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# Passive safety injection characteristics of SMART-ITL during SI break test

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## 1. Introduction

SMART has two representative passive safety systems (PSSs), which consists of a passive safety injection system (PSIS) for the reactor coolant system (RCS) and a passive residual heat removal system (PRHRS) for the secondary system. The PSIS of SMART is composed of four trains and two stages of an automatic depressurization system (ADS) additionally. A single train consists of a core makeup tank (CMT) and a safety injection tank (SIT).

To verify the design and performance of this SMART PSIS [1, 2], four-train PSIS equipment were designed by a volume scale law of 1/49 and then installed additionally in the SMART-ITL facility, an integral test loop of the SMART [3, 4].

An SBLOCA test breaking a single passive safety injection line was carried out using SMART-ITL equipped with the PSIS with the same function to SMART PSIS to maintain the reactor in a safe condition without any AC power to drive the safety injection pumps and operator action with no more than 72 hours during the design basis accident.

This paper describes the procedure and result of an SBLOCA test to evaluate the performance of the PSIS. The initial condition of this transient test is the same as the steady-state operating conditions of the SMART. The test was carried out according to the sequence of events (SOE) for an SBLOCA scenario.

Most of the thermal-hydraulic parameters such as the pressure, temperature, flow rate, and water level showed partially oscillating behavior during the operation of the passive safety system, but the overall injection characteristics of the CMT and SIT showed good and stable behavior.

## 2. Methods and Results

### *2.1 Overview of SMART-ITL*

SMART is a 330 MW thermal power reactor, and its core exit temperature and PZR pressure are 323℃ and 15 MPa during normal operating conditions, respectively. The maximum power of the core heater in SMART-ITL (Fig. 1) is 30% of scaled full power for the volume scale ratio. The reactor coolant system of SMART-ITL[3,4] was designed to operate under the same conditions as SMART [5].

The reactor coolant system of the SMART-ITL consists of a pressurizer, four reactor coolant pumps (RCPs), and core heater bundles. All of these major components are contained in a single reactor pressure vessel except four steam generators (SGs).

Four reactor coolant pumps are installed on the outer wall of the upper downcomer of the pressure vessel at an angle of 90 $^{o}$. Four once-through steam generators with a helical coil were installed at the same azimuth as the RCP outside the reactor pressure vessel of SMART-ITL. The steam generator consists of primary and secondary sides. The steam generator of primary side makes a reactor coolant cool down, and that of secondary side changes the feedwater into the super-heated steam.

The secondary system consists of a feed water supply system, steam supply system, and condensation and cooling system. It is important to supply the feed water with a constant temperature and to generate the super-heated steam as the boundary values in the secondary system.

The passive residual heat removal system (PRHRS) has a function of removing the residual heat of the core when an accident that decreases or increase the RCS pressure, occurs. It consists of four trains. Each train has an emergency coolant tank, heat exchanger for the condensation of the steam, and makeup tank. Individual components were scaled down by the volume scale ratio, and the pipes were designed for conserving the similarity of the pressure drop.

### *2.2 Passive Safety Injection System*

The passive safety injection system (PSIS) includes the core makeup tank (CMT) and safety injection tank (SIT). Each tank is connected with the pressure balance pipe on the top side and injection pipe on the bottom side. This system is representatively operated when a small break loss of coolant accident (SBLOCA) or steam line break (SLB) occurs. There are no active pumps on any connecting lines to supply the coolant. This system is only actuated by the gravity force by the height difference because all tanks are higher than the injection nozzle around the reactor coolant pumps (RCPs).

Fig. 2 shows schematics of one train for the passive safety system of SMART-ITL. Each pipe has an isolation valve and flow meter. The differential pressure and temperature can be measured for every pipe and tank. A level and pressure transmitter is installed in each tank.

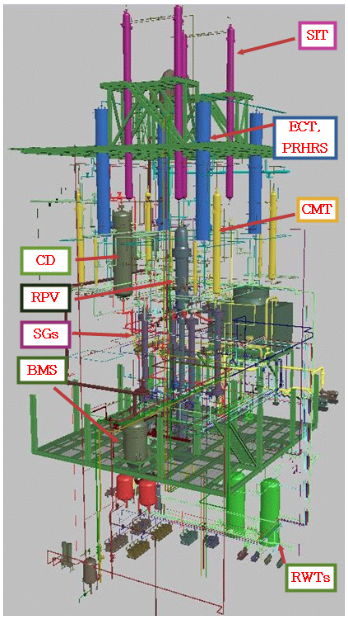

Fig. 1. Schematics of the SMART-ITL.

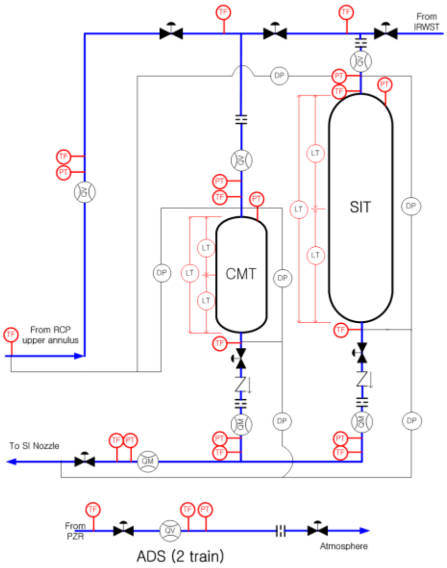

Fig. 2 Schematics of the test facility for SMART passive safety system

The phenomena of flashing and direct contact condensation are expected to occur in the CMT, SIT, and pipes at the early stage. Appropriate thermocouples have to be installed in the pipes and tanks to investigate the multiple thermal-hydraulic phenomena after the system is operated by opening the isolation valve.

### *2.3 Scaling Methodology*

CMT and SIT are scaled down using the volume scale law of 1/49. Their heights are conserved. The diameter is scaled down to 1/7, and the area of the tank cross-section is scaled to 1/49. The primary scale variables are listed in table I.

*Table I: Primary scale variables*

| *Parameters* | *Scale Ratio* | *Value* |
|---|---|---|
| *Length*, $l_{OR}$ | $l_{OR}$ | *1/1* |
| *Diameter*, $d_{OR}$ | $d_{OR}$ | *1/7* |
| *Area*, $a_{OR}$ | $d^2_{OR}$ | *1/49* |
| *Volume*, $V_{OR}$ | $d^2_{OR}\ l_{OR}$ | *1/49* |
| *Time scale* | $l^{1/2}_{0R}$ | *1/1* |
| *Velocity* | $l^{1/2}_{0R}$ | *1/1* |
| *Flow rate* | $a_{OR}\ l^{1/2}_{0R}$ | *1/49* |

*Table II: Local scale variables*

| *Parameters* | *Scale Ratio* | *Value* |
|---|---|---|
| *Length*, $l_L$ | $l_L$ | $V_{OR} / k^2$ |
| *Diameter*, $d_L$ | $d_L$ | $k$ |
| *Area*, $a_L$ | $d^2_L$ | $k^2$ |
| *Volume*, $V_L$ | $V_L$ | $V_{OR}$ |
| *Time scale* | $l^{1/2}_L$ | $(V_{OR})^{1/2} / k$ |
| *Velocity* | $l^{1/2}_L$ | $(V_{OR})^{1/2} / k$ |
| *Flow rate* | $a_{OR}\ l^{1/2}_{0R}$ | $k * (V_{OR})^{1/2}$ |

*Table III: Description of the steady-state condition*

| *Parameter* | *Normalized state-state condition (Measurement / Target value, %)* |
|---|---|
| *Power* | *113* |
| *PZR pressure* | *100* |
| *1$^{st}$ flowrate* | *99* |
| *SG 1$^{st}$ inlet temperature* | *100* |
| *SG 1$^{st}$ outlet temperature* | *101* |
| *Feed Water. flow rate* | *99* |
| *SG 2$^{nd}$ outlet Pressure* | *100* |

To maintain the pressure drop distribution in the pipes between the prototype plant and the test facility, a local-phenomena scaling method was applied. The local scale variables are listed in Table II. First, a scale factor, k, for the diameter to satisfy the volume ratio of the pipes was assumed. A length ratio was derived by substituting the factor into the volume scale ratio. Using these two ratios, a temporary $k_1$ can be selected to satisfy the Friction Number and Orifice Number. Second, another $k_2$ was selected to satisfy the ratio of the pressure drop, flow rate, and so on. Finally, through the best estimation, a specific k was determined to avoid the distortion of the real phenomena.

### *2.4 Steady State Condition*

Steady-state conditions were applied to satisfy the initial test conditions presented in the test requirement, and boundary conditions for the transient test were properly simulated.

A steady-state operation was maintained over 600 seconds prior to the transient test. Table III shows the normalized-major parameters of the target values and test results during the steady-state conditions.

Table IV: Major Sequence of the SBLOCA

| Event | Set Point | Time After Break (seconds) |
|---|---|---|
| Break | | 0 |
| LPP set-point | $P_{LPP}$ | 744 |
| Reactor trip signal<br>- Pump coastdown<br>- FW stop<br>- CMT Actuation Signal | LPP+1.1 s | 745 |
| Reactor trip-curve start | LPP+1.6 s | 746 |
| CMT injection start | LPP+2.2 s | 747 |
| PRHR actuation signal | LPP+5.2 s | - |
| PRHRS IV open | LPP+10.2 s | 754 |
| MSIV / FIV close | LPP+25.2 s | 755 |
| SIT injection signal | $P_{SITAS}$ | - |
| SIT injection start | SITAS+1.1s | 4,282 |
| ADS #1 open | CMT Level | 25,589 |
| Stop the test | 72 hr or<br>Complete injection | 301,258 |

The pressure behavior of the RCS system is a major control parameter to generate the reactor trip signal, by which the reactor core is protected.

Table IV shows the major sequence of events for the SBLOCA test as the boundary conditions. Once a line of PSIS was broken, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point ($P_{LPP}$) at 744 s, the reactor trip was generated about 1 s after the LPP signal. Consequently, the reactor coolant pump started to coast down. The CMT actuation signal was generated. It was shown that a PRHRS actuation signal also occurred. Then the SIT was actuated after the safety injection actuation signal ($P_{SITAS}$). The individual signal was sequentially actuated.

### *2.5 SBLOCA test of SI Break*

A Safety Injection System (SIS) has a function to make up the reactor coolant during the loss-of-coolant accident, in which the pressure and volume of the RCS are decreased. SI lines are connected to the reactor vessel and the makeup water is supplied to itself during a certain accident. In the present test, the SBLOCA test was simulated by breaking a SI line. Three trains of PSIS were operated except for the break line.

The break type is a guillotine break, and its break location is on the SI line (nozzle part of the RCP discharge). The thermal-hydraulic behavior in SMART-ITL happens at the same time to SMART designs according to the time scale ratio. The scaled-down break nozzle diameter is 7.26 mm in the SMART-ITL.

An SBLOCA test on the SI line break was carried out according to the sequence of events as follows: The steady-state conditions (constant high pressure and temperature) → break(pressure, temperature, and water level decrease) → LPP → RCP coast down, feedwater stop, heater trip (residual heat decay curve) → CMT actuation → PRHRS → isolation of the feedwater and steam lines → SIT actuation → ADS open.

The constant high pressure and temperature condition of the RCS, which satisfy the required steady state condition, decreases rapidly after the break starts, as shown in Fig. 3. Individual actuation signals such as the RCP coast down, heater trip and the actuations of CMT, PRHRS and SIT worked properly after the pressure reached a specific value, $P_{LPP}$. The system was cooled down by the safety system from that time. When decreasing the RCS pressure, the working time of the CMT and SIT were displayed, as shown in Fig. 3 as ① and ②, respectively. This means that the pressure vessel cooled down efficiently with the operation of the PSS, including the CMT, SIT and PRHRS.

### *2.6 Injection Characteristics*

Fig. 4 shows the flow rate of the CMTs. After opening an isolation valve located on the injection line of the CMT (①), the injection of the core makeup water began. In this initial stage of the CMT injection, steam from the RCS was mixed with the relatively cold coolant at the upper header of the CMT, and thus direct condensation was expected to occur. The initial injection flow rate showed unstable behavior while repeatedly increasing and decreasing.

Before the SIT started working, there was a pressure difference between the RCS and SIT, as shown in ② of Fig. 3. When the SIT began working, the flow rate was suddenly decreased (②→②’) and then increased (②’→②”) for a short time as shown in Fig. 4. This is the time to reach the pressure equilibrium. The flow rate after this time (②”) was slightly higher than the previous one because this flow rate indicates the sum of the CMT and SIT. This merged flow rate with the CMT and SIT was gradually decreased and efficiently injected. The decreasing slope of the reactor coolant level of the primary system was changed from about 4,500 seconds in Fig. 5, which was the same time as point ②” of Figs. 3 and 4. From this point ②” , i.e., around 4,500 seconds, the collapsed level of the primary system was rapidly increased as shown in Fig. 5. This increasing trend is changed gradually after a sudden peak in the level when the ADS began working around 25,000 seconds (③). It reveals that the reactor coolant inventory is sufficiently recovered with a proper operation of safety injection systems.

## 3. Conclusions

An SBLOCA test on the SI line break was conducted to evaluate the performance of the PSIS using the CMT and SIT of the SMART design. All of the major parameters satisfied the initial steady-state condition and the actuating sequences were operated on time corresponding to the boundary condition.

- After the SI break was simulated, the RCS pressure was decreased rapidly and the coolant of the CMT and SIT was injected in an unstable manner. It is expected that a direct contact condensation of steam occurred during the thermal mixing of high-temperature steam with the water on the upper head of the CMT.
- After the SITs were operated, the CMT injection flow merged with the SIT injection flow and then this injection flow became stable.
- The coolant of the CMTs and SITs was injected efficiently and the collapsed level decreased in the early stage of the test was sufficiently recovered in the end stage.
- The final pressure and collapsed level revealed that the RV was cooled down efficiently and the reactor coolant inventory was sufficiently recovered by the operation of three trains of PSIS.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] Y. M. Bae, Report of Passive Safety System, SER-410-FS403-SD, 2012.
[2] K. K. Kim, et al., SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering, 8, 94-102, 2014.
[3] H. S. Park, S. J. Yi, and C. H. Song, SMR Accident Simulation in Experimental Test Loop, Nuclear Engineering International, November 2013, 12-15.
[4] H. Bae, D. E. Kim, S. J. Yi, and H. S. Park, Test Facility Design for the Validation of SMART Passive Safety System". Transactions of the Korean Nuclear Society Spring Meeting, Gwangju, Korea, May 2013. pp. 30-31.
[5] H. Bae, S. U. Ryu, H. B. Ryu, W. S. Kim, S. J. Lee, and H. S. Park, An Experimental Investigation on thermal-hydraulic Interaction between Core Makeup Tank and Safety Injection Tank of an Integral Small Reactor during a Small Break Loss-of-Coolant Accident, Proceedings of the ASME-JSME-KSME Joint Fluids Engineering Conference 2015, July 26-31, 2015, Seoul, Korea.

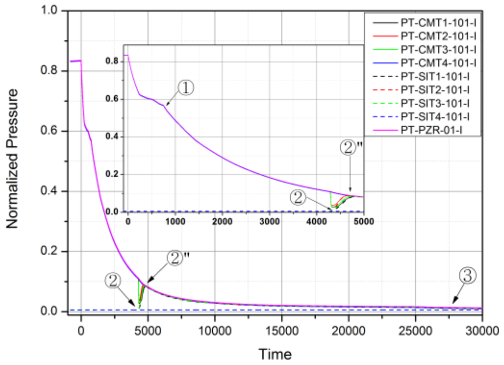

Fig. 3 Pressure of PZR, CMT, and SIT

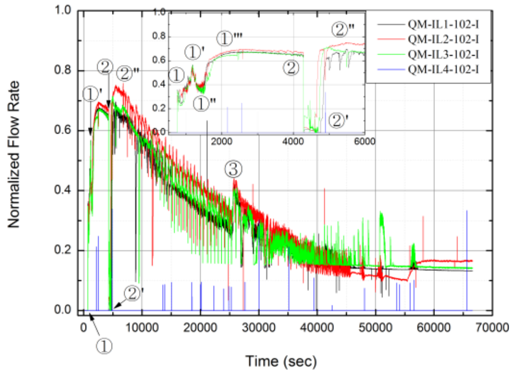

Fig. 4 Injection Flow Rate of CMTs and SITs

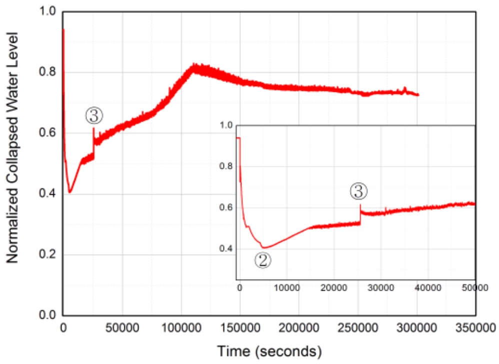

Fig. 5 Collapsed Level of Reactor Coolant System