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Simulated high burnup fuel cladding and its ballooning and burst behavior under Loss-of-coolant accident condition

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ABSTRACT*: For the safety evaluation of fuel cladding during the injection of emergency core coolant, simulated loss-of-coolant accident (LOCA) test was performed by using Zr alloy fuel cladding samples. To better understand high burn-up effects, study of hydrogen effects on LOCA-related behavior of high burn-up fuel cladding and their database on experimental results are essentially required. In particular, ballooning and burst behaviors of pressurized Zr alloy tube samples with and without hydrogen pre-charging were mainly investigated under various ramp rate conditions. As a result, pre-hydrided cladding sample showed a lower deformation in ballooned area and lower rupture temperature than as-received cladding sample. Ballooned cladding without hydrogen charging showed no significant difference in mechanical property in spite of a wide range of values for circumferential strain and different balloon shape caused by different heating rate. Pre-hydrided cladding, however, showed an increase in maximum load with increasing heating rate. Strong relationship between hydrogen content and burst behavior during loss-of-coolant accident was analyzed and the mechanism of hardening by hydrogen in zirconium alloy was explained.*

KEYWORDS*: Loss-of-coolant accident, Zr alloy, fuel cladding, High burn-up, Hydrogen*

I. INTRODUCTION

The nuclear fuel cladding should maintain good performance without serious degradation under not only normal operating conditions, but also various accident condition such as loss-of-coolant accident(LOCA). Therefore, it is very important to investigate the behavior or performance of fuel cladding under simulated accident condition. A current LOCA criterion is based on the results obtained from non-pressurized claddings specimens under simulated LOCA condition. However, integrity of fuel cladding can be significantly affected by ballooning and rupture that caused by pressure difference between inner and outer cladding during LOCA. Ballooning may cause the fuel relocation or fuel dispersal due to its rupture opening during accidents. In addition, wall thickness of cladding can be reduced and local regions near the rupture open would become heavily oxidized and hydrided [1]. Therefore, integral test that can simulate whole process during LOCA should be carried out for comprehensive safety analysis. Although a number of researches have been conducted, most investigations of them were performed using as-received cladding specimens.

In this study, burst behavior of several kinds of zirconium based alloys was investigated by integral LOCA test and high burnup effects on the burst behavior of fuel cladding were also examined using H charged cladding sample.

II. METHODS and RESULTS

In this section some of the techniques and experimental apparatus used to simulate the LOCA situation are described. Then, the highlight data will be shown with detailed explanation.

II.A. Experimental Procedure

Figure 1 shows the schematic illustration of integral LOCA test apparatus used in this study. For integral LOCA tests, 400 mm long cladding sample was used and filled with 10 mm-long alumina pellets to simulate the heat capacity of the fuel. The stack length of these pellets was about 360 mm long. The pressure was injected through stainless tube at the top and the cladding specimen was supported at the top to minimize specimen bowing. For comparison study, as-received and prehydrided (300 wppm) cladding sample were used. The Specimen temperature was measured by type-R thermocouple located near the sample center and the quartz tube provides an enclosed volume for steam flow and water quench, both of which are into the chamber, furnace heating started for a pre-test hold temperature of 300℃. Steam flow and 300℃ of sample temperature were stabilized within 180 s. Heating rate was 1, 14, and 28℃ /s from 300℃ to 1200℃. After oxidation at 1200ºC with hold time of 300s, the tube was cooled slowly and quenched at ≈800°C by bottom flooding. Representative temperature and pressure profiles from several LOCA tests were shown in Fig.2.

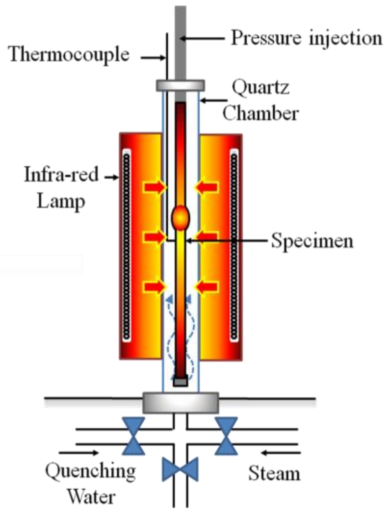

Fig. 1. Schematic illustration for the integral LOCA apparatus.

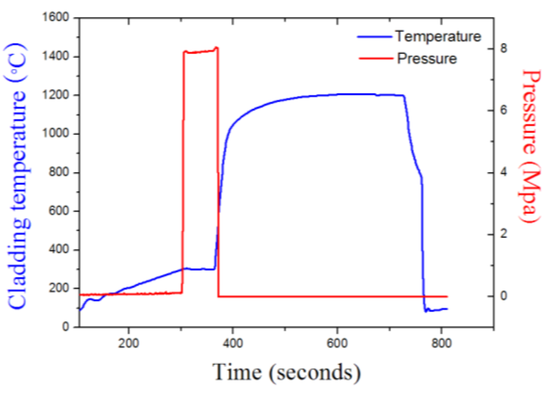

Fig. 2. Typical temperature and pressure profiles of integral LOCA test.

II.B. Results

Fig.3 shows rupture temperature data as a function of internal pressure for a range from 1 to 8 MPa. Integral LOCA test was performed using Zircaloy-4 and H4 cladding samples. This result shows general trend. Rupture temperature decreases with increasing internal pressure in both cases. Rupture temperature of H4 cladding was similar or slightly higher than that of Zircaloy-4. Cross-sectional images of the test samples of H4 alloy were obtained at burst midplane and shown in Fig. 4. Figs. 4 (a) and (b) show a burst behavior of H4 claddings with heating rate of 28℃/s. As received and prehydrided (300 wppm) sample shows similar circumferential strain at burst midplane. On the other hand, H4 claddings with heating rate of 1℃/s show a significant difference in circumferential strain. Prehydrided (300 wppm) H4 cladding shows a lower circumferential strain than that of as-received sample. Rupture size of as-received cladding was larger than that of prehydrided cladding. Fig. 5 shows Burst temperature and maximum circumferential strain of as-received and H charged H4 samples after integral LOCA test. H precharged cladding samples shows much lower burst temperature regardless of their heating rate. Burst strain at the location of rupture generally depends on temperature, internal pressure, and heating rate. Fig. 5 (b) shows burst strain as a function of heating rate. Internal pressure was fixed as 8 MPa. Difference in maximum circumferential strain of as-received and prehydrided cladding was increased with decreasing heating rate.

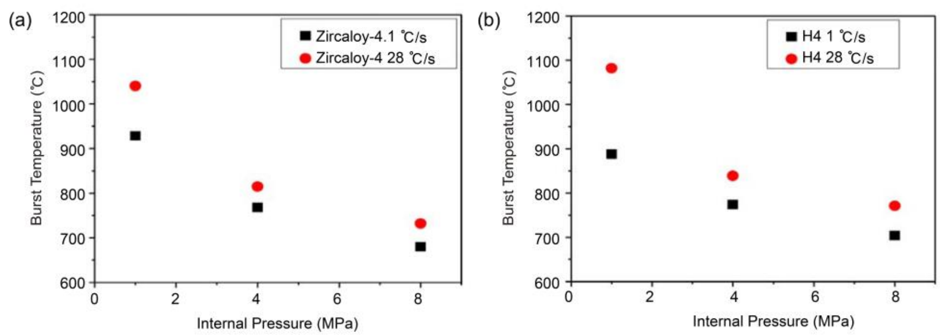

Fig. 3. Burst temperature as a function of internal pressure for (a) Zircaloy-4 and (b) H4 cladding specimens.

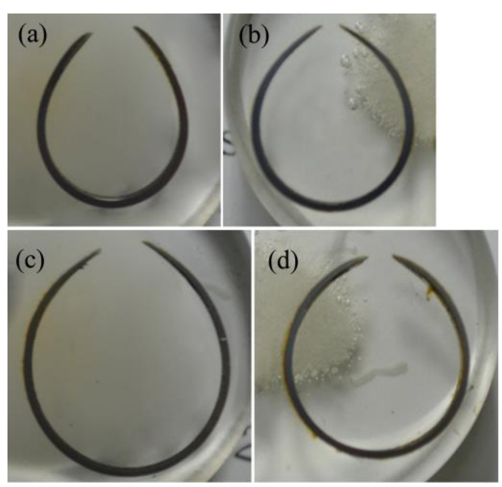

Fig. 4. Cross-sectional optical micrographic images at burst midplane for (a) as-received H4 cladding with heating rate of 28℃/s, (b) prehydrided (300 wppm) H4 cladding with heating rate of 28℃/s, (c) as-received H4 cladding with heating rate of 1℃/s, and (d) prehydrided (300 wppm) H4 cladding with heating rate of 1℃/s.

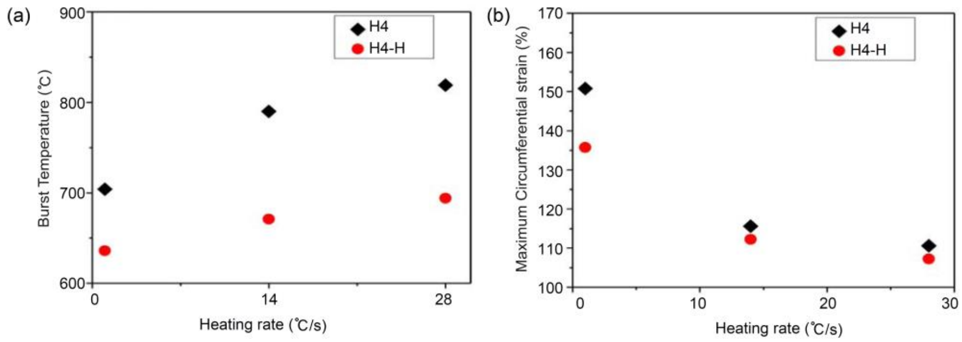

Fig. 5. (a) Burst temperature and (b) maximum circumferential strain as a function of heating rate for H4 and H4 cladding specimens.

II. CONCLUSIONS

To investigate the high burnup effects on rupture behavior of fuel cladding during the LOCA, H charged claddings were examined. Prehydrided H4 cladding shows the lower burst temperature and circumferential strain than that of as-received cladding. This is probably because the increase in oxygen solubility by hydrogen has reduced the ductility of the cladding. These results indicate that hydrogen uptake in high burnup fuel cladding may affect significantly on the burst behavior during LOCA condition

ACKNOWLEDGMENTS

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REFERENCES

1. M. Billone, Y. Yan, T. Burtseva, and R. Daum, Cladding Embrittlement during Postulated Loss-of-Coolant Accidents, NUREG/CR-6967, 2008 (available online in NRC ADAMS as ML082130389 at http://www.nrc.gov/NRC/reading-rm/adams.html.