Effects of Fuel Relocation Model of FAMILY Code in Halden IFA-650.4 LOCA Test

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1. Introduction

KINS has developed FAMILY (**F**RAPTRAN **A**nd **M**ARS-KS **I**ntegrated for Safety Ana**LY**sis) code in which system thermal-hydraulic code, MARS-KS and fuel performance code, FRAPTRAN are fully integrated[1]. In FAMILY code, FRAPTRAN calculates the performance of a single fuel rod when MARS-KS calculates the thermal-hydraulic parameters of system and provides thermal-hydraulic conditions around a fuel rod for FRAPTRAN iteratively.

Fuel models such as fuel relocation and thermal resistance of crud have been developed to accurately predict fuel behavior and its effect on thermal-hydraulic conditions in FAMILY code. Out of the developed models, fuel relocation model resulting from fuel cladding burst due to excessive deformation can directly change the distribution of heat source in a fuel rod[2]. To investigate the effect of fuel relocation model, Halden IFA-650.4 loss-of-coolant accident (LOCA) test was evaluated in this study because large deformation and relocation of fuel resulting in power redistribution were dominant in Halden IFA-650.4 test with high burnup condition.

2. Overview of Halden IFA-650.4 LOCA Test

Fig. 1 shows a schematic of the Halden IFA-650.4 LOCA test rig with its instrumentation and Fig. 2 shows the cross-sectional geometry of the test rig, respectively.

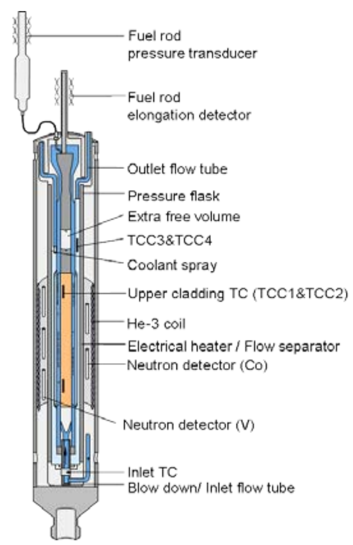

Fig. 1. A schematic of Halden IFA-650.4 test rig

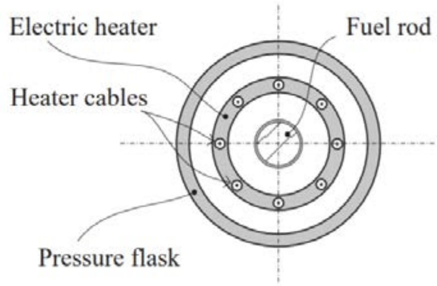

Fig. 2. Cross section of Halden IFA-650.4 test rig

Table I shows major parameters of Halden IFA-650.4 LOCA test[3,4]. Fuel burnup and target peak cladding temperature (PCT) after blowdown are 92.3 MWd/kgU and 800°C. The thermal power of a fuel rod and an electrical heater were adjusted to 9.3 W/cm and 15 W/cm, respectively. The electrical heater simulates the adjacent fuel rods around a fuel rod at the center. The length of the active fuel rod is 480 mm. Two thermocouples, TCC1 and TCC2 were located at 80 mm below the top of fuel to measure fuel cladding temperature. Other two thermocouples, TCH1 and TCH2 were located at 100 mm and 275 mm below the top of fuel respectively, to measure the temperature of the electrical heater.

At first, the outer circulation loop and the test rig are disconnected each other to make a natural circulation condition. Then coolant flows upwards through the flow path between a fuel rod and an electrical heater, and the coolant flows downwards through the flow path between electrical heater and pressure flask. When the coolant temperature is stabilized, blowdown valve is opened to the dump tank to initiate coolant blowdown.

Table I. Major parameters of Halden IFA-650.4 LOCA test

Parameter	Value
Effective fuel length [mm]	480
Fuel weight [kg UO_2]	0.320
Burnup [MWd/kgU]	92.3
Theoretical fuel density [%]	95.2
Pellet length [mm]	11
Clad oxide thickness [㎛]	mean 10 / max 11
Clad O.D. [mm]	10.75
Clad thickness [mm]	0.725
Flask I.D./O.D. [mm]	34/40
Electrical heater length [mm]	518
Target PCT [°C]	800

3. Modeling of FAMILY Code

FAMILY code was used for the evaluation of Halden IFA-650.4 test. The initial conditions of pre-irradiated fuel rod were obtained by FRAPCON code[5]. FAMILY code has a fuel relocation model developed by Quantum Technology(QT) and linear heat generation model of QT fuel relocation model was improved in previous studies[1]. Additionally, axial fuel power model was also improved to reflect the history of decay heat[1].

Fig. 3 shows the nodalization of Halden IFA-650.4 test rig in FAMILY code based on the modeling of RELAP5 in previous studies[6]. It has been identified that radiation heat transfer between a fuel rod and an electrical heater has much influence on the fuel cladding temperature in Halden IFA series tests[7,8]. Radiation due to high heat flux from adjacent heat structure, i.e. an electrical heater in this experiment, could be dominantly effective in heat transfer phenomena. Therefore, radiation heat transfers (between fuel rod and electrical heater/between electrical heater and outer flask) were modeled. The emissivity of fuel was assumed to be 0.8 based on the material property of ZrO_2.

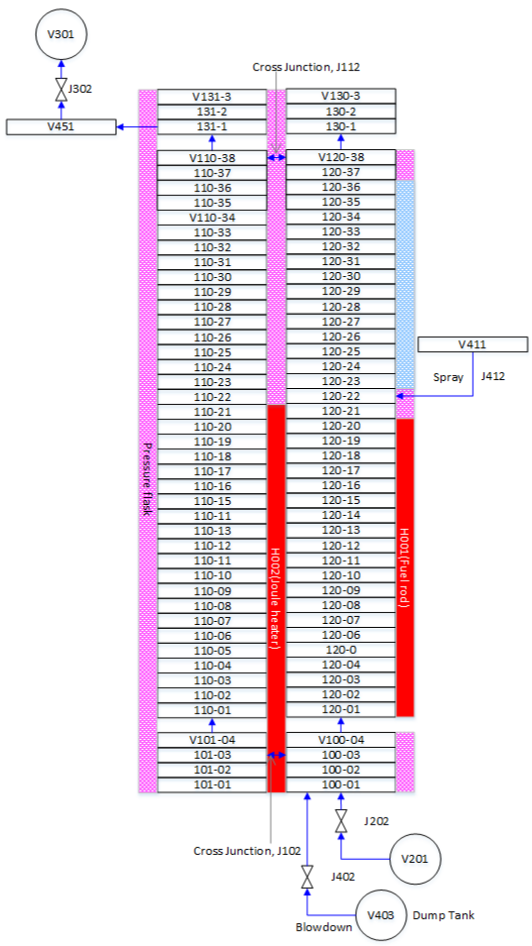

Fig. 3. Nodalization of Halden IFA-650.4 test rig in FAMILY code

4. Results and Discussion

Fig. 4 shows the fuel cladding temperature at TCC1 thermocouple in experiment and calculation. After the fuel cladding temperature increases continuously due to heat-up during blowdown phase, it decreases rapidly after the fuel cladding burst since there is no fuel producing heat at the elevation of TCC1.

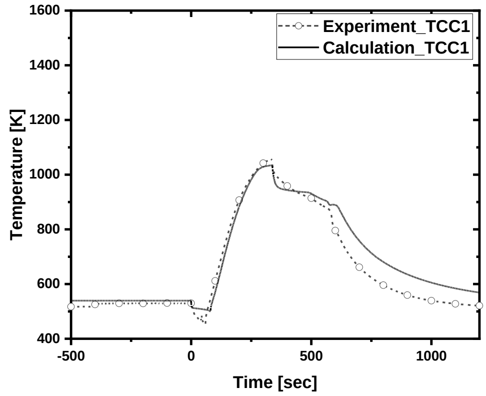

Fig. 4. Cladding temperatures at TCC1 thermocouple position

Fig. 5 illustrates calculation results of the fuel cladding temperature along the axial direction. Before the occurrence of fuel cladding burst, the fuel cladding temperatures of 20 axial nodes are similar each other. However, the fuel cladding temperatures changes differently along the axial direction as the fuel from the upper part of the rod dropped into the ballooned region after the fuel cladding burst. Therefore, the fuel cladding temperatures of the nodes at higher elevation decreases rapidly since the fuel mass became 0 after fuel cladding burst as shown in Fig. 6. The fuel cladding temperatures at lower elevation increases significantly due to the increased fuel mass after the fuel cladding burst.

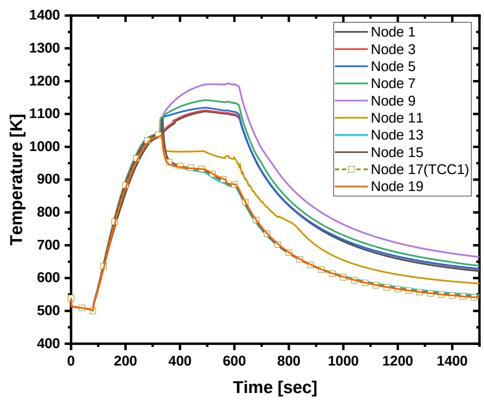

Fig. 5. Calculated fuel cladding temperatures in axial direction

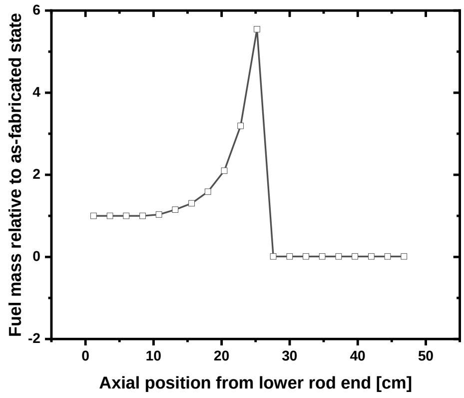

Fig. 6. Predicted fuel mass distribution in axial direction after burst

Except the cooling phase after the reactor scram, heat-up due to blowdown and cool-down after fuel burst are predicted well. Fuel cladding temperature after the reactor scram is not predicted to decrease rapidly like experiment, because the radiation heat transfer between the fuel rod and the electrical heater, and heat transfer rate to the outer flask as a boundary condition are not optimized well based on heat transfer characteristics of test rig which were not provided.

Fig. 7 compares the electrical heater surface temperatures at TCH1 and TCH2 thermocouple in experiment and calculation. The temperatures of TCH1 and TCH2 are predicted to be lower before the occurrence of fuel cladding burst, since the radiation heat transfer and boundary conditions of heat transfer through outer flask are not optimized well as explained previously. However, the cooling rates after the burst are predicted well.

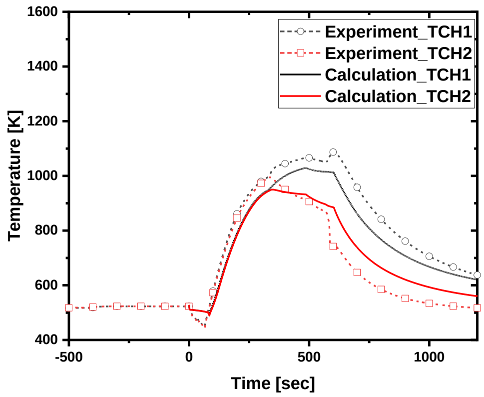

Fig. 7. Electrical heater temperatures at TCH1 and TCH2 thermocouple position

Fig. 8 shows the effect of fuel relocation model in FAMILY code. When the fuel relocation model is not applied, the fuel cladding temperature at TCC1 continues to increase after the fuel cladding burst since the fuel does not drop into ballooned region. However, when the fuel relocation model is applied, the temperature decreases rapidy since the elevation at TCC1 where no more fuel producing heat exists is higher than the elevation of fuel cladding burst.

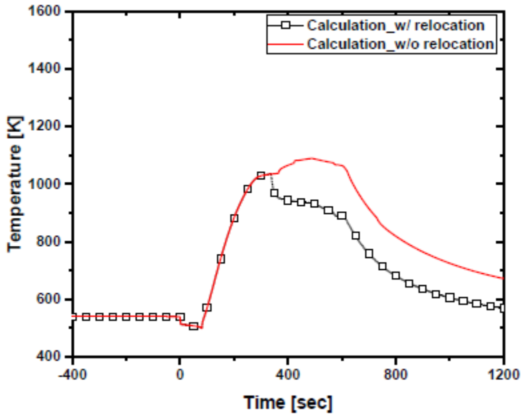

Fig. 8. Calculated fuel cladding temperature according to the application of fuel relocation model

Fig. 9 shows the calculated oxide thickness along the axial direction calculated by Cathcart-Powel cladding oxidation model. Since the oxidation rate is affected by the temperature, the oxide thickness is larger around the burst location due to the high power resulting from the fuel relocation.

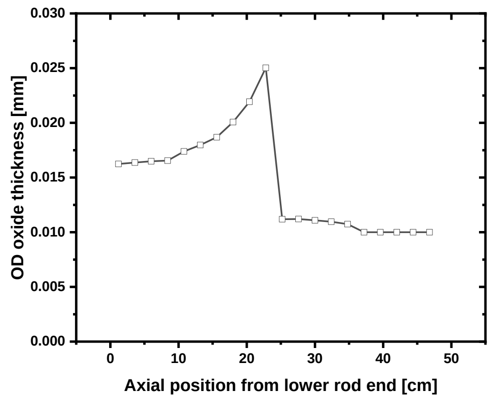

Fig. 9. Calculated oxide thickness at outside of fuel rod calculated by Cathcart-Powel cladding oxidation model

5. Conclusions

The effect of fuel relocation model of FAMILY code was evaluated by the analysis of Halden IFA-650.4 LOCA test. The fuel cladding temperature until reactor scram is predicted well by the application of fuel relocation model. Although the calculated temperatures of the electrical heater are not agreed well with the measured temperatures, the heating rate before the burst and cooling rate after the reactor scram are predicted comparatively well. As a further study, radiation heat transfer characteristics and boundary conditions of outer flask needs to be investigated. In addition, the effect of fuel parameters related with fuel deformation and burst such as burst strain needs to be further studied.

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