

Effect of Passive Safety Features on System Thermal Hydraulics

Seok Cho^{a*}, Byoung-Uhn Bae^a, Yusun Park^a, Jae Bong Lee^a, Jongrok Kim^a, Nam Hyun Choi^a, Kyoung-Ho Kang^a
^aKorea Atomic Energy Research Institute, Daedeok-daero 989 Beon-Gil, Yuseong-gu, Daejeon 34057, Korea
^{*}Corresponding author: scho@kaeri.re.kr

1. Introduction

Passive safety feature is getting importance with the focusing on an inherent safety function of nuclear system. The Korean nuclear industry proposed passive safety features such as hybrid safety injection tank (HSIT) and 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).

Considering an importance of passive safety features and related accident mitigation measures, two integral effect tests were carried out using advance thermal hydraulic loop for accident simulation (ATLAS) test facility to investigate a passive performance of HSIT and PECCS during emergency conditions.

A station blackout (SBO) test along with an availability of the HSIT and a cold leg SBLOCA test with the PECCS were selected as a main scenarios for an investigation of the passive injection features. These two tests were named as B2.1 and B2.2 for the HSIT and for the PECCS, respectively.

The test objective is to investigate a passive injection performance and system behaviour when the HSIT and the PECCS are in an available condition during the SBO and SBLOCA situations, respectively.

2. Descriptions on the Test

Fig. 1 and Fig. 2 show the schematics of test configurations for B2.1 and B2.2, respectively. In the B2.1, four pressure balance lines (PBLs) were connected from the top of the pressurizer to the HSITs at the upper section. Therefore, initial pressure of the HSIT is the same with that of the primary system. Four injection valves which were initially closed were installed in the injection lines (ILs) from the HSITs and to the corresponding DVI nozzles.

HSIT-1 and HSIT-2 were actuated when the IL valves were opened, triggering condition of which was the first opening of the POSRV. On the other hand, actuation of HSIT-3 and HSIT-4 was triggered when the one of the cladding temperatures increased higher than 450 °C. Safety injection from the HSITs were set to be terminated when the bottom fluid temperature of the corresponding HSIT became higher than 70 °C.

The PECCS has two major functions to mitigate a DBA situation. First one is automatic depressurization of the primary pressure through automatic

depressurization valves (ADVs). Second function is passive safety injection using high pressure safety injection tanks (HPSITs) and safety injection tanks (SITs). To achieving these design function, the PECCS consists of four major subsystems such as two stage of automatic depressurization (ADV-1 and ADV-2), two high pressure safety injection tanks (2 HPSITs), two safety injection tanks (2 SITs), and finally long term cooling injection from IRWST.

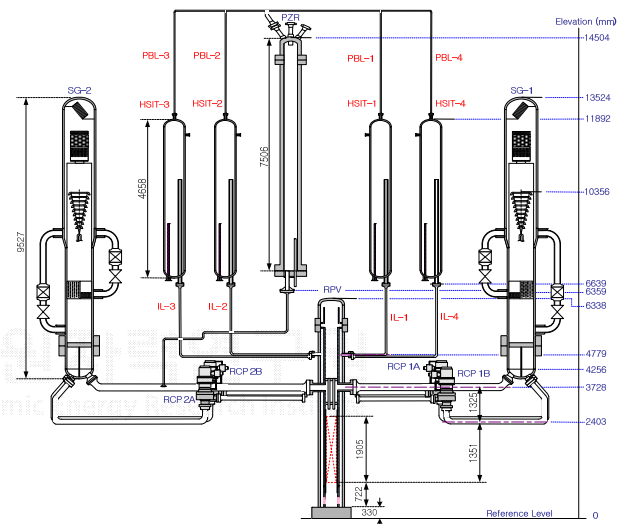


Fig. 1 Schematic diagram of test configuration of the B2.1

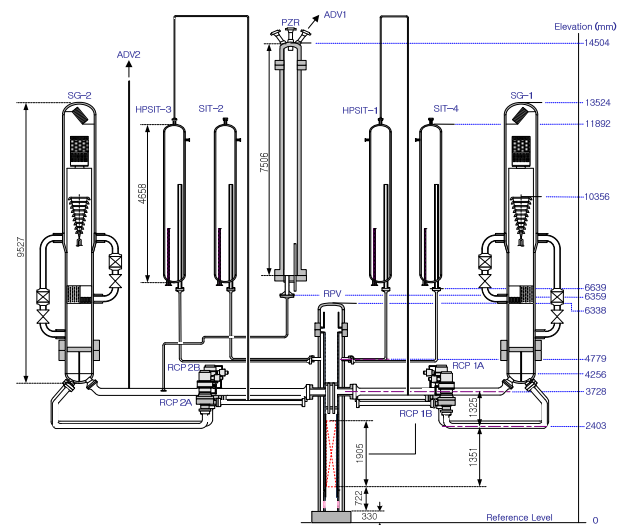


Fig. 2 Schematic diagram of test configuration of the B2.2

Table I: Actual sequence of events observed in the B2.1

Event	Description
SBO start	-Reactor coast down start -RCP, and MFP trip/MFIV/MSIV close
Decay power start	8% with 12 s delay
MSSV 1 st OPEN	PT-SGSD1,2-01 (Open @ 8.1 MPa / Close @ 7.7 MPa)
SG-1 Depletion SG-2 Depletion	By LT-SGSDRS1/2-01
POSRV 1 st OPEN	FCV-SDS-01
Actuation of HSIT-1 and -2	With the 1 st opening of the POSRV
Termination of HSIT-1 / HSIT-2	If TF-HSIT1/2-24 > 70 °C
Loop seal clearing	At intermediate leg 1B (LT-IL1B-03)
Cladding Temperature increase	More than 450 °C
Actuation of HSIT-3 and -4	If PCT > 450 °C
Termination of HSIT-3 / HSIT-4	If TF-HSIT3/4-24 > 70 °C
Loop seal re-clearing	At intermediate leg 2B (LT-IL2B-03)
PCT overshoot and test end	If PCT > 550 °C

Table II: Actual sequence of events observed in the B2.2

Event	Description
Test start (Break @ CL-1A)	2 inch CL SBLOCA
Pressurizer heater power termination	By water level interlock (LT-PZR-01 < 1.2 m)
Low Pressurizer Pressure (LPP) signal	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 start	12.7 s delay
HPSIT-1 and HPSIT-3 open	PT-PZR-01 < 10.0 MPa
Loop seal clearing	Occurred at IL-1A and IL-1B
Start of 1st excursion of max. clad temp.	-
ADV1 open	T _{max, clad} > 380 °C
ADV2 open	T _{max, clad} > 410 °C
SIT-2 and SIT-4 open	PT-PZR-01 < 4.2 MPa
SIT-2 and SIT-4 close	LT-SIT2/4-01 < 0.63 m
HPSIT-1 and HPSIT-3 close	LT-SIT1/3-01 < 0.63 m
Start of 2nd excursion of max. clad temp.	-
Termination of test	TH-CO-G1/G2/G3-MAX > 450 °C

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 by 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 B2.2, the long term cooling injection from IRWST was not simulated.

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 1.630 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. The heater power was then controlled to follow the specified decay curve after 12.7 seconds from the reactor trip.

Detail descriptions on the sequence and related set points of corresponding sub-systems or devices can be found in Table I and Table II for the B2.1 and B2.2, respectively.

3. Test Results

3.1 System behavior in B2.1 test [1]

Fig. 3 shows the trends of the safety injection flow rate from the HSITs. As mentioned, the HSIT-1 and HSIT-2 were triggered by the first opening of the POSRV (can be compared with Fig. 4), and the HSIT-3 and HSIT-4 were actuated when the maximum clad temperature increased higher than 450 °C (can be compared with Fig. 5).

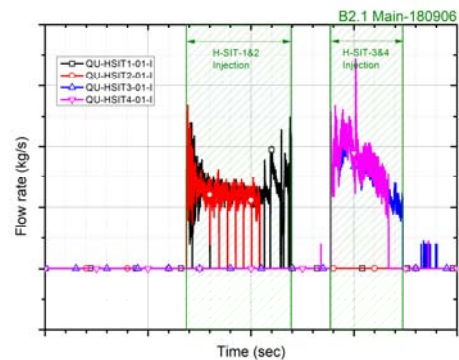


Fig. 3 Injection flow trends of the HSITs

The primary and secondary system pressure behavior can be observed in Fig. 4. The primary and secondary system pressures experienced several cycles of periodic fluctuations with the open-close hysteresis of the POSRV and the MSSVs, respectively. The primary system pressure increased sharply after the

depletion of the secondary water inventory due to reduced heat transfer through the SG U-tubes. The primary system pressure showed an obvious decrease with the start of the safety injection from the HSITs.

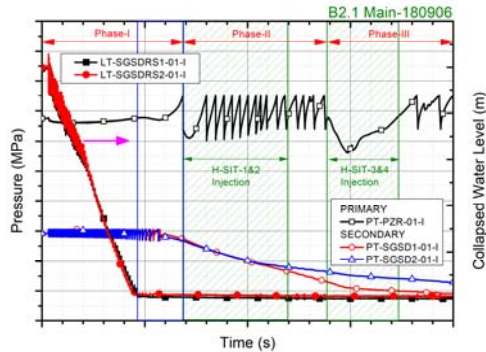


Fig. 4 Pressure trends of the systems with water level behavior of SG secondary side

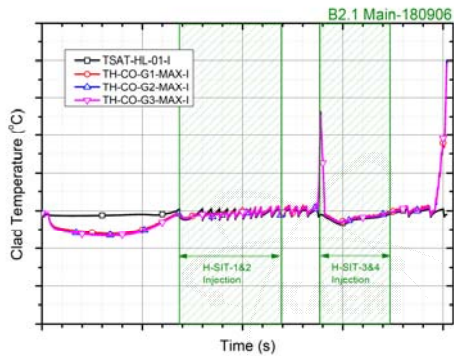


Fig. 5 Maximum clad temperature behavior

Measured water level trends in the pressurizer and in the RPV can be observed in Fig. 6 and Fig. 7, respectively. The water level of the pressurizer decreased with the start of the SBO due to the increased heat removal rate of the secondary system led by the MSSVs hysteresis. With a depletion of the secondary system, the pressurizer water level gradually increased up to the full height level due to an increase of the primary coolant temperature.

During the injection period of the HSIT-1 and HSIT-2, the full water level in the pressurizer and in the RPV was maintained. However, the water levels showed a continuous decrease after the termination of the HSIT-1 and HSIT-2 injections with an inventory discharge through the POSRV. The continuous decrease of the primary inventory induced partial exposure of the active core. With the excursion of the maximum clad temperature higher than 450 °C, safety injection from the HSIT-3 and HSIT-4 were started.

From the observation of the experimental phenomena along with the major boundary conditions, the entire test period was divided into three characteristic phases, namely, the coolant depletion

phase, the natural circulation phase, and finally the loop seal oscillation phase.

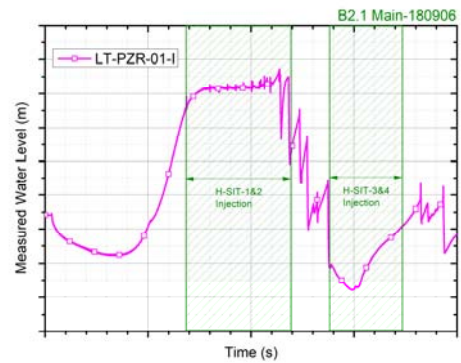


Fig. 6 Measured water level trend in the pressurizer

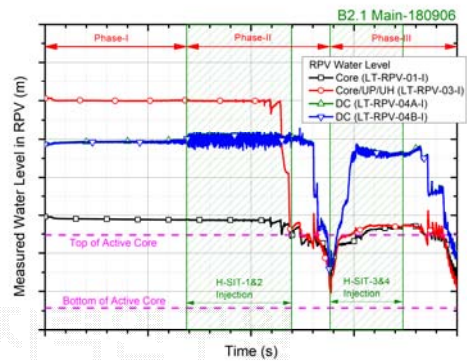


Fig. 7 Measured water level trends in the RPV

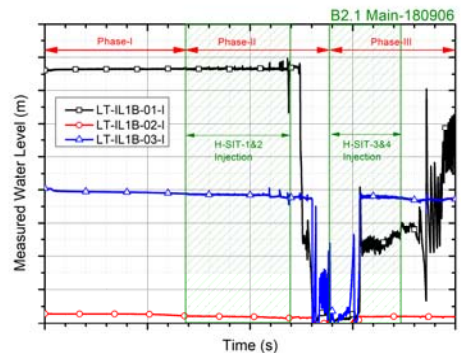


Fig. 8 Measured water levels in the IL-1B

Fig. 8 shows the water level trends in the intermediate leg-1B (IL-1B). In the figures, LT-ILj-01 is the SG side vertical water level, LT-ILj-02 is the water level of the horizontal section, and LT-ILj-03 is the RCP side vertical water level. As can be overved in Fig.8, rapid depletion of the SG side vertical water level (LT-IL1B-01) was followed by the loop seal clearing (LSC) in the horizontal and RCP side vertical water levels (LT-IL1B-02 and LT-IL1B-03) during phase-II. On the other hand, in the IL-2B, LSC was occurred during phase-III.

3.2 System behavior in B2.2 test [2]

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. 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.

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 by the condition of the lower pressurizer pressure than 4.2 MPa. In Fig. 9 and Fig. 10 show the injection flow trends from the HPSITs and SITs, respectively.

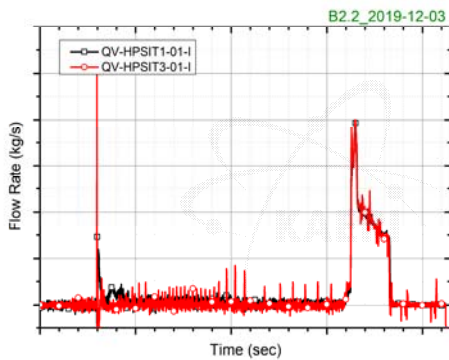


Fig. 9 Injection flow trends of the HPSITs

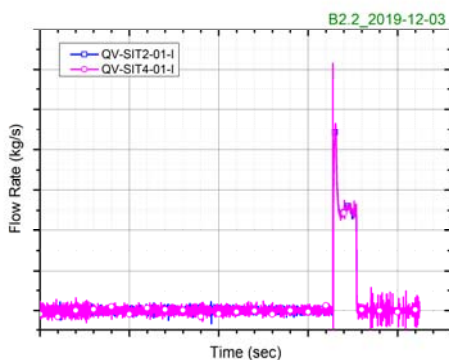


Fig. 10 Injection flow trends of the SITs

After the termination of all safety injections, maximum clad temperature was increased again. The B2.2 test was controlled to terminate the core power when the maximum cladding temperature increased higher than 450 °C.

Fig. 11 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.

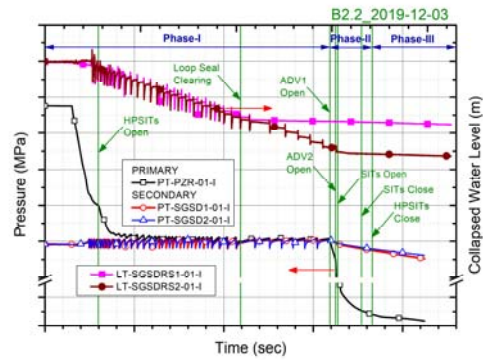


Fig. 11 System pressure trends with water levels in 2nd-side of SGs

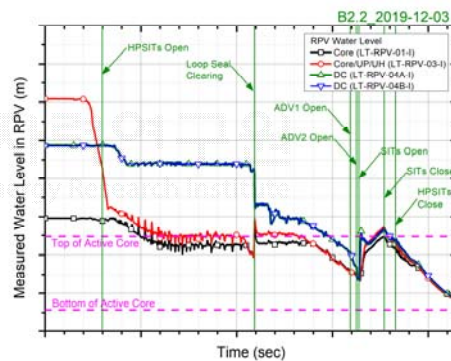


Fig. 12 Variation of measured water levels in the RPV vs. timing of major sequence of events

With a start of the 2 inch cold leg break, 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 with several fluctuations induced from the hysteresis action of the MSSVs.

The secondary side water levels were continuously decreased with water inventory losses through 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 of loop-1.



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 third phase can be called as the clad temperature excursion phase.

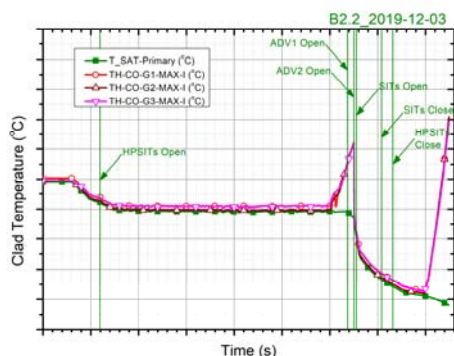


Fig. 13 Trends of the maximum clad temperatures

The inventory shift is one of the typical phenomenon of a loop seal clearing occurred at the loop-1 (IL-1A and IL-1B) in B2.2. In Fig. 12, 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. This decrease of the core water level led a clad temperature increase higher than 380 °C and 410 °C, which were the triggering set-points of the ADV1 and ADV2, respectively. With the openings of the ADV1 and ADV2, the HPSIT injections were actually started. 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. Fig. 13 shows an observed trends of the maximum clad temperatures of each power group.

4. Conclusions

The two tests described in the paper was performed using a thermal-hydraulic integral effect test facility, ATLAS. The target scenarios of the B2.1 and B2.2 test are the SBO condition with HSITs and the cold leg small break loss of coolant accident (CL SBLOCA) along with PECCS to investigate the performance of the passive safety features.

From the observation of thermal hydraulic phenomena and boundary conditions, three characteristic phases were identified. For the B2.1, the three phases are the coolant depletion phase, the natural

circulation phase, and the loop seal oscillation phase. For the B2.2, the pressure plateau phase, the safety injection phase, and the clad temperature excursion phase.

During the injection period from the HSITs, the core was cooled effectively by the safety injection flow from the HSITs. There were no PCT excursions during the two safety injection periods. Only after the termination of the safety injection flow, the cladding temperature increase was observed. The HSITs as a passive safety feature showed an effective core cooling performance.

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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