AN SBLOCA TEST OF PRESSURIZER SAFETY VALVE LINE BREAK WITH THE SMART-ITL FACILITY AND ITS MARS-KS CODE SIMULATION

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ABSTRACT

An SBLOCA test of a pressurizer safety valve line break was carried out using the integral-effect test loop for SMART (System-integrated Modular Advanced ReacTor), i.e., the SMART-ITL Facility. Its post-test calculation was performed using the best-estimate safety analysis code, MARS-KS. This paper investigated the thermal-hydraulic phenomena during a transient accident. The results show that the adopted active safety injection system functions well as an emergency core cooling system. For an analysis with the MARS-KS code, the steady-state conditions were maintained to satisfy the initial test conditions presented in the test requirement, and its boundary conditions were properly simulated. The scenarios of SBLOCA for the SMART design were reproduced well using the SMART-ITL facility and MARS-KS code. The simulation results using the MARS-KS code are in good agreement with the test results using the SMART-ITL.

KEYWORDS
SMART, SMART-ITL, SBLOCA, MARS-KS, Safety Injection, PSV Line Break

1. INTRODUCTION

SMART [1,2] is a small and medium reactor designed by the Korea Atomic Energy Research Institute (KAERI) and received standard design approval by the Korean regulatory body in July 2012. The main components include a pressurizer, steam generators, and reactor coolant pumps. They are installed in a reactor pressure vessel, and there are no large-size pipes. The safety systems could be simplified as an LBLOCA (Large-Break Loss of Coolant Accident) scenario was inherently excluded in the design stage. The SMART design has a thermal power of 330 MW. Its core exit temperature and pressurizer pressure are 323 ^{o}C and 15 MPa during normal operating conditions, respectively.

SMART-ITL [3,4] was designed to simulate the integral thermal-hydraulic behavior of SMART. The objectives of SMART-ITL are to investigate and understand the integral performance of the reactor systems and components, and the thermal-hydraulic phenomena occurring in the system during normal and emergency conditions, and to verify the system safety during various design basis events of SMART. The integral-effect test data will also be used to validate the related thermal-hydraulic models of the safety analysis code such as TASS/SMR-S [5] which is used for a performance and accident analysis of the SMART design. In addition, a scoping analysis [6] on the scaling difference between the standard design of SMART and the basic design of SMART-ITL was performed for an SBLOCA (Small-Break Loss of Coolant Accident) scenario using a best-estimate safety analysis code, MARS-KS [7]. This paper introduces a comparison of an SBLOCA test of a pressurizer safety valve line break using SMART-ITL with its post-test calculation using the MARS-KS code. The scenarios of SBLOCA in the SMART design were reproduced well using the SMART-ITL facility and the MARS-KS code

2. SCALING AND DESIGN OF THE SMART-ITL

2.1. Scaling of the SMART-ITL

SMART-ITL was designed following a three-level scaling methodology consisting of integral scaling, boundary flow scaling, and local phenomena scaling. Its height is preserved to the full scale, and its area and volume are scaled down to 1/49 compared with the prototype plant, SMART. The maximum core power is 2.0 MW, which is about 30% of the full scaled power. The design pressure and temperature of SMART-ITL can simulate the maximum operating conditions, that is, 18.0 MPa and 350 ^{o}C. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table I.

Table I. Major scaling parameters of the SMART-ITL facility

Parameters	Scale Ratio	Value
Length	l_{0R}	1/1
Diameter	d_{0R}	1/7
Area	d_{0R}^{2}	1/49
Volume	$l_{0R}\ d_{0R}^{2}$	1/49
Time scale, Velocity	$l_{0R}^{1/2}$	1/1
Power, Volume, Heat flux	$l_{0R}^{-1/2}$	1/1
Core power, Flow rate	$d_{0R}^{2}\ l_{0R}^{1/2}$	1/49
Pump head, Pressure drop	l_{0R}	1/1

2.1.1. Basic Design of the SMART-ITL

Fig. 1 shows a schematic diagram of the SMART-ITL facility, which can simulate the operational and accidental transients that occur in the integral effect test loop in view of thermal hydraulics. SMART-ITL consists of a primary system, four steam generators (SGs), a secondary system, four trains of a passive residual heat removal system (PRHRS), four trains of a safety injection system (SIS), two trains of a shutdown cooling system (SCS), a break simulator (BS), a break flowrate measuring system (BMS), and auxiliary systems. The primary system includes a reactor pressure vessel (RPV), a steam pressurizer, shell sides of four SGs, and four reactor coolant pumps (RCPs) to simulate asymmetric loop effects. An annular downcomer design is applied at the upper part to simulate a multi-dimensional effect. However, as the scaled-down annular downcomer of SMART-ITL is not sufficient to contain the SGs, four SGs are installed outside of the RPV using two connecting pipes above and below each SG like hot and cold legs, respectively, which facilitates relevant measurements. In the secondary system, four steam lines are lumped into a direct condenser tank where the steam generated by four SGs is condensed and the condensed feedwater is again injected into the SGs.

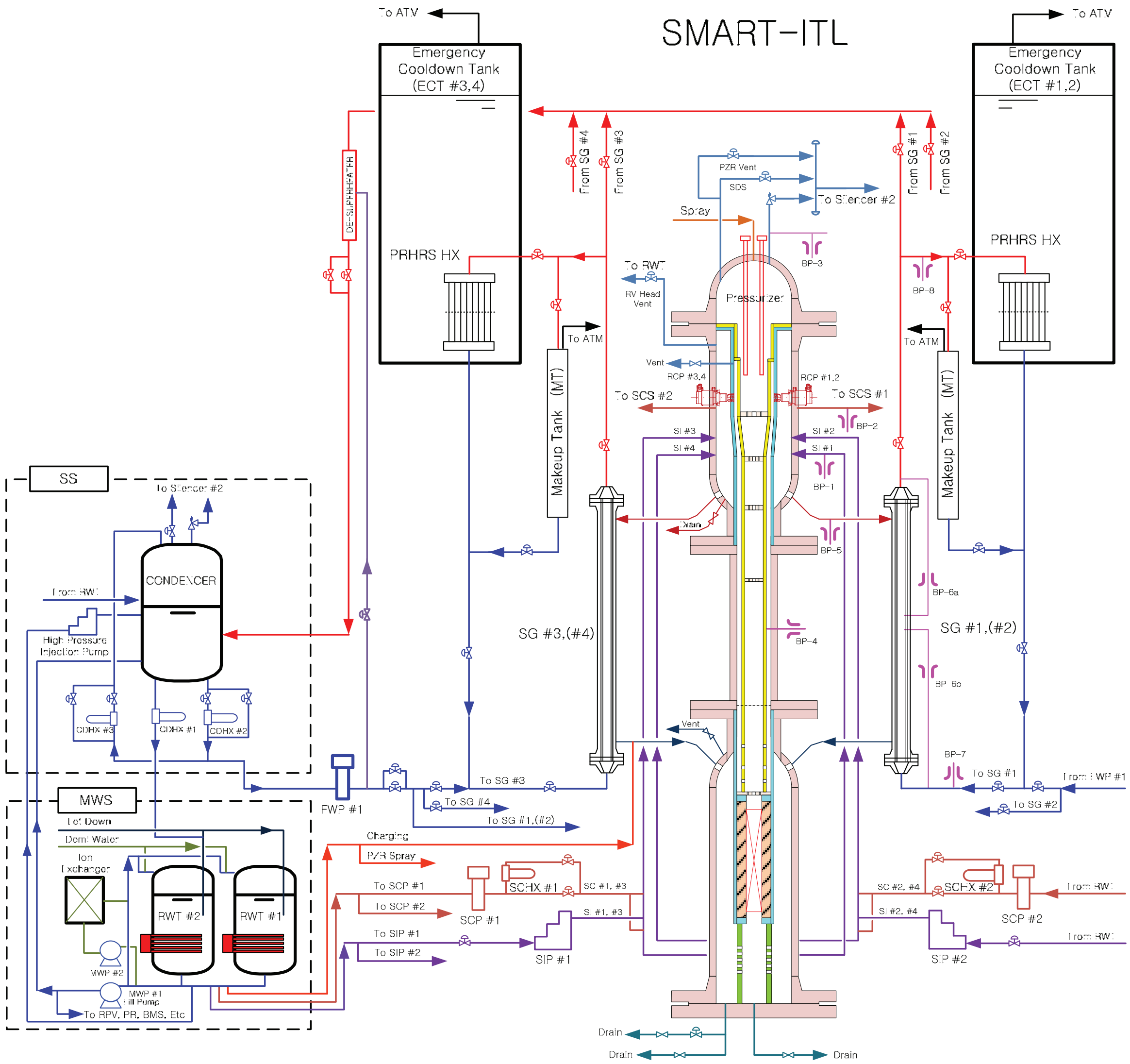

Figure 1. Schematic Diagram of the SMART-ITL Facility.

The PRHRS is composed of four trains, each of which includes an emergency cooldown tank (ECT), a heat exchanger (HX), a makeup tank (MT), several valves, and connecting pipes. It is connected to the feedwater and steam lines of the secondary system, and a natural circulation flow path is formed by opening the isolation valves by the actuation signal. It was designed to have the same pressure drop and heat transfer characteristics, and arranged to have the same elevation and position as those of SMART to preserve the natural circulation phenomenon. In addition, the diameter, thickness, pitch, and orientation of the heat exchanger tubes of the SMART-ITL facility are the same as those of SMART. During the PRHRS operation, the superheated steam generated from the steam generator secondary side is directed to and condensed in the PRHRS heat exchangers by natural circulation. The condensed water flows downward through the PRHRS condensate line and returns to the feedwater line. The condensing heat is transferred to the ECT, which is filled with water and functions as an ultimate heat sink.

The SIS and SCS can simulate several operation modes such as a safety injection, long-term cooling, shutdown cooling, and recirculating operations. The BS consists of a quick opening valve, a break nozzle, and instruments. The BMS collects the break flow and maintains a specified pressure to simulate the

back-pressure of the containment. A separator in the BMS separates a liquid phase from a two-phase break flow, and each separated flow rate in a single phase condition is measured by a different measuring technique. The separated liquid and gas flow rates are measured respectively by weighing a mass of accumulated water and by a dedicated flowmeter. SMART-ITL is also equipped with some auxiliary systems such as a makeup water system (MWS), a component cooling water system (CWS), a compressed air system (CAS), a steam supply system (SSS), a vacuum system (VS), and a heat tracing system (HTS).
The control and data acquisition system of SMART-ITL has been built with a hybrid distributed control system (DCS). The input and output modules are distributed into five cabinets, which are controlled by two central processing units (CPUs). The raw signals from the field are processed in a system server and the converted signals are monitored and controlled through a human-machine interface (HMI), which consists of 52 processing windows classified according to the SMART fluid system.
The number of instruments is up to 1,014 at present. Instrument signals can be categorized according to the instrument type, such as the temperature, static pressure, collapsed water level, differential pressure, flow rate, power, and weight. The core heater cladding temperatures are measured for several radial and axial locations with more than 260 thermocouples, and the fluid temperatures in the RPV are measured with more than 100 thermocouples.

3. PSV LINE BREAK TEST AND ITS POST-TEST CALCULATION

The SMART-ITL has been used to investigate the thermal-hydraulic behavior for SMART during the operational transients and a design basis accident. One of the SBLOCA tests was successfully performed using the SMART-ITL facility. The break type is a guillotine break, and its break location is on the PSV (Pressurizer Safety Valve) line which is connected to the top side of pressurizer. The thermal-hydraulic behavior occurs at the same time in the SMART-ITL and SMART designs according to the time scale ratio. Table II shows the major sequence of events for the SBLOCA simulation test.
As a PSV line is broken in the SMART design, the primary system pressure decreases with the discharge of the coolant through the break. When the primary pressure reaches the low pressurizer pressure (LPP) set-point, the reactor trip signal is generated with a 1.1 s delay. As the turbine trip and the loss of off-site power (LOOP) are assumed to occur consequently after the reactor trip, the feedwater is not supplied and the RCP begins to coast-down. With an additional 0.5 s delay, the control rod is inserted. When the PRHRS actuation signal is generated by the low feedwater flowrate 2.34 s after the LPP, the SG is isolated from the turbine by the isolation of the main steam and feedwater isolation valves, and is connected to the PRHRS. The safety injection actuation signal (SIAS) was generated when the RCS pressure reaches below the SIAS setpoint, and the SI water is injected with a time delay of 30 s.
The break nozzle diameter is 50.8 mm in the SMART design and the scaled-down value is 7.26 mm in the SMART-ITL.

3.1. SMART-ITL Nodalization

A post-calculation was performed for the experimental SBLOCA scenario using a best-estimate safety analysis code, MARS-KS. During the simulation of the SBLOCA, it is assumed that the break occurs on the PSV line at the same position. In addition, the set-point and sequence of events in the SBLOCA scenario were the same as those used in the test, as shown in Table II.
The nodalization of SMART-ITL was based on an isometric drawing and design reports provided by KAERI. In addition, some assumptions and modifications were made. A MARS-KS nodalization diagram for SMART-ITL is represented in Fig. 2. The nodalization for a MARS-KS analysis includes all reactor coolant systems, a safety injection system, and a secondary system including the PRHRS.

Table II. Major sequence of SBLOCA simulation test

Event	Trip signal and Set-point
	SMART-ITL
Break	- -
LPP set-point	PZR Press = P_{LPP}
LPP reactor trip signal - FW stop - Pump coastdown	LPP+1.1 s
Control rod insert	LPP+1.6 s
PRHR actuation signal	LPP+2.34 s
PRHRS IV open FIV close	PRHRAS+5.0 s
MSIV close	PRHRAS+15.0 s
Safety injection signal	PZR Press = P_{SIAS}
Safety injection start	SIAS+30.0 s

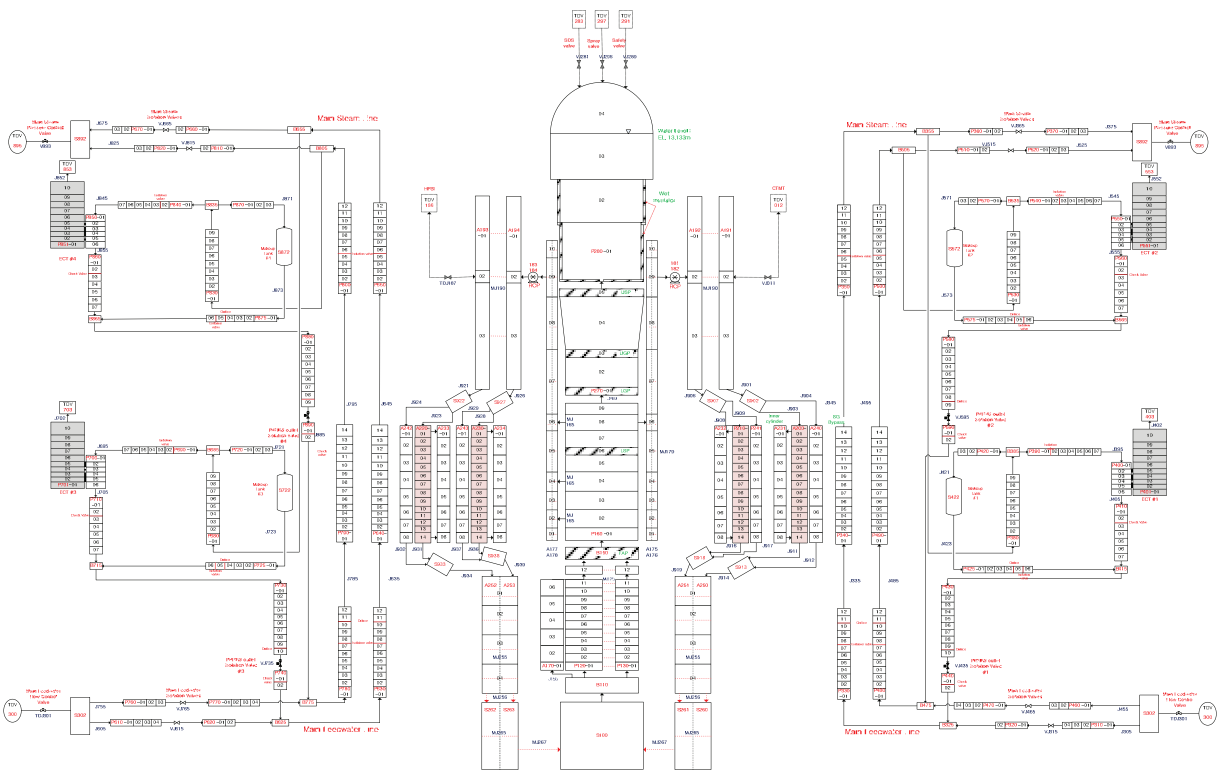

Figure 2. Nodalization diagram of SMART-ITL for MARS-KS model.

3.2 Simulation Conditions

For the SBLOCA scenario of the pressurizer safety valve line break, the break line is assumed to be one of the available safety lines, and only one of the four safety injections is assumed to be active based on a single failure assumption. The safety injection flow rate of SMART-ITL is 1/49 that of SMART with the same pre-specified safety injection pump characteristics. The break size is set to be reduced according to an area scale ratio of 1/49.

Table III. Comparison of the major parameters at a steady state condition

Parameter	SMART-ITL (Target value)	SB-PSV-01 (Measured value)	MARS-KS (Calculation)
Power (kW)	1346.9	1482.14	1482.6
PZR pres.(MPa)	15.0	14.97	14.97
1^{st} flowrate(kg/s)	8.53	7.748	7.9166
SG 1^{st} inlet temp.(℃)	323.0	324.04	323.05
SG 1^{st} outlet temp.(℃)	295.7	293.76	292.60
SG 2^{nd} outlet P.(MPa)	5.2	5.29	5.29
Feed Water temp.(℃)	200	200.88	200.82
Steam temp.(℃)	> 296	316.84	323.06
Feed Water flowrate(kg/s)	0.66	0.6577	0.6557

* Heat loss in primary system is included.

3.3. Comparison of SBLOCA Test with MARS-KS Simulation

A steady-state condition was operated over 600 seconds before the start of the break simulation. The major parameters agreed well with the target value. After a pressurizer safety line was simulated to be broken, a transient injection test was performed according to the small-break loss-of-coolant accident (SBLOCA) scenario. Coolant injections were started by actuating the safety injection pumps. Several thermal-hydraulic phenomena such as a depressurization, cooling, and natural circulation were locally observed in a reactor coolant system and secondary system, respectively. The reactor coolant level was maintained higher than that of a fuel assembly plate during the SBLOCA test.

Table III shows a comparison of the major parameters between the test and simulation under a steady state condition. The averaged values for the major parameters during the steady-state operation were listed in Table III. The primary system flow rate of the test and simulation for a 20% core power are 7.748 kg/s and 7.9166 kg/s, respectively. The secondary system flow rate of the test and simulation are the equal at 0.6557 kg/s. The primary system pressure of a 20% core power condition is 14.97 MPa. The inlet/outlet temperatures of the steam generator's primary side in the test are 324.04 ℃ and 293.76 ℃, respectively. Those in the simulation are 323.05 ℃ and 292.60 ℃, respectively.

Table IV shows the test results of the major sequence for the SBLOCA simulation test. When a PSV line was broken, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point (PLPP) after the PSV line break, the reactor trip was generated about 0.5 s after the LPP signal, which was generated at 58 s in the test and 80.3 s in the code simulation after the break. Consequently, with the reactor trip signal, the feed water was stopped and the reactor coolant pump started to coast-down. It was shown that the PRHRS actuation signal occurred. The safety injection water was injected 30 s after the safety injection actuation signal (SIAS). The individual signal is sequentially actuated. An LPP set-point of the simulation was reached, however, about 22.3 s later than that of the test. This time gap was gradually increased until 66.2 s when the safety injection started. This means that the amount of the depressurization is a little less in the simulation than in the test during the beginning stage of the break. The steady-state conditions were operated to satisfy the initial test conditions presented in the test requirement, and its boundary conditions were properly simulated.

Fig. 3 through 8 shows the variations of the major parameters. All data presented in the graphs were normalized from 0 to 1 only to show their general trends to be compared.

The decay power curve and safety injection flow rate were well provided as the boundary conditions for the test and code analysis. Fig. 3 shows the decay power curve, which were well matched between the test and code analysis.

Fig. 4 shows the pressure behavior of the primary system. The primary pressure decreased rapidly during the early stage. Since the PSV was installed on the top side of the pressurizer consisting of a steam region, the single-phase steam was expected to be only discharged though a break nozzle during the transient simulation. The pressure decrease was slowed down during the middle stage, and the pressure then decreased gradually during the final stage. The depressurization in the test and calculation maintained the similar trends qualitatively even though a little quantitative difference was present.

Fig. 5 shows the primary system temperature. As the PSV line break occurred and the primary pressure decreased rapidly during the early stage and steadily after the middle stage, the primary temperature in the inlet of the SGs also decreased along the saturation temperature. The temperature range in the outlet was under the saturation temperature. The decay heat of the primary side was appropriately removed by the PRHRS in both the test and simulation while the reactor coolant was cooled down along the saturation temperature. The calculated temperature distribution was good in agreement with the test results during the transient simulation.

Fig. 6 shows the collapsed water level of the primary hot side. The collapsed water level was decreased by the PSV line break and recovered by the SI injection worked. It was under-predicted in the simulation than in the test.

Fig. 7 shows the secondary system pressure. At the beginning of the transient, the pressure increased rapidly. It decreased gradually after arriving at the peak pressure. As a feed-water pump was stopped, the PRHRS was actuated, and the feed-water isolation valve and main steam isolation valve were closed, the secondary pressure increased. After a natural circulation of the secondary system by the balance between the steam generators and PRHRS started up and safety injection actuated, it decreased. The peak pressure of the simulation was over-predicted and the secondary system pressure of the simulation was under-predicted after it decreased.

Fig. 8 shows the secondary system flow rate. As the PRHRS system operated, the feed-water flow rate showed a dramatic change at the beginning, and natural circulation was achieved within a few seconds. After that, the natural circulation flow rate showed gradual decrease at a constant rate. The flow rate in the code simulation was a little less than in the test. The flow rate under a natural circulation condition is dependent on the heat balance between the heat exchanger and the SG, and the hydraulic resistance in the loop. It is supposed that the hydraulic resistance of the test facility is different from that of the code simulation.

Fig. 9 shows the steam generator's temperature of secondary side. The temperature decreased after a natural circulation started up. The temperature difference between the inlet and the outlet was reduced more in the simulation than in the test. Heat balance between the steam generator and PRHRS should be checked more carefully with the behavior of pressure, temperature, and flow rate of secondary system and PRHRS.

The secondary system pressure and steam temperature of MARS-KS simulation decreased faster than those of the test and the flow rate of the natural circulation were less in the simulation than in the test for whole transient time. It means that the heat removal of PRHRS from the steam generator is less in the MARS-KS than in the test. In general, the properties of primary and secondary side such as pressure, temperature and flow-rate, were under-predicted in the MARS-KS simulation than in the test. A detailed verification calculation for the test is required to find out the differences occurring the test and simulation.

The flow rate of the safety injection is programmed by following the pressure of the RCS, and is well injected according to the pressure programmed into the control logic, as shown in Fig. 10.

Test and code analyses of the SBLOCA for a pressurizer safety valve line break (SB-PSV-01) were performed. The experimental results were properly reproduced by the code analysis using MARS-KS.

In the present simulation, the similarity between the SMART-ITL data and its simulation results was reasonable for the major thermal-hydraulic parameters as described in Figs. 3-10.

Table IV. Test results of major sequence for SBLOCA

Event	SB-PSV-01 Time After Break (seconds)	
Sequence	Test	Code
Break	0	0
LPP set-point	58	80.3
LPP trip signal - FW stop - Pump coastdown	61	81.4
Reactor trip-curve start	61	81.9
PRHR actuation signal	62	82.6
PRHRS IV open	67	87.6
FIV close MSIV close	67 82	
Safety injection signal	541	607.2
Safety injection start	572	637.2

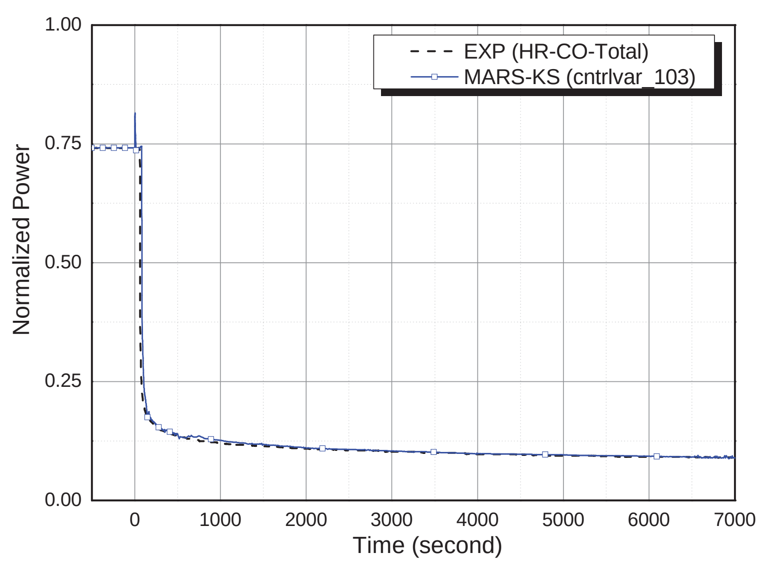

Figure 3. Core Power

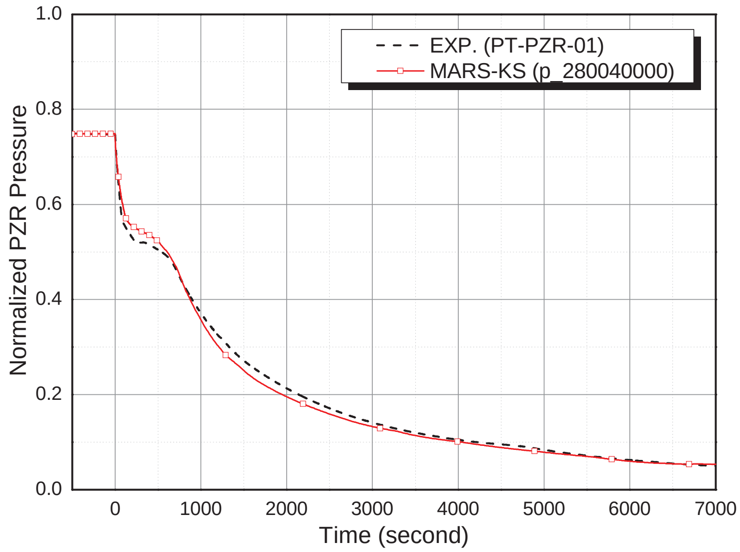

Figure 4. Primary System Pressure

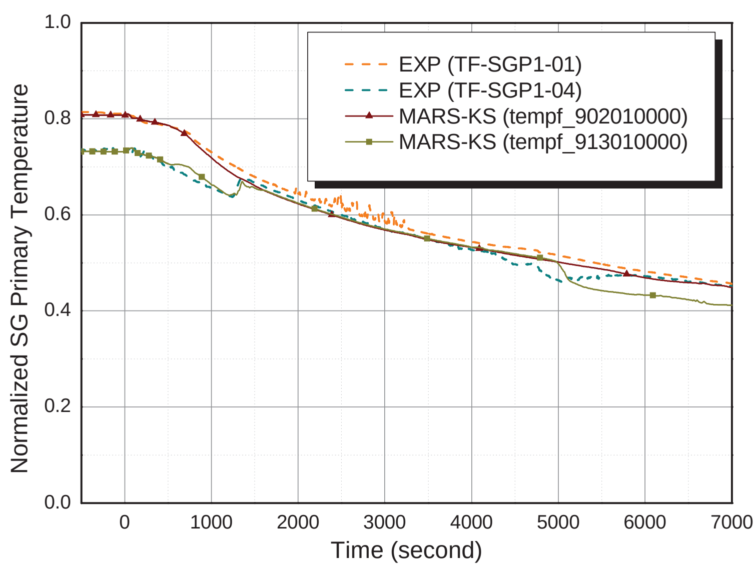

Figure 5. Primary System Temperature

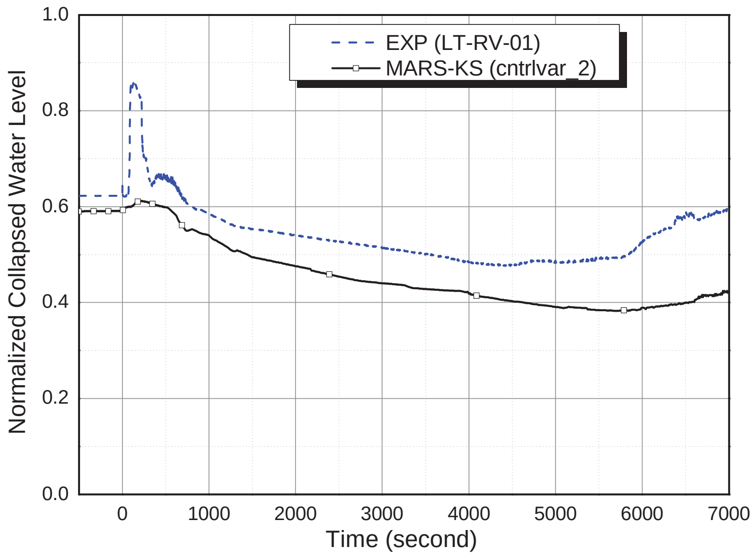

Figure 6. Collapsed Water Level of Primary System

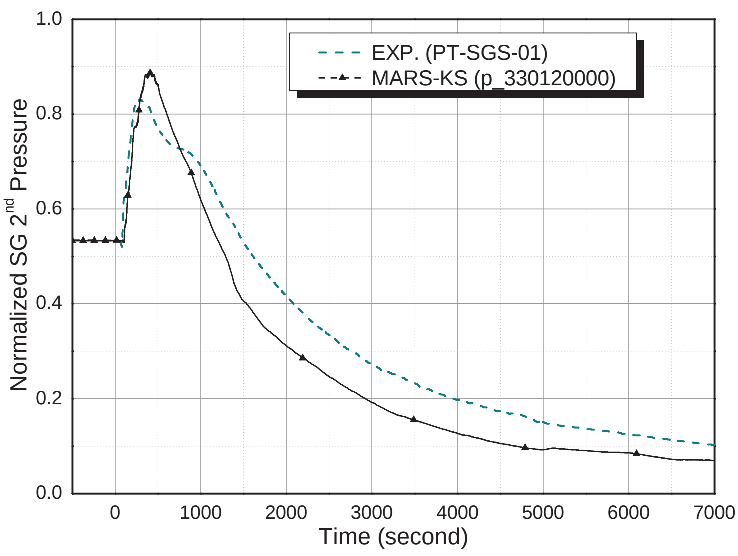

Figure 7. Secondary System Pressure

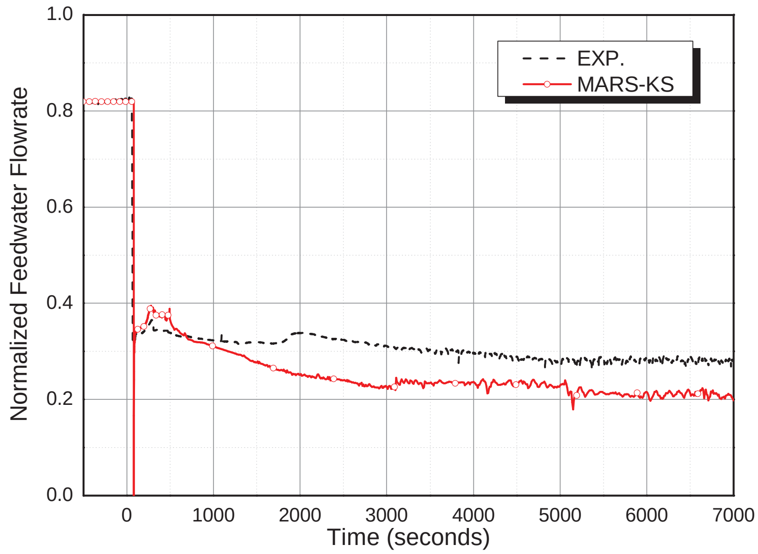

Figure 8. PRHRS Flow Rate

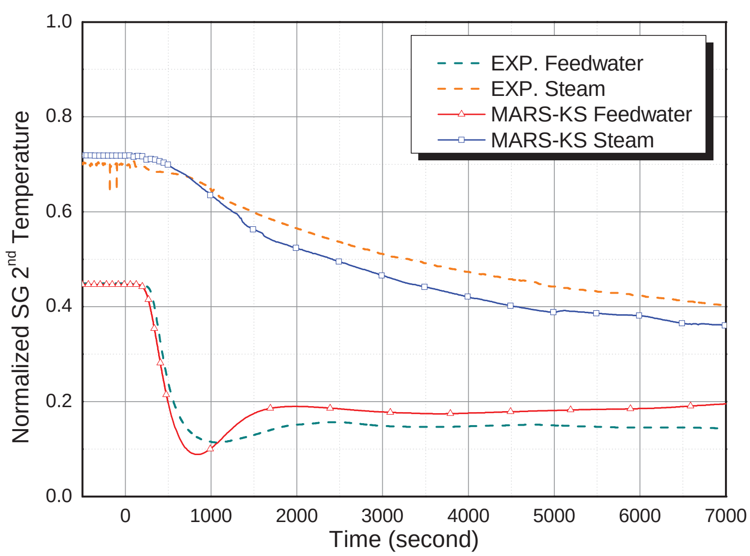

Figure 9. Secondary System Temperature

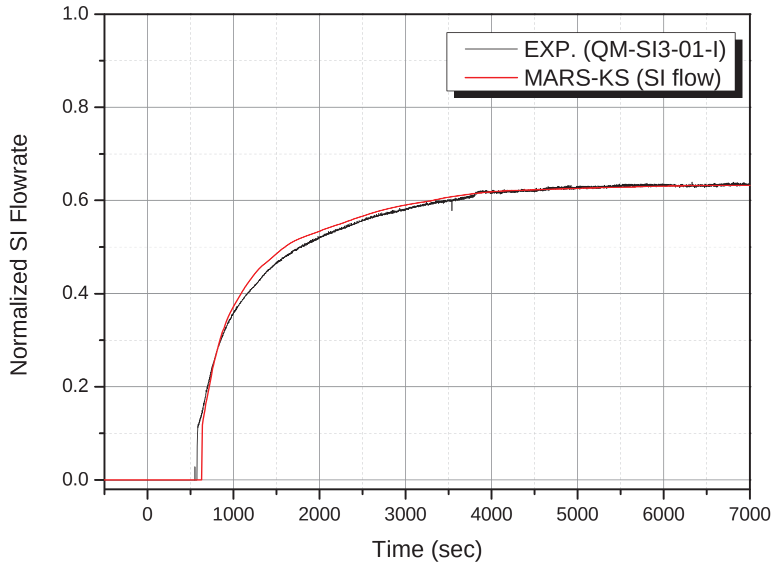

Figure 10. Safety Injection Flow Rate

CONCLUSIONS

An SBLOCA test and its post-test calculation were successfully performed using the SMART-ITL facility and MARS-KS code. The SBLOCA break is a guillotine break, and its location is on the PSV line.
The steady-state conditions were achieved to satisfy the initial test conditions presented in the test requirement, and its boundary conditions were properly simulated. The scenarios of SBLOCA in the SMART design were reproduced well using the SMART-ITL facility and the MARS-KS code. The major parameters of pressures and temperatures show reasonable behaviors during the SBLOCA scenario both for the test and simulation. The simulation trends using the MARS-KS code were in good agreement with the test results using the SMART-ITL.

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