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Simulation of IFA-650.10 Test Using a Modified Version of RELAP5/MOD3.1

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1. Introduction

In order to address the performance of the advanced cladding alloys under LOCA, especially at high burnup operation, the U.S.NRC has established newly revised LOCA acceptance criteria (10 CFR 50.46c) to ensure adequate safety margin [1, 2]. As the current LOCA methodology and related fuel rod model in the thermal-hydraulic system code, RELAP5, do not meet the revised criteria, code and methodology improvement reflecting the proposed acceptance criteria should be made. Thus the fuel rod model in RELAP5 was improved and assessed against the Instrumented Fuel Assembly (IFA)-650.10 test. To make a fuel rod in RELAP5 calculations have the same initial conditions produced by ROPER, the rod initialization procedure was also developed.

2. Calculation Method

2.1 Analysis Procedure

RELAP5/MOD3.1 thermal hydraulic system code [3] and ROPER fuel code [4] were used for the calculation. Some modifications were made to RELAP5 to reflect the proposed LOCA acceptance criteria. The models related to pellet-clad gap conductance and rod internal pressure prediction were modified to better simulate the fuel rod transient behavior. The code was also improved to have the capability of modeling the low conductivity of oxide and to have a user option turning on the two-side oxidation model.

The rod initial conditions such as the gap conductance, the pellet average temperature, or the gap size at hot power condition were taken from the calculation results using the ROPER code, fuel performance code KNF developed.

As the fuel rod model in RELAP5, even with the modification mentioned above, cannot be the exactly same as in ROPER, a method or a procedure was needed to make a fuel rod in RELAP5 calculations have the same initial conditions produced by ROPER. So, the rod initialization procedure outlined in Fig. 1 was developed. The main purpose of this procedure is to make the steady state hot power gap conductance predicted by RELAP5 be nearly the same as calculated by ROPER. For this purpose, the radial pellet and clad displacement due to swelling and creep down in RELAP5 is adjusted iteratively until the gap conductance predicted by the code approaches close to that predicted by ROPER. Other rod initial conditions such as the rod internal pressure, gap gas composition, and void volumes in the rod are taken from the ROPER calculation results directly.

2.2 RELAP5 modeling

RELAP5 input was prepared utilizing the information in the IFA-650.10 experimental report [5]. The averaged linear heat generation rate (LHGR) and heater temperature etc. referred to the measured data but some information not presented in the report such as the blowdown rate and spray flow rate were set to appropriate values by a trial-and-error method.

Heat structures in the test rig were modelled using eight components but only two components modeling the fuel rod and the electrical heater, respectively have significant effect on the fuel rod temperature predictions as they acted as a heat source. Note that the electrical heater acted also as a wall-to-wall radiation heat sink and that modeling accurately the radiation heat transfer between the fuel rod and the heater is essential to get reasonable fuel temperature transient. As the wall-to-wall radiation heat transfer rather than the convective heat transfer to superheated steam was the dominant heat removal mechanism at the rod surface, the time dependent temperature of heater inner surface was given as a boundary condition in this calculation. The active fuel rod region was divided into 20 equal length axial nodes and 8 radial meshes were used to model the radial inner-rod heat transfer. The improved fuel rod model including the modified version of rod deformation model, gas gap conductance model, and clad oxidation model were used in this calculation.

3. Halden LOCA Experiment

The LOCA experiments conducted at Halden reactor are integral in-pile single rod tests which address various LOCA issues. A total of 15 experiments has been conducted using PWR, BWR or VVER fuel rods. The tenth LOCA test (IFA-650.10) was selected for this study to assess the new fuel rod model because its rod burnup was very close to the burnup limit in Korea. The test was carried out in May 2010 using the fuel rod which had been irradiated in a commercial PWR up to 61 GWd/MTU. The length of the fuel stack was ~440 mm and no end pellets were inserted. The fuel rod was located in a standard high-pressure flask in the IFA-650 test rig, which was connected to a high-pressure heavy water and a blow-down system (Fig. 2). Details of the fuel and cladding geometries and chemical compositions are given in Table 1 [5].

The general test scheme of IFA-650.10 can be divided into several periods. They are the forced circulation period, the natural circulation period, the blowdown period, the heat-up and temperature transient period, and the cooling period. Through the sequential periods, the fuel rod experienced the transient shown in Fig. 3. As shown in this figure, cladding failure occurred ~249 s after blowdown at ~755 °C. Spray was started 12 s after the burst in order to ensure that the fission products are transported out of the loop. The test was terminated by a reactor scram ~418 s after the blowdown initiation. At the end of the test, the rig was filled with helium for dry storage. As time went by, the rod temperature and rod internal pressure varied due to the depletion of the coolant, the elastic and plastic deformation of clad, and rod rupture.

4. Result and Discussion

4.1 Clad Surface Temperature

Fig. 4 shows the clad surface temperature evolution of IFA-650.10, measured ~110 mm above from the bottom of fuel stack. The clad surface temperature was predicted to be slightly higher than that of the measured data. The difference of a peak clad temperature was only ~40 K and the overall transient behavior of rod temperature was predicted very well.

4.2 Rod Internal Pressure

Fig. 5 compares the predicted rod internal pressure to the measured one. As shown in the figure, the predicted rod internal pressure was much higher than that of the measured data before rod burst (at 249 s) and the rod burst was also predicted earlier than the measured one. The over-prediction of rod internal pressure was mainly caused by the over-prediction of rod plenum temperature which is given in the calculation as the surface area weighted average of pellet average temperature and clad inner surface temperature at the fuel top. In the case of IFA-650.10 fuel rod, pellet and clad temperatures were relatively high compared to the fuel rods in the plant as the axial power distribution was nearly flat. So, the current rod internal pressure model, which was developed for commercial fuel rods in plants, may not appropriate to be applied to IFA-650.10 fuel rod. Note also that the rod plenum of IFA-650.10 fuel rod was much longer than that of commercial fuel rods.

4.3 Gap Width

Fig. 6 shows the change of gap width after blowdown initiation. As shown in the figure, predicted gap width was augmented into about 0.5 mm. It was mainly caused by a high temperature creep occurred when the clad temperature reaches the onset of a plastic deformation. In this case, the rapid increase of gap width at a time of about 150 s was due to the deformation model equipped with the RELAP5 code. Meanwhile there was little change on gap width owing to the clad burst at about 200 s.

4.4 Heat Transfer Coefficient

Fig. 7 shows the change of gap conductance during the LOCA. As shown in the figure, the rapid decrease of gap conductance was occurred after about 150 s. This happened primary due to the increase of gap width mentioned in Fig. 6. Reduction of gap conductance makes the pellet temperature augmented. Meanwhile, it was observed that the ratio of radiation conductance is augmented. Since the radiation conductance is proportional to the fourth power of the temperature, this contributes to enhance the heat transfer within the gap by the augmented pellet temperature.

On the other hand, the heating rate of clad surface decreases owing to the wall-to-wall radiation between a clad surface and an electric heater. Consequently, as shown in Fig. 4, the increasing rate of a clad surface temperature is gradually reduced with increasing time.

5. Summary

An assessment on the Halden IFA-650.10 LOCA test was conducted by the modified RELAP5 code and the ROPER code. To better simulate the fuel rod transient behavior, rod initialization procedure between ROPER and the modified RELAP5 code were established and developed respectively. Consequences are as follows.

The clad surface temperature was predicted to be slightly higher than that of the measured data but the overall transient behavior of rod temperature was predicted very well.

On the other hand, the predicted rod internal pressure was much higher before rod burst and its time is also earlier. This discrepancy is due to the over-prediction of rod plenum temperature. As clad surface temperature increases, gap width increases but gap conductance decreases mainly due to a high temperature creep.

REFERENCES

[1] ″Fourth Status Report on Study of Risk-informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria),″ SECY-02-0057, 2002.03.

[2] ″Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,″ RIL-0801, U.S.NRC, 2008.05.

[3] ″RELAP5/MOD3 Code Manual,″ NUREG/CR-5535, U.S.NRC, 1991.08.

[4] ″ROPER Fuel Rod Design System,″ KNF-TR-CDT-08002/N/A, Rev. 0. KNF, 2015.05.

[5] Alexandre. Lavoil, ″LOCA Testing at Halden, the Tenth Experiment IFA-650.10,″ HWR-974, OECD Halden Reactor Project, 2010. 12.

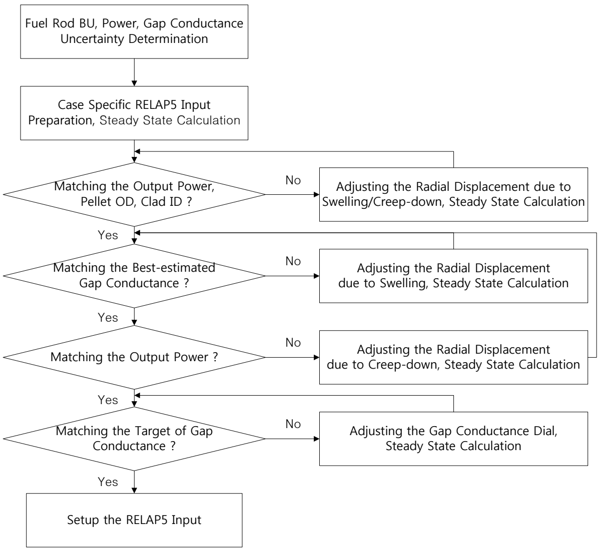


Fig. 1. Linked calculation procedure between ROPER data and RELAP5 input

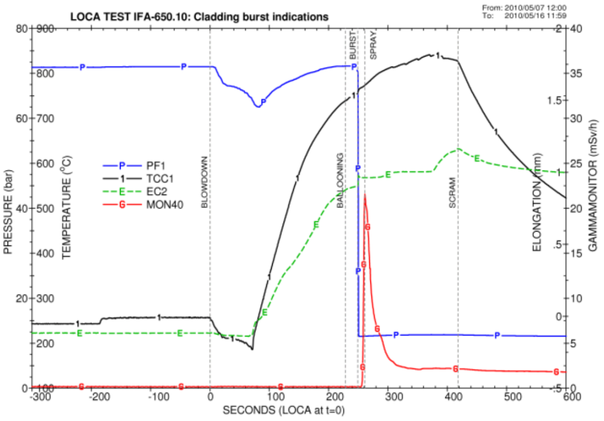
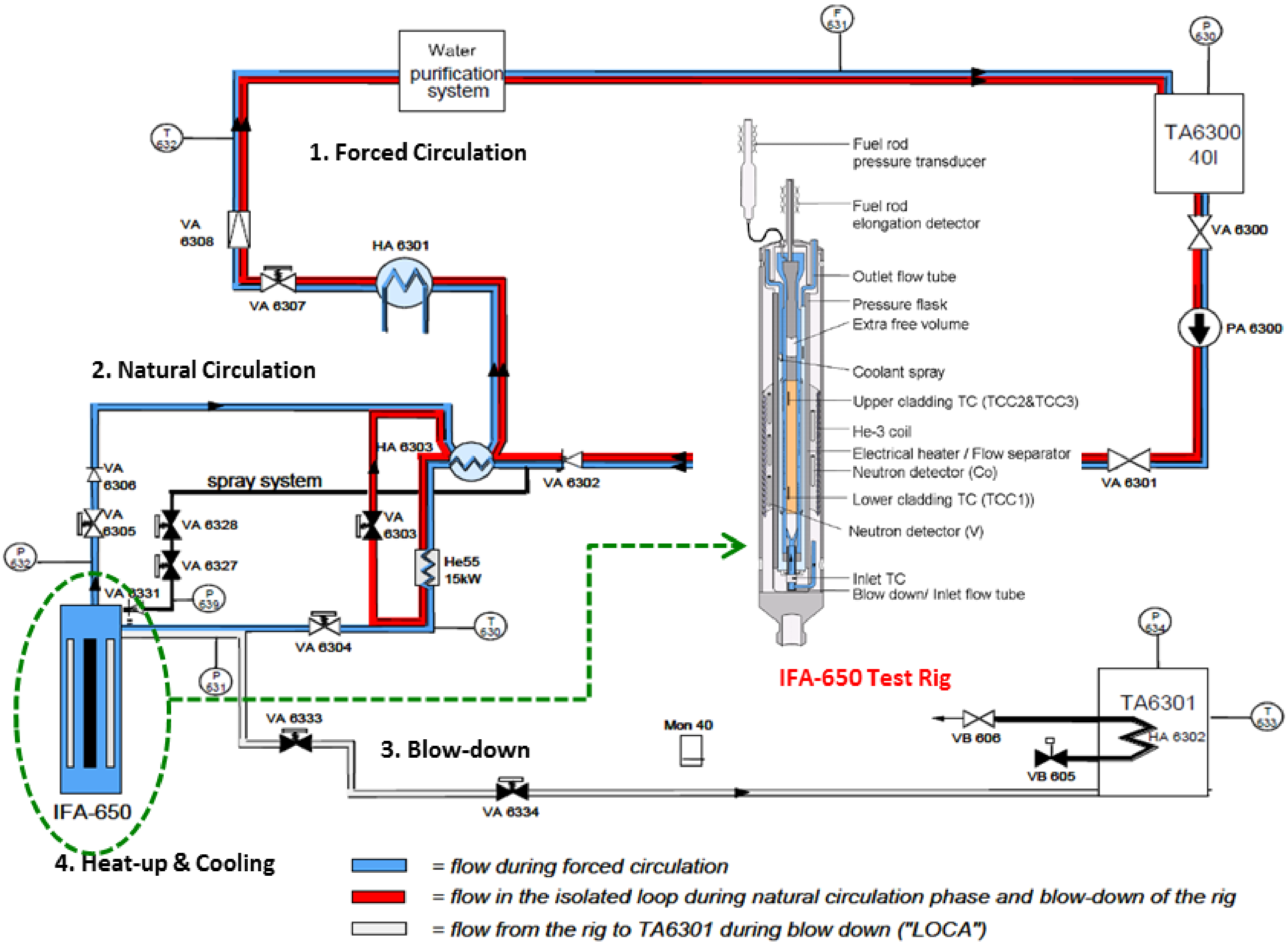


Fig. 2. Rod pressure (PF1), clad temperature (TCC1), elongation (EC2) and gamma monitor response (MON40) [5]



🟦 = *flow during forced circulation*
🟥 = *flow in the isolated loop during natural circulation phase and blow-down of the rig*
⬜ = *flow from the rig to TA6301 during blow down ("LOCA")*

Fig. 3. Simplified drawing of the loop used for IFA-650.10 [5]

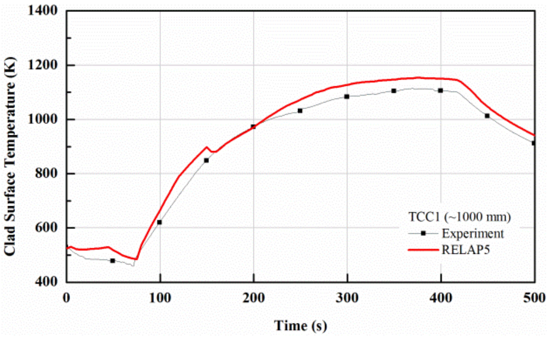


Fig. 4. Comparison of clad surface temperature evolution between measured and code calculated results during the LOCA

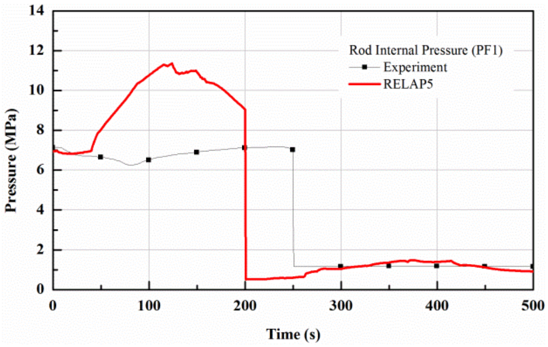


Fig. 5. Comparison of fuel rod internal pressure evolution between measured and code predicted pressure

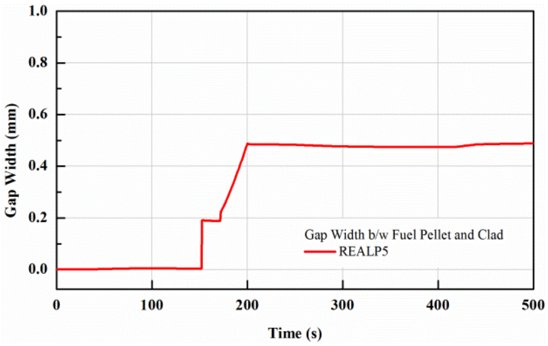


Fig. 6. Change of gap width after blowdown initiation

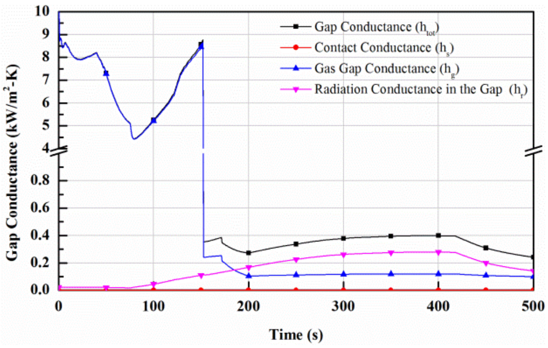


Fig. 7. Change of gap conductance during the LOCA

Table I: Details of the fuel / clad geometrics and chemical compositions

Test Assembly Data	**IFA-650.10 [5]**
Fuel Form	UO_2
Active Fuel Length [mm]	440
Burnup [MWd/kgUO2]	53.8 (61 MWd/kgU)
Fuel Density [%]	95.32
Fuel Diameter [mm]	8.33
Pellet Length [mm]	10
Cladding Material	Zry-4
Cladding Oxide Thickness Mean/Max	20~30 micron
Filler Gas/Pressure	0.95 Ar + 0.05 He / 40bar (70 bar in hot phase)
Cladding Outer Diamter [mm]	9.5
Cladding Thick. [mm]	0.57
Cladding Inner Diameter [mm]	8.36
Total Free Gas Volume [cc]	16/17 (plenum/free volume)
Channel Power [kW]	about 2.5 kW during LOCA test, fuel 1.5 kW, heater 1.0 kW
Avg. Heat Rating [W/cm]	about 25 W/cm during LOCA test, fuel 14 W/cm, heater 12 W/cm