 g/cm^3), which can be accelerated in a neutron environment at a temperature of about 300 to 400°C, is due to the occurrence of a large compressive stress by the volume expansion [13]. Therefore, a phase design different from the phase showing REO characteristics formed by Gd_2O_3 through mixing with various transition metal oxides is absolutely necessary.

4. Conclusions

In order to control the excess reactivity of the newly designed boron-free-operated i-SMR, the development of a new type of burnable absorber is currently underway, and the design and evaluation of suitable candidates are in progress. In order to control the excess reactivity stably until the end of the designed life cycle, chemical and structural stability must be maintained. Al_2O_3-B_4C, UO_2 with high content of Gd_2O_3, and transition metal oxide-diluted Gd_2O_3 were evaluated in the aspects of critical behavior in reactor and the areas requiring improvement for each candidate were identified.

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