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Out-of-pile Tests and Analyses for Performance Evaluation and Behavior Assessment of High Thermal Conductive ATF Pellet

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1. Introduction

KAERI has been developing high thermal conductive ATF pellet technologies, involving metallic microcell and microplate fuel pellets [1-5]. The high thermal conductive ATF pellet technology aims to enhance fuel performance and safety during normal operations, transients, and accidents by providing higher thermal conductivity and lower fuel pellet temperatures [6-7]. Enhanced thermal conductivity UO_2 fuel pellets can reduce fission product diffusion and mobility, as well as mitigate pellet thermal stress by maintaining lower fuel pellet temperatures and temperature gradients. Importantly, reducing stored energy in low-temperature fuel pellets significantly increases the fuel safety margin during accidents.

The development of the high thermal conductive ATF pellet technology encompasses various aspects, including concept design, material and performance design, fabrication technology development [4, 8], out-of-pile testing and computational analysis, in-pile testing and evaluation [9], and commercial manufacturing compatibility tests. Recent efforts have extended to enhancing technology levels through the establishment of a lab-scale quality assurance system.

Within a field of the out-of-pile testing and computational analysis, material property measurements (Basic characteristics, thermal properties, mechanical properties, etc.), fuel performance prediction and evaluation, and behavior assessment of fuel pellets are being undertaken. These efforts aim to acquire data for predicting and evaluating the behavior of fuel pellets in various anticipated conditions (Normal operation, transients, and accident conditions).

Out-of-pile tests and computational analyses can be regarded as the indispensable steps in nuclear fuel technology development. This paper aims to introduce the representative results of various out-of-pile tests, computations, analyses, and evaluations performed in the high thermal conductive pellet technology development.

2. Material Properties Measurements and Evaluations

Various basic characteristics and material properties (microstructure, density, grain size, thermal expansion, thermal conductivity, specific heat, creep deformation, in-reactor densification, melting temperature, etc.) of high thermal conductive ATF pellets, fabricated using the developed fabrication technology, are measured and evaluated through testing. The measurement test data are used as input for fuel design and performance analyses.

3. Fuel Performance Analyses and Numerical Calculations

In order to evaluate the fuel performance of high thermal conductive ATF pellets, the fuel temperatures and temperature gradients are calculated using a fuel performance code. Calculations of fuel performance factors (Fission gas release (FGR), rod internal pressure (RIP), gaseous swelling, pellet-cladding gap closure, etc.) are conducted to assess the enhanced fuel operational margin enabled by high thermal conductive pellets [10]. Quantitative evaluations of changes in nuclear fuel temperature and peak cladding temperature (PCT) under accident conditions are performed to assess the improved fuel safety margin facilitated by high thermal conductive ATF pellets.

The FGR reduction attributed to high thermal conductive ATF pellets was evaluated using modelling and numerical calculation. Comparative analysis of FGR fractions at a burnup of 60 MWd/kgU demonstrates

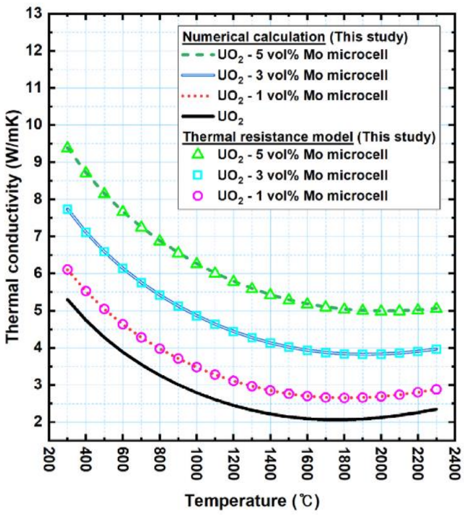

Fig. 1. Computational analysis of effective thermal conductivity of high thermal conductive ATF pellets (UO_2-Mo microcell fuel pellet) [14].

substantial reduction in FGR, with high thermal conductive pellets exhibiting about 3-5% FGR compared to approximately 15-20% for conventional UO_2 pellets [11].

Numerical analyses and calculations of fuel performance of high thermal conductive pellets were conducted. The radial strain of expansion of metallic microcell fuel pellet is considerably reduced, compared to that of UO_2 fuel pellet. It is the great beneficial effects on the mechanical behavior of fuel pellet (Pellet-cladding mechanical interaction, etc.) under transient condition. The benefits encompass not only diminished fuel pellet deformation, but also substantial mitigation of pellet cracking initiation and propagation within the fuel pellet [12, 13].

Figure 1 shows computational analysis results of thermal conductivity of high thermal conductive ATF pellets, indicating the potential for performance verification and utilization of data in modeling and analysis, integrated with experimental data [14, 15]. Additionally, the combination of out-of-pile test measurements and modeling efforts, extending to irradiation data, has yielded burnup-dependent thermal conductivity variations [16].

4. Out-of-pile Tests and Analyses for Fuel Pellet Behavior Assessments

Steam oxidation tests [17-19]: Oxidation tests were conducted on high thermal conductive ATF pellets and UO_2 pellets in steam environments at various temperatures (500, 800, 1100 °C). Results revealed UO_2 pellets exhibited pulverization under steam oxidation at 500 °C for 1100 h. In contrast, the Mo metallic microcell UO_2 pellet demonstrated reduced oxidation and preservation of metal phases within the pellet. Below 1000 °C, the primary structural-damage mechanism is oxidation-induced pulverization for UO_2 pellet, whereas for high thermal conductive ATF pellets, the delayed pulverization of metallic Mo contributed to greater stability (Figure 2). Above 1100 °C, while oxidation and surface volatilization were observed for Mo, pellet structure remained stable.

Water coolant compatibility tests: Compatibility tests involving the exposure of UO_2-Mo microcell and microplate pellet specimens to coolant water chemistry-simulated conditions (1200 ppm-B, 2.2 ppm-Li) at 346 °C and 150 bar were conducted. The structural integrity of the UO_2-Mo microcell and microplate pellet was observed, along with the confirmation of compatibility with coolant conditions (Figure 3).

Pellet compressive creep tests: Compressive creep deformation tests were conducted on UO_2-Mo microcell and microplate fuel pellets at 1450 °C and 60 MPa. Results indicated accelerated high-temperature deformation behavior compared to UO_2, attributed to the continuous arrangement of metallic networks within the pellet (Figure 4). This is expected to result in a substantial reduction in contact stress transferred to the

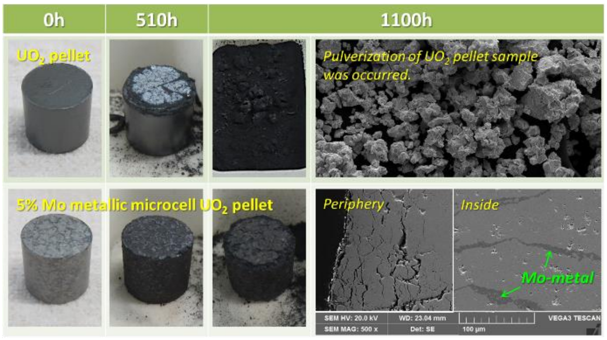

Fig. 2. Pellet morphology changes of UO_2-Mo microcell pellet and UO_2 pellet under steam oxidation conditions at 500 °C for 1100 h.

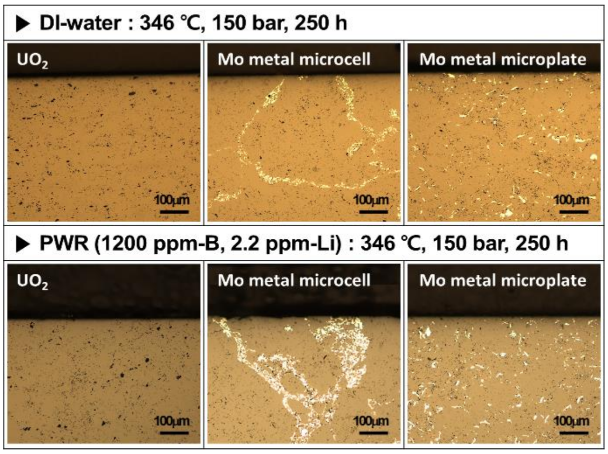

Fig. 3. Compatibility tests involving the exposure of UO_2-Mo microcell and microplate pellet specimens to coolant water chemistry simulated conditions at 346 °C and 150 bar.

cladding due to pellet deformation during power transient conditions.

Temperature transient tests: Tests involving rapid heating to 1200 °C at rates of 20, 50, 100 °C/s confirmed microstructural stability of UO_2-Mo microcell fuel pellets. Notably, the microstructure of high thermal conductive ATF pellets remained stable even under rapid heating conditions.

High temperature annealing tests exceeding the melting temperature of cell-wall material [20]: Annealing tests evaluated the behavior of UO_2-Mo microcell fuel pellets under conditions exceeding the melting temperature of cell-wall material. By maintaining temperatures higher than the melting point of Mo (2623 °C), the pellet behavior was evaluated concerning structural integrity, cell-wall material stability, microstructure, density/dimension changes, and the effects of cell-wall material melting. Results indicated sustained structural integrity and retention of the metallic form, even though melting caused the appearance of rounded metallic shapes. While pellet density increased and dimensions slightly decreased, no significant chemical interactions between UO_2 and melted Mo were observed in annealing tests conducted on UO_2-Mo pellets at temperatures exceeding the melting temperature of Mo.

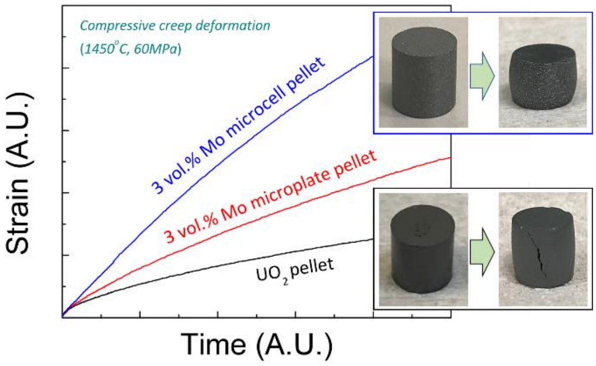

Fig. 4. Comparison of high-temperature deformation behavior of UO_2-Mo microcell pellet, microplate pellet, UO_2 pellet through compressive creep deformation test at 1450 °C and 60 MPa.

Rapid cooling-induced crack behavior tests: Tests involving the rapid cooling of UO_2-Mo pellets, producing a maximum temperature gradient of 1600 °C, were performed to observe pellet crack behavior. The temperature gradient formed within the pellet during rapid cooling generates internal stresses exceeding yield strength, leading to internal pellet cracking (Figure 5). UO_2-Mo pellets exhibited a reduced tendency for crack formation compared to UO_2 pellets, likely due to the enhanced resistance to crack propagation resulting from the arrangement of metallic plates and cells within the UO_2 matrix.

Crack behavior tests under pellet temperature gradients [21]: Tests simulating temperature gradients within the pellet were conducted to observe and analyze pellet crack behavior under conditions resembling in-reactor environments. UO_2-Mo pellets did not exhibit cracks under conditions associated with crack formation in UO_2 samples. The reduction in crack formation in UO_2-Mo pellets can be attributed to the mitigation of temperature gradients within the pellets, coupled with improved mechanical properties and enhanced thermal shock resistance conferred by the metallic particles.

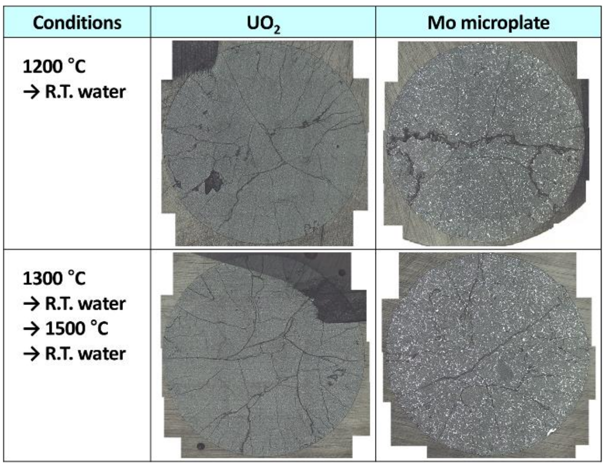

Fig. 5. Rapid cooling-induced crack behavior tests of UO_2-Mo microplate pellet, producing a maximum temperature gradient of 1600 °C. The UO_2-Mo pellets exhibited a reduced tendency for crack formation compared to UO_2 pellet.

Steam oxidation tests of simulated defective fuel rod: Fuel rod integrity was evaluated by simulating environments where defects caused steam to infiltrate the fuel rod, consisting of UO_2-Mo pellets and Zr-based alloy cladding. The oxidation of Zr forming ZrO_2 is thermodynamically more favorable than oxidation reactions involving UO_2 or Mo. Consequently, Zr cladding is preferentially oxidized, delaying oxidation within the pellets.

Mo-Zr interdiffusion behavior tests: It is experimentally confirmed that the degradation factors resulting from interdiffusion between Mo and Zr do not significantly affect the integrity of UO_2-Mo pellets. No interdiffusion reactions were observed in a 700 °C, 100 h test. Slight reaction layer formation was observed after maintaining the test at 1200 °C for 100 h. An annealing treatment at elevated temperatures and loads (1300 °C, 300 kg) revealed the formation of the Mo_2Zr intermetallic compound.

5. Summary

The high thermal conductive ATF pellet technology has been developed in various aspects, including concept design, material and performance design, fabrication technology development, out-of-pile testing and computational analysis, in-pile testing and evaluation, and commercial manufacturing compatibility tests. Within a field of the out-of-pile testing and computational analysis, material property measurements, fuel performance prediction and evaluation, and behavior assessment of fuel pellets are being undertaken. Further technological enhancement through various out-of-pile tests, computational analyses, and modeling incorporating in-pile data is currently in progress.

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