2-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. A test program to validate the performance of the SMART PSS was launched in 2013 and its scaled-down test facility was additionally installed at the existing SMART-ITL facility. 1-train PSS validation tests have been performed during 2014 and their results were analyzed thereafter. [4, 5]

In this paper, the major results from the 2-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.

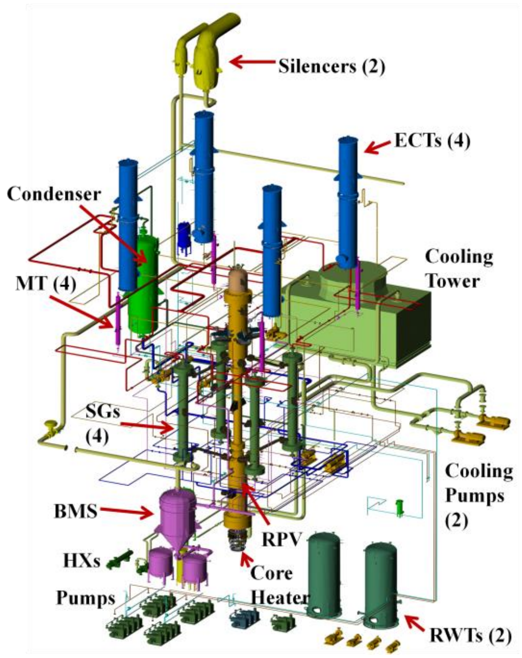


Fig. 1 Schematics of the SMART-ITL.

2. Methods and Results

2.1 SMART-ITL

SMART is an integral-type reactor and thus 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 ratio of the hydraulic diameter is 1/7, and the flow area and volume are scaled down to 1/49. The scaling ratios adopted in SMART-ITL with respect to SMART are summarized in Table 1.

Table 1 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

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.

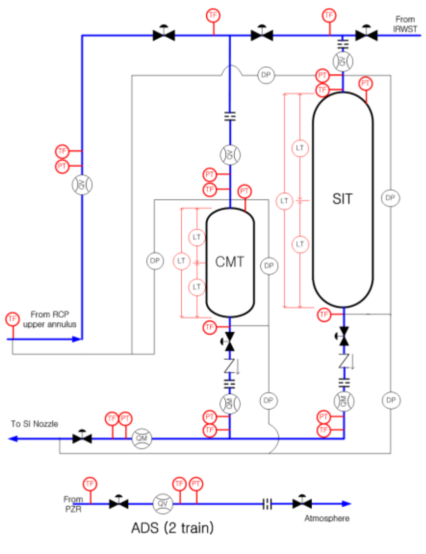


Fig. 2 Schematic of the Test Facility for SMART PSS

2.3 2-Train 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 [6-8].

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.

Two trains of the SMART passive safety injection system were simulated by attaching it to the existing SMART-ITL 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 2 shows the selected test matrix of 2-Train SMART PSS tests. Five different kinds of tests were conducted for a SBLOCA scenario to understand the following: 1) the effects of separate CMT and SIT operation, 2) the coupling effect of the CMTs and SITs, 3) the effect of different break sizes of 2 and 0.4 inches, and 4) the effect of two different types of SITs (back-pressure or pressurized SITs).

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

Case	Break (inch)	CMT Trains	SIT Trains	Description	1-Train Test ID
T101	2	#1, #3	-	CMT only	S105
T102	2	-	#1, #3	SIT only	S107
T103	2	#1, #3	#1, #3	Reference case	S108
T108	0.4	#1, #3	#1, #3	Break size	S110
T201	2	#1, #3	#1, #3	Pressurized SIT	S201

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.

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.

Table 3. Test results of major sequence for the SBLOCA tests

Event	Trip signal and Set-point	Time after break (s)		
		T 103	T 108	T 201
Break	-	0	0	0
LPP set-point	PZR Press = P_{LPP}	718	3,831	704
Reactor trip signal - Pump coastdown - CMT Act. Signal (CMTAS)	LPP+1.1 s	720	3,833	706
Reactor trip-curve start	LPP+1.6 s	721	3,834	707
MSHP set-point	LPP+4.1 s	-	-	709
CMT injection start	CMTAS+1.1s	722	3,834	707
PRHR actuation signal	MSHP+1.1 s	723	3,838	710
PRHRS IV open	PRHRAS+ 5.0 s	728	3,842	715
FIV close MSIV/ FW close	PRHRAS+ 20.0 s	744	3,857	730
SIT injection signal (SITAS)	PZR Press = P_{SITAS}	3,728	40,939	5,642
SIT injection start	SITAS+1.1 s	3,729	40,940	5,643
ADS #1 open	CMT level $< L_{ADS\#1}$	20,947	34,984	28,885
ADS #2 open	SIT level $< L_{ADS\#2}$	187,530	241,943	-
Test stop	-	326,597	369,558	49,321

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 #1 valve is opened as the CMT level falls below 35% of its full height, and the ADS #2 valve is opened as the SIT level falls below 23% 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 SMART-ITL 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 SMART-ITL.

2.5 Comparison between three 2-train SMART PSS Tests (T103, T108 and T201)

Table 3 also shows the major sequences of the T103, T108 and T201 tests. When a SIS line was broken during the T108 test, the RCS began to be depressurized. As the pressurizer pressure reached the LPP trip set-point (LPP) at 718 s, the reactor trip was generated about 2 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.

Figures 3 through 6 show the comparison results of T103, T108 and T201. Using these data, the effects of break size and different SITs 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.

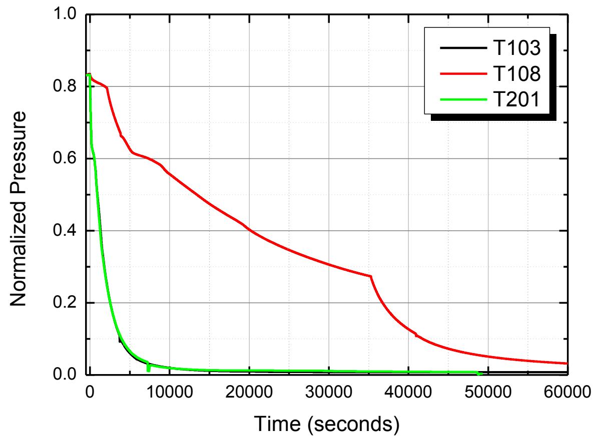
As shown in Fig. 3, the primary pressures have similar trends during the 2 inch break cases of T103 and T201, but it decreases very slowly during the 0.4 inch break cases of S108. The pressure trend is very similar to that expected during the typical SBLOCA scenario. The pressure decrease around 35,000 seconds during the S201 test is due to the actuation of ADS #1. Pressure trends were similar in both trains.

As shown in Fig. 4(a) and 4(b), the fluid temperatures in the CMTs have the similar trends during T103 and T201, but they increase later and higher during the T108 test. As shown in Fig. 4(c) & 4(d), the fluid temperatures in the SITs show different trends. After the pressure balancing line is connected to the SITs during T103 and T108, the temperatures increase abruptly with the SIT injection signal. The injection time is earlier during T103 than T201. However, the fluid temperature in the SIT decreases slightly as the concept of the pressurized SIT is adopted during the T201 test. Fluid temperature trends were also similar in both trains.

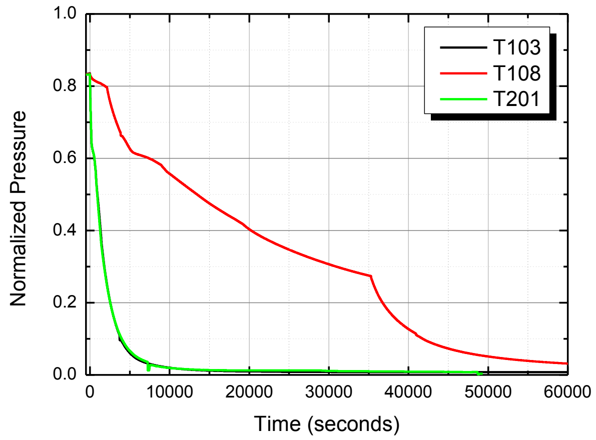
As shown in Fig. 5(a), the pressurizer level decrease very rapidly as the break occurs, and is then recovered as ADS #1 is operated. As shown in Fig. 5(b) and 5(c), the CMT level decreases as the CMT inventory is injected into the reactor pressure vessel. In particular, the CMT level decreases faster with a back-pressure SIT (T103) than with a pressurized SIT (T201) after around 7,000 seconds. Instead, as shown in Fig. 5(d) and 5(e), the SIT level decreases more slowly with the back-pressure SIT (T103) than with the pressurized SIT

(T201). Level trends in pressurizer, CMT and SIT were also similar in both trains.

As shown in Fig. 6, the injected flow rates have similar trends during the 2 inch break cases of T103 and T201, but the injection is delayed during the T108 test. During the T108 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 41,000 seconds with the SIT actuation signal. Flowrates in injection line were also similar in both trains but the fluctuation time were different.

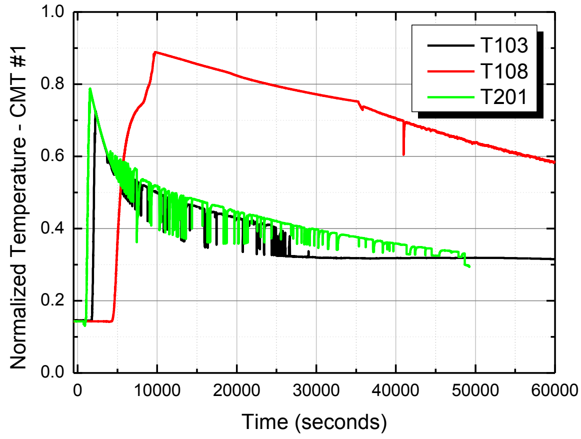


(a) CMT #1

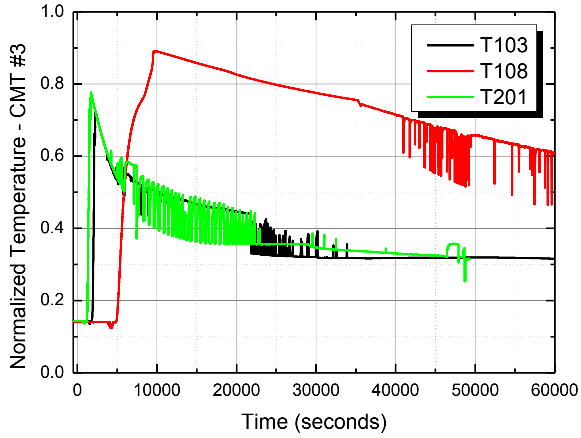


(b) CMT #3

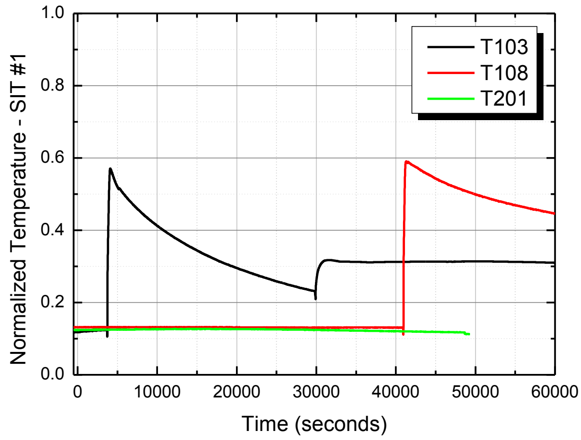
Figure 3 Comparison of CMT pressures.



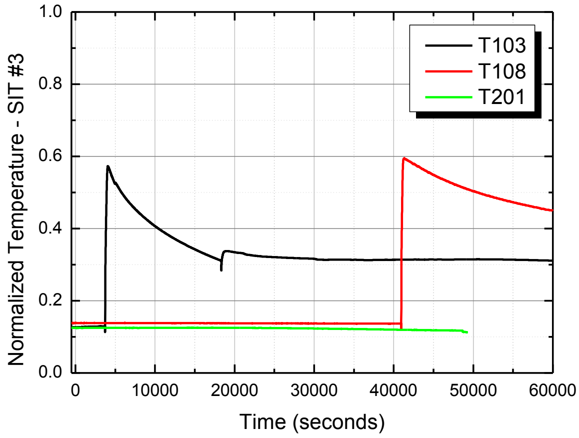
(a) Temperatures in CMT #1



(b) Temperatures in CMT #3

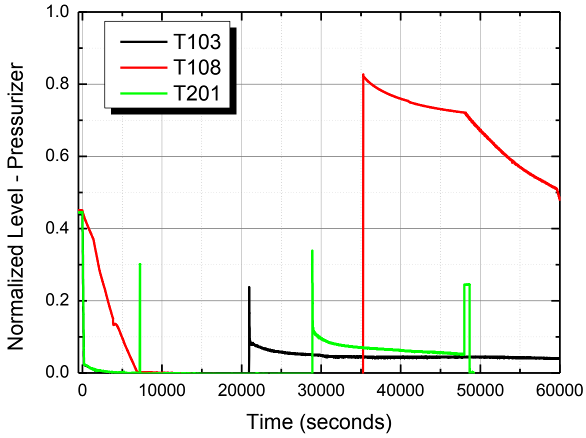


(c) Temperatures in SIT #1

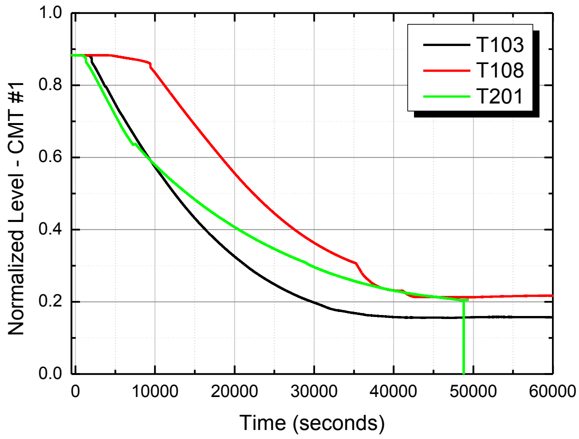


(d) Temperatures in SIT #3

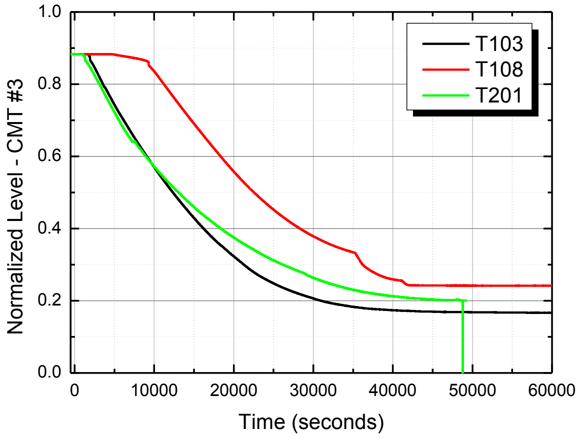
Figure 4 Comparison of fluid temperatures in CMT and SIT.



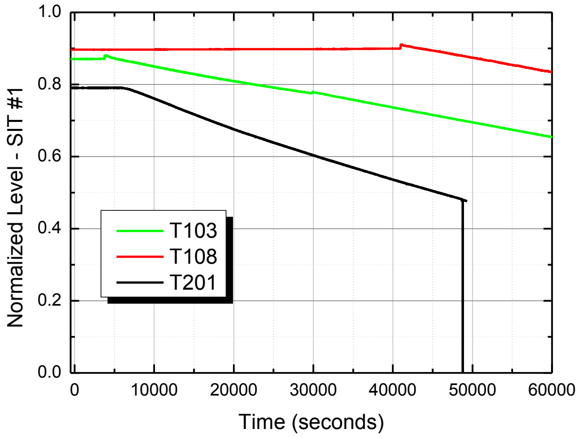
(a) Pressurizer level



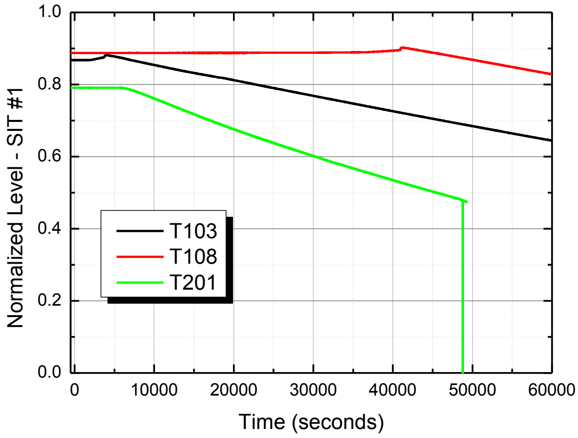
(b) CMT #1 level



(c) CMT #3 level

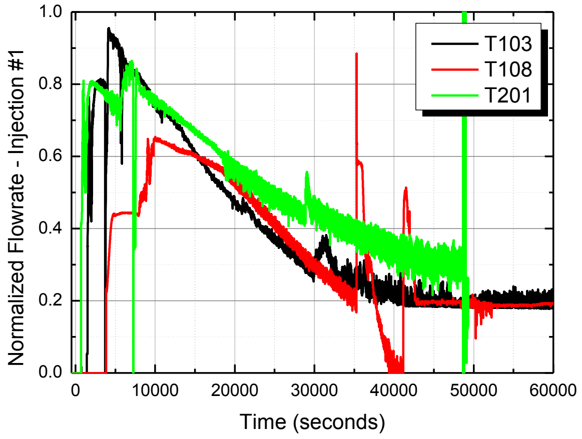


(d) SIT #1 level

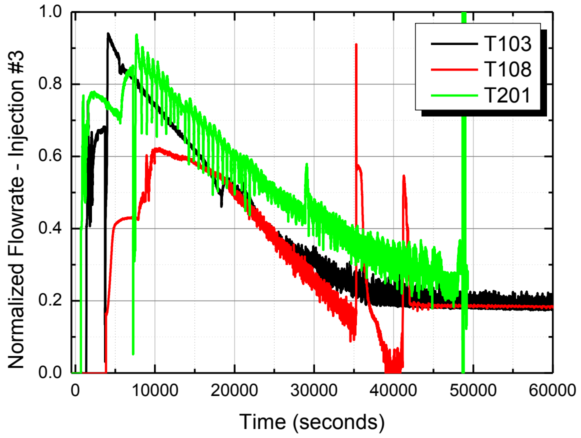


(e) SIT #3 level

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



(a) Injection Line #1 (CMT+SIT)



(b) Injection Line #3 (CMT+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 2-train test facility were summarized. They include five SMART PSS tests using 2-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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REFERENCES

[1] K. K. Kim, et al., SMART: The First Licensed Advanced Integral Reactor, *Journal of Energy and Power Engineering*, 8, 94-102, 2014.

[2] Y. M. Bae, et al., Report of Passive Safety System, SER-410-FS403-SD, KAERI Internal Report, 2012.

[3] Park, H.S., Yi, S.J., Song, C.H., SMR Accident Simulation in Experimental Test Loop, *Nuclear Engineering International*, November 2013, 12-15, 2013.

[4] H. S. Park, et al., Major Results from 1-Train Passive Safety System Tests for the SMRT Design with the SMART-ITL Facility, *Transactions of the Korean Nuclear Society Spring Meeting*, Jeju, Korea, May 7-8, 2015.

[5] S. U. Ryu, et al., Experimental Study of SBLOCA Simulation of Safety-Injection Line Break with Single Train Passive Safety System of SMART-ITL, *Trans. Korean Soc. Mech. Eng. B*, 40(3), 165-172, 2016.

[6] K. T. Park, et al., Assessment of MARS for Direct Contact Condensation in the Core Makeup Tank, *Journal of Computational Fluids Engineering*, 19(1), pp. 64-72, 2014.

[7] S. I. Lee, Two-Stage Scaling Methodology and Direct Contact Condensation of the Core Makeup Tank in a Passive PWR, Ph.D Thesis, KAIST, 2013.

[8] J. Tuunanen, et al., Assessment of Passive Injection Systems of ALWRs, Final Report of the European Commission 4th Framework Programme Project FI4I-CT95-0004, Technical Research Centre of Finland, 1999.