Benchmark Tests to Develop Analytical Time-Temperature Limit for HANA-6 Cladding for Compliance with New LOCA Criteria

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1. Introduction

U.S. Nuclear Regulatory Commission (NRC) issued final draft version of LOCA criteria (10CFR50.46c) to address recent research finding related to high burn-up fuel. According to 10CFR50.46c, two analytical time and temperature limits for breakaway oxidation and post-quench ductility (PQD) should be determined by approved experimental procedure as described in NRC Regulatory Guide (RG) 1.222 and 1.223 [1,2].

According to RG 1.222 and 1.223, rigorous qualification requirements for test system are required, such as thermal and weight gain benchmarks. In addition, because it is known that the high temperature (HT) oxidation kinetics of Zr-Nb alloys could be markedly lower than Cathcart-Pawel(CP) correlation [3] which is best-estimate HT oxidation model of Zircaly-4, vendor proprietary HT oxidation model should be used. In order to meet these requirements, KEPCO NF has developed the new special facility to evaluate LOCA performance of zirconium alloy cladding [4]. In this paper, qualification results for test facility and HT oxidation model for HANA-6 are summarized.

2. Experimental procedures

2.1 HT Oxidation Tests

HT oxidation tests were performed in steam/argon mixed environment by using the simultaneous thermal analyzer (STA, Netzsch STA 499-F3). Test conditions were from 1000 ^{o}C to 1200 ^{o}C with 50 ^{o}C intervals, steam flow rate was 1.12 mg/cm^{2}s and in-situ weighing is possible with all the time-temperature range. Tests to develop the HT oxidation model of HANA-6 were performed in 30 ^{o}C/min heating rate.

2.2 Benchmark Test

Benchmark test of LOCA HT oxidation tester was conducted according with RG 1.222 and 1.223 appendix A-6 for the ZIRLO cladding tube. The thermal benchmarking should be showed agreement in the long time hold among the thermocouples (TC) welded onto the sample. TCs were calibrated by KOLAS correction agency. Thermal benchmark tests were performed at four temperature; 800, 1000, 1100 and 1200 ^{o}C. About the 30-mm-long tube specimen, TCs position is 10 mm, 20 mm, 30 mm (for the longitudinal temperature variation) and 0^{o}, 180^{o} (for the azimuthal temperature variation).

The RG for proposed LOCA criteria in appendix A requires [1, 2]: For a single sample, the axial temperature variation should be less than or equal to 10 ^{o}C and the circumferential temperature variation should be less than or equal to 20 ^{o}C. The heating rate from the initial sample hold temperature to 1000 ^{o}C should be relatively fast (it greater than 20 ^{o}C/s or less than 35 seconds) and the heating rate from 1000 ^{o}C to 1200 ^{o}C should be greater than 2 ^{o}C/s or less than 100-second duration. Also temperature overshoot during heat up should be limited to less than or equal to 20 ^{o}C for less than equal to 20 seconds. The temperature overshoot is not much of an issue for long time oxidation temperature ≤ 1100 ^{o}C, but it can be a significant embrittlement effect for HT oxidation [5]. As shown in Fig. 1, sample holder of the LOCA HT oxidation tester was composed of Inconel bar and alumina spacer, and temperature of zirconium tube was controlled by the control TC which was connected to upper Inconel holder. It brings up the temperature difference between the control TC and the zirconium specimen in dynamic heating phase.

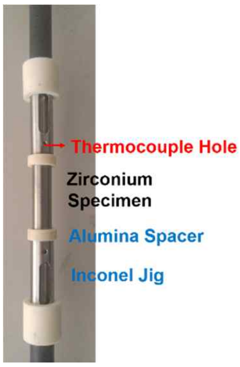

Fig. 1. Sample holder of LOCA HT oxidation tester

3. Results and discussion

3.1 HT Oxidation Model of HANA-6

Fig. 2 shows the parabolic rate constant (K_p) of HANA-6 cladding. Initial HT oxidation tests were performed under the steam/argon mixed environment at heating phase and isothermal phase by using STA. These results are shown in Fig. 2, the HANA-6 K_p line is the significantly low K_p compared with the CP correlation line. It was determined the effect of the pre-forming oxide which is formed at relatively low temperature in heating phase. As the case stands, HT oxidation test was modified in inert environment heating by purged argon gas. The K_p of HANA-6 was similar to CP correlation at

1200 ºC, but at 1000 ºC, significantly lower parabolic rate constant in HANA-6 cladding than CP correlation was observed. The HT oxidation model of HANA-6 was similar to oxidation rate of M5 cladding [3].

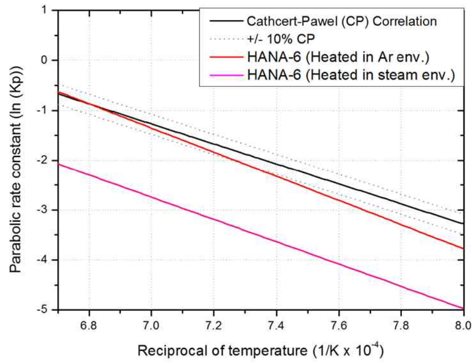

Fig. 2. High temperature oxidation model of HANA-6.

3.2 Benchmark Test Results

LOCA HT oxidation tester was constructed for determination of breakaway oxidation analytical limit and PQD oxidation test. This equipment can be heated rapidly (maximum heating rate is about 50 ºC/s) by using radiant heating furnace with infrared lamp and water quenching. The steam was supplied to specimen part for maintaining the steam environment and amount of steam was about 10 mg/cm^{2}s. The apparatus shown in Fig. 3 was used for HT oxidation in simulated LOCA transient compatible test procedure in RG 1.222 and 1.223 appendix A [1, 2].

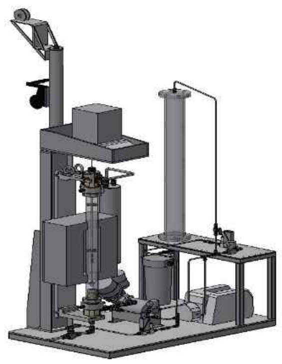

Fig. 3. The schematic of LOCA HT oxidation tester.

Fig. 4 shows the result of thermal benchmark test at 800, 1000, 1100 and 1200 ºC. At the 1200 ºC, the maximum axial temperature variation is ± 9 ºC, the circumferential variation is less than ± 2 ºC and the overshoot is 2 ºC. Also, at another temperature conditions, thermal benchmark test results were satisfied for RG criteria. The overshoot at low temperature (800, 1000 ºC) meets the requirements of RG criteria but relatively high ~ 17 ºC. These results were considered as insignificant effect on the oxidation result because lower temperature is not embrittlement test condition [5] and the long time test at these temperature conditions.

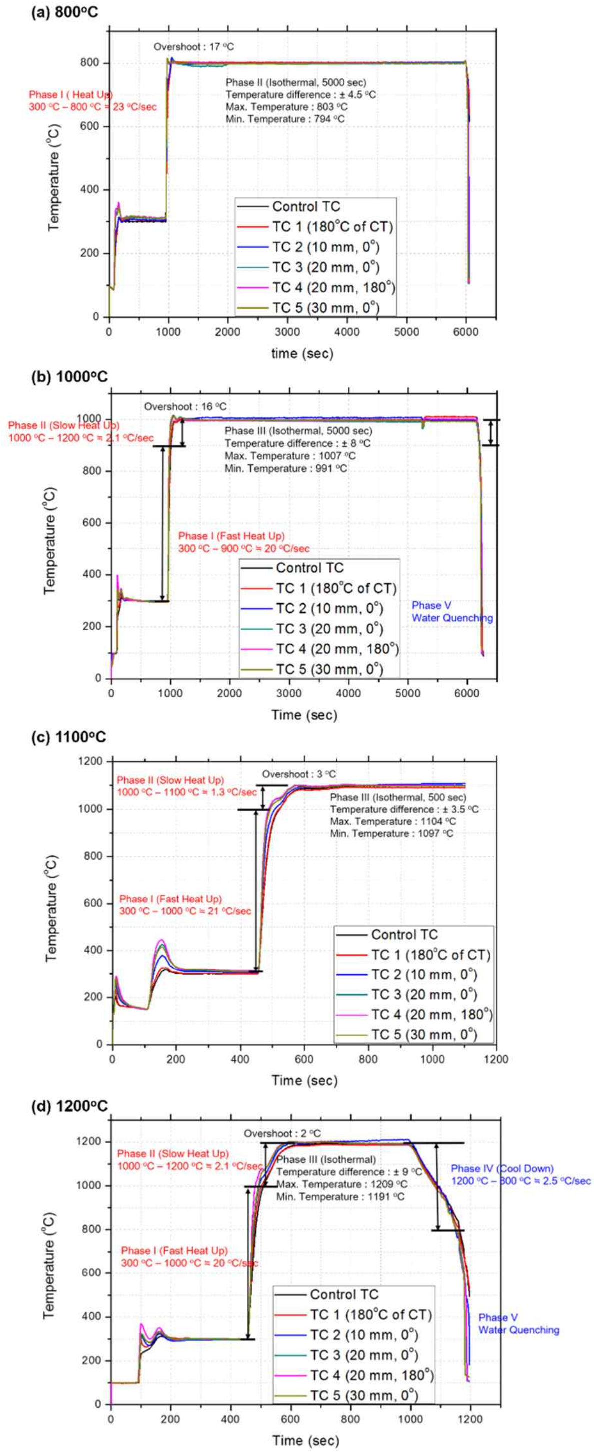

Fig. 4. Thermal benchmark test results at (a) 800 ºC, (b) 1000 ºC, (c) 1100 ºC and (d) 1200 ºC.

The weight-gain benchmark tests were performed using ZIRLO at 1200 ºC and 10% CP-ECR time (98 s), as shown in Fig. 5. Weight gain results of ZIRLO were similar to CP correlation, and this result corresponded the NUREG/CR-6967 oxidation test results [5]. Additional weight-gain benchmark tests will be performed to evaluate HANA-6 cladding at the other temperature conditions (800, 1000 and 1100 ºC). Furthermore, determination of breakaway analytical limit and PQD oxidation test will be conducted on the basis of benchmark test result.

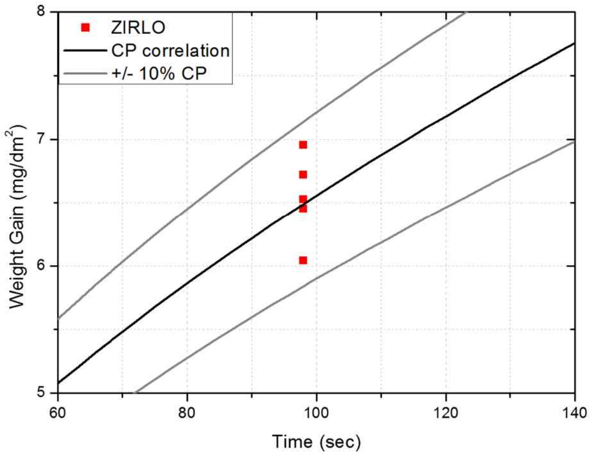

Fig. 5. Weight-gain benchmark test results at 1200 °C of ZIRLO cladding.

4. Conclusions

The results of thermal benchmark tests of LOCA HT oxidation tester is summarized as follows.

1. The best estimate HT oxidation model of HANA-6 was developed for the vender proprietary HT oxidation model.
2. In accordance with the RG 1.222 and 1.223, Benchmark tests were performed by using LOCA HT oxidation tester
3. The maximum axial and circumferential temperature difference are ± 9 °C and ± 2 °C at 1200 °C, respectively. At the other temperature conditions, temperature difference is less than 1200 °C result. Thermal benchmark test results meet the requirements of NRC RG 1.222 and 1.223.
4. Results of weight-gain benchmark test of ZIRLO cladding were similar to CP correlation at 1200 °C

5. Acknowledgements

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