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Simulation of high burn-up fuel cladding and its safety assessment under LOCA condition

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1. Introduction

Current LOCA safety criteria was established in the beginning of 1970s and based on the results obtained from non-irradiated Zircaloy-4 claddings. Because of major advantages in fuel-cycle costs, reactor operation, and waste management, the increase in fuel discharge burn-up is current worldwide trend in the nuclear industry. As the fuel burn-up increases, various phenomena unexpected have been reported due to changes in the condition of reactor operation and in-core environment. Since, it should be considered whether the current Loss-of-coolant accident (LOCA) criteria is suitable for high burn-up fuel cladding or not. In addition, many fuel vendors have recently developed new cladding alloys superior to Zircaloy-4 cladding. The performance of these advanced cladding alloys under LOCA, especially at high burn-up, is not well understood at this time.

To better understand high burn-up effects and commercialize new cladding alloys, study of LOCA-related behavior of various types of high burn-up fuel cladding and their data base is essentially required. In this background, postulated LOCA test has been carried out with prehydrided Zircaloy-4 cladding as a surrogate for high burn-up cladding and the relevant results obtained are discussed.

2. Methods

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.

2.1 Experimental Procedure

Fig. 1 shows an illustration of a apparatus used for simulated LOCA test. A Zircaloy-4 tube which has a 40 mm length was used in this study and specimen temperature was measured by thermocouple located near the sample ends. Steam flow was initiated at a test chamber temperature of ≈30ºC. Following introduction of steam 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. After oxidation, the tube was cooled slowly and quenched at ≈800°C by bottom flooding. Several short ring specimens having 8 mm long length were cut from the tube for testing of post-quench ductility. Slow ring-compression tests were performed at 135℃ at compression rate of 0.033 mm/s.

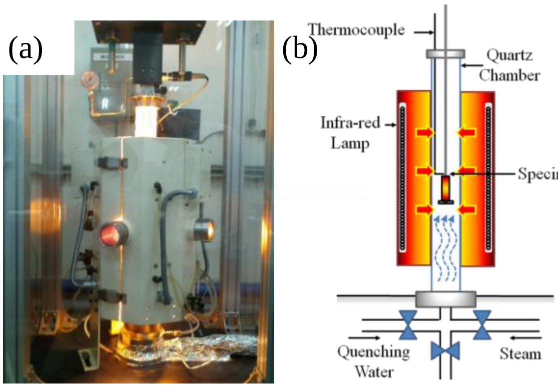

Fig.1. (a) Overview of the LOCA simulating test apparatus and (b) its schematic illustration

Hydrogen charging by the Sievert method was performed at 400℃ in a closed quartz chamber with a gas mixture of H_2 in argon at near ambient pressure (Ar: 200 Torr, H_2: 150 Torr). Uniform distribution of circumferential hydrides across the wall of Zry-4 prehydrided from 100 to 1000 wppm H is shown in Fig. 2.

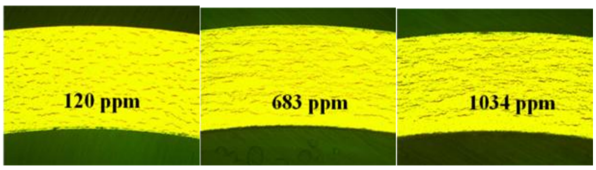

Fig.2. Uniform distribution of circumferential hydrides across the wall of Zircaloy-4 prehydrided from 100 to 1000 wppm.

2.2 Test Matrix for Safety Evaluation

The goal is to oxidize samples to different equivalent cladding reacted (ECR) so that the ductile-to-brittle (DTB) transition can be bracketed. Test matrix for target Cathcart-Pawel (CP) -ECR is tabulated in Table 1.

Table 1. Test matrix for high temperature steam oxidation.

Hydrogen Content (ppm)	Target CP ECR (%)		
As-Built	16	18	20
200	10	12	14
400	4	6	8
600	3	5	7

3. Results and Discussions

Ring compression tests were conducted by using prehydrided Zry-4 samples oxidized at 1200℃ and results are shown in Fig. 3. Post-test appearance is also shown in same Fig. Equivalent cladding reacted (ECR) values were calculated using the CP weight gain correlation.

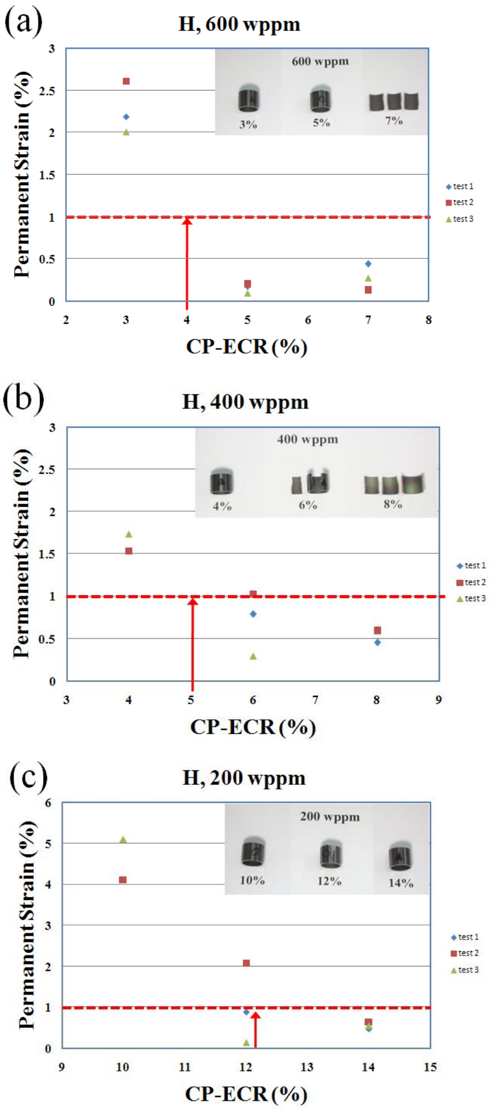

Fig. 3. Postquench ductility and appearance of Zircaloy-4 ring samples prehydrided to (a) 600, (b) 400, and (c) 200 wppm.

If a single, tight, through-wall crack is found, the post-test diameter in the loading direction was measured and the permanent displacement was determined. For permanent strain less than 1%, samples are classified as brittle.

The DTB transition CP-ECRs of Zircaloy-4 cladding prehydrided to 600, 400, and 200 wppm were 4, 5, and 12 %, respectively. Compared with DTB transition ECR of as-received Zircaloy-4 caldding oxidized at same temperature (17%, not shown here), prehydrided sample shows much lower DTB transition ECR. DTB transition ECR was decreased with an increasing of hydrogen content. These indicate that embrittlement was highly sensitive to hydrogen content. Based on the results of Mardon et al. [1], it is considered that precharged hydrogen would cause the solubility limit of oxygen in the prior-beta layer to increase relative to as-received material oxidized at 1200℃. Higher oxidation solubility may result in increased hardness and embrittlement in the prior-beta layer.

Post-quench mechanical behavior of H precharged Zircaloy-4 cladding in our study is very similar to that of irradiated Zircaloy-4 cladding [2]

4. Conclusions

DTB transition oxidation level (CP-ECR) as a function of pretest hydrogen content in cladding material for prehydrided Zircaloy-4 cladding materials were obtained after LOCA simulated test. The resulting behavior of prehydrided cladding embrittlement as a function of hydrogen content correspond closely with that of irradiated cladding. Thus, it can be concluded that prehydrided Zircaloy-4 cladding would be a good surrogate for high-burnup Zircaloy-4 in terms of post-quench ductility and transition CP-ECR

REFERENCES

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