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Researches on Nuclear Fuel Pellets and Neutron Absorbers with an Overview of the Irradiation Tests at KAERI

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1. Introduction

Research reactors play an indispensable role in comprehending the behavior of nuclear fuel pellets through irradiation tests before their licensing and commercialization. These examinations are crucial for evaluating the pellets' performance under operational conditions, investigating dimensional and microstructural changes, improving fuel design, and most importantly, guaranteeing their safety. These efforts not only propel scientific advancement but also facilitate regulatory compliance and informed decision-making.

Over the years, KAERI has developed a variety of nuclear fuel pellets, such as large-grained doped pellets[1], dual-cooled annular pellets[2], and pellets aimed at mitigating pellet-cladding mechanical interaction (PCMI). Currently, the focus is on the development of accident-tolerant fuel (ATF) pellets designed to enhance safety during normal operations and in the event of severe accidents, while still maintaining optimal performance. Additionally, KAERI's research extends beyond UO_2 fuel pellets to include the development of reactor core components like burnable absorbers and neutron-absorbing materials for control rods. This is aimed at improving the efficiency of neutron control in response to anticipated future requirements. Both in-pile and out-of-pile tests have been conducted on these materials, revealing their promising advantages.

This presentation will outline the in-pile tests performed at the HANARO research reactor for both fuel and core component materials, highlighting the ongoing efforts to mitigate fission gas release and enhance thermal conductivity within the scope of ATF initiatives. An unique design of burnable absorber fuel pellet and various candidates for neutron absorber materials intended to replace conventional B_4C in control rods will also be discussed.

2. Accident-Tolerant Fuel Pellets

The development of accident-tolerant fuels for light water reactors has become a priority post-Fukushima, shifting focus from optimizing power generation to enhancing safety during severe incidents. These efforts aim to integrate ATFs into existing reactors, necessitating advancements in fuel technology and the establishment of appropriate regulatory frameworks.

KAERI has been at the forefront of this transition, specifically targeting the enhancement of thermal conductivity in UO_2 fuel pellets to address operational challenges posed by low thermal conductivity, such as increased thermal gradients and centerline temperatures [3]. Experimental advancements have shown that incorporating metallic particles for developing micro-cell and microplate structures significantly boosted thermal conductivity. These developments not only enhance safety margins by reducing the mobility of fission gases and improving dimensional stability but also offer potential for safer operational practices and power uprates in LWRs, marking significant progress in the quest for more accident-tolerant nuclear fuel systems.

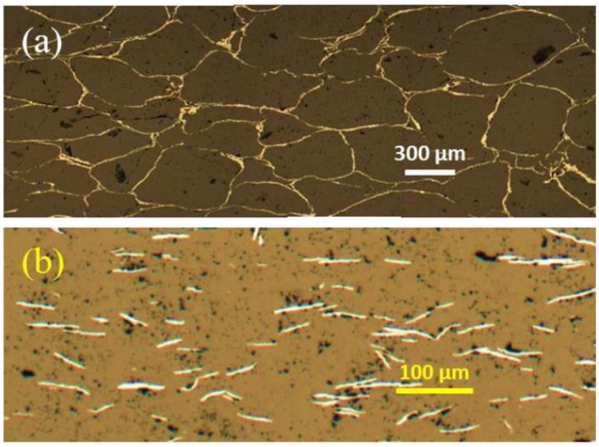

Fig. 1. Microstructure image of (a) microcell fuel and (b) microplate fuel (bright lines are Mo metal phase)

3. Burnable Absorber Fuel Pellets

Burnable absorber(poison) rods, essential for controlling excess reactivity in the early stages of fuel burnup in light water reactors, are comprised of UO_2 fuel pellets mixed with neutron-absorbing elements like Gadolinium (Gd) and Erbium(Er). These elements, chosen for their high neutron absorption cross-section, are blended with UO_2 to form a solid solution, enhancing the reactor's safety and operational efficiency. Facing the need for higher economic efficiency and safety, the nuclear industry is exploring enriched fuels and longer fuel cycles, among other strategies. These developments require BA pellets with increased absorber content for better reactivity control, despite the challenges of decreased thermal conductivity and the adverse effects on fuel's physical properties due to the dopants.

To address these challenges, one innovative solution has been the redesign of burnable absorber fuel pellets, specifically through the introduction of the centrally-shielded burnable absorber (CSBA) concept[4-6]. This approach strategically places the neutron-absorbing material at the core of the pellet, significantly enhancing neutron absorption efficiency while mitigating the drawbacks associated with decreased thermal conductivity and the physical properties of the fuel.

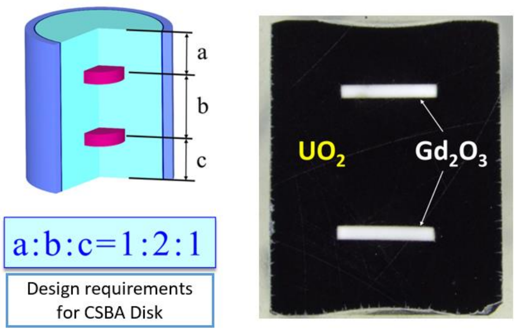

Fig. 2. Schematics of CSBA-loaded UO_2 fuel pellet design and the cross-section of a fabricated BA Pellet.

4. Neutron Absorber Materials

Control rods, critical for managing the fission rate in nuclear reactors, incorporate neutron absorber pellets within a metal tube to modulate reactor reactivity. Traditionally, materials like B_4C and Ag-In-Cd (AIC) alloys, known for their high neutron absorption cross-section, are employed in PWRs and BWRs respectively. However, challenges such as helium gas production from B_4C pellets and the dimensional changes in AIC alloys due to swelling impact the longevity and reliability of control rods. Furthermore, the risk of eutectic reactions between absorber materials and tube metals under high temperatures could jeopardize reactor safety during severe incidents.

Addressing these concerns, efforts to develop new oxide-based neutron absorber materials for control rods are actively underway, with a focus on enhancing in-reactor stability and accident tolerance[7]. This research explores compositions with oxides based on elements such as Europium (Eu), Samarium (Sm), Dysprosium (Dy), Gadolinium (Gd), Hafnium (Hf), Zirconium (Zr), and Titanium (Ti). The initiative is aimed at extending the lifetimes of control rods and improving overall reactor safety, marking a significant shift toward developing more resilient nuclear reactor components. The current advancements in these advanced materials highlight the progress towards achieving these objectives.

5. HANARO Irradiation Test

The HANARO research reactor stands as a cornerstone facility for nuclear fuel research, facilitating irradiation tests for the development of innovative nuclear fuel and core components, as previously described. The ongoing irradiation tests are essential for assessing important characteristics like the dimensional stability and also microstructural aspects of the materials being tested. Preparing and conducting these irradiation tests needs extensive preparatory works with safety evaluations[8,9]. Such efforts underscore the comprehensive approach required in advancing nuclear fuel research. Through these meticulous processes, HANARO enables the validation of each development of nuclear fuels performance, contributing significantly to the field of nuclear energy with a focus on enhancing reactor safety and efficiency.

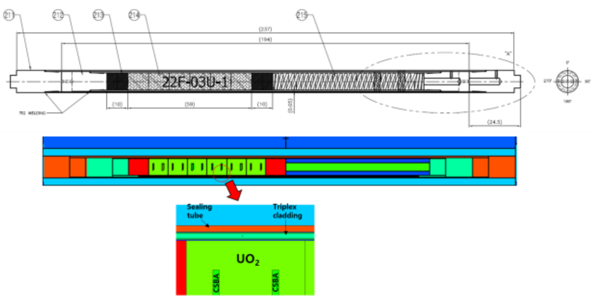

Fig. 3. Schematic illustration model of the irradiation test fuel rod for safety analysis by MCNP6 for CSBA fuel pellets.

4. Summary

This presentation will highlight key developments in nuclear fuel and component research, with a focus on the role of the research reactor. It will cover advancements in accident-tolerant fuel pellets, burnable absorber designs, and neutron absorber materials. The irradiation tests at HANARO are essential for evaluating these innovations, particularly their stability and performance under reactor conditions. These efforts contribute to making nuclear energy safer and more efficient, marking progress in nuclear technology.

ACKNOWLEDGEMENT

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