In-pile Test Results of *HANA* Claddings in Halden Research Reactor

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1. Introduction

It is a kind of facing tasks in the nuclear industry to develop advanced claddings for high burn-up fuel which is safer and more economical than the existing conventional ones. Since 1997, taking an initiative in KAERI, the Zr cladding development team has carried out the R&D activities for the development of the advanced claddings to be used in the high burn-up fuel ($\geq$ 70,000 MWD.MTU). The team had produced the advanced claddings (*HANA*, High-performance Alloy for Nuclear Application) from the patented composition and manufacturing process in the international collaboration with U.S. and Japan. Now, the *HANA* claddings have being demonstrated their good performances from the out-of-pile tests including the corrosion, creep, burst, tensile, microstructures LOCA, RIA, wear, and so on [1]. In parallel to the out-of-pile performance tests, the *HANA* claddings are being undertaken to evaluate their in-pile properties in Halden research reactor. In this study, it is included the test overviews, conditions, and results of the *HANA* claddings in the Halden reactor.

2. Overviews

The irradiation rigs IFA-673 and IFA-674 are devoted to the *HANA* claddings conducted at the Halden Reactor (HBWR) in Norway. This test is similar to the Joint Program IFA-638 test series [2], with two parts to the experiment: one using fuelled cladding sections and the other using unfuelled coupons. The positioning of the coupons is in holders both above the test fuel rods and also along the center of the rig. The addition of these unfuelled cladding sectors will allow the effects of heat flux on corrosion behavior to be assessed. The schematic view of the test rig is shown in Figure 1.

The two rigs IFA-673 and IFA-674 have been irradiated in the HBWR since February 2004 (i.e. a total of 2 reactor cycles and ~185 FPD) during exposure to water chemistry, fluence and thermal hydraulic conditions similar to those found in commercial PWRs. The corrosion behavior of the test materials (in the form of fuelled tube claddings and/or coupons) is assessed by means of once-a-year interim inspections, the first of which was performed in November 2004.

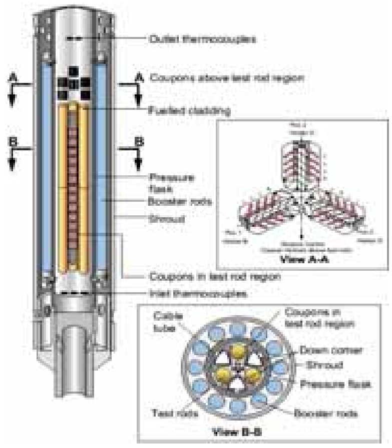

Figure 1 Schematic view of irradiation test rig

3. Test Conditions

Heat rate: The average linear heat rate has been in the range from 30 to 35 kW/m during most of the irradiation in all the rods.

Neutron flux and fluence: The fast neutron flux levels ($\geq$ 1 MeV) within the fuel rod region ranges from 2.0 to 3.5 x 10^{13} n/cm^2/s. Calculated fast neutron fluence levels at the fuelled section were 0.3 to 0.5 $\times$ 10^{21} n/cm^2-s.

Coolant temperature: The coolant temperature measured at the inlet of the test rig was 291^{o}C with about 25^{o}C rise in temperature through the channel.

Coolant pressure and flow rate: The coolant flow rate and pressure have been kept at about 1.68m/s and from 163 to 166 bar, respectively, for the main part of the irradiation. The thermal hydraulic conditions along the axial length of the fuel rods have been calculated (using the Halden thermal hydraulic code VISTA [3]) from the start-up. The results of these calculations, which are based on the average measured oxide thickness for each segment assuming that the thermal conductivity of zirconium oxide is 0.020 W/cm-K.

Water chemistry: It is measured the concentrations of lithium (2 ppm) and boron (700 ppm) from the coolant analysis and calculated the pH_{300} (~7.1) in IFA-673 and IFA-674. The hydrogen content has been maintained at about 2 ppm, and no oxygen has been measured in the coolant.

4. Test Results

4.1 Test methods

The interim inspections of IFA-673 and IFA-674 cover the following; photography of cladding segments (both before and after brushing), diameter measurements of fuelled cladding segments, oxide thickness measurements on fuelled cladding segments by means of an eddy current proximity probe (based on an individual calibration for each material type), eddy current measurements on fuelled cladding segments to look for effects of hydrides and possible cladding defects, and photography and weighing of coupons

The coupons were ultrasonically cleaned for 10 minutes in de-mineralized water, and then dried for 1 hour at 100°C before weighing on a five-point balance.

4.2 Test results of fuelled test rods

Corrosion: The oxide thicknesses on the fuel rods range from ~5 μm to ~17 μm depending on alloy and axial position (i.e. heat flux). The average oxide thickness for the highest region of each segment (top of lower segment and bottom of upper segment) is plotted in Figure 2 for all alloys. It is seen that, in general, the *HANA* claddings show better corrosion resistance than the two reference alloys (A-cladding and Zry4). All of the *HANA* claddings had an excellent corrosion resistance in the comparison with the references, as shown in Figure 2. The corrosion resistance of some *HANA* claddings was improved by 40~50 % when compared with the reference A-cladding on the basis of the oxide thickness measurements.

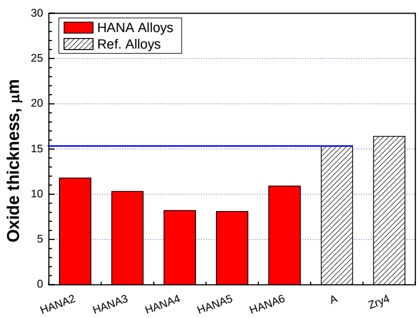

Figure 2 In-pile oxide thicknesses of HANA claddings

Creep: Fig. 3 shows that the creep-downs of the *HANA* claddings were superior to those of the two references (A-Cladding and Zry4). Especially, the creep resistance of *HANA4* was improved by about 70%, compared with the reference A-cladding.

Hydrides and defects: No evidence of clad defects was seen from these scans on any of the fuel rods.

Visual inspection: No irregularities were seen on any of the rods.

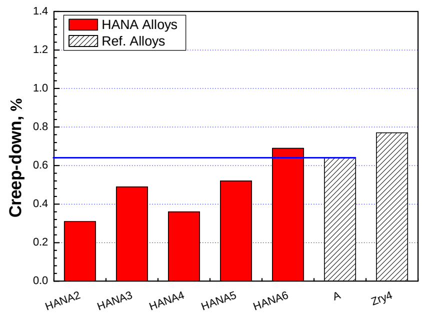

Figure 3 In-pile creep-downs of HANA claddings

4.3 Test results of unfuelled corrosion coupons

Corrosion: All coupons showed weight gain in the range 21 mg/dm^2 to 56 mg/dm^2 depending on alloy and axial position.

Visual inspection: No irregularities were seen on any of the coupons.

4. Summary

1. The oxide thickness on the fuelled test rods was within the following range from 7 μm to 17 μm. In general, the *HANA* claddings showed better corrosion behavior than the two reference alloys (A-Cladding and Zr-4).
2. The weight gains of corrosion coupons were ranged from 21 to 56 mg/dm^2.

ACKNOWLEDGEMENT

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