Experimental Study on the Station Block Out (SBO) Accompanied by a Small Break Loss of Coolant Accident (SBLOCA)

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1. Introduction

In the consideration of the safety relevance, the integral effect test considering a small break loss of coolant accident (SBLOCA) under a station block out (SBO) condition was studied experimentally using the ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) [1] test facility under the framework of OECD-ATLAS3 project.

In the view point of the multiple failure accident, the multiple failure accident under an SBO condition and an SBLOCA with total failure of safety injection are considered as relatively high core damage frequency (CDF) in the not only deterministic safety analysis (DSA) but also probabilistic safety analysis (PSA) method. [2], [3]

The test objective of this test, which was named C4.1, is to obtain the thermal-hydraulic insight into the system response of the multiple failure accident and to provide integral effect test data for validating the safety analysis codes for a kind of multiple failure accident scenario.

2. Description of the Test Facility

2.1 ATLAS Test Facility

ATLAS was designed to model a reduced-height primary system of APR1400 (Advanced Power Reactor 1400 MWe) which has the 1/2-height, 1/144-area and 1/288-volume scales for APR1400. ATLAS can be used to provide the unique test data for a loop arrangement of 2 hot legs and 4 cold legs for the reactor coolant system with a direct vessel injection (DVI) of emergency core cooling (ECC) system. ATLAS can simulate full pressure and temperature conditions of APR1400. The total inventory of the primary system is 1.6381 m^3.

The fluid system of ATLAS consists of a primary system, a secondary system, a safety injection system, a break simulation system, a containment simulation system, and auxiliary systems.

The primary system includes a reactor pressure vessel (RPV), two hot legs, four cold legs, a pressurizer, four reactor coolant pumps, and two steam generators. The secondary system of ATLAS is simplified to be a circulating loop-type. The steam generated at two steam generators is condensed in a direct condenser tank, and the condensed feedwater is re-circulated to the steam generators. A scaling method of the ATLAS design [4] and the detailed design and description of ATLAS facility can be found in the literature [5].

2.2 Break Simulation System

In this C4.1 test, the break was simulated on the hot-leg (1A) with 6 inch break size for prototype power plant with upward direction.

The 6 inch break size was scaled down in the consideration of the ALTAS scaling ratio and the inner diameter of the break nozzle was determined as 10.68 mm. The sectional drawing of the break nozzle is shown in Fig. 1. The break nozzle was installed at the vertical part of the break simulation system.

The break simulation system of the SBLOCA consists of a quick opening valve, break flow discharging line, and related instruments such as pressure transmitters and thermocouples. The break flow discharged from the system was collected in the refueling water tank (RWT) to measure the integrated mass.

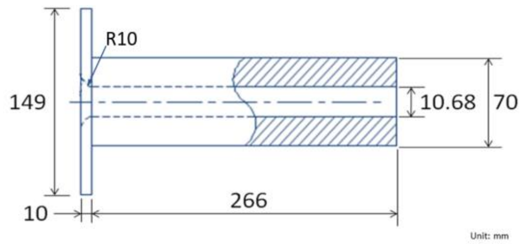

Fig. 1. Configuration of the break nozzle

3. Test Procedure

When the whole system of ATLAS reached a specified initial condition for the test, the steady-state conditions of the primary and secondary systems were maintained for more than 30 minutes.

After that, the test was started by the simulation of an SBO and the reactor trip signal was actuated. With the reactor trip signal, the core power started to decay. Followed by the reactor trip signal, the main feedwater isolation signal (MFIS) was generated to close the main feedwater isolation valves (MFIVs) and the turbine was isolated by closing a main steam control valve (MSCV).

With the closure of the main steam isolation valves (MSIVs), the secondary system was isolated finally.

The MSSVs on both steam generators were periodically operated to remove the decay heat. The inventory of the steam generator secondary system was discharged through MSSVs and the collapsed water level reached almost zero. The auxiliary feedwater was not available in this test scenario, so the decay heat could not be removed from the system anymore. Thus the pressure and temperature of the primary system increased. It led the full collapsed water level in the pressurizer so the POSRV started to operate. With the continuous periodic operation of the POSRV, the collapsed water level in the pressurizer started to decrease.

When the collapsed water level of the RPV decreased to the top of the active core, the SBLOCA was initiated as planned in this test scenario. With the break simulation valve opening, the primary system pressure decreased rapidly. The safety injection from SITs was initiated as the primary system pressure decreased. However, the safety injection from SITs was not enough to effectively cool down core heaters. The maximum surface temperature of the core heater rods reached the core heater protection temperature. Thus core heaters were turned off by the control logic and the test was terminated.

The whole sequence of event in the C4.1 test is summarized in Table I with non-dimensional time.

Table I: Sequence of event

No	Description	Remark (set point)	Non-dimensional Time
1	SBO start	Test start	0.0342
2	Reactor trip	Coincidence with SBO	0.0342
3	Secondary System isolation	MSCV close MSIS MFIS	0.0346 0.0349 0.0353
4	Decay power start	Following the scaled decay curve	0.0359
5	MSSV operation	Between set-points of SG dome pressure	0.0361
6	SG 1/2 dryout	LT-SGSDRS1/2-01 ~ 0 m	0.5034
7	POSRV operation	Between set-points of PZR pressure	0.7177
8	Core uncover	Collapsed water level at the top of the active core	0.9529
9	SBLOCA start	Coincidence with core uncover	0.9530
11	SIT actuation	set-points of the downcomer pressure	0.9920
12	Peak cladding temperature	At heater group-1	1.0000
13	Core stop	End of the test	1.0000
14	End of the test	Stop of the data saving	1.0274

4. Test Result

Considering the confidential problem of test data, all of the test results in this paper were normalized by an arbitrary value including the time frame.

Fig. 2 shows the variation of the system pressures. With SBO start, the secondary system was isolated so MSSVs on both steam generators operated periodically. Due to the MSSVs operation, the primary system pressure was also oscillated slightly. After the inventory in the steam generator secondary system dried out at 0.5034 non-dimensional time, the period between the open and close of the MSSVs became longer and the MSSVs were not operated after 0.6207 non-dimensional time. The decay heat could not be removed by the secondary system anymore and it made the primary system pressure increase. Thus the POSRV operated to control the primary system pressure. After initiation of the SBLOCA at 0.9530 non-dimensional time, the primary system pressure decreased rapidly.

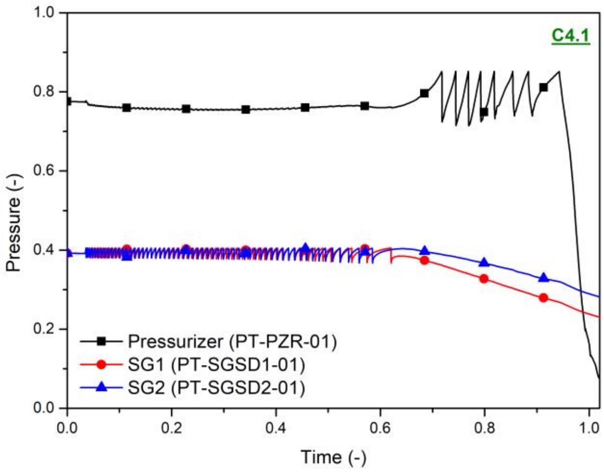

Fig. 2. System pressure

Fig. 3 shows flow rates of the primary loop. The continuous loop flow rate by the natural circulation was formed during MSSVs operation and the flow rate of each loop was kept before initiation of an SBLOCA. The flow rate of loop-2 which is connected with the pressurizer fluctuated with POSRV operation at the little bit higher value than the flow rate of loop-1. After break initiation on the hot leg-1 at 0.9530 non-dimensional time, the loop flow rate of loop-1 increased abruptly.

Fig. 4 shows collapsed water levels of the RPV. Because there was no inventory loss from the primary system before the POSRV operation during SBO transient, the collapsed water levels in the RPV were kept as initial steady state until the POSRV operation. After several operations of POSRV, the collapsed water level in the RPV started to decrease from the upper head. When the collapsed water level in the RPV decreased to the top of the active core, the SBLOCA was initiated. The collapsed water level in the down-comer decreased at last as the primary system pressure decreased with break initiation. The collapsed water level in the core region decreased drastically with break initiation so the most part of the active core was exposed to the steam.

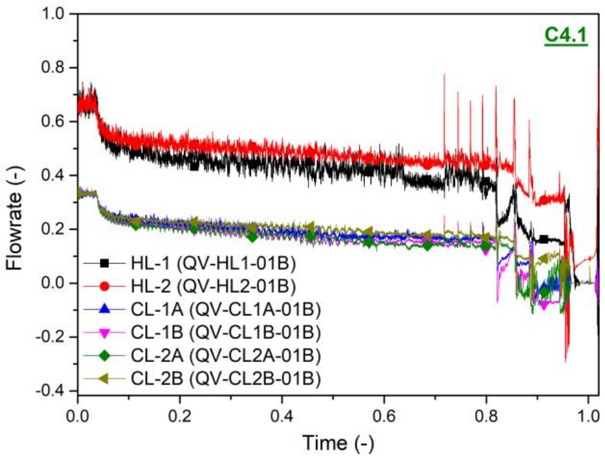

Fig. 3. Flow rates of RCS

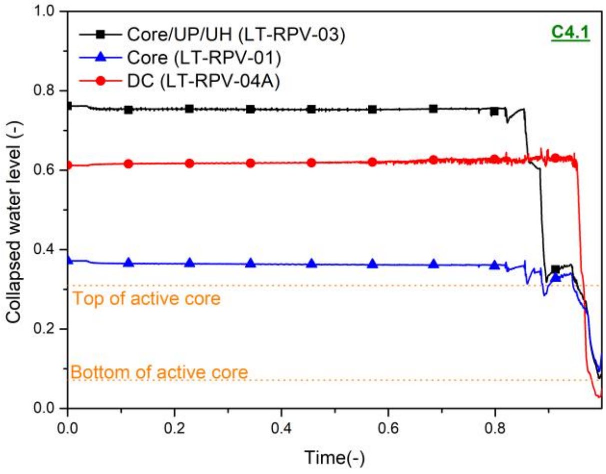

Fig. 4. Collapsed water levels of the RPV

The collapsed water level in the steam generator secondary system decreased continuously with periodic operation of MSSVs, as shown in Fig. 5. However, the auxiliary feed water was not supplied and the secondary system of steam generators was kept empty until the end of the test.

Fig. 6 shows the integrated mass of discharged inventory from the system. The sharp increase of the integrated mass of discharged inventory was slowed down about 0.0456 non-dimensional time after the SBLOCA initiation. It was not the result from the phase change of the break flow but the cause of dry out of the primary system inventory.

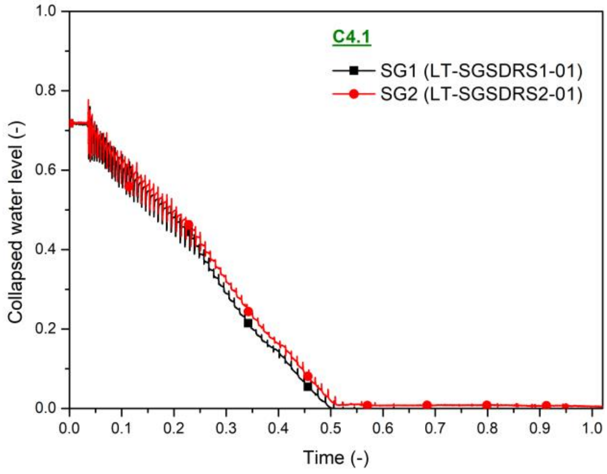

Fig. 5. Collapsed water levels of the SG secondary system

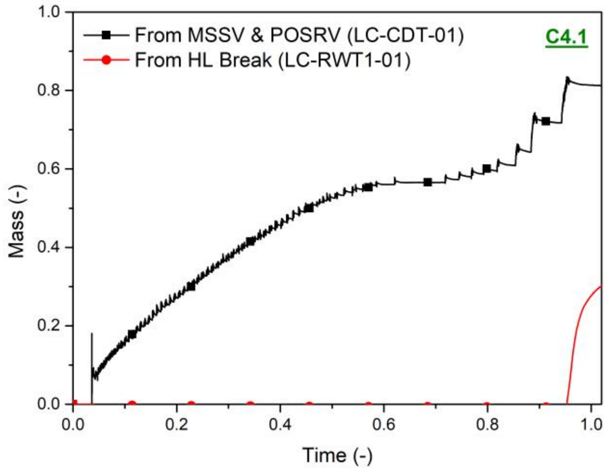

Fig. 6. Integrated mass of inventory discharge

With the initiation of an SBLOCA, the collapsed water level of the RPV core region decreased rapidly and the surface temperature of core heaters increased as shown in Fig. 7. The excursion of the heater rod surface temperature occurred although the collapsed water level in the RPV core increased by the SITs actuation. The peak cladding temperature was observed at the upper part of the core and the center region, heater group-1.

Before core heaters were quenched by the emergency core cooling water from SITs, the maximum heater rod surface temperature reached the limitation temperature of core protection control logic. Thus the core heaters were turned off and the test was terminated.

The 6 inches break size is relatively large break size in the SBLOCA spectrum and the primary system pressure decreased rapidly after the SBLOCA initiation. However, decrease trend of the primary system pressure was deficient to provide the enough driving force of the pressure difference for the coolant injection from SITs.

Thus, the total amount of inventory which was supplied to the RPV core after the SBLOCA initiation was insufficient to cool down the core and the maximum heater rod surface temperature reached the limitation temperature of core protection control logic. So the core heaters were turned off and the planned accident management action, operation of one train of SIP, was not actuated.

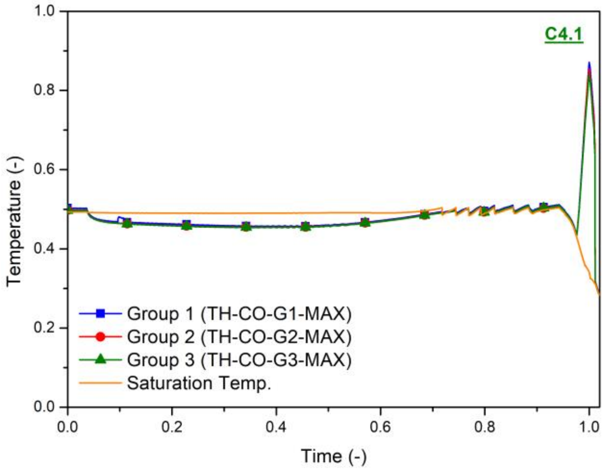

Fig. 7. Maximum heater rod surface temperature behavior

5. Conclusions

The C4.1 test was performed to simulate a multiple failure accident of an SBO accident accompanied by an SBLOCA.

During the transient simulation for the C4.1 test, major thermal-hydraulic parameters such as the system pressures, the collapsed water levels, the flows in the primary loops, and the break flows were measured and analysed. The major conclusions of the C4.1 test can be summarized as follows:

- During the early transient of the SBO accident, the natural circulation in the primary loop was formed and the decay heat was removed by steam generators. Thus the primary system pressure was kept and the core heaters were submerged in the coolant before dry out of the steam generator secondary system.
- After POSRV operation, the inventory of the primary system decreased and the initiation of the SBLOCA transient accelerated the primary system inventory loss.
- Due to the system pressure decrease with break initiation, the emergency core cooling water from SITs was supplied to the RPV core which was exposed to the steam. In the view point of the core cooling, the SBLOCA initiation could give the positive effect on the core cooling.
- However, the role of SITs was insufficient to cool down the system and the excursion of the heater rod surface temperature occurred finally.
- From this result, we can conclude that more active strategy by an operator is required to cool down the system stably under this kind of multiple failure accident. Earlier repair of the emergency diesel generator to supply auxiliary feedwater to steam generators or to operate the safety injection pumps, or earlier injection of the coolant to the primary system by an external supplement can be suggested as more active accident mitigation strategies.

The C4.1 test data can be utilized to evaluate the prediction capability of the existing or newly developed safety analysis codes for a kind of multiple failure accident scenario.

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