Major Results from 1-Train Passive Safety System Tests for the SMART Design with the SMART-ITL Facility

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1. Introduction

The Standard Design Approval (SDA) for SMART [1] was certificated in 2012 at the Korea Atomic Energy Research Institute (KAERI). To satisfy the domestic and international needs for nuclear safety improvement after the Fukushima accident, an effort to improve its safety has been studied, and a Passive Safety System (PSS) for SMART has been designed [2].

In addition, an Integral Test Loop for the SMART design (SMART-ITL, or FESTA) [3] has been constructed and it finished its commissioning tests in 2012. Consequently, a set of Design Base Accident (DBA) scenarios have been simulated using SMART-ITL. Recently, a test program to validate the performance of the SMART PSS was launched and its scaled-down test facility was additionally installed at the existing SMART-ITL facility [4, 5].

In this paper, the major results from the 1-train passive safety system validation tests with the SMART-ITL facility will be summarized. The acquired data will be used to validate the safety analysis code and its related models, to evaluate the performance of SMART PSS, and to provide base data during the application phase of the SDA revision and construction licensing.

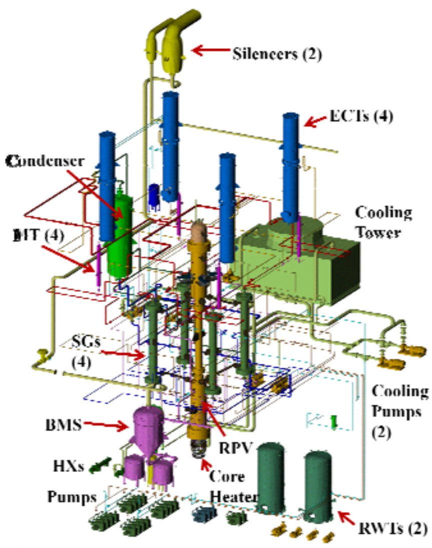


Fig. 1 Schematics of the SMART-ITL.

2. Methods and Results

2.1 SMART-ITL (FESTA)

SMART is an integral-type reactor. A single pressure vessel contains all of the major components, which are the pressurizer, core, steam generator, reactor coolant pump, and so on.

SMART-ITL is scaled down using the volume scaling methodology and has all the fluid systems of SMART together with the break system and instruments, as shown in Fig. 1. The height of the individual components is conserved between SMART and SMART-ITL. The flow area and volume are scaled down to 1/49. The ratio of the hydraulic diameter is 1/7. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table 1.

Table 1 Major Scaling Parameters of the FESTA 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

All primary components except for the steam generators are equipped in a reactor pressure vessel. However, as the space of the annulus used to locate the steam generator is too narrow to install itself inside the SMART-ITL, the steam generator was connected to the hot-leg and cold-leg outside the pressure vessel where the instruments are installed.

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

2.2 SMART Passive Safety System

The SMART PSS design is composed of four Core Makeup Tanks (CMTs), four Safety Injection Tanks (SITs), and two-stage Automatic Depressurization Systems (ADSs) [2]. Individual tanks are connected with the pressure-balanced pipes on the top side and injection pipes on the bottom side. This system is operated when a small break loss of coolant accident (SBLOCA) or the steam line break (SLB) occurs. There are no active pumps on the pipe lines to supply the coolant. This system is only actuated by the passive means of gravity force caused by the height difference because all of the tanks are higher than the injection nozzle around the reactor coolant pumps (RCPs).

The CMTs and SITs were designed based on the volume scale methodology, which is the same methodology used for SMART-ITL. Their heights are conserved, their diameters are scaled down to 1/7, and the area of the tank cross-section is scaled down to 1/49. Detailed scaled values are shown in Table 1.

Fig. 2 shows a schematic of one train for the passive safety system of the SMART-ITL. Each pipe has an isolation valve and a flow meter. The pressure, differential pressure, and temperature can be measured at every pipe and tank. The level and pressure transmitters are installed in each tank.

The phenomena of flashing, condensation, and thermal stratification are expected to occur in the CMT, SITs, and pipes during the early stage. Appropriate thermo-couples have to be installed in the pipes and tanks to investigate the complex thermal-hydraulic phenomena after the system is operated by opening the isolation valve in the injection line.

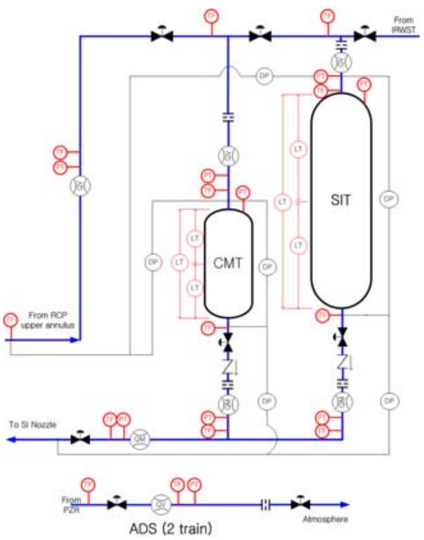


Fig. 2 Schematic of the Test Facility for SMART PSS

2.3 Validation Tests for SMART PSS

The objectives of this research are to construct a scaled-down test facility, to assess the performance of the CMTs and SITs for SMART, and to analyze the thermal-hydraulic phenomena of flashing, wall film condensation, interfacial direct contact condensation, and thermal stratification expected to occur inside of the tank [6, 7].

An experimental facility design for validating the SMART PSS was introduced. Through the validation tests, the general thermal-hydraulic performance of the passive safety system can be understood, and the performance of the nozzle geometry of the flow distributor, break size, and tank geometry can be assessed. Thus, the obtained quantitative data can be applied to a real system design and safety analysis code. Furthermore, by analyzing the experimental data, the existing condensation models for a wall film and interfacial condensation occurring in the CMTs and SITs will be assessed.

One train of the SMART passive safety injection system was simulated by attaching it to the existing FESTA facility. Appropriate orifices in the pressure balancing and injection lines were chosen, and the flow distributor type was selected based on the test data. The effect of the break size on the thermal-hydraulic behavior during a SBLOCA scenario was also simulated. Table II shows the selected test matrix of 1-Train SMART PSS tests. Eleven different kinds of tests were conducted for a SBLOCA scenario to understand the following: 1) the selection of flow distributor types of A, B, and C; 2) the effect of two different CMTs of #1-1 (full-height, 1/49-volume compared with SMART) and #1-2 (Half-height, same scaled volume), 3) the effect of different break sizes of 2 and 0.4 inches, 4) the coupling effect of the CMTs and SITs, and 5) the effect of two different types of SITs (back-pressure or pressurized SITs).

Table 2 Test Matrix of 1-Train SMART PSS Tests.

Case	Break (inch)	CMT Type	Flow Distributor	Description
S100	2	#1-2	NA	No FD
S101	2	#1-1	Type C	FD (B)
S102	2	#1-2	Type B	FD (A)
S103	2	#1-2	Type A	FD (C)
S104	2	#1-2	Type C	FD (C)
S105	2	#1-1	Type A	FD (A)
S106	0.4	#1-1	Type C	FD(C), Size
S107	2	-	Type C	SIT Test
S108	2	#1-1	Type C	CMT (#1-1)
S109	2	#1-2	Type C	CMT (#1-2)
S110	0.4	#1-1	Type C	Size
S201	2	#1-1	Type C	Pressurized SIT

2.4 SBLOCA Scenario of SMART PSS

A SBLOCA scenario was simulated using the SMART-ITL facility. The break type is a guillotine break, and its break location is on the safety injection system (SIS) line, which is located at the nozzle part of the RCP discharge. The thermal-hydraulic behavior occurs at the same time scale in the SMART-ITL and SMART designs because the SMART-ITL is a full-height test facility. Table 3 shows the major sequence of events for the SBLOCA simulation test.

Table 3 Major Sequence of SBLOCA Tests

Event	Trip signal and Set-point
Break	-
LPP set-point	PZR Press = P_{LPP}
LPP reactor trip signal	LPP+1.1 s

- FW stop, Pump Coastdown - CMTAS triggering	
Control rod insert	LPP+1.6 s
MSHP set-point	LPP+4.1 s
PRHR actuation signal (PRHRAS)	MSHP+1.1 s (=LPP+5.2 s)
PRHRS IV open, FIV close	PRHRAS+5.0 s
MSIV close	PRHRAS+20.0 s
CMT injection start	CMTAS+300 s
SIT actuation signal (SITAS)	PZR Press = P_{SITAS}
SIT injection start	SITAS+300 s
ADS #1 open	CMT level < 35%
Test end	-

When a SIS line in the SMART is broken, the primary system pressure decreases with the coolant discharge 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. Because a turbine trip and loss of off-site power (LOOP) are assumed to occur consequently after a reactor trip, the feedwater is not supplied and the RCP begins to coast-down. In addition, a CMT actuation signal (CMTAS) is generated coincidently with a reactor trip signal. With an additional 0.5 s delay, the control rod is inserted. When the PRHRS actuation signal is generated by the trip signal of the main steam high pressure (MSHP) 4.1 s after the LPP, the SG secondary side is connected to the PRHRS with a 5 s delay and is isolated from the turbine by the isolation of the main steam and feedwater isolation valves with a 20 s delay. CMT injection starts following CMTAS with a time delay of 300 s by opening the isolation valve installed on the injection line downstream of the CMT.

An SIT actuation signal (SITAS) is generated when the RCS pressure reaches below the SITAS setpoint, and the SIT tank is connected to the RPV with a 300 s delay when the isolation valve in the injection line downstream of the CMT is opened. The ADS valve is opened as the CMT level falls below 35% of its full height.

The break nozzle diameter is 50.8 mm in the SMART design and the scaled-down value is 7.26 mm in the FESTA for a 2.0 inch break. A 0.4 inch break is simulated using an orifice with an inner diameter of 1.45 mm in FESTA.

2.5 Major Findings from SMART PSS Tests

Table 4 shows the major sequences of the S108, S109, S110 and S201 tests. When a SIS line was broken during the S108 test, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point (LPP) at 755 s, the reactor trip was generated about 7 s after the LPP signal. Consequently, the reactor coolant pump started to coast down. The CMT actuation signal was generated. It was shown that the PRHRS actuation signal also occurred. The SIT was then actuated after the safety injection actuation signal (SIAS). The individual signal is sequentially actuated.

Table 4. Test results of major sequence for the SBLOCA tests

Event	**Time After Break (seconds)**			
	S108	**S109**	**S110**	**S201**
Break	0	0	0	0
LPP set-point	755	718	3312	766
Reactor trip signal - Pump coastdown - CMT Actuation Signal	762	723	3313	768
Reactor trip-curve start	770	726	NA	769
CMT injection start	765	725	3315	770
PRHR actuation signal	771	732	-	777
FIV close MSIV/ FW close	788 818	748 769	3,337 3,357	792 812
SIT injection signal	4,126	3,654	41,542	6,040
SIT injection start	4,130	3,656	41,543	6,045
ADS #1 open	19,403	25,844	35,702	25,242
ADS #2 open	-	203,115	-	104,089
Test stop	-	-	-	-

Figures 3 through 6 show the comparison results of S108, S109, S110 and S201. Using these data, the effects of two different CMTs (S108 versus S109), two different break sizes (S108 versus S110), and two different types of SITs (S108 versus S201) are discussed. The major thermal-hydraulic parameters include the primary pressure, fluid temperatures in the CMTs and SITs, the levels in the pressurizer, the CMTs and SITs, and the injection flow rate.

As shown in Fig. 3, the primary pressures have similar trends during the 2 inch break cases of S108, S109, and S201, but it decreases very slowly during the 0.4 inch break cases of S110. The pressure trend is very similar to that expected during the typical SBLOCA scenario. The pressure decrease around 35,000 seconds during the S201 test is due to the actuation of ADS #1.

As shown in Fig. 4(a), the fluid temperatures in the CMTs have the similar trends during S108, S109, and S201, but they increase later and higher during the

S110 test. As shown in Fig. 4(b), the fluid temperatures in the SITs show different trends. After the pressure balancing line is connected to the SITs during S108, S109, and S201, the temperatures increase abruptly with the SIT injection signal. The injection time is similar between S108 and S109, and is later during the S110 test. However, the fluid temperature in the SIT decreases slightly as the concept of the pressurized SIT is adopted during the S201 test.

As shown in Fig. 5(a), the pressurizer level decrease very rapidly as the break occurs, and is then recovered as ADS #1 is operated. As shown in Fig. 5(b), the CMT level decreases as the CMT inventory is injected into the reactor pressure vessel. In particular, the CMT level decreases faster with a back-pressure SIT (S108) than with a pressurized SIT (S201) after around 6,000 seconds. Instead, as shown in Fig. 5(c), the SIT level decreases more slowly with the back-pressure SIT (S108) than with the pressurized SIT (S201).

As shown in Fig. 6, the injected flow rates have similar trends during the 2 inch break cases of S108, S109, and S201, but the injection is delayed during the S110 test. During the S110 test, there was an abrupt increase in the injection flow rate at around 35,000 seconds with the actuation of ADS #1, and a smaller abrupt increase in the injection flow rate around 41,500 seconds with the SIT actuation signal.

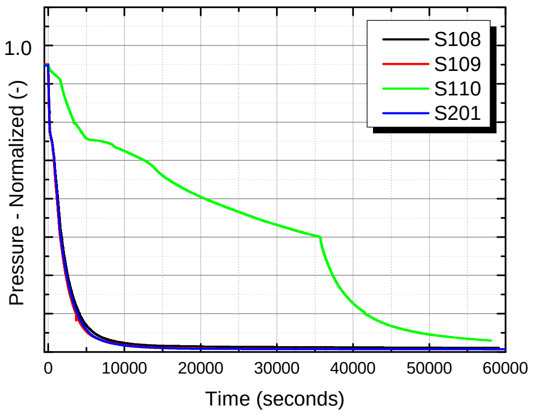
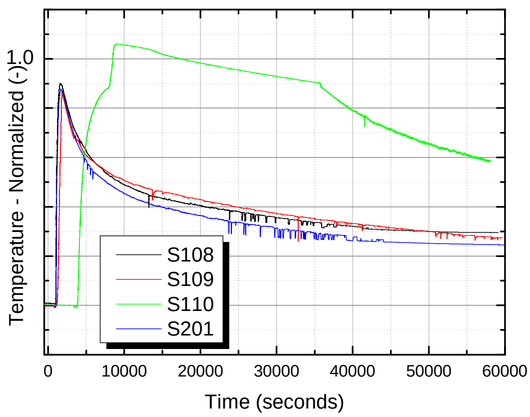
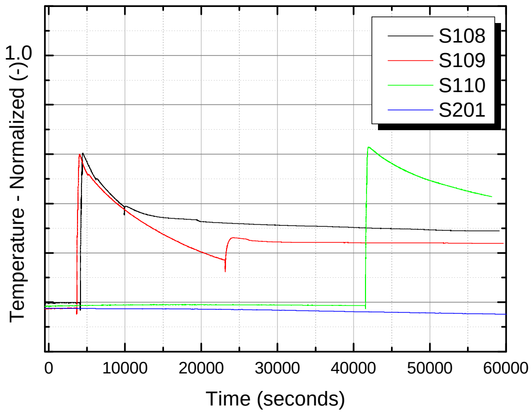


Figure 3 Comparison of primary pressures.

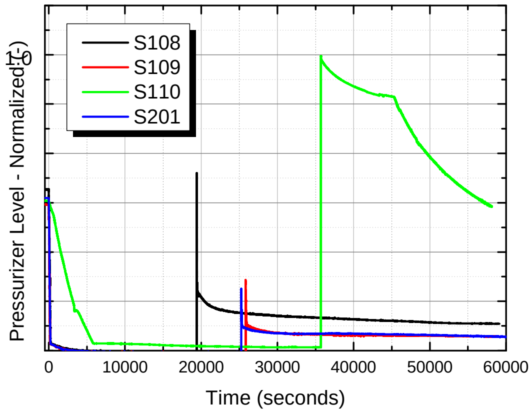


(a) Temperatures in CMT

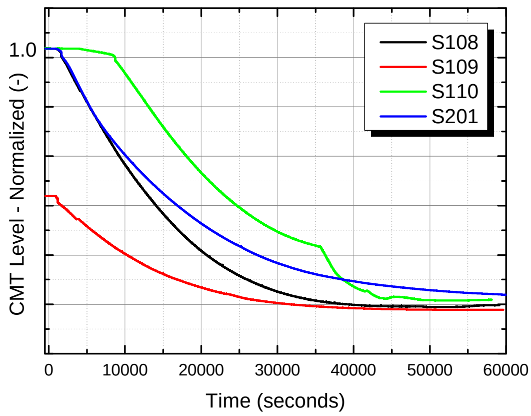


(b) Temperatures in SIT

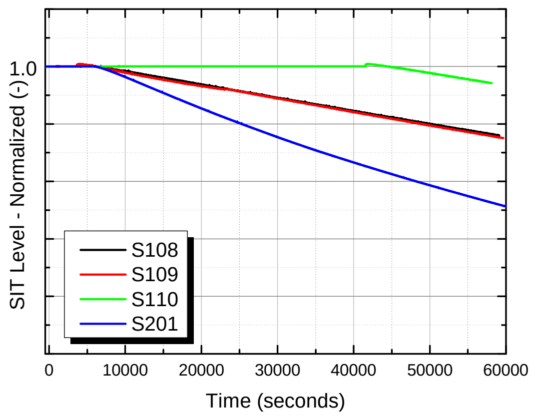
Figure 4 Comparison of fluid temperatures in CMT and SIT.



(a) Pressurizer level



(b) CMT level



(c) SIT level

Figure 5 Comparison of levels in Pressurizer, CMT and SIT.

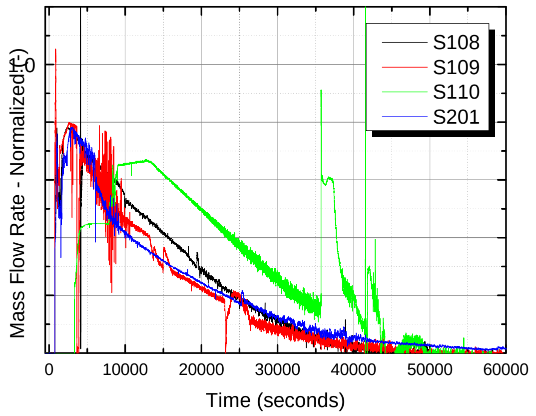


Figure 6 Comparison of injection flowrates.

3. Conclusions

A test program used to validate the performance of SMARS PSS was launched with an additional scaled-down test facility of SMART PSS, which was installed at the existing SMART-ITL facility. In this paper, the major results from the validation tests of the SMART passive safety system using a 1-train test facility were summarized. They include a dozen of SMART PSS tests using 1-train SMART PSS tests.

From the test results, it was estimated that the SMART PSS has sufficient cooling capability to deal with the SBLOCA scenario of SMART. During the SBLOCA scenario, in the CMT, the water layer inventory was well stratified thermally and the safety injection water was injected efficiently into the RPV from the initial period, and cools down the RCS properly.

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