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Accident Tolerant LWR Fuel Pellets Development: Micro-cell and High-Density Pellets

Jae Ho Yang*, Dong-Joo Kim, Keon Sik Kim, Young-Woo Rhee, Jang-Soo Oh, Jong Hun Kim, Yang-Hyun Koo
LWR Fuel Technology Division, Korea Atomic Energy Research Institute,
989-111 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author: yangjh@kaeri.re.kr*

1. Introduction

After the Fukushima accident, enhancing the accident tolerance of light water reactor (LWR) fuels is drawing attention worldwide. Accident tolerant fuel pellets (ATF pellets), in comparison with the standard UO_2 pellets currently used by the nuclear industry, can tolerate a loss of active cooling for a considerably longer time period, while maintaining or improving performance during normal operations and operational transients and also enhancing fuel safety for accidental events[1].

At the beginning of 2012, the Advanced LWR fuel pellet development laboratory in KAERI has launched a research program to develop advanced LWR fuel pellets with enhanced accident tolerance. The objectives of this 5-year project are to design and select the potential candidates for ATF fuel pellets, test out-of-pile performances, and establish databases for fuel materials, start the irradiation test of ATF pellets in research reactors.

This paper shows the design and preliminary feasibility for fuel pellet fabrication of micro-cell UO_2 pellet and high uranium density ceramic composite pellets. Micro-cell UO_2 pellets are characterized by enhanced fission products retention capability and thermal conductivity. High uranium density ceramic pellet is composite pellets consisted of UO_2 and non-oxide ceramics such as nitrides. These composite pellets are expected to increase the thermal conductivity and uranium density of fuel pellets.

Those ATF pellets are expected to effectively enhance the robustness of the fuel rods even under accident conditions such as a LOCA, as well as under normal operation conditions. Our long-term and challenging goal is to establish generic technology of ATF pellets and apply those pellets for lead test rods (LTRs) by the end of 2022, which would be subjected to in-reactor testing in a commercial power plant.

2. Microcell UO_2 pellets [2-3]

Micro-cell UO_2 pellets are being developed to enhance the retention ability of highly radioactive and corrosive fission products, especially volatile Cs and I. The key idea of micro-cell UO_2 pellets is to immobilize Cs and I by providing multiple chemical traps inside the pellet, and/or reducing their diffusivities.

Figure 1 shows the conceptual schematic of a micro-cell UO_2 pellet. The micro-cell UO_2 pellet consists of UO_2 grains enveloped by thin cell walls. Tiny inclusions can be contained in the UO_2 grains optionally.

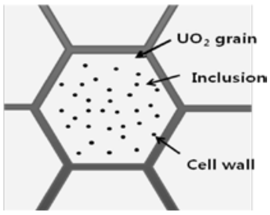

Figure 1. Conceptual schematic of micro-cell UO_2 pellet.

The improved retention capability of fission products would reduce stress corrosion cracking at the cladding inner surface caused by iodine and/or cesium as well as the internal pressure of the fuel rod. A mesh-like rigid wall structure is expected to prevent the massive fragmentation of pellets during severe accidents. The thermal conductivity of a micro-cell pellet can be increased by adopting the cell wall material with high thermal conductivity.

Fabrication feasibility for ceramic and metal micro-cell UO_2 pellets was successfully demonstrated. A simple annealing experiment to test the Cs capture ability of the cell wall phase showed that Cs was preferentially segregated in the ceramic wall, which was composed of oxides having chemical affinity to Cs and/or I. Thermo-physical measurement results showed that the thermal diffusivity was increased by 50~100% in metal micro-cell UO_2 pellets.

2. High Density Ceramic Pellets [4-8]

Uranium nitride (UN), which was developed in 1960's for fast reactor or nuclear propulsion system, shows excellent thermo-physical property and uranium loading density. For example, UN has a high thermal conductivity (27.33 W/m·K at 500°C) and high uranium metal atom density (13.55g/cm^3) like metallic fuel and similar melting temperature (2600°C), compared to UO_2 fuel. Those benefits can significantly improve the performance of water reactor. The high thermal conductivity and high melting temperature would allow low fuel temperature and large thermal safety margin for a given linear power. The high metal atom density allows a high burnup and long-life operation, leading to enhanced fuel cycle economy and reduced spent fuel generation.

Especially, after Fukushima nuclear accident in March 2011, international consensus has been reached that inherent tolerance of nuclear fuel to severe accidents needs to be increased significantly to prevent accident or mitigate consequences. In this respect, uranium nitride-based fuel has resurfaced recently as promising candidates for accident-tolerant light water reactors (LWRs) fuel in that UN has intrinsic safety feature of high thermal conductivity.

Nevertheless, there are several technical issues to be resolved before UN can be used as a fuel for water reactors. The primary technical challenge to utilization of UN is to enhance its water compatibility to avoid serious deterioration of structural integrity in coolant water. Pure phase of UN is not stable at coolant water temperature of 350°C. The UN readily reacts with water and easily loses its structural integrity. Reaction with water results in fuel pellet washout and relocation, which are unacceptable and should be avoided during reactor operation.

Since the corrosion behavior of UN in water is an intrinsic material property, there is limit to increasing the corrosion resistance of UN sufficiently by physical modification such as enlarging grain size, density and microstructure. Therefore, suitable method of modification of UN should be found in order to achieve comparable performance with water reactors. Modifying an atomic structure with minor alloying elements and/or providing multiple protective layers with inert phases are anticipated to give a promising solution.

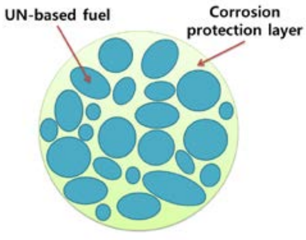

Fig.2. Conceptual microstructure of UN-based pellets with multiple protection layers

New concepts are being developed regarding chemical protection and physical protection from corrosion. Chemical protection is being tried by alloying oxidation resistant element with UN. It is expected that the corrosion resistance of UN can be increased by alloying with metal elements. Physical protection concept is also being tried by providing multiple protection layers in UN-based pellets. This concept is based on the reasonable assumption that inert protective layers enveloping individual grains or granules would prohibit direct contact between nitride and steam or water and would act as a barrier for oxygen diffusion into fuel materials. Fig. 2 shows the conceptual microstructure of UN-based fuel pellet having multiple protection layers in a pellet. To determine the phase and composition of protection layer, analysis of thermodynamic phase stability should be performed to avoid the massive chemical reaction between UN-based fuels and protection layer during fabrication or service condition (irradiation).

Two concepts of chemical and physical protection can be synergistically combined; Nitride alloy fuel meat can be enveloped by corrosion protection layer, which would acts as a first barrier to corrosion. To minimize the use of alloy elements or protection layer while maintaining the corrosion resistant is a key mission in the design of UN-based fuel pellets.

Other challenges are to develop fabrication technique of high purity and sinter-active nitride alloy fuel powders, manufacture corrosion resistant multiple layer structure with a small volume of inert phase, establish evaluation technique to demonstrate the performance of fuel pellets, and perform feasibility test and irradiation test in HANARO research reactors.

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