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Invited Article

Development Status of Accident-tolerant Fuel for Light Water Reactors in Korea

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ABSTRACT

For a long time, a top priority in the nuclear industry was the safe, reliable, and economic operation of light water reactors. However, the development of accident-tolerant fuel (ATF) became a hot topic in the nuclear research field after the March 2011 events at Fukushima, Japan. In Korea, innovative concepts of ATF have been developing to increase fuel safety and reliability during normal operations, operational transients, and also accident events. The microcell UO_2 and high-density composite pellet concepts are being developed as ATF pellets. A microcell UO_2 pellet is envisaged to have the enhanced retention capabilities of highly radioactive and corrosive fission products. High-density pellets are expected to be used in combination with the particular ATF cladding concepts. Two concepts—surface-modified Zr-based alloy and SiC composite material—are being developed as ATF cladding, as these innovative concepts can effectively suppress hydrogen explosions and the release of radionuclides into the environment.

1. Introduction

The Fukushima earthquake in Japan generated serious issues concerning light water reactor (LWR) fuel performance under accident conditions. In severe nuclear power plant accidents, a large amount of radioactivity is released into the environment from the reactor containment. From the experience of the Fukushima accident, it was recognized that hydrogen explosions and the release of radionuclides can have a serious impact on the public [1]. These two problems—hydrogen explosion and release of radionuclides—are caused by the severe damage of current nuclear fuels, composed of fuel pellets and fuel cladding, during an accident.

Under the high-temperature steam environment of accident conditions, the oxidation rate of current Zr-based alloys rapidly increases. This results in hydrogen generation and explosions. In addition, the release of radionuclides into the environment is directly caused by the ballooning and opening of Zr-based alloy cladding during accident conditions. Thus, it is known that fuel claddings have to maintain their

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inherent performance during normal operation, as well as in accident conditions, to enhance the reliability and safety of nuclear power plants. From this, the development of accident-tolerant fuel (ATF) is a major concern of LWR research at present [2–8].

In comparison with the standard UO_2–Zr alloy system, ATF can tolerate loss of active cooling for a considerably longer period than current fuels, while maintaining or improving performance during normal operations and operational transients. It can also enhance fuel safety for beyond-design-basis events [1]. In detail, ATF includes design and/or material characteristics that prevent or delay the release of radionuclides during an accident event. The accident-tolerant characteristics may also include improvements in the integrity of fission product (FP) barriers [9]. ATF concepts basically consist of two components: fuel pellets and fuel cladding.

Several ATF pellet concepts are currently being suggested and evaluated around the world to mitigate the consequences of an accident [1,10–14]. Desirable attributes for ATF pellets include enhancing the thermal conductivity and retention of FPs. A high uranium density fuel is also desired, in particular, ATF cladding concepts, to compensate for the anticipated reduction of the fuel cycle length [15,16]. For example, a ceramic composite cladding likely gives rise to a smaller volume of fuel pellets owing to the thick cladding wall and low thermal conductivity [15,16]. Advanced non-Zr-alloy claddings, meanwhile, have a high neutron absorption cross section [7]. To alleviate the cost penalty, therefore, it might be necessary to use high-density pellets in combination with the proposed ATF cladding materials.

Many ATF cladding concepts are being considered to improve on the performance of current Zr-based alloys, especially in terms of oxidation resistance and mechanical strength under accident conditions [2–8]. The research concepts for enhanced ATF cladding development consist of Mo–Zr cladding [3], cladding coating [4,5], iron-based alloy cladding [7,8], and SiC_f/SiC cladding [8]. Regarding the ATF designs, cladding concepts must consider various factors such as safety, economics, fuel cycle, technological challenge, and the development schedule. As a midterm application, coating, iron-based alloy, and Mo–Zr claddings are being developed, whereas silicon carbide (SiC) cladding is considered a long-term application.

At the Korea Atomic Energy Research Institute (KAERI), two kinds of ATF pellet concepts are being evaluated [1,17–19]. As for midterm technology, a microcell UO_2 pellet is being studied to enhance the retention capability of highly radioactive and corrosive FPs. Our focus is to use existing infrastructure, experience, and expertise to the maximum extent possible, so that this evolutionary concept can be used in the relatively near future. For the long-term perspective, we are studying nitride- and silicide-based composite pellets that have a high uranium density and high thermal conductivity. In addition, surface-modified Zr alloy and the SiC composite concepts are considered as an ATF cladding as a way to decrease hydrogen generation as well as to decrease the ballooning and rupture opening during accident conditions. The development plan of the surface-modified Zr alloy concept is focused on as a near-term application and that of the SiC composite concept is considered a long-term application. This article deals with the development status of ATF pellets and claddings for LWRs in Korea.

2. Development status of ATF pellet

2.1. Microcell UO_2 pellets

2.1.1. Concepts and design

Microcell UO_2 pellets are envisaged as having the potential to enhance the performance and safety of current LWR fuels under normal operation conditions as well as during transients/accidents. Fig. 1 shows the conceptual schematic of a microcell UO_2 pellet, where all UO_2 grains or granules are covered by thin cell walls. The cell walls are designed to provide multiple chemical traps or a physical barrier against the movement of volatile FPs, or to enhance the thermal conductivity of pellets. There are two kinds of microcell UO_2 pellets under development at KAERI, classified according to the material type composing the cell wall. The first is a metallic microcell UO_2 pellet and the second is a ceramic microcell UO_2 pellet.

The metallic microcell UO_2 pellet is a high thermal conductive pellet with a continuously connected metallic wall. Recent impact assessments of the thermal conductivity of the fuel in a loss-of-coolant accident (LOCA) progressing in a pressurized water reactor (PWR) showed that an increase in thermal conductivity reduces both the peak cladding temperature and the quench time of the fuel rod [20,21]. Mo and Cr were primarily selected as the wall materials for the metallic

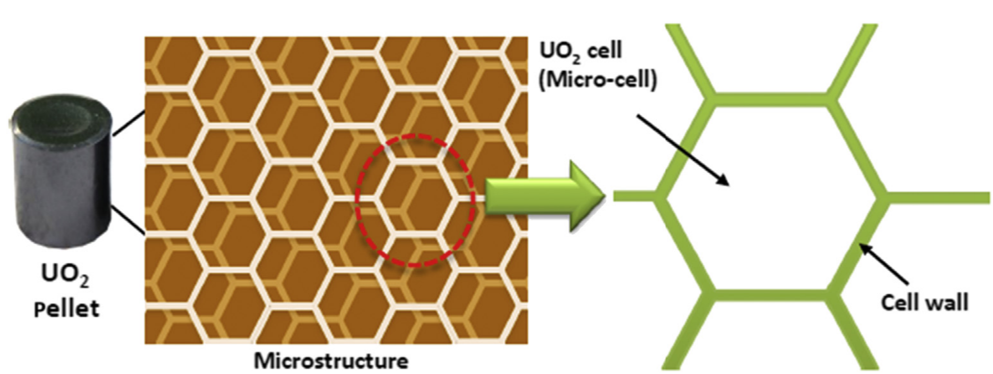

Fig. 1 – Conceptual schematic of microcell UO_2 pellet.