Status of LOCA Performance Tests of HANA-6 Cladding

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1. Introduction

HANA (High performance alloy for nuclear application) alloy was developed in order to meet the global demand for an extension of the fuel discharge burn-up to more than 70 GWd/MtU. Several lead test rod (LTR) and lead test assembly (LTA) programs have been successfully conducted in commercial reactors [1]. Superior properties of HANA-6 cladding were verified from pool-side examination (PSE) after LTR and LTA programs [1, 2]. Also, post-irradiated examination (PIE) of HANA-6 cladding irradiated in commercial reactors is being conducted. However, although performance of HANA-6 cladding in loss-of-coolant accident (LOCA) condition has been evaluated [3], additional tests are needed to verify the performance of HANA-6 cladding in LOCA condition.

Furthermore, US NRC recently issued new LOCA criteria (10CFR50.46c) to address recent research finding related to high burn-up fuel [4-7]. According to 10CFR50.46c, an analytical time limit on breakaway oxidation should be determined and periodically confirmed based on an acceptable experimental technique [4, 5]. In addition, an analytical limit on peak cladding temperature (PCT) and integral time at temperature (ITT) have been proposed to ensure maintaining the cladding ductility under LOCA condition [4, 7].

In this regard, LOCA performance tests of HANA-6 cladding with development of new test systems were being performed to develop LOCA analytical models. In this paper, status of LOCA performance tests was summarized.

2. Results and Discussion

The LOCA performance tests of HANA-6 cladding have been chosen as bellows.

- High temperature oxidation model
- Breakaway oxidation analytical limit
- Post-quench Ductility (PQD) analytical limit
- LOCA burst model
- LOCA ballooning model

2.1 High Temperature Oxidation Model

High temperature oxidation tests were performed in steam/Ar mixed environment using Netzsch STA 499–F3. Table I shows high temperature oxidation test conditions. The steam flow rate was 1.12 mg/cm^2s, which comply with RG.1.223 recommendation to mitigate steam starvation [6]. The heating rate up to test temperatures was 30 $^oC/min$. To mitigate the pre-oxidation during heating stage, the inert environments was maintained by using high purity Ar gas. Two tests were performed at given test condition to confirm the reproducibility.

Table I: High temperature oxidation test conditions.

Temperature (^oC)	Time (s)	CP–ECR (%)
1000	2700	18
1050	1800	20
1100	900	18.5
1150	600	19.5
1200	480	22

Figure 1 shows parabolic rate constant (Kp) of HANA-6 and reference alloys. The parabolic rate constant of HANA-6 were lower than those of Zircaloy-4 and reference alloy at all tested temperatures. In addition, at tested temperature above 1050 ^oC, the measured parabolic rate constant of HANA-6 cladding was comparable with Cathcert-Pawel (CP) correlation. However, at 1000 ^oC, significantly lower parabolic rate constant in HANA-6 cladding than CP correlation was observed. It was similar to the oxidation rate of M5 cladding [8]. To verify the experimental model, additional tests will be conducted.

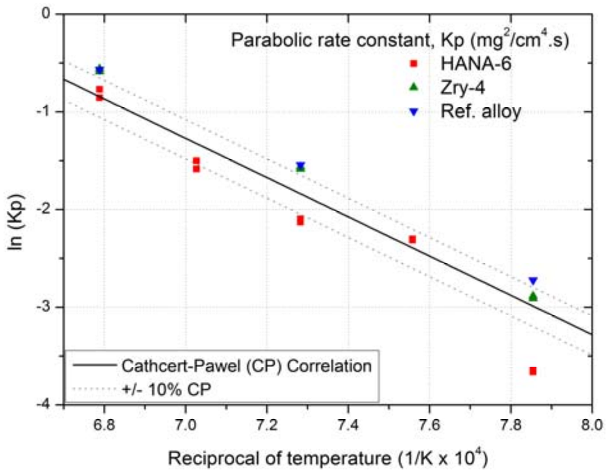


Fig. 1. High temperature oxidation test results of HANA-6 and reference alloys.

2.2 Breakaway Oxidation Analytical Limit

Breakaway oxidation is known as a phenomena which is a sudden or catastrophic increase of the oxidation rate due to phase transformation of oxide layer from tetragonal to monoclinic, thereby decreasing cladding ductility [5]. The new criteria in 10CFR50.46c require that an analytical time limit to preclude breakaway oxidation using an acceptable experimental technique should be determined [4, 5].

As shown in Fig. 2, a flow chart for determining the breakaway oxidation analytical time limit of HANA-6 cladding has been developed based on RG-1.222 [5]. Breakaway oxidation tests of HANA-6 cladding were performed in steam/Ar mixed environment by using Netzsch STA 499–F3. The heating rate and test environment during heat-up phase were same with high temperature oxidation tests.

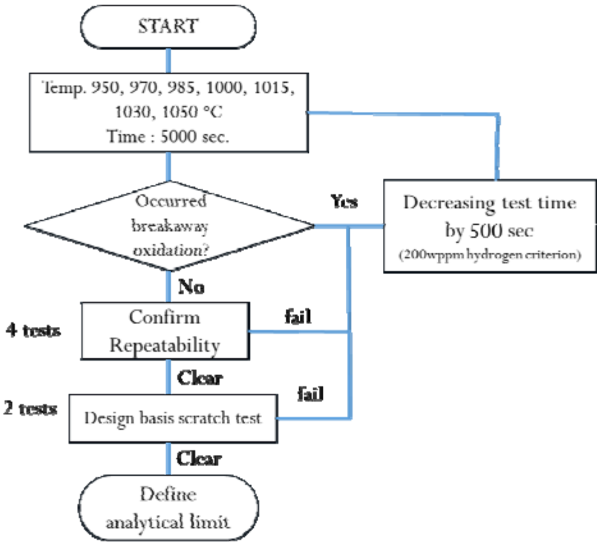


Fig. 2. Flow chart for determining breakaway oxidation analytical time limit of HANA-6 cladding.

Figure 3 showed outer surface appearances of samples oxidized at given temperatures for 5000 seconds. The color of outer surfaces of all tested samples were lustrous black which could indicate breakaway oxidation did not occurred [5]. In addition, the hydrogen contents of tested samples were below 200 wppm criterion of RG 1.222 [5]. Four repeatability tests at 1000 °C have been additionally performed. In results, the appearances of tested samples were lustrous black although those are not shown in this paper.

For the breakaway oxidation tests of design basis scratched HANA-6 cladding, the samples were fabricated with scratch which have a dimension of 30 um in depth and 150 um in width along axial direction. Two tests were performed at 1000 °C for 5000 and 7000 seconds, respectively. As shown in Fig. 4, the outer surface appearances of design basis scratched samples after oxidation tests were lustrous black. And, hydrogen content at design scratched region of samples were below 200 wppm hydrogen criterion. Therefore, the breakaway oxidation analytical time limit of HANA-6 cladding fabricated by KEPCO NF could be above 5000 seconds.

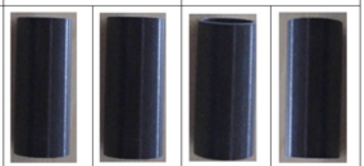
Additional breakaway oxidation tests will be performed to evaluate the effect of heating rates on breakaway oxidation. According to RG 1.223, the heating rate from 650 °C to the target temperature should be greater than or equal to 5 °C/s. However, the heating rate used in this work was 0.5 °C/s (30 °C/min) due to limitation of test machine.

Therefore, to achieve higher heating rates, new test system has been designed. Thermal benchmarks test and weight gain benchmarks which are required in RG 1.222 are under progress as described in Sub-section 2.3.

Fig. 3. Appearance of Breakaway oxidation test samples and their hydrogen content.

	Test temperature (°C)						
	950	970	985	1000	1015	1030	1050
Outer surface appearance							
Hydrogen Contents (ppm)	19	23	55	48	50	35	28

Fig. 4. Appearance of design basis scratch test samples and their hydrogen content.

	Test temperature (°C)			
Time (sec)	5000		7000	
Outer surface appearance				
Hydrogen Contents (ppm)	70		101	

2.3 Post-quench Ductility (PQD) Analytical Limit

The analytical limit on PCT and ITT defined in Figure 2 of RG 1.224 can be established for HANA-6 cladding by demonstrating that PQD data generated with an NRC-approved experimental technique (RG 1.223) is greater than or equal to the analytical limits provided in Figure 2 of RG 1.224 [6,7]. According to RG 1.224, the CP-ECR (equivalent cladding reacted) at which ductile to brittle transition (DBT) occurred should be identified for as-received cladding material and for at least two hydrogen content levels: (1) within 100 wppm of the maximum hydrogen content specified at end of life (EOL), and (2) within 100 wppm of half of the maximum hydrogen content specified at EOL [7].

To produce the hydrogen pre-charged sample, hydrogen charging tests by using 50 mm of samples were performed at 400°C in pure hydrogen gas. After hydrogen charging, pre-characterization of samples was performed by hydrogen analysis at adjacent PQD sample (30 mm) as shown in Fig. 5. Three specimens which have a hydrogen content of 200 wppm have been produced. Additional hydrogen charging tests will be performed for the hydrogen content of 400 wppm or above.

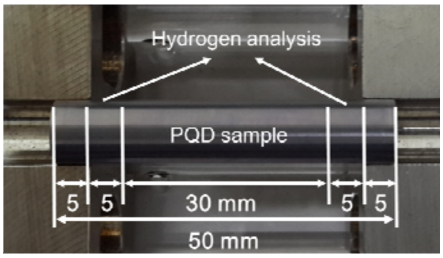


Fig. 5. Position of hydrogen analysis of PQD sample for evaluation of hydrogen end to end variations.

A new test system has been designed and qualified for high temperature oxidation tests of HANA-6 cladding as well as breakaway oxidation test. The experimental method described in RG 1.223 required thermal and weight gain benchmark tests before starting the PQD tests [6]. These two benchmark tests are used to check that the target temperature and hold time at test temperatures are achieved. Thermal benchmark test at 1100 °C was performed as shown in Fig. 6. Three thermocouples (TCs) were welded directly on outer surface in axial direction. And, one TC was welded in circumferential direction. In results, the temperature variations along axial and circumferential directions were within ±20 °C and ±10 °C, respectively, which are satisfied the requirements of RG 1.223 [6]. Thermal and weight gain benchmark tests are still under progress.

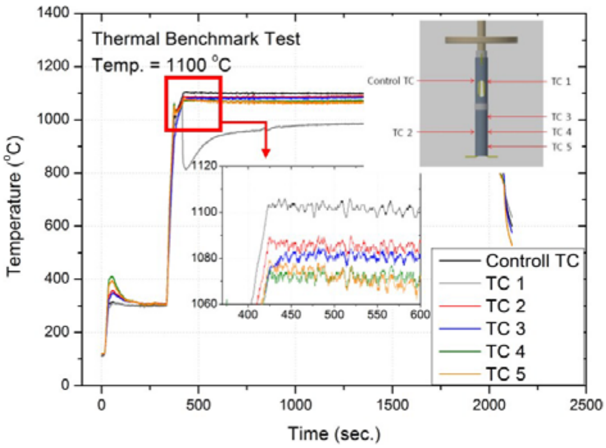


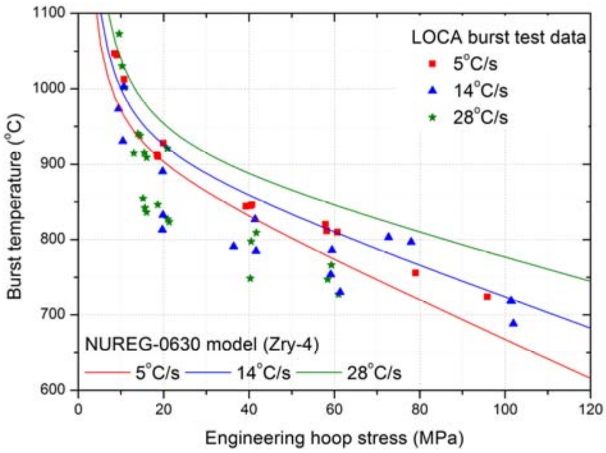
Fig. 6. Thermal benchmark test result at 1100°C.

2.4 LOCA Burst Model

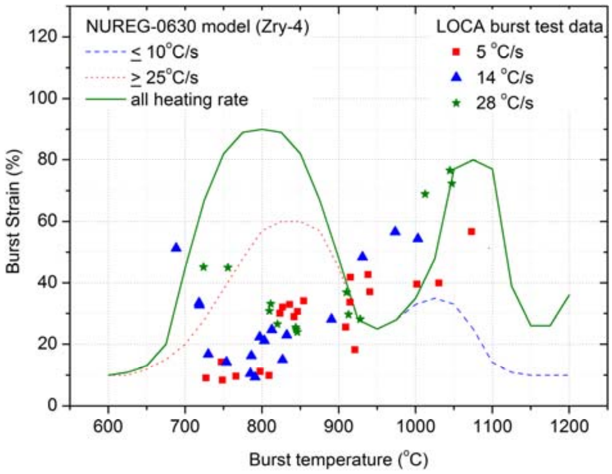
To develop the burst model of HANA-6 cladding, a special set-up was developed and qualified. The test system was designed with 6 infra-red (IR) heaters and steam generator. For qualification of test system, axial and circumferential temperature variations were verified in range of 80 mm in total 300 mm of cladding specimen. The heating rates were controlled to 5, 14 28 °C/s. The internal pressure was controlled at which engineering hoop stress of tube is equal to 7, 10, 20, 40, 60, 80, 100 MPa.

Figure 7 shows LOCA burst test results of HANA-6 cladding. The test results were compared with NUREG-0630 model which was based on experimental data of Zircaloy-4 [9]. The burst temperature of HANA-6 cladding at given hoop stress showed different from NUREG-0630 model as well as the burst strain at given burst temperature. The burst temperature was not dependent on heating rates. The reason why this independence of burst temperature on heating rate has not been founded in this study. Furthermore, the lowest burst strain of HANA-6 cladding was observed in temperature range from 800 to 900 °C. It has been known that the ductility drop in these temperature range is due to the low ductility of the mixed phase of alpha and beta [9]. Therefore, the ductility drop in the lower temperature range when compared with NUREG-0630 model is due to lower phase transition temperature of HANA-6 (740 ~ 960 °C) than Zircaloy-4 (820 ~ 975 °C).

To develop the LOCA burst model, the test will be continued to produce more experimental data.



(a) Engineering hoop stress vs. burst temperature



(b) Burst temperature vs. burst strain

Fig. 7. LOCA burst test result of HANA-6 cladding.

2.5 LOCA Ballooning Model

Ballooning behavior of HANA-6 in LOCA condition is one of important parameter affecting heat-transfer from fuel to cladding and degree of coolant blockage [9]. To develop the LOCA ballooning model of HANA-6 cladding, a special test system which can measure cladding diameter change by in-situ at constant temperature up to 1200 °C has been developed. The test system is capable of controlling heating rate, steam flow rate, rod pressure by program-based software. Qualification of test system will be conducted.

3. Conclusions

Current status of LOCA performance tests of HANA-6 cladding is summarized as follows.

1. The high temperature oxidation of HANA-6 was lower than at 1000°C, but, similar at above 1050 °C in comparison with CP correlation.
2. The breakaway oxidation analytical time limit of HANA-6 cladding could be above 5000 seconds. Additional tests will be performed by using new test system to comply with RG 1.222.
3. For post-quench ductility test, production of qualified hydrogen pre-charged samples and qualification of new test system are being performed.
4. LOCA burst test data of HANA-6 cladding were different from NUREG-0630 model. LOCA burst model for HANA-6 cladding will be developed.
5. A test system with in-situ cladding diameter measurement system has been designed to develop LOCA ballooning model.

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