Major Results from Integral Effect Tests using SMART-ITL for SMART Pre-Project Engineering

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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), which was only equipped with passive residual heat removal system (PRHRS). To satisfy the domestic and international needs for nuclear safety improvement after the Fukushima accident, a couple of passive safety systems (PSSs) of passive safety injection system (PSIS) and automatic depressurization system (ADS) were newly developed. [2]

Afterwards Saudi Arabia and Korea have just finished conducting a three-year project of Pre-Project Engineering (PPE) from December 2015 to prepare a Preliminary Safety Analysis Report (PSAR) and to review the feasibility of constructing SMART reactors in Saudi Arabia. During the SMART PPE period, the SMART adopts a new PCCS (Passive Containment Cooling System) concept of CPRSS (Containment Pressure and Radioactivity Suppression System). In addition the thermal power of SMART increased from 330 to 365 MWt and some geometrical changes were given during the SMART PPE project. Therefore, there are strong needs both to understand the thermal-hydraulic phenomena expected to occur during the operation, transient and accident scenarios and to validate its performance for the SMART design.

In this paper, the major results from integral effect tests using SMART-ITL will be discussed. They include integral effect tests on SR (Safety Related accident scenario), SP (System Performance) and OM (Operation and Maintenance) using the SMART-ITL facility, which is an Integral Test Loop for the SMART design (SMART-ITL, or FESTA) [3].

Recently three participants of KHNP, KAERI and K.A.CARE are preparing a new project to deal with the renewal of SMART standard design approval during which a couple of thermal-hydraulic validation tests will be performed.

2. Test Facilities

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.

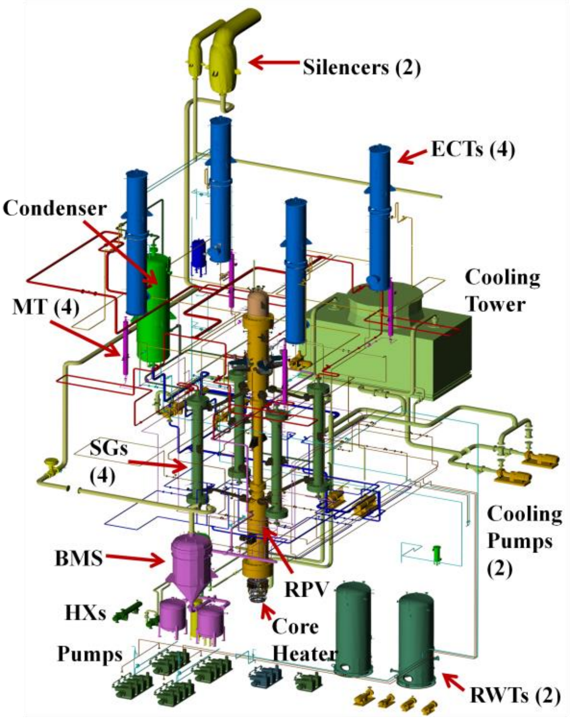


Figure 1. Schematics of SMART-ITL.

Table 1. Major Scaling Parameters of SMART-ITL.

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 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 365 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 SMART-ITL was designed to operate under the same condition as SMART.

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 pressure-balanced pipes at the top and injection pipes at the bottom. This system is operated when a small break loss of coolant accident (SBLOCA) or a steam line break (SLB) occurs. There are no active pumps in 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 CMT and SIT 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. The detailed scaled values are shown in Table 1.

SMART-ITL is equipped with four trains of the PSIS, two stages of the ADS, and four trains of the PRHRS. Each pipe has an isolation valve and a flow meter. The pressure, differential pressure, and temperature can be measured at every pipe and tank. Level and pressure transmitters are installed in each tank.

After commissioned in 2012, a set of Design Basis Accident (DBA) scenarios have been simulated using SMART-ITL without PSIS and ADS. [4] 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. Thereafter various kinds of validation tests on SMART PSS have been performed during 2014-2016. [5]

3. Integral Effect Tests for SMART PPE

Integral effect tests using SMART-ITL for SMART PPE include several integral effect tests on SR (Safety Related accident scenario), SP (System Performance), and OM (Operation and Maintenance).

3.1 SR Tests and Their Major Results

There are various safety-related accident scenarios. Among them seven kinds of scenarios such as feedwater line break (FLB), complete loss of reactor coolant system (RCS) flowrate (CLOF), uncontrolled control rod assembly (CRA) withdrawal, small-break loss-of-coolant-accident (SBLOCA), steam generator tube rupture (SGTR), total loss of secondary heat removal (TLOSHR), and natural circulation (NC) could be validated through the DBA tests.

The feed line break (FLB) accident is initiated by partial or total rupture of a feedwater line located inside or outside a reactor building.

A complete loss of primary flow rate (CLOF) is a non-LOCA scenario without flow rate by RCPs. When a CLOF event occurs, the forced convection of the coolant is not sustained and the reactor coolant flow rate rapidly decreases since all RCPs fail simultaneously.

The uncontrolled control rod assembly (CRA) withdrawal at power condition is an event that can occur by the failure of the control rod driving mechanism (CRDM) control system or the operator error during a power operation.

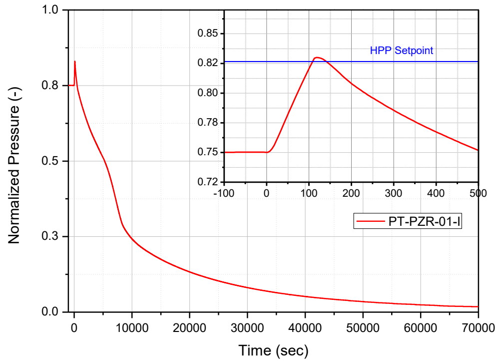
The SBLOCA is initiated by the break of safety injection system (SIS) or pressurizer safety valve (PSV) lines and the RCS inventory is discharged through the break.

The steam generator tube rupture (SGTR) is a postulated accident, where one tube inside a steam generator (SG) is ruptured. The helical tubes inside SG isolate the secondary system form the reactor coolant system, preventing leakage of radioactive materials toward the environment. The rupture of pressure boundary between the primary and the secondary system is an important accident in view of the radioactive material release.

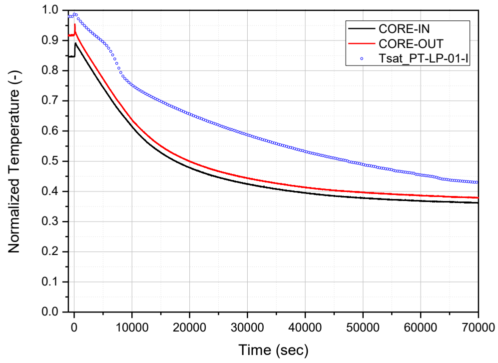
A total loss of secondary heat removal (TLOSHR) accident is a beyond design basis accident (BDBA) resulting from a hypothetical loss of main feedwater and emergency feedwater to steam generators (SGs).

To investigate thermal hydraulic phenomena under natural circulation conditions considering the SMART specific characteristics, single phase and two phase natural circulation test are performed using the SMART-ITL facility. The first case is a stepwise reduction of the core power to decay heat level in the test facility while maintaining at constant primary coolant inventory. The objective is to examine the effect of power effect on natural circulation. The second case involves a stepwise reduction in primary mass inventory in the test facility while operating at decay power. The objective is to examine the effect of inventory reduction on natural circulation and mass distribution in the reactor coolant system.

Fig. 2(a) shows the typical test results of pressurizer pressure during FLB scenario. At 109 seconds, the pressure reached the reactor trip setpoint. Because the core power in SMART-ITL was 20 % of the scaled power of SMART, the pressure rise was sluggish. According to the preliminary analysis against the SMART prototype, the high pressurizer pressure (HPP) was reached at around 30 seconds. Though the HPP time difference between SMART-ITL and SMART was unavoidable, its effect on the overall behavior of RCS and secondary systems was expected to be negligible because the RCS pressure at trip was fixed at a certain pressure. After the HPP, or the reactor trip, RCS pressure declined smoothly because the heat removal through PRHRS and PSIS exceeded the decay heat. Fig. 2(b) shows the typical results of core inlet and outlet temperatures during FLB scenario. The temperatures are monotonically decreasing after the short initial transient. It is estimated that there is a steady flow rate in the primary loop and the subcooled states are sustained during FLB scenario. It is because there is no inventory loss in the primary loop and the system is cooled down efficiently by the actuation of passive systems of CMT and PRHRS.



(a) Primary pressure



(b) Core inlet and outlet temperatures

Fig. 2. Typical test results during FLB scenario

3.2 SP Tests and Their Major Results

There are various performance-related accident scenarios. Among them the system performance (SP) of passive safety injection system (PSIS) and passive residual heat removal system (PRHRS) will be validated through the SP tests. The PSIS performance could be investigated by reducing the number of PSIS trains used during the CLOF scenario. Similarly, the PRHRS performance could be investigated by reducing the number of PRHRS trains used during the CLOF scenario.

Among various SP tests a typical test results on PRHRS are summarized as follows. The passive residual heat removal system (PRHRS) consists of one ECT and a heat exchanger for each train. The upper part of the heat exchanger immersed in the ECT water is connected to the main steam line and the lower part of it is connected to the feedwater line. The SP-PRHRS-01 and SP-PRHRS-02 tests for evaluating the performance of the PRHRS were carried out maintaining the ECT temperature at 100 ℃. The steady state experiments were performed for more than 10 minutes while reducing the train number of PRHRS in the order of 4 → 3 → 2 → 1 and 0. The 0 train tests were performed to quantify heat loss of RCS. The SP-PRHRS-01 was a test changing the number of trains of PRHRS while fixing the core outlet temperature at 300 ℃ and the ECT temperature at 100 ℃. The results were measured based on the steady state experimental results according to the number of trains.

Fig. 3 shows the typical steady-state results during SP-PRHRS-02. Test data were acquired for 20 minutes. The graphs present the flow rates of PRHRS with the 0, 1, 2, 3, 4 trains of PRHRS operation. Based on these data, the heat transfer rate in the secondary side of SG is analyzed. It shows the proportionality of the heat transfer to the number of PRHRS trains.

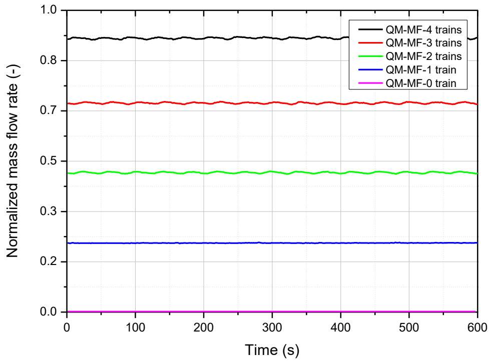


Fig. 3. Typical test results of mass flow rate during SP-PRHRS-02

3.3 OM Tests and Their Major Results

SMART operation procedure includes startup operation, power operation, and shutdown operation and their separate procedures were analyzed. Among them startup operation and shutdown operation could be validated through the operation and maintenance (OM) tests.

The startup operation is composed of auxiliary heatup operation, core critical operation and reactor startup operation. The power operation is to increase the power level from 20% to 100%. And the shutdown operation is a series of processes which is divided into isolation of power conversion system, reactor trip, RCS cooling by feedwater, connection of LTOP valve and RCS cooling by SCS.

Among a couple of OM tests a typical test results are summarized for the shutdown operation case as follows. The normal shutdown operation test using SMART-ITL was carried out under limited conditions because there is no Component Cooling Water System (CCWS). The test was performed to simulate the cooling of the reactor coolant system until the shutdown cooling initiation temperature (150 ℃) was reached.

The transient of normal shutdown operation test was started with the decay heat simulation by inserting the core power from heater rod (1,480 seconds) and the heat loss was added to the decay heat curve to compensate the heat loss effect of RCS. The reactor coolant pump was operated at 100%. After the decay heat was simulated, in the 8.6 seconds, the feedwater and main steam isolation valves (OV-MF2, 3, 4-01, OV-MS2, 3, 4-01) except for the first train (OV-MF1-01, OV-MS1-01) were closed. And only one train of the secondary system was operated with more than 0.097 kg/s of mass flow rate. The cooling rate of RCS should be maintained under 40 ℃/hr. The test was terminated when the temperature of the RCS was below 150 ℃. For normal shutdown operation in SMART, the CVCS is manually or automatically activated to maintain the water level of the pressurizer, but it must be activated manually in SMART-ITL. Therefore, it was necessary to intervene by the operator during the normal shutdown operation test and the inventory of the RCS was refilled. In this test, the operator intervention was simulated by stopping the RCP before the level where the RCP was not exposed and refilling the coolant into the RCS. The time duration the operator intervened and stopped the RCP was from 14,546 seconds to 17,775 seconds. Natural cooling during operator intervention and the time at which the RPM of the RCP was recovered up to 100% operating conditions (18,401 s) was excluded from the cooling rate calculation.

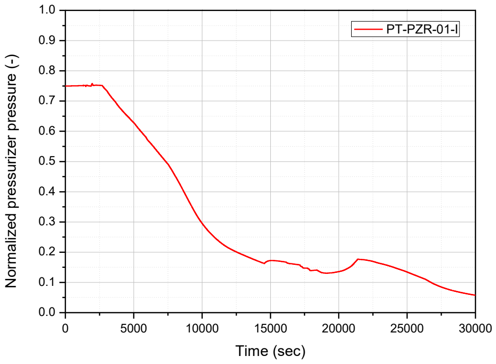


Fig. 4. Typical test results of pressurizer pressure during normal shutdown operation (OM-CD-01)

Fig. 4 shows the pressurizer pressure of the RCS. After the start of the normal shutdown operation test (1,480 s), the pressure did not decrease because the heat source which compensates the heat loss to the decay heat was larger than heat sink (cooling) until about 2,700 seconds. After a further decrease of decay heat, the pressurizer pressure began to decrease. When the operator intervened (14,546-18,401 s), the pressurizer pressure has fluctuated. After pressure recovering with inventory refilling and RCP operation, it decreased to less than 1.2 MPa at the time when the normal shutdown operation test ended (30,135 s).

4. Discussion and Conclusions

In this paper, the integral effect tests during the SMART PPE period were summarized and their major results were discussed. They include integral effect tests on SR (Safety Related accident scenario), SP (System Performance) and OM (Operation and Maintenance) using the SMART-ITL facility.

From the tests and their results analysis, it was shown that the SMART had sufficient cooling capability to deal with the various safety related accident scenarios of SMART, the PSIS worked well under the smallest break case to ensure the reactor safety, the heat removal rate of PRHRS could be calculated according to the number of train with fixed boundary condition, and within the limited test conditions the measured startup operation parameters were sufficient enough to the target design values at two steady-state conditions and the averaged cooling rates were sufficient enough to limit its cooling rate under the target value.

After finishing the SMART PPE project successfully, the SMART FOAK (First-Of-A-Kind) plant is planned to be built in Saudi Arabia. To get a construction license, more validation tests is necessary to resolve licensing issues for CP (Construction Permit) and OL (Operation License).

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