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Experimental Study on the Steam Line Break (SLB) with the Multiple Steam Generator Tube Rupture (MSGTR)

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1. Introduction

In Korea, the nuclear safety regulation was revised to define the safety regulation clearly, in 2015. In the revised nuclear safety regulation, the "Multiple failure" is defined as "Over the single failure, the failure is occurred in more than two component and loss of their safety function". To investigate the sequence of these multiple failure accidents, an SLB accident which is accompanied by a SGTR accident was conducted using the ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) facility [1]. This multiple failure accident is considered as an accident having a high core damage frequency (CDF) in the not only deterministic safety analysis (DSA) but also probabilistic safety analysis (PSA) method [2]. Thus, an integrated effect test to simulate an SLB accident accompanied by a SGTR, which was named SLB-SGTR-02 test, was performed to investigate the thermal hydraulic phenomena during this multiple failure accident.

2. Description of the test Facility

2.1 ATLAS

The reference plant of the ATLAS facility is the APR1400 (Advanced Power Reactor 1400 MWe), which has a loop arrangement of 2 hot legs and 4 cold legs for the reactor coolant system. 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 [3, 4] and the detailed design and description of ATLAS facility can be found in the literature [5].

2.2 SLB simulation

The break simulation system of an SLB consists of two quick opening valves (OV-BS-09, and -10), break flow discharging lines, a flow restrictor, and related instruments. The detailed installation drawing of the SLB line is shown in Fig. 1. The break flow discharging line is connected to the condensation tank to measure the integrated mass of the break flow. A flow restrictor was installed at the steam exit nozzle of SG-1 and SG-2 to restrict the steam flow rate within the critical flow rate during an SLB accident. The minimum inner diameter of the flow restrictor was 36.0 mm for the choking condition in the present test.

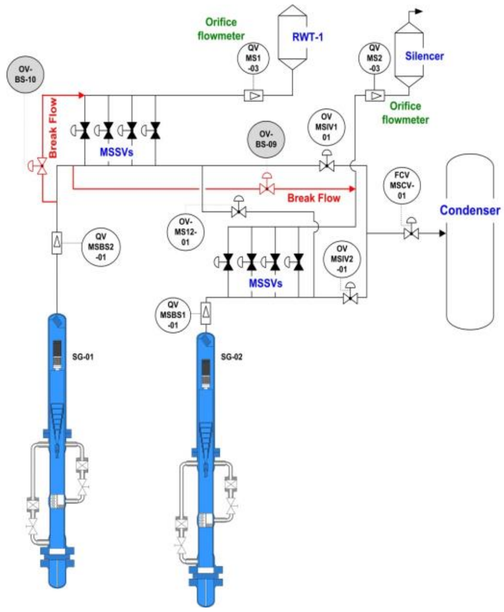

Fig. 1. Piping arrangement of SLB simulation system

2.3 SGTR Simulation

In the SGTR simulation, the double-ended guillotine break of five U-tubes was modeled. To simulate a SGTR in ATLAS, the primary system inventory was discharged from the hot side of the lower plenum to the upper location of the steam generator secondary hot-side. Fig. 2 shows a piping arrangement of the break simulation system which consists of a break simulation valve (OV-BS-04), an orifice flow meter, and a break nozzle.

In this study, the break nozzle was designed as a combination of an orifice and a break tube to satisfy the scaling law of the break flow rate for both the choking and the non-choking flow conditions. The diameter and the length of the break tube were adjusted to preserve the break flow rate for the non-choking flow condition as well, so that the differential pressure through the entire break nozzle can be as close as the APR1400. A schematic diagram of the break nozzle used in the present test is shown in Fig. 3.

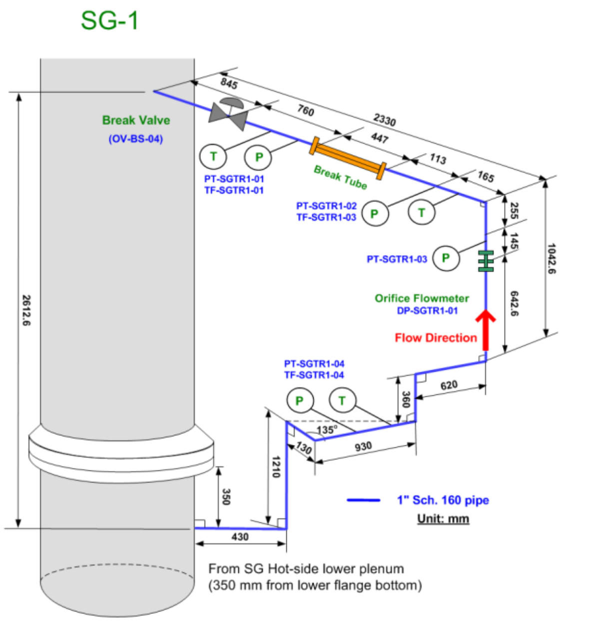

Fig. 2. Piping arrangement of SGTR simulation system

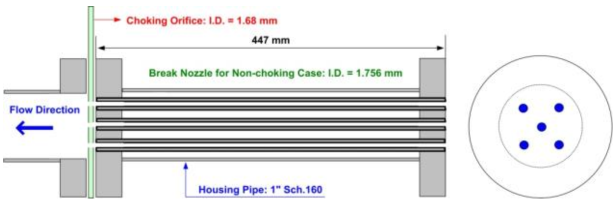

Fig. 3. Schematic diagram of the break nozzle of SGTR

3. Test Procedure

The initial and boundary conditions for this test were obtained by applying the scaling ratios to the MARS-KS (Multi-dimensional Analysis of Reactor Safety-KINS Standard) calculation results for APR1400.

When the whole system 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 storing the data during a steady state period from -10 to 300 seconds, the transient was initiated by the opening signal of the steam line break valves (OV-BS-09 and OV-BS-10).

When the secondary system pressure of SG-1 decreased below 6.11 MPa, low steam generator pressure (LSGP) trip signal was actuated. With the LSGP signal, the reactor scram signal was actuated. After that, the secondary system was isolated with a closure of the main steam isolation valves (MSIVs). The core power started to decay at the scram signal with 12.07 seconds delay. The water level of the affected steam generator (SG-1) decreased rapidly and reached the set-point of the auxiliary feedwater actuation signal (AFAS), 2.78 m of the wide range collapsed water level of SG-1.

When the wide-range collapsed water level of SG-1 decreased to 0.1 m, the SGTR was initiated by opening the break valve (OV-BS-04). Due to the inventory loss by the SGTR, the primary system pressure decreased. When the primary system pressure reached 10.72 MPa, the safety injection pumps (SIPs) injection signal was actuated.

The test ended by the operator's decision when the system was cooled down enough.

The whole sequence of event in this test is summarized in Table 1.

Table I: Sequence of Event

Description	Remark(Set-point)
SLB Start	OV-BS-09, OV-BS-10 Open
PZR Heater off	Coincidence with break
MFIS*	Coincidence with break
MSCV** Close	Coincidence with break
LSGP Signal	SG Pressure < 6.11 MPa
Reactor Trip	Coincidence with LSGP
RCP Trip	Reactor trip + 1.0 sec delay
MSIS***	Reactor trip + 3.54 sec delay
AFAS	SG-1 level < 2.78(m)
Decay Power	Reactor trip + 12.07 sec delay
Aux Injection into SG-1	AFAS+43.45 sec delay LT-SGSDRS1-01 level = 2.78m/3.9m(on/off)
SG-1 Dry-out	SG-1 level < 0.1 (m)
SGTR Initiation	OV-BS-04 Open Coincidence with SG-1 Dry-out
SIP Actuation	LPP****(10.72 MPa) + 28.28 sec delay

*MFIS: Main feedwater isolation signal
**MSCV: Main steam control valve
*** MSIS: Main steam isolation signal
****LPP: Low pressurizer pressure

4. Test Results

In this study, all of the test results including the event time in Table 1, were normalized by an arbitrary value including the time frame considering the confidential problem of test data.

Fig. 4 shows the variation of the system pressure. At the start of the transient, the secondary system pressure of SG-1 started to decrease rapidly with the break valve opening. The primary system pressure also decreased during the initial transient period because of the excessive heat removal through the SG-1. When the SGTR was initiated, the depressurization rate of the primary system pressure increased slightly. However, the primary system pressure recovered with the actuation of SIP injection.

The collapsed water levels of the pressurizer and the steam generator secondary sides are shown in Fig. 5. In the SG-1, due to an SLB, the collapsed water level of the secondary side decreased rapidly. After initiation of 5-tubes SGTR, the collapsed water level of the SG-1 secondary side increased again. In the pressurizer, the collapsed water level decreased initially due to the excessive heat removal by the SG-1 and the inventory loss through the SGTR. However, it was also recovered with the continuous injection of the SIPs.

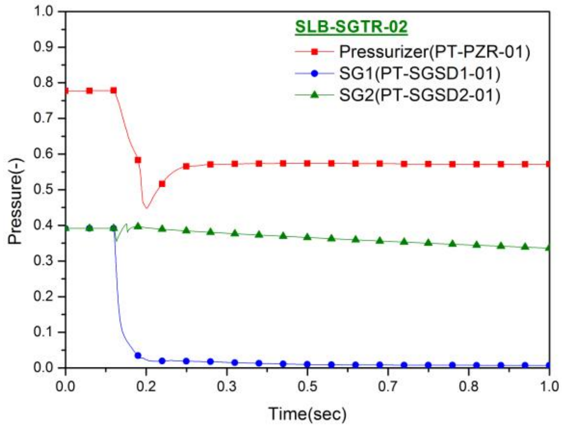

Fig. 4. Variation of the system pressures

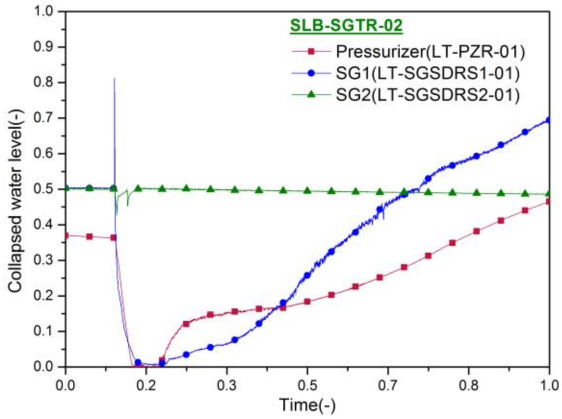

Fig. 5. Variation of the collapsed water levels

Flow rates in the primary loop are shown in Fig. 6. With the start of the transient, the flow rates of loop-1 (1A and 1B) increased. This high flow rate during the initial transient was due to the excessive heat removal through the SG-1. The flow rate of loop-1 decreased with the initiation of SGTR and, after that, it kept a continuous flow rate as the primary system pressure was stabilized with the SIPs injection. On the contrary, the flow rates of loop-2 (2A and 2B) decreased during the initial blowdown period because the SG-2 was isolated and there might be no heat removal through the SG-2. The flows in loop-2 had an effect on the cooling of the SG-2 so the pressure of the SG-2 decreased slightly during the transient as shown in Fig. 4.

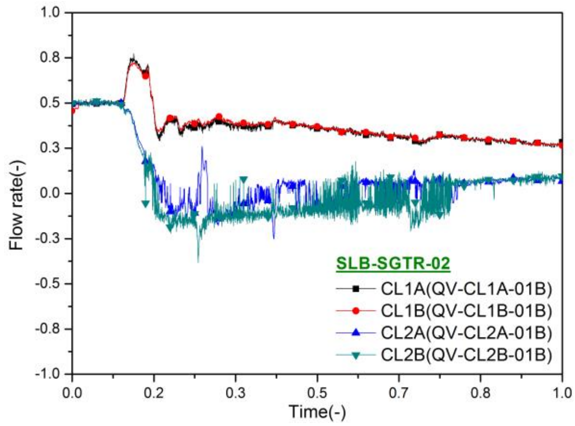

Fig. 6. Flow rates of cold-leg

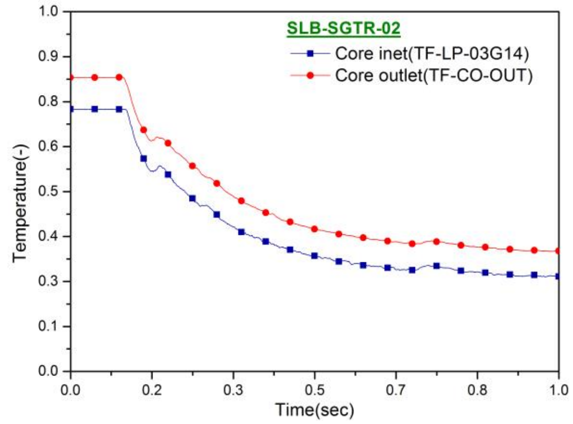

Fig. 7. Core inlet and outlet fluid temperatures

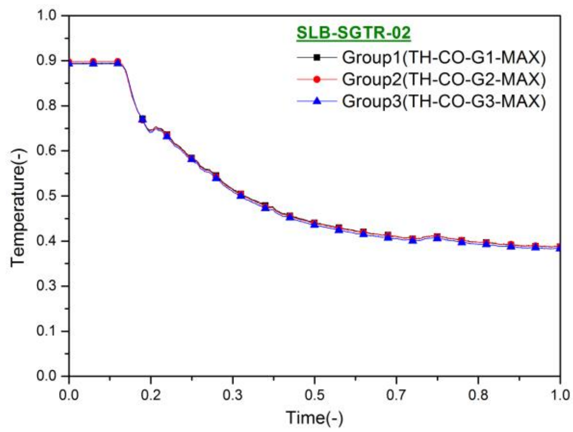

Fig. 8. Maximum fuel rod surface temperatures

By the natural circulation cooling, the primary system was cooled-down during the transient. The temperature difference between core inlet and outlet maintained stable value of were kept around 30^{o}C as shown in Fig.

7. Due to the continuous injection of the emergency core cooling (ECC) water, the excursion of the heater rod surface temperature was not occurred as shown in Fig. 8.

The break flow from the steam line break was condensed in a condensation tank. The break flow could be estimated based on the inventory increase in the condensation tank. In Fig. 9, the integrated mass of steam line break flow in the condensation tank is shown.

After showing the high peak flow rate at the initial transient, the break flow of an SLB decreased rapidly until the SGTR initiation. After SGTR initiation, the collapsed water level of the steam generator secondary side of SG-1 was recovered due to the SGTR break flow in addition to the auxiliary feedwater injection.

In this test, an orifice flow meter was installed at the upstream of the break nozzle of SGTR. The break flow was measured directly at the SGTR simulation pipe and the result is shown in Fig. 10. As the primary system pressure started to increase with the SIP injection, the break flow rate also increased. And the break flow rate was kept at a constant rate (around 0.6 kg/s) during the late period of the transient as the pressure difference between the primary and secondary systems was kept stationary.

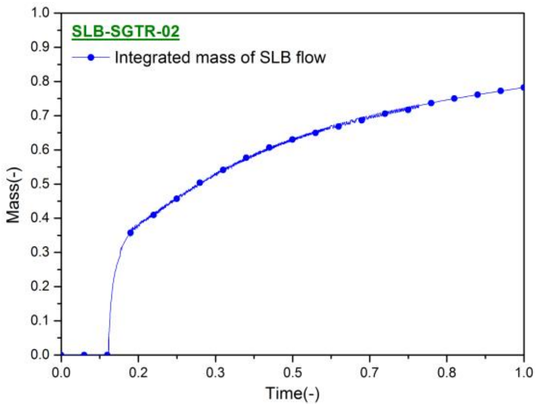

Fig. 9. Integrated mass of SLB

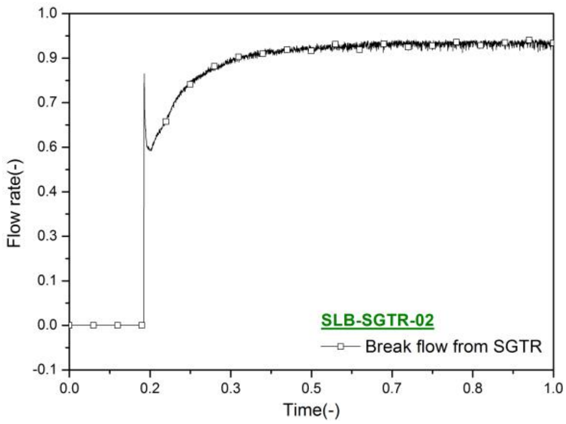

Fig. 10. Break flow rate of SGTR

5. Conclusions

An SLB accompanied by a SGTR scenario was successfully simulated using the ATLAS facility, and the major thermal hydraulic phenomena that can be anticipated in the scenario were observed.

The SLB accident makes the primary system pressure decrease with an excessive heat removal through a steam generator. With the SGTR accident, the primary inventory was transferred to the SG secondary system and a continuous SGTR break flow rate was kept based on the pressure difference between a primary and secondary system. However, with the full injection of the SIPs, and the collapsed water level in the SG-1 was recovered and the whole system was cool down successfully.

Thus, we can conclude that the system can be cooled down stably in the case of this multiple failure accident, an SLB with a SGTR, if the emergency core cooling systems are operated successfully such as SIPs and Auxiliary feedwater.

ACKNOWLEDGMENTS

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