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Integral LOCA experiment to study FFRD phenomena of high burnup ATF clad fuels

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1. Introduction

The burnup of nuclear fuel has been continuously increased to improve the economics of nuclear power plants until it reached the peak rod average burnup of 62 GWd/MTU, which is the safety regulatory limit [1]. However, the US nuclear power industry is currently working to increase the burnup limit from 62 GWd/MTU to 75 GWd/MTU [2], and Korean operators are also forming a consensus. There are several technical safety limiting factors in increasing the burnup limit, but the most critical issue among them is FFRD (fuel fragmentation, relocation, and dispersal).

Until now, safety regulations of the nuclear fuel in an accident have been centered on cladding. This was because the risk of fuel leakage in low burnup nuclear fuel could be mainly caused by cladding embrittlement and subsequent rupture. However, it was revealed in the IFA-650.4 test at the Halden reactor in 2006 that high burnup nuclear fuel can be fragmented into small particles and leaked in large quantities to the outside without cladding failure [3]. Therefore, the need for additional safety regulations for nuclear fuel pellets has emerged. However, to date, not only the number of experimental data for FFRD is not sufficient, but also the variables that affect the phenomenon are complexly entangled in FFRD, making it difficult to identify the phenomenon of FFRD. Accordingly, Seoul National University built an integral LOCA experiment facility (i-LOCA) to improve understanding of high burnup nuclear fuel FFRD, conducted experiments under various conditions, and analyzed FFRD phenomena.

2. Experiment

A schematic diagram of the integral LOCA experiment facility (i-LOCA) built at Seoul National University is shown in Figure 1. The 1.5m test Zircaloy rod specimens are inserted into the equipment, and 1 to 4 rods can be tested simultaneously. The specimen is heated by an induction heating coil, and the temperature of the specimen is measured by three pyrometers and an infra-red camera. The area where the rupture occurs is recorded using a high-speed video camera. During the experiment, steam generated from the steam generator is injected into the quartz tube to simulate the steam oxidation environment in an accident. At the end of the experiment, hot water is injected from below to simulate quenching through ECCS injection. Data is stored via a connected computer.

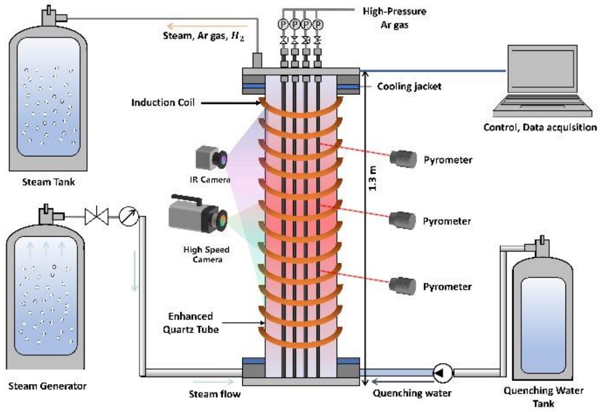

Fig. 1. Schematic diagram of integral LOCA facility

Figure 2 shows the surrogate pellet inserted inside the cladding in the experiments. Cylinder pellet simulates low burnup nuclear fuel without fragmentation, and powder pellet simulates high burnup nuclear fuel with fragmentation and pulverization. Single powder pellet (d=0.5mm) simulates nuclear fuel with a burnup of over 80 GWd/MTU where fuel fragmentation is severe. Mixed powder pellet (d=0.3,1,2,3,5 mm, with the same mass fraction) simulates nuclear fuel of burnup 70 GWd/MTU based on the size distribution of the experimental data in Studsvik [4]. They were inserted into the rod at different positions according to the experimental conditions. Pellet materials are alumina and zirconia.

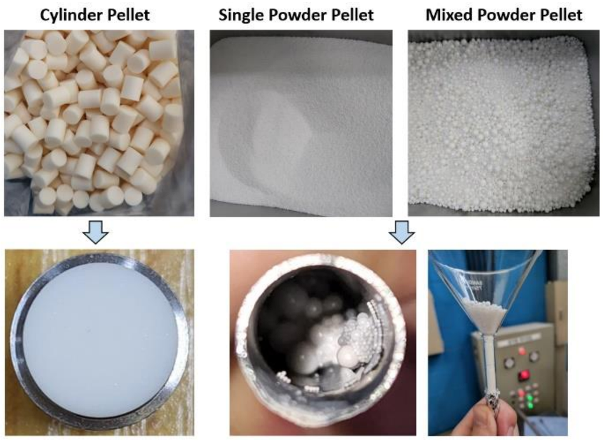

Fig. 2. Surrogate pellets used in the experiments

3. Results and Discussion

3.1 Burst behavior of Zircaloy and Cr-coated Zircaloy

In order to compare the burst and FFRD behavior of conventional zircaloy and chromium-coated zircaloy in an accident, experiments were conducted under the same conditions. Powder pellets were inserted into the 50 cm area of the heating center, and cylinder pellets were inserted in the remaining areas simulating a high burnup nuclear fuel rod. The inside of the nuclear fuel was pressurized to 5 MPa at room temperature with Ar gas, and the cold void volume was adjusted to about 30 cm^3. The results after the LOCA experiment are shown in Figure 3. Both of them burst at around 700℃, and more than 90% of the surrogate fuel was dispersed. There was no significant difference in the degree of deformation of the cladding. Therefore, even if the Cr coating is applied to the cladding, it is expected that there will be no significant difference in the FFRD phenomenon of high burnup fuel.

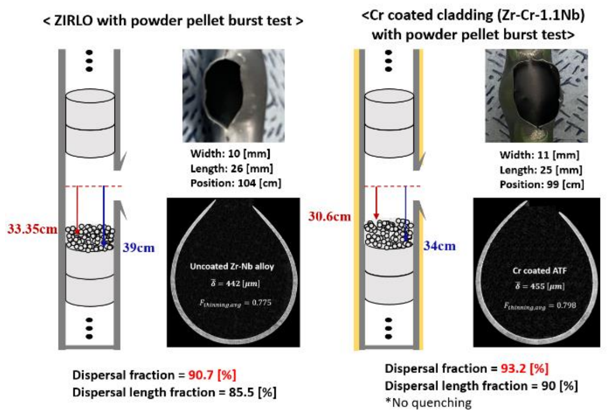

Fig. 3. Burst and fuel dispersal behavior of Zircaloy and Cr-coated Zircaloy

3.2 Pellet dispersal behavior with different fuel size distribution

Depending on the burnup of the nuclear fuel, the size distribution of the pellet changes, and the FFRD phenomenon also changes. Therefore, the experiments with different size distributions of the surrogate nuclear fuel ware conducted. Figure 4 shows the experimental conditions and results. The single powder case simulates a fuel of burnup over 80 GWd/MTU, and the mixed powder simulates a fuel of burnup 70 GWd/MTU. For both cases, the burst temperature occurred at about 800℃. However, in the case of single powder, the size of the burst was larger and the amount of dispersed nuclear fuel was much larger. This difference is thought to be resulted from the difference in fuel packing fraction and void volume. It is expected that the higher the fuel burnup, the greater the amount of nuclear fuel dispersal in the event of an accident.

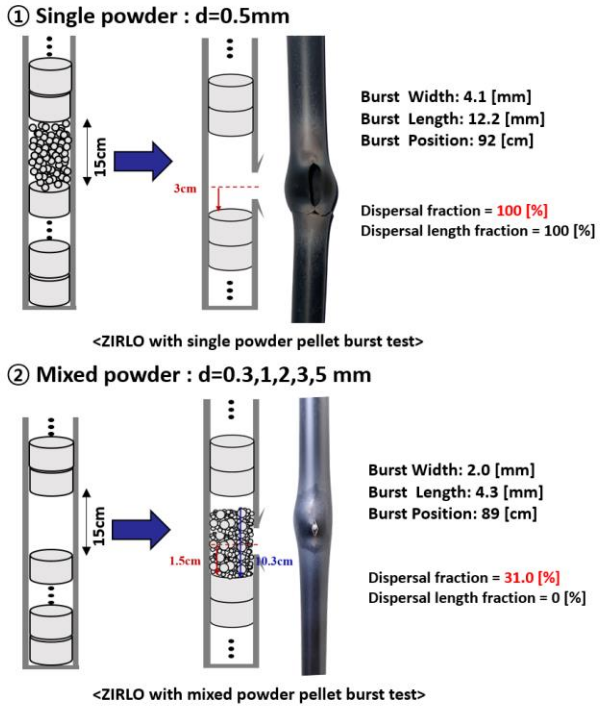

Fig. 4. LOCA experiment with different size distribution

During the experiment, the moment of the cladding burst was recorded through a high-speed video camera, and the images taken with 0.1 ms intervals are shown in Figure 5. The cladding burst proceeded in a short time of about 0.2 ms, and the surrogate nuclear fuel was dispersed at the same time as the cladding burst. Depending on the pressure inside and the size of the rupture opening, the dispersal velocity and amount of surrogate fuel are expected to vary.

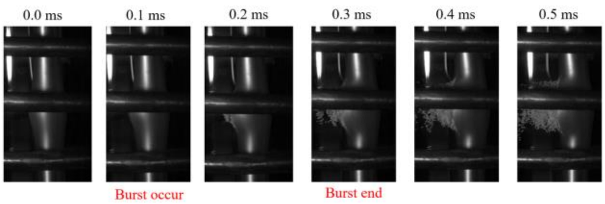

Fig. 5. Fuel dispersal behavior captured with high speed camera

After the experiment, the ruptured part was cut to observe the cross section of the cladding. The inner and outer oxide thickness, and the hydrogen concentration were measured (Figure 6). Inner side of the cladding was not much oxidized due to small size of the burst opening and remaining fuel after burst. Secondary hydriding caused by hydrogen generated from the inner wall oxidation was also observed. Through the analysis, it was confirmed that the equipment can successfully simulate the large deformation of the cladding and the steam oxidation environment in the event of an accident.

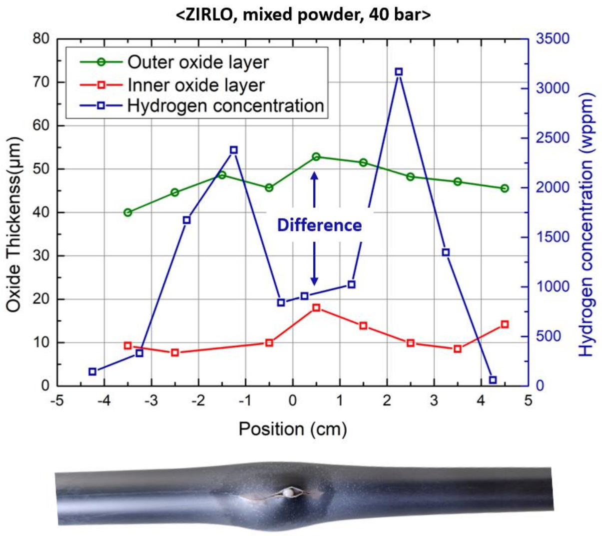

Fig. 6. Post characterization of test specimen

4. Conclusions

Through the conducted experiments, it was confirmed that an integral LOCA facility (i-LOCA) which simulates nuclear fuel ballooning, burst, and FFRD was successfully constructed. Based on the experimental results, it is expected that there will be no significant change in the FFRD phenomenon even if the chrome-coated cladding is applied. However, the size distribution of the nuclear fuel is expected to have a great effect on FFRD. We are planning to conduct additional experiments to clarify the variables that affect various phenomena related to FFRD and analyze the sensitivity to those variables.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Geelhood, K. J. (2019). Fuel Performance Considerations and Data Needs for Burnup above 62 GWd/MTU, PNNL-29368. Pacific Northwest National Laboratory.

[2] Capps, N., Jensen, C., Cappia, F., Harp, J., Terrani, K., Woolstenhulme, N., & Wachs, D. (2021). A critical review of high burnup fuel fragmentation, relocation, and dispersal under loss-of-coolant accident conditions. Journal of Nuclear Materials, 546, 152750.

[3] Raynaud, P. A. (2012). Fuel fragmentation, relocation, and dispersal during the loss-of-coolant accident. US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

[4] Sonnenburg, H., et al. "Report on fuel fragmentation, relocation and dispersal." NEA/CSNI/R (2016) 16. Organization for Economic Co-operation and Development, 2016.