Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Development of Technology of Control Rod Neutron Absorber Materials with Extended Control Rod Lifetime and Enhanced Safety for LWRs

Dong-Joo Kim[a,*], Jae Ho Yang[a], Dong Seok Kim[a], Ji-Hae Yoon[a], Heung Soo Lee[a], Kwang-Young Lim[b], Jihyeon Lee[c], Jae-Yong Kim[a]

[a] *Korea Atomic Energy Research Institute, 111, Daedeok-daero 989Beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[b] *KEPCO Nuclear Fuel, 242, Daedeok-daero 989Beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[c] *Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Korea*

[*] *Corresponding author: djkim@kaeri.re.kr*

1. Introduction

The control rod has been used to control the fission rate of the nuclear fuel in the nuclear reactors. The number and depth of the control rods inserted strongly influence the reactivity of the nuclear reactors. The control rod is main core component to control the reactivity during reactor operation and is also used to slowly or quickly shutdown of the reactor.

The control rod consists of numbers of the neutron absorber pellets and a metal tube (mainly SUS or Inconel). The control rod neutron absorber pellet materials include elements, such as B, Ag, In, Cd, Hf, etc. with high neutron absorption cross section. As the control rod neutron absorber for PWRs, the B_4C pellet and Ag-In-Cd (AIC) alloy is mainly used in the rod type. And the B_4C pellet is mainly used in the cruciform blade type as the control rod neutron absorber for BWRs [1-3].

For a selection of the control rod neutron absorber materials, neutron absorption cross section, in-reactor dimensional and phase stability, compatibility with cladding materials, oxidation and corrosion resistance, mechanical strength, thermo-physical properties, etc. are important considerations.

However, the B_4C pellet, a major control rod neutron absorber material, inevitably produces helium gas through an (n, α) reaction. The B_4C pellet swelling [4], and the internal pressure increase in the control rod tube can be caused by the accumulated helium gas. The in-reactor dimensional change of the AIC alloy can be also occurred by the swelling. These dimensional change and gas accumulation in the tube are the critical factor of the control rod lifetime determination [5-8].

The control rod neutron absorbers B_4C and AIC may undergo a eutectic reaction with the tube materials. For example, B may undergo a eutectic reaction with Ni at about 1080 °C and Fe at about 1165 °C [9-11]. If the eutectic reaction between the neutron absorber and the tube materials occurs, the possibility of a core and fuel degradation during severe accidents in LWRs may increase [12, 13].

If the control rod neutron absorber is exposed to an oxygen and/or steam atmosphere, an oxidation reaction (from about 600 °C) can occur, and hydrogen can be generated due to this reaction [14, 15]. And the relatively low melting point (about 800 °C) of the AIC is also a concern from a safety perspective.

In addition, it is possible that the damage to the control rod in the accident condition can precede that to the nuclear fuel, leading to reduce in the advantage of the accident tolerant fuel. So, new neutron absorber materials for control rod (accident tolerant control rod) with oxide-based compositions (Eu_2O_3, Sm_2O_3, Dy_2O_3, Gd_2O_3, HfO_2, ZrO_2, TiO_2, etc.) to solve these various issues are actively being developed [16-19].

We have begun to develop the oxide-based neutron absorber materials for control rod, which have the advantage of extending lifetime by ensuring the in-reactor dimensional stability and enhancing safety under accident conditions. It is intended to present the current status of our development.

2. Design of Control Rod Neutron Absorber Material Candidates

First of all, various requirements were derived for the design of candidates for the control rod neutron absorber material. The neutronic worth should be sufficient compared to the conventional control rod neutron absorber materials. The melting temperature and the eutectic temperature with the tube materials should be high. The stability should be ensured in nuclear water chemistry and steam environments. The swelling and dimensional change in the in-reactor conditions should be small enough.

To meet these requirements, material candidates for control rod neutron absorber have been mainly designed with the combination of elements that have the role of neutron worth, stabilizer, and oxide-based composition.

3. Manufacturability Test for Designed Neutron Absorber Material Candidates

The preliminary manufacturability have been tested for the various designed material candidates that are expected to meet the requirements for the material of the control rod neutron absorber. The material candidates are classified into groups of zirconate, hafnate, and titanate according to the oxide-based composition. The material candidates have been fabricated using a conventional ceramic sintering method (mixing, milling, molding, sintering, etc.).

Figure 1 shows microstructure images of preliminary fabricated samples of control rod neutron absorber material candidates of the hafnate and zirconate groups. The appearances of preliminary fabricated samples of the titanate group are shown in Figure 2. The fabricated samples with a high sintered density of 95% TD or more are obtained.

4. Neutronic Calculation and Analysis for Designed Neutron Absorber Material Candidates

In the view point of the neutronics, the control rod worth, reactivity, material depletion efficiency, etc. of various material candidates for control rod neutron absorber are being evaluated to select material candidates with excellent neutronic characteristics.

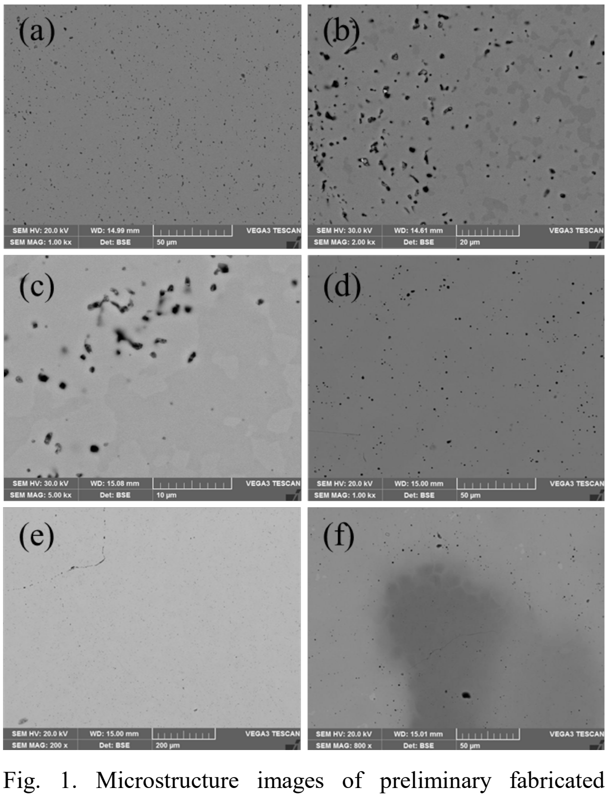

Fig. 1. Microstructure images of preliminary fabricated samples of control rod neutron absorber material candidate; (a)-(c) hafnate group and (d)-(f) zirconate group.

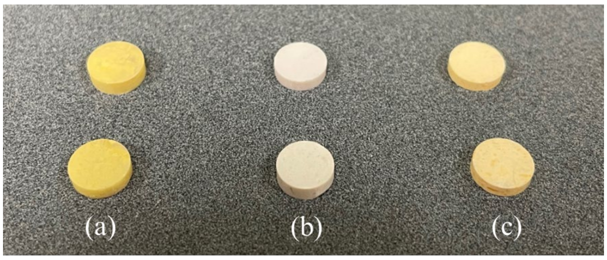

Fig. 2. Appearances of preliminary fabricated samples of control rod neutron absorber material candidates; (a)-(c) titanate group.

The neutronic calculation and analysis are in progress for each composition of various material candidates, and the comparative assessments of characteristics of each composition are in progress.

5. Summary

The control rod neutron absorbers with extended control rod lifetime and enhanced safety are being developed. The assessment of the material candidates for the control rod neutron absorber are in progress from various perspective, and material candidates with excellent characteristics are being selected. Various out-of-pile tests (neutron absorber phase stability, oxidation and corrosion resistance, control rod tube and neutron absorber material interaction, eutectic reaction, melting behavior, etc.) will be performed on the selected material candidates. It will also conduct an in-reactor swelling test of the selected material candidates at the HANARO research reactor.

ACKNOWLEDGEMENT

This work was supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (No. 20217810100050).

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