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Simulation test of a 2 inch cold leg SBLOCA with passive emergency core cooling system in ATLAS

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1. Introduction

The Korean nuclear industry proposed the passive emergency core cooling system (PECCS) to maintain efficient core cooling and prevent nuclear fuel damage in the event of design basis accident (DBA) of nuclear power plant (NPP). It has a design characteristic that allows an unpowered passive safety injection instead of the pump-driven active injection method. The PECCS has two major functions to mitigate a DBA situation. First one is automatic depressurization of the primary pressure through automatic depressurization valve (ADV). Second function is passive safety injection using HPSITs and SITs. To achieving these design function, the PECCS consists of four major subsystems such as four automatic depressurization valves (4 ADVs) for an automatic depressurization of the primary loop, two high pressure safety injection tanks (2 HPSITs), two safety injection tanks (2 SITs), and finally long term cooling injection from IRWST.

Considering an importance of a passive safety features and related accident mitigation measures, a cold leg SBLOCA scenario with the PECCS was selected as the main topic of B2.2 experiment of the OECD-ATLAS2 project [1]. The HPSIT is a passive safety injection tank, which can be operated at a relatively higher pressure condition than the SITs. The upper parts of the HPSITs are connected with the top head of the pressurizer, namely PECCS lines, and the lower parts are connected to the corresponding direct vessel injection (DVI) nozzles, namely injection lines (ILs). Therefore, with the opening of the PECCS valves and IL valves, the cooling water in the HPSITs can be injected to the primary system by the gravity driven natural injection flow. In the present test, the long term cooling injection from IRWST was not simulated and the four ADVs were simplified into two ADVs (ADV1 from the pressurizer and ADV2 from the hot leg-1).

The test objective is to investigate a performance of the PECCS during a CL SBLOCA accident on a cooling and depressurization of the primary system in the framework of the OECD-ATLAS2 project, and to produce clear knowledge of the actual phenomena, and provide the best guidelines for accident management. The B2.2 test will contribute to providing physical insight into the system response during a cold leg SBLOCA with a passive safety features such as the PECCS and to producing integral effect test data for the validation of the best-estimate safety analysis codes.

2. Descriptions on the Test

The initial conditions were determined by a pre-test calculation with a best-estimate thermal–hydraulic safety analysis code, MARS-KS (Multi-dimensional Analysis of Reactor Safety-KS). First, a transient calculation was performed for APR1400 to obtain the reference initial and boundary conditions. The initial and boundary conditions for the present test were obtained by applying the scaling ratios to the MARS-KS calculation results for APR1400 [2].

The decay heat was simulated to be 1.2 times that of the ANS-73 decay curve for the conservative condition. The initial heater power was controlled to be maintained at approximately 1.632 MW, which was equal to the sum of the scaled-down core power (1.566 MW) and the heat-loss-rate of the primary system (approximately 66 kW). The heater power was then controlled to follow the specified decay curve after 12.7 seconds from the reactor trip. In the B2.2 test, a uniform radial power distribution was applied. Regarding the axial power profile, the chopped cosine power shape was applied. Pressurizer heater power was interlocked to terminate when the pressurizer water level, LT-PZR-01, decreased lower than 1.2 m.

3. Test Results

3.1 Sequence of events and safety injection

When the whole system reached the specified initial condition for the test, the steady-state conditions of the primary and secondary systems were maintained for more than 30 minutes. After storing the data during this steady-state period for 310 seconds, CL SBLOCA transient was initiated by the opening of the break valve, OV-BS-06. With an inventory loss of the primary system, water level of the pressurizer was steeply decreased under the set-point of the pressurizer heater power termination at 376 s, and low pressurizer pressure (LPP) signal was issued at 485 s by the lower pressure than 10.7 MPa of pressurizer.

Core power decay was started at 498 s with 12.7 seconds delay and controlled to follow the scaled ANS 73 decay curve. The discharged break flow from the CL-1A was collected in the condensate drain tank (CDT), and accumulated mass of break flow was measured by the load cell system, LC-CDT-01.

The secondary system was isolated by LPP signal with a closing of valves including the feed water isolation valves and the main steam isolation valves. Due to the continuous heat transfer from the U-tubes, pressures of the secondary side of SGs were gradually increased up to the opening set-point of the MSSVs. With an open-close hysteresis of the MSSVs, the secondary side water inventory was continuously discharged and the water level was also decreased. In ATLAS, there are three banks of MSSVs. In the B2.2 test, the first bank of MSSVs was used only for the convenience of the facility operation.

The first bank of MSSVs is installed in the steam discharge line whose dimension is 1.25 in and Sch. 80 (inner diameter and wall thickness are 32.46 mm and 4.85 mm, respectively). The MSSV valves, named OV-MSSV1-01 (SG-1) and OV-MSSV2-01 (SG-2), are GLOBE-type valves whose flow area is 0.000346 m^2. The MSSV was controlled to be opened at 8.1 MPa and closed at 7.7 MPa depending on the secondary system pressure of the steam generator (reference pressure signal: PT-SGSD1-01, PT-SGSD2-01). The flow from the MSSVs was discharged to atmosphere through silencer. The 1st opening time of the MSSVs was recorded at 492 s.

Table I: Actual sequence of events observed in the test

Event	Description
Test start (Break @ CL-1A)	2 inch CL SBLOCA
Pressurizer heater power termination	By LT-PZR-01
Low Pressurizer Pressure (LPP)	PT-PZR-01 < 10.7 MPa
SG 2nd system isolation	Main steam and feed valve closed
1st open of MSSV of SGs	OV-MSSV1-01 / OV-MSSV2-01
Core power decay	12.7 s delay
HPSITs open	PT-PZR-01 < 10.0 MPa
Loop seal clearing	@ IL-1B
1st excursion of max. clad Temp.	-
ADV1 open	$T_{max\_clad} > 380$ °C
ADV2 open	$T_{max\_clad} > 410$ °C
SITs open	PT-PZR-01 < 4.2 MPa
SITs close	LT-SIT2/4-01 < 0.63 m
HPSITs close	LT-SIT1/3-01 < 0.63 m
2nd excursion of max. clad Temp.	-
Termination of test	$T_{max\_clad} >$ (and =) 450 °C

The HPSIT-1 and HPSIT-3 were activated at 596 s with opening of the IL valves (FCV-SIT1-01 and FCV-SIT3-01) and the PECCS line valves (FCV-PEC1-01 and FCV-PEC2-01), the triggering condition of which was the pressurizer pressure lower than 10.0 MPa. With the opening of the PECCS line valves, some of the primary inventory flowed from the cold legs to the corresponding HPSITs. This inventory flows resulted in an increase of the HPSITs pressure. However, in this initial stage, actually no safety injections from the HPSITs were injected to the primary system due to a relatively small driving force between the HPSITs to the downcomer.

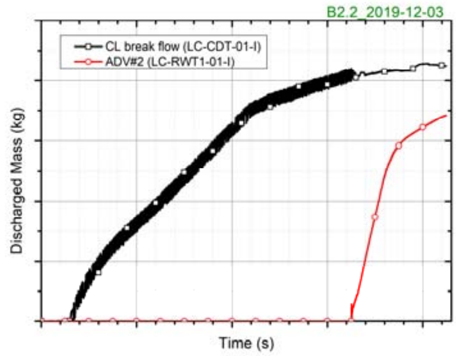

Fig. 1 Accumulated water mass from the CL break and the ADV2

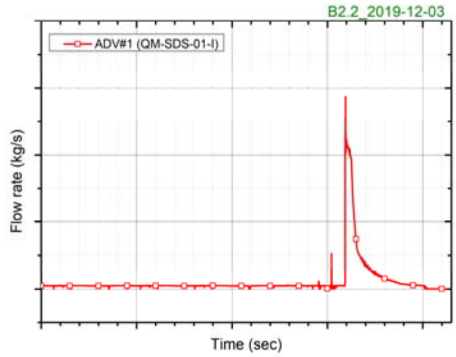

Fig. 2 Discharging flow trend of the ADV1

With a continuous discharging of water inventory from the break and actually no safety injection from the HPSITs, the water level in the core decreased and the active core region was uncovered, which led a gradual increase of a clad temperature higher than 380 °C. The ADV1 was controlled to open with this set-point of the maximum clad temperature at 3185 s. The opening of the ADV1, however, seemed not enough for a steep depressurization of the primary system. Increasing of the clad temperature was maintained up to 410 °C that actuated the opening of the ADV2 at 3250 s. The flow trend of ADV1 and ADV2 can be observed in Fig. 1 and Fig. 2, respectively.

With the opening of the ADV1 and ADV2, the safety injection flows from the HPSITs were increased, resulted in a steep decrease of the primary pressure below 4.2 MPa. The actuation of the SIT-2 and SIT-4 was triggered at 3276 s by the condition of the lower pressurizer pressure than 4.2 MPa. In Fig. 3 and Fig. 4 show the injection flow trends from the HPSITs and SITs, respectively.

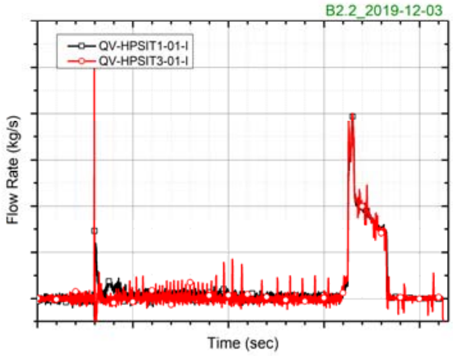

Fig. 3 Injection flow trends of the HPSITs

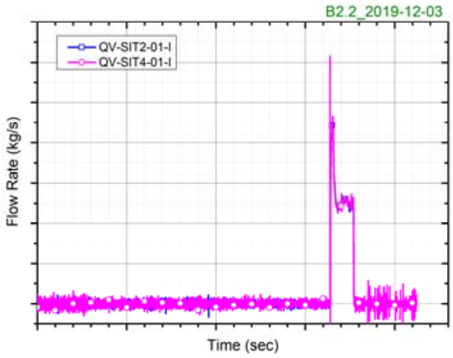

Fig. 4 Injection flow trends of the SITs

After the termination of all safety injections, maximum clad temperature was increased again from 3990 s. The present test was controlled to terminate the core power when the maximum cladding temperature increased higher than 450 ^oC. Table I presents a summary of the actual sequence of events of the present test.

3.2 System pressure

Fig. 5 shows pressure trends of the primary and secondary systems along with measured water levels of the two SGs. The trends show a typical pressure behavior of the primary and secondary system during the SBLCOA transient condition such as a rapid depressurization of the primary system, followed by a certain period of pressure plateau around secondary system pressure, and then re-depressurization of the primary loop.

With a start of the 2 inch CL break at 302 s, primary system pressure started to decrease rapidly to a little bit higher pressure condition than those of the secondary system, and then it was experienced the pressure plateau condition longer than 2100 s with several fluctuations induced from the hysteresis action of the MSSVs as indicated in Fig. 5.

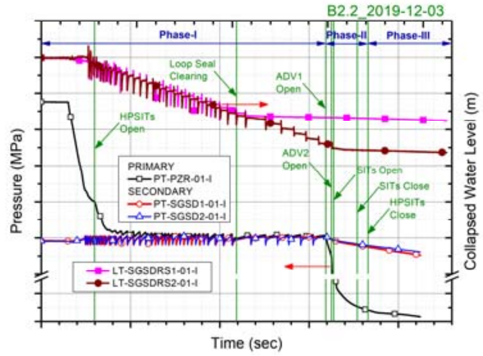

Fig. 5 System pressure trends with water levels in 2nd-side of SGs

The secondary side water levels were continuously decreased with water inventory losses resulted from the MSSVs hysteresis. The measured water levels of the two SGs showed a different behavior in SG1 and SG2, especially after the loop seal clearing occurred in the intermediated leg (IL)-1B at 2185 s.

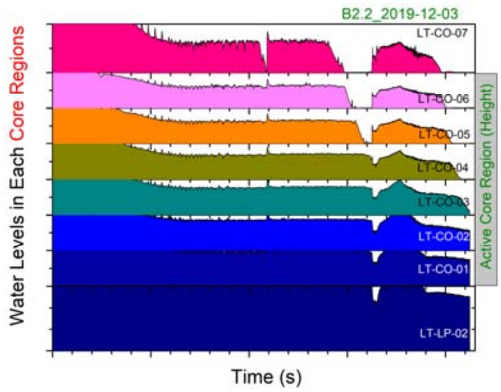

Fig. 6 Segmented water levels in the core region

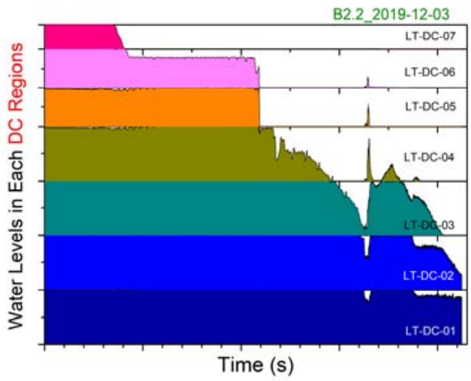

Fig. 7 Segmented water levels in the downcomer region

The whole test period can be divided into three characteristic phases. The first phase, pressure plateau phase, starts from the opening of the break valve to the actuation of ADV1, and the second phase, safety injection phase, covers the period from the opening of

ADV1 to the close of HPSITs. The final third phase can be called as the clad temperature excursion phase.

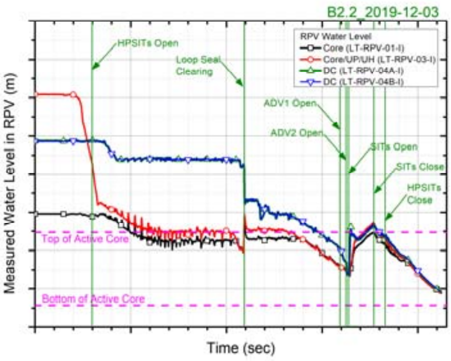

Fig. 8 Variation of measured water levels in the RPV vs. timing of major sequence of events

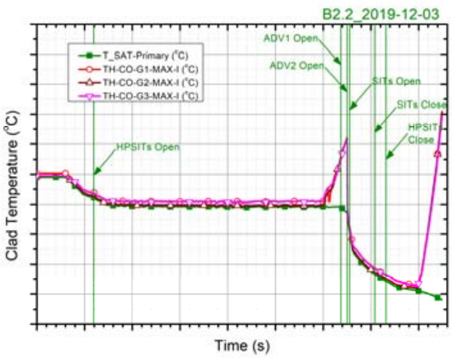

Fig. 9 Trends of the maximum clad temperatures

3.3 Core water level and clad temperature

Fig. 6 and Fig. 7 present the segmented water level trends in the core and downcomer regions, respectively. After the depletion of the upper head region, measured water level in the core region started to decrease at several axial elevations. This decrease, however, was intermittently interrupted by the loop seal clearing occurred in the CL-1B at 2185 s as described in Table I. At this time, the measured water levels in the core region were slightly increased as presented in Fig. 6. On the other hand, measured water levels in the downcomer region show an abrupt decrease due to a coolant inventory shift from the downcomer region to the core region as in Fig. 7. The inventory shift is one of the typical phenomenon of a loop seal clearing. In Fig. 8, trends of the measured water levels in the core and downcomer region were compared with time indications of the major sequence of events.

After the loop seal clearing, water levels in the downcomer region continuously decreased. Resultantly, the core water level, LT-CO-07, started to decrease from 2800 s. This decrease of the core water level led a clad temperature increase higher than 380 ºC and 410 ºC, which were the triggering set-points of the ADV1 and ADV2, respectively. With the openings of the ADV1 and ADV2 at 3185 s and 3250 s, respectively, the HPSIT flows started its active injections as presented in Fig. 3**.** The safety injections from the SITs were started at 3276 s. The safety injections from the HPSITs and SITs were controlled to terminate when the corresponding water levels of the HPSITs or SITs were decreased below 0.63 m. After the termination of all safety injections, the maximum clad temperature started an increase again at 3990 s. Fig. 8 shows an observed trends of the maximum clad temperatures of each power group.

4. Conclusions

The B2.2 experiment of the OECD-ATLAS2 project was performed using a thermal-hydraulic integral effect test facility, ATLAS, on December 3, 2019. The target scenario of the B2.2 test is a cold leg small break loss of coolant accident (CL SBLOCA) along with an availability of passive emergency core cooling system (PECCS). In the present test, the long term cooling injection from IRWST was not simulated. Major findings of the B2.2 test can be summarized as follows:

From the observation of thermal hydraulic phenomena and boundary conditions, three characteristic phases were identified such as the pressure plateau phase, the safety injection phase, and the clad temperature excursion phase.

The safety injections from HPSITs were not effectively injected in the phase-I. Only after the opening of the ADV1 and ADV2, the safety injections were injected to the system resulted in a nice decrease of the maximum clad temperatures. However, the clad temperatures increased again after the termination of the safety injection flows.

ACKNOWLEDGMENTS

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