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Effect of CRUD layer on the heat transfer in the reflood situation using the SPACE

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1. Introduction

In commercial light water reactor (LWR), corrosion product is generated at primary side such steam generator. These corrosion products are called CRUD (Chalk River Unidentified Deposits) and deposited at the fuel cladding. The CRUD deposited at the fuel cladding makes some issues like CIPS (CRUD induced power shift) and CILC (CRUD induced localized corrosion). Besides, the CRUD layer works as thermal resistance because of the CRUD materials which are the corrosion products and have low thermal conductivity compared to the fuel cladding in reflood situation. As a result, the CRUD layer makes the cooling performance decrease and the peak cladding temperature (PCT) rise [1].

Meanwhile, there are many researches that wettability and porosity increase the CHF [2,3]. Also, prior researchers reported that quenching is influenced by the porosity and the surface roughness [4,5]. Park [6] showed the characteristics of CRUD which has porous, rough and hydrophilic structural characteristics. In this respect, Buongiorno [7], Jin Yoo et al [8], Park [6] reported that CRUD may enhance the heat transfer by accelerating quenching or lowering the PCT during the reflood situation.

In this research, the boiling enhancement effect due to the CRUD surface structural characteristics in contrast to the thermal resistance addition effect due to thermal properties of the CRUD was evaluated with the LOFT L2-5 test using the SPACE for the thermohydraulic safety analysis.

2. LOFT experiment

In this study, the analysis for the LOFT (Loss of fluid test) experiment using the SPACE code was conducted for the effect of CRUD deposition on the fuel cladding surface at the PWR to the reflood heat transfer behavior. The LOFT experiment was performed for simulating several accidents which can be occurred in the PWR as integral experiment. The experimental purpose was predicting the performance of engineered safety feature (ESF) including emergency core cooling system (ECCS) [9,10,11].

The LOFT test facility was the 50 MWt system for simulating the PWR and consisted of the five systems which are reactor pressure vessel (RPV) including reactor core, primary coolant system, secondary coolant system, blowdown suppression system, and emergency core cooling system. The primary coolant system consists of the intact loop and the broken loop. The intact loop is general primary loop which has steam generator, pressurizer, and two reactor coolant pumps (RCP). The broken loop was designed for simulating the cold leg or hot leg break accidents using the quick opening valve. The ECCS is consisted of the high pressure injection systems (HPIS), the low pressure injection system (LPIS) and the accumulator.

The LOFT experiment was conducted the LB-LOCA experiment in the several conditions. In this study, the LOFT L2-5 test case, which was conducted for simulating the double-ended cold leg break accidents, was chosen for analyzing the effect of CRUD layer on reflood heat transfer during LB-LOCA and simulated using the SPACE code.

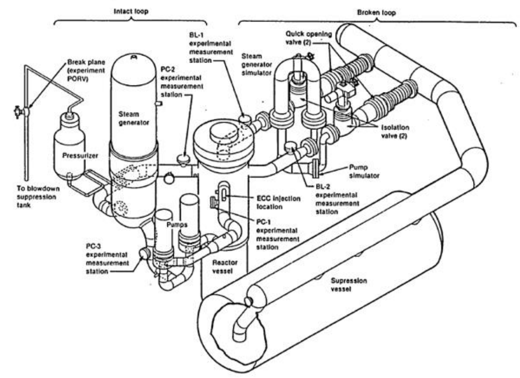

Figure 1. Schematic of LOFT experiment facility [9]

3. SPACE simulation

The nodalization of LOFT L2-5 using SPACE code is shown in figure 2. The entire system of the LOFT L2-5 experiment was nodalized including the broken loop and the intact loop. The HPIS and the LPIS was simulated for the ECCS in the intact loop. In broken loop, the reflood assistant bypass (RABs) was simulated.

To analyze the peak cladding temperature during the test, the wall temperature at the 9^{th} radial mesh point which is the outermost mesh in the 4^{th} axial node out of the 9 point which indicate the 0.731 m location was used. In addition, the following scenario was simulated to analyze LOFT L2-5 experiment. The cold leg break accident was occurred at the 0s. After the 0.24 second, the reactor was tripped automatically, and the RCP was also tripped at 0.94s. The primary coolant system was decompressed by saturation of the coolant material. This decompression of the primary system makes the accumulator valve open to the cold leg of the intact loop and start ECCS injection. The HPIS was started at 23.9s and the LPIS was operated at 37.32s for injection the coolant to the core. By this scenario, the fuel was quenched 65 seconds after the injection of coolant. The detail of this scenario was shown at the table 1.

The total three case of simulation was proceeded which are bare surface (Case A), CRUD surface with the thermal properties (Case B), and CRUD surface with the thermal properties and the boiling heat transfer enhancement (Case C).

In the SPACE, CRUD deposited fuel was simulated as the figure 3 [8]. There was stainless steel layer with 4.749 mm. The ZrO2 layer of 20 μm and the CRUD layer of 30 μm were simulated on the surface of stainless steel. In the case of A, the analysis was performed with the bare surface which did not include the CRUD layer. The case B and C were performed with the CRUD layer as figure 3. To apply the effect of heat transfer enhancement by the CRUD layer, the CHF was enhanced by 80% and the parameter of minimum film boiling temperature correlation named the surface condition parameter, γ which reflects the surface condition effects, was changed 5 to 7.5 to increase the minimum film boiling temperature.

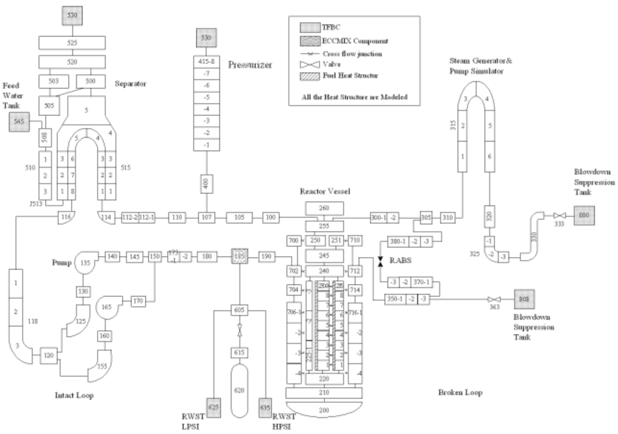

Figure 2. Nodalization of LOFT L2-5 test

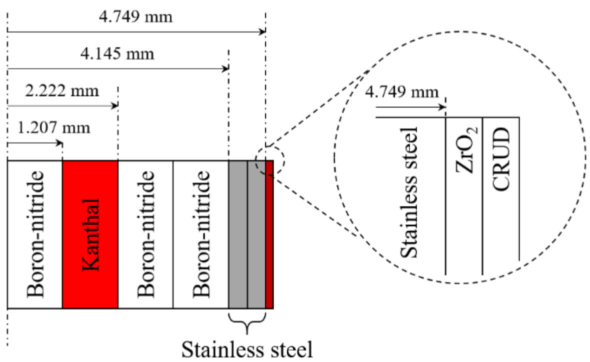

Figure 3. Composition of fuel rod in the radial direction at the SPACE[8]

Table 1. Scenario of LOFT L2-5 test [12]

Event	Time after experiment initiation, (sec)
Experiment L2-5 initiated	0.0
Subcooled blowdown ended	0.043 ± 0.01
Reactor scrammed	0.24 ± 0.01
Cladding temperatures initially deviated from saturation (DNB in core)	0.91 ± 0.2
Primary coolant pumps tripped	0.94 ± 0.01
Subcooled break flow ended in cold leg	3.4 ± 0.5
Partial top-down rewet initiated	12.1 ± 1.0
Pressurizer emptied	15.4 ± 1.0
Accumulator A injection initiated	16.8 ± 0.1
Partial top-down rewet ended	22.7 ± 1.0
HPIS injection initiated	23.90 ± 0.02
Maximum cladding temperature reached	28.47 ± 0.02
LPIS injection initiated	37.32 ± 0.02
Accumulator emptied	49.6 ± 0.1
Core cladding fully quenched	65 ± 2.0
Blowdown Suppression Tank maximum pressure reached	72.5 ± 1.0
LPIS injection terminated	107.1 ± 0.4

4. Results

The figure 4 shows the comparison results between the bare surface and the CRUD surface which does not reflect the heat transfer enhancement effect but only apply the thermal properties. In this figure, the PCT of the CRUD surface was 804.7°C which is higher than the bare surface for 37.6°C. In addition, quenching time was slightly increased by 4 sec. The minimum film boiling temperature of CRUD was 232.74°C which was decreased by 98.87°C compared to bare surface.

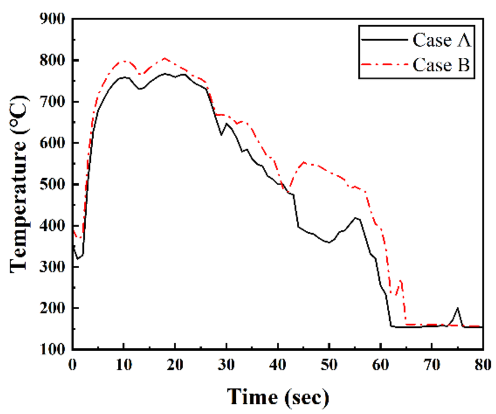

Figure 4. Temperature behavior of the case A and B

The figure 5 shows the simulation results of the bare surface and the enhanced heat transfer case by the CRUD layer. In this figure, the PCT of the bare surface was 767.1°C and the PCT of the enhanced heat transfer case was 774°C. This result shows there is no significant change in the PCT. However, the quenching time was dramatically reduced to 49 sec compared to the bare surface results which is 61 sec. In this case, the minimum film boiling temperature of heat transfer enhanced case by CRUD was 406.6°C and it is higher than bare surface by 75.0°C.

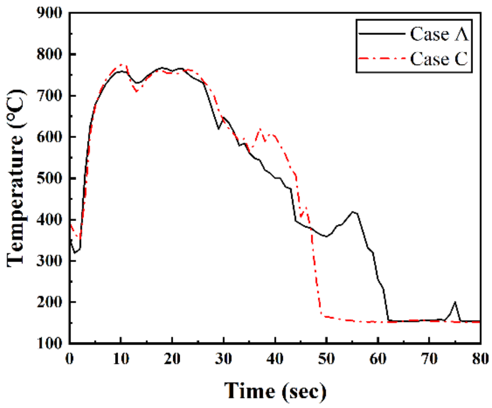

Figure 5. Temperature behavior of the case A and C

The simulation results of three different cases were shown in figure 6. Only applying thermal properties of CRUD, PCT was significantly increased compared to other two cases which are bare surface and heat transfer enhancement case. To confirm the reason for the increase in PCT, the average heat transfer coefficients near the PCT were compared and shown in Table 2. The average heat transfer coefficients were calculated by averaging the value for 5 seconds after PCT occurs. The heat transfer coefficient obtained from case B was 157.57 W/m^{2}K which was lower than other cases as 13~ 25 W/m^{2}K. This seems to be due to the decrease in the effective heat transfer coefficient by low heat transfer coefficient of the CRUD. In the case C, the quenching time was dramatically decreased compared to case A and B. The vapor flow rate was 0.0496 kg/s which is higher than other two cases about 10 % and this is reason for the better quenching performance at case C.

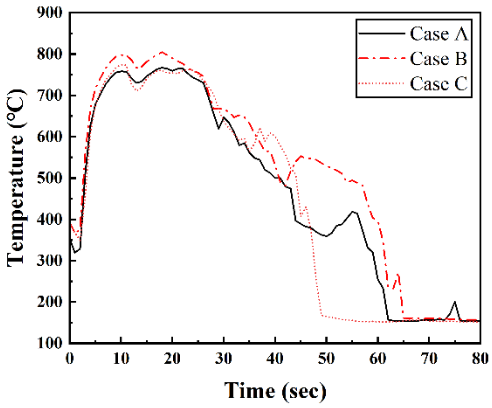

Figure 6. Reflood simulation results with the difference surface characteristics (Case A, B, C)

Table 2. Simulation results of LOFT L2-5 test

	Case A	Case B	Case C
PCT (°C)	767.09	804.7	774.6
Minimum film boiling temperature (°C)	331.6	232.7	406.6
Quenching time (sec)	62	66	50
Heat transfer coefficient during PCT (W/m^{2}K)	171.15	157.57	183.03
Vapor flow rate after PCT (kg/s)	0.0450	0.0446	0.0496

5. Conclusions

In this study, the LOFT L2-5 simulation using SPACE was conducted for confirming the effect of the CRUD layer for the thermal-hydraulic safety analysis especially reflood situation. The three case of simulations were conducted which were the bare surface case, the CRUD surface case with the thermal properties, and the CRUD surface case with the thermal properties and the boiling heat transfer enhancement. As a result of simulations, PCT and quenching time were deceased and minimum film boiling temperature were increased in heat transfer enhancement case compared to other cases due to increase of heat transfer coefficient and vapor flow rate. In these regards, the CRUD deposition on cladding may improve safety margin in nuclear power plants.

Acknowledgement

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