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Assessment of Fuel Relocation on Halden IFA-650.5 Using FRAPTRAN

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1. Introduction

If ballooning and successive burst of fuel cladding happens for a postulated loss-of-coolant accident (LOCA), there is a possibility that fragmented and pulverized fuel pellets can be relocated into the deformed regions. Fuel relocation can change the distribution of local heat source along the fuel rod. And it will influence the rod performances related to the safety criteria such as fuel temperature and oxidation characteristics of cladding.

Halden IFA 650.5 LOCA test was conducted in 2006 [1]. Used fuel for the test was a pre-irradiated commercial PWR rod and had a high burnup, 83 MWd/kgU. The peak cladding temperature (PCT) achieved at the test was 1,050 ℃. Burst hoop strain of cladding was ~15 %, and small amount of fuel dispersal was observed. After the test, extensive post-irradiation-examination (PIE), including the metallography of cladding has been conducted [2]. Through the PIE, thickness of oxygen rich alpha (α) layer and ZrO_2 oxide layer of cladding, which were formed during a LOCA transient was measured also.

In this paper, studies focused on the assessment of fuel relocation in terms of the simulation of cladding temperatures. Thickness of α and ZrO_2 oxide layer were also assessed by factorizing fuel relocation. FRAPTRAN-2.0P1 computer code was used [3].

2. Halden IFA-650.5 LOCA Test

Halden IFA-650.5 LOCA test, the third test with pre-irradiated PWR fuel, was conducted on October 23rd, 2006. Length of active fuel stack was 48 cm. Temperatures were measured axially three different positions. One cladding surface thermocouple, TCC1, was located 10 cm above the fuel stack bottom, and the other two, TCC2 and TCC3, were attached 8 cm below the top of the stack. Unfortunately, one of the two thermocouples in the upper part, TCC2, was damaged and did not give reliable measurements. The temperature of the heater was measured by three embedded thermocouples (TCH); TCH1 at the same elevation as TCC1, and TCH2 and TCH3 were attached 3.5 cm below the fuel mid plane and 10 cm below the fuel top, respectively. Test was carried out using low fission power (25 W/cm) to achieve the desired conditions for ballooning and oxidation. A heater surrounding the rod and operating at 17 W/cm was used for simulating the heat from adjacent rods. The peak cladding temperature was achieved ~1,050 °C, and the hold time was ~5 minutes (from burst to scram). Rod overpressure at hot conditions was ~65 bar. Cladding failure occurred ~178 seconds after blowdown at ~750 °C. The average cladding temperature increase rate during the heat-up was 5.0-5.5 °C/s. More details on the test are described in ref. 1.

Diameter measurements, based on the visual inspection and neutron radiography were made to estimate the LOCA induced fuel diameter increase and the cladding distension. Fig. 1(a) shows the results of diameter measurements. In the lower end of the rod cladding diameter increased steeply and rapidly to its maximum and burst. Cladding burst was found 7-8 cm above the lower end active fuel stack.

Metallography was performed at 6 different locations along the fuel rod. Measured oxide thickness prior to LOCA was 70-80 μm, whereas oxide growth due to LOCA period was about 11 μm. Oxygen rich and hard α layer was observed on both inner and outer surface of cladding. The thickness was 20-30 μm, and inner surface α layer was slightly thicker, ~2 μm, than the outer layer. The α layer measured at the burst region is thicker than the others, and the differences between inner and outer layer are also relatively large, ~5 μm. Fig.1(b) shows the thickness of measured oxide and α layer along the rod. Details on the PIE results are described in ref. 2.

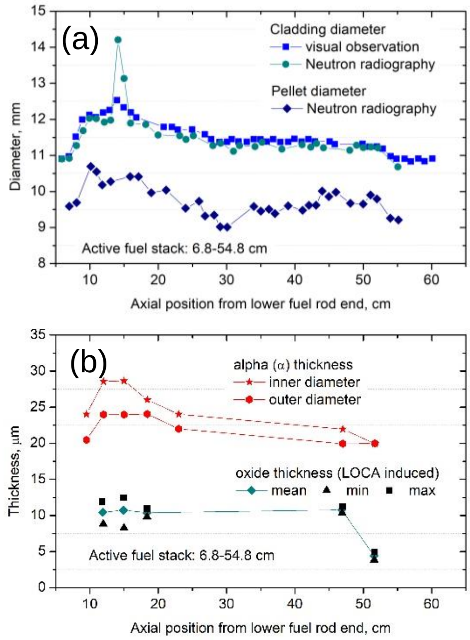

Fig.1. (a) Measured cladding diameters and (b) oxide and α layer thickness, data from ref. 2.

3. Analysis Details

3.1 High temperature oxidation models

In FRAPTRAN-2.0P1, there are two well-known high temperature oxidation models on zirconium alloys. One is Cathcart-Pawel (CP) and the other is Baker-Just (BJ) model. It is known that the BJ model produces a relatively conservative result than the CP predicted within this LOCA temperature of concerned [4]. Thus we used CP correlations for calculation of oxide and α layer thickness. Following are correlations [5];

For ZrO_2 oxide layer, 1273 K < T < 1723 K

$$\delta\, d\delta/dt = 0.01126 \exp(-35{,}890/RT)\ cm^2/s \qquad (1)$$

For α layer, 1173 K < T < 1723 K

$$\delta\, d\delta/dt = 0.7615 \exp(-48{,}140/RT)\ cm^2/s \qquad (2)$$

where,

δ = *thickness of the layer (cm)*
T = *temperature (K)*

3.2 Modeling details

Initial conditions of pre-irradiated fuel rod before LOCA experiment were calculated by FRAPCON-4.0 [6]. Input for FRAPCON was prepared by Pacific Northwest National Lab (PNNL). In the input, for more detailed analysis, we changed the number of axial node from 9 to 20. And gas compositions and initial moles of gases were adjusted according to the refabricated rod conditions. FRAPTRAN-2.0P1 was used for the simulation of fuel behaviors of IFA-650.5 test. For the simulation, following methods and assumptions were made.

- Measured heater temperatures (TCH1, TCH3) were used as coolant temperatures.
- Heat transfer coefficients (HTCs) during transient were deduced from measured cladding temperature (TCC3) and heater temperature (TCH3). And these HTCs were imposed entire fuel rods.
- Internal pressure of fuel rod was adjusted for the simulation of burst time and temperature of cladding.
- Permanent hoop strain of cladding along the rod was given as a boundary condition after fuel rod burst. Permanent strain was derived from the measurement data of neutron radiography, as shown in Fig.1(a).
- Quantum Technology (QT) fuel relocation model was used for the simulation of fuel relocation at the burst region.
- Radial relocation of fuel pellets without axial relocation was simulated as imposing a minimum gap thickness (2 μm) for the thermal calculation of fuel.

4. Results

4.1 Cladding temperatures

Fig. 2 shows the comparison of cladding temperatures between measured (TCC3) and FRAPTRAN calculated ones. There are two cases of code calculation. One is a normal gap condition and the other is a minimum gap.

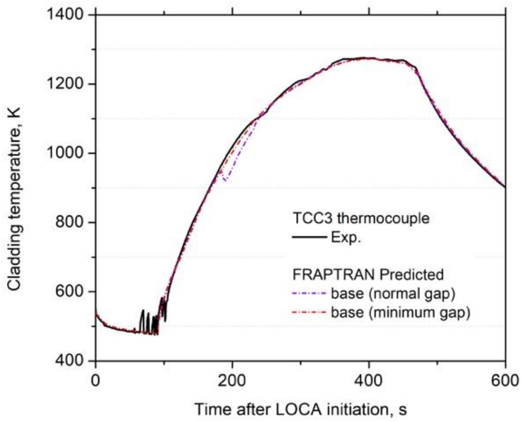

Fig.2. Cladding temperature evolutions with factorization of radial relocation in TCC3 thermocouple position (8 cm below the top of fuel stack).

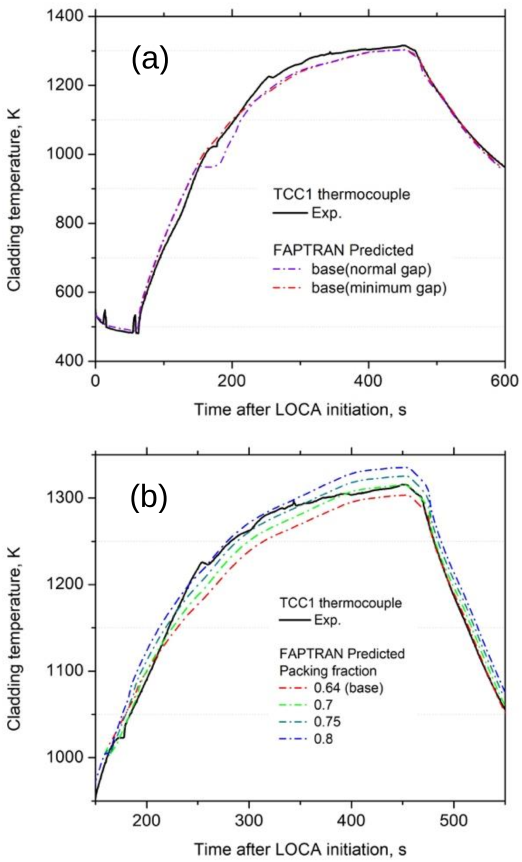

Fig.3. Cladding temperature evolutions with (a) factorization of radial relocation, and (b) changes of packing fraction in TCC1 thermocouple position (10 cm above the bottom of fuel stack).

Normal gap means any radial relocation of fuel pellet is not considered during analysis, thus gap size is changed depending on the deformation of fuel and cladding. But, minimum gap condition is that the gap size is given as 2 μm throughout the LOCA transient, irrespective of fuel and cladding deformation.

Fig. 2 showed that in the normal gap condition, small amount of temperature drops of cladding (~27 K) was observed at the time of fuel rod burst (~180 s), and some differences of cladding temperature between measured and calculated ones were observed until the time reached to ~240 s. However, except this period, calculated cladding temperatures are fairly well agreement with the measured one. Meanwhile, if we imposed the minimum gap, cladding temperatures are very good agreement with the experimental in whole period of LOCA.

Fig. 3 shows the comparison of cladding temperatures in the TCC1 thermocouple position. Trends of calculated cladding temperature are similar to the results of TCC3, shown in Fig. 2, but some differences are also discovered. In the normal gap condition, shown in Fig.3(a), cladding temperatures were not increased at the ballooning and burst period of time from 150 s to 180 s. And cladding temperatures were lower than the experimental until the time reached to ~470 s. Meanwhile as we imposed the minimum gap, cladding temperatures are good agreement until the time of ~ 200 s. But still lower cladding temperatures were predicted compared to the measured ones from ~200 s to ~470 s.

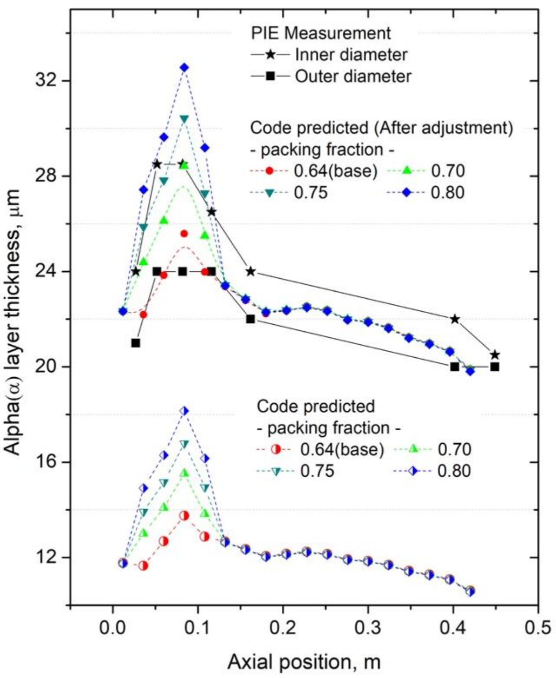

Fig.4. Comparison of α layer thickness between measurement and code predicted with variations of packing fraction.

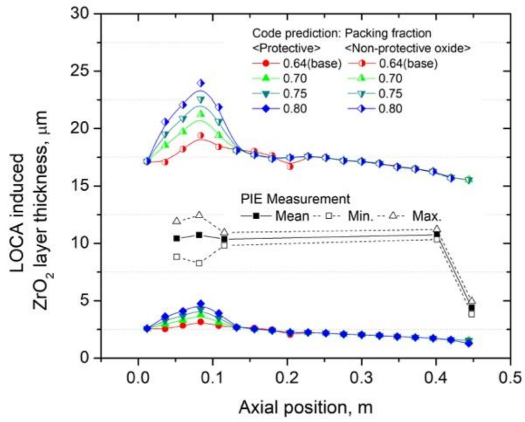

Fig.5. Comparison of ZrO_2 layer thickness between measurement and code predicted with variations of packing fraction.

Fig.3(b) shows the comparison of cladding temperatures with variation of packing fraction in TCC1 thermocouple position. Packing fraction varied from 0.64 to 0.8. Packing fraction of 0.64 is the base case. It means only radial relocation is taken into account, thus it is almost identical to the minimum gap condition in Fig.3(a). As the fraction increased every 0.05 step, cladding temperature increased about 10 K. The results revealed that as the fraction was given in between 0.7 and 0.75, calculated cladding temperatures became very similar to the experimental values.

4.2 LOCA induced α layer

Fig.4 shows the comparison of α layer thickness between measured, from metallographic observation and code calculated with variations of packing fraction. In the base case, predicted α layer thickness was in range of ~11~14 μm. And the packing fraction increased from 0.64 (base) to 0.7, 0.75 and 0.8, the maximum thickness of α increased to about 16, 17, 18 μm, respectively. These values, however, are ~10 μm lower than the measured thickness. This means the current CP model of α layer growth predicts lower thickness in this 650.5 test.

For the assessment of effects of packing fraction through PIE results, cladding temperatures were adjusted. Temperature adjustment was done with the application of multiplication factor of 1.095 on coolant temperature. After adjustment it showed similar thickness of α layer with the PIE of the upper part of fuel rod. In the base case, maximum thickness of α was ~25 μm. And the packing fraction was set as 0.70, 0.75, 0.8, it increased to ~28, 30, 32 μm, respectively. Thus, packing fraction below ~0.75 may be reasonable for the simulation of α layer.

4.3 LOCA induced ZrO_2 layer

Fig.5 shows the comparison of LOCA induced ZrO_2 layer between measured and code calculated. In the calculations, two options were used. One is set the initial oxide as protective, and the other is set as non-protective.

In the protective case, predicted oxide thickness was in range of ~2~3 μm along the fuel rod. And packing fraction do not induce much impacts. As the fraction was set as 0.8, maximum oxide thickness was ~5 μm. This is still lower than the measured thickness, ~11 μm. In the non-protective case, much thicker oxide layer was predicted. In the base case predicted thickness was in range of ~16~19 μm along the fuel rod. And as the packing fraction was given as 0.7, 0.75 and 0.8, maximum oxide thickness increased to ~ 21, 23, 24 μm, respectively. These are almost two times thicker than the measurements. This analysis suggests the experimentally observed oxide was found in between protective and non-protective oxidation model of CP.

5. Summary

Assessment of fuel relocation on Halden IFA-650.5 was carried out through the simulation of cladding temperature, thickness of LOCA induced α and ZrO_2 layer. Following results can be drawn temporary.

- Cladding temperatures of IFA-650.5 were successfully simulated with the factorization of radial relocation of fuel pellets, especially for the period of ballooning and burst.
- According to the predicted cladding temperature and thickness of α layer in the ballooned and busted region, some amount of axial relocation of fuel pellet may be expected. Packing fraction may be ranging about 0.70~0.75.
- Thickness of α layer predicted by Carthcart-Pawel (CP) oxidation model was smaller than the results of experimental observation.
- Measured thickness of LOCA induced ZrO_2 layer was found in between the protective and non-protective CP model prediction.

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