Experimental Study on SMART Steam Generator Tube Rupture Scenario using SMART-ITL

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1. Introduction

A steam generator tube rupture (SGTR) of SMART reactor [1] is a postulated accident, where one tube inside a steam generator (SG) is ruptured [2, 3]. The helical tubes inside SG isolate the secondary system from the reactor coolant system (RCS), preventing leakage of radioactive materials toward the environment.

The rupture of the pressure boundary between the reactor coolant system and the secondary system is an important accident in view of radioactive material release as well as thermal hydrodynamic aspects. Through the ruptured tube, the reactor coolant containing radioactive materials is transported to a condenser through turbines until their stoppage and mixed with the secondary system fluid. Radioactive gas is transported to the condenser air ejector which vents non-condensable gas. Through the radioactivity sensors installed in the secondary loop, the alarm signal for the high level radioactivity leakage is generated.

A simulation test for the SGTR [4] was performed using SMART-ITL facility [5]. A single tube rupture of a steam generator of the SMART was carried out according to the SGTR accident scenario of the SMART reactor. When the SGTR occurs, a passive residual heat removal system (PRHRS) removes the residual heat of the core, and a passive safety injection system [6] which consists of the core makeup tank (CMT) and safety injection tank (SIT) recovers the inventory of the reactor coolant system (RCS). The test results were sufficient to show that the SMART reactor was in a safe condition during the SGTR scenario.

2. Methods and Results

2.1 Sequence of Event for SGTR

As the accident progresses, the low pressurizer pressure or the low pressurizer level actuates the reactor trip signal. The core heat is removed by the secondary system if the secondary system is available at the time of reactor trip. However, if loss of offsite power (LOOP) is assumed to occur at the time of turbine trip, as a coincidental occurrence, which occurs at the same time as the reactor trip, the feedwater pump is stopped, and thus the feedwater flow decreases. As the feedwater flow rate falls to the PRHR actuation setpoint, the SGs are isolated by the feedwater and main-steam isolation valves, and are connected to the PRHRS. Because of the isolation, the flow of the fluid containing the radioactive materials is limited to inside the PRHRS. As the PRHRS is a closed loop, the RCS coolant that leaked through the ruptured part is not leaked to outside. By natural circulation through the PRHRS, the reactor is cooled gradually. In the meantime, the RCS coolant is continuously leaked through the ruptured tube and increases the secondary system pressure. As the secondary system pressure increases, the ruptured flow rate from the primary side to the secondary side decreases.

The SGTR is assumed to occur at the lower part of the steam generator of the SMART-ITL facility. In order to simulate this, a nozzle was installed in the lower part of the outer wall of the steam generator, and the pipe was connected to the main steam pipe so that the reactor coolant was mixed with the fluid of the secondary system. A rupture simulator valve was installed in the connecting pipe. The rupture nozzle of the SMART steam generator helical tube inner diameter was reduced to the scale of the test facility at the front of the valve. Although the steam generator tube is assumed to be double-ended break, there is no reactor coolant exiting the feedwater line from the ruptured tube because the check valve is installed in the SMART reactor feedwater pipe. In the test, the rupture nozzle was manufactured considering only one cross section of the helical tube. The passive safety injection system is composed of CMT and SIT.

Table I: Description of the steady-state condition

Parameter	Normalized state-state condition (Measurement / Target value, %)
Power	111
PZR pressure	99
1^{st} flowrate	87
SG 1^{st} inlet temperature	101
SG 1^{st} outlet temperature	101
Feedwater flow rate	99
SG 2^{nd} outlet pressure	100

2.2 Steady State Condition

SGTR starts by measuring the steady state value for about 646 seconds and then opening the break valve installed in the SGTR accident simulator of the break simulation system. The normalized mean values of the steady-state measurement parameters shown in Table I reveals that measured values sufficiently satisfy the target values as initial and boundary conditions for transient tests.

The sub-cooled feedwater supplied to the lower part of the steam generator absorbs the heat supplied from the reactor coolant system and changes the phase to superheated steam. The reactor coolant system and the secondary system are in thermal equilibrium while maintaining constant thermal-hydraulic values during the steady state operation.

The sequence of events is provided in Table II [7]. As a single helical tube of the steam generator is ruptured in the SMART design, the coolant of the RCS is released through the ruptured tube and mixed with the coolant of the secondary system. The pressure and level of the RCS decrease. When the RCS level reaches the low pressurizer level (LPL) setpoint, the reactor trip signal is generated with 1.1 seconds delay. With an additional 0.5 seconds delay, the control rod is inserted. The PRHR actuation signal (PRHRAS) and chemical and volume control system (CVCS) isolation actuation signal (CVCSIAS) are generated by LPL with 1.45 seconds delay. When the PRHRAS is generated, the SG secondary side is isolated from the turbine by closing the main steam and feedwater isolation valves, and is connected to the PRHRS with 5 seconds delay after PRHRAS. The CMT actuation signal (CMTAS) is generated by the PRHRAS with 1.45 seconds delay and the CMT water is passively injected by gravity head. The SIT actuation signal (SITAS) is generated when the pressurizer pressure reaches the SIT setpoint and the SIT water begins the passive injection by gravity head as well.

Table II: Major sequence of SGTR simulation

Event	Trip signal and Set-point
	SMART-ITL
Break	CVCS max. charging
LPL set-point	Low PZR Level = L_{LPL}
LPL reactor trip signal	LPL+1.1 s
Control rod insert	LPL+1.6 s
PRHR Actuation Signal CVCS Isolation Actuation Signal	LPL+1.45 s
CMT Actuation Signal	PRHRAS+1.45 s
CMT injection	CMTAS+1.45 s
PRHRS IV open MSIV/FIV close	PRHRAS+5.0 s
SIT Actuation Signal	PZR Press = P_{SIT}
SIT injection	SITAS+1.45 s

2.3 Test Results

When the SGTR is started, the reactor coolant flows into the main steam line #1 through the nozzle installed on the outer wall of the steam generator primary side #1. As the breaking flow exceeds the charging flow rate, the reactor coolant system begins to depressurize (Fig. 1) and the water level begins to fall (Fig. 2). In this case, it is assumed that one break of the steam generator tube does not affect the secondary side of the steam generator except the corresponding steam line. In the actual simulation test, it was confirmed that even if the reactor coolant on the primary side of the steam generator flows into the main steam line on the secondary side due to the rupture, the pressure and temperature of the other steam generators are not significantly affected (Fig. 3 and 4).

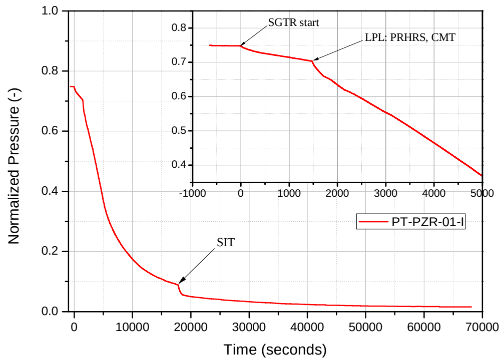

Fig. 1 Pressurizer Pressure in the Reactor Coolant System.

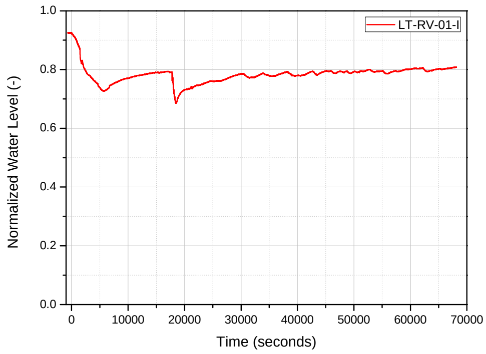

Fig. 2. Collapsed Water Level of Reactor Pressure Vessel.

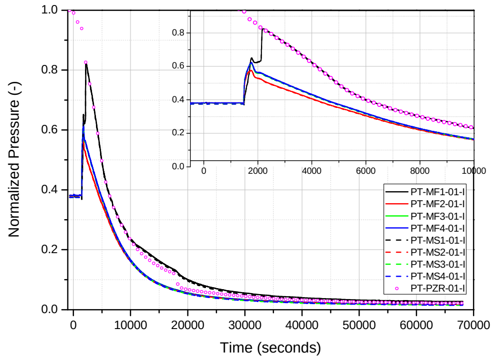

Fig. 3. Pressure of Secondary System.

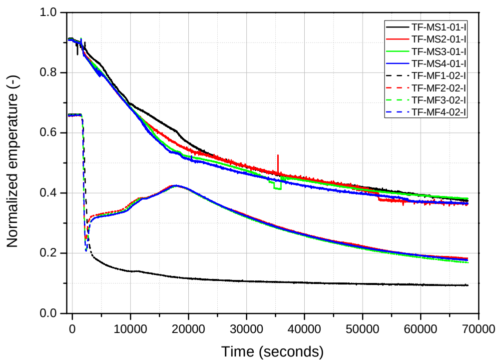

Fig. 4. Fluid Temperature of Main Steam and Feedwater Line.

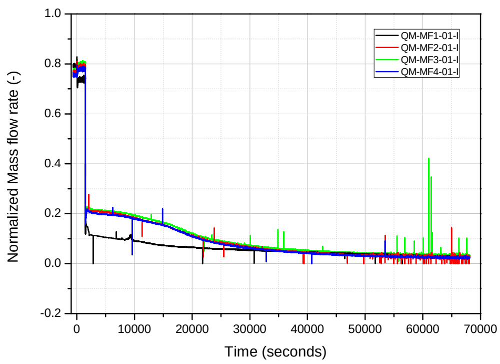

Fig. 5. Flow Rate of Secondary System (PRHRS).

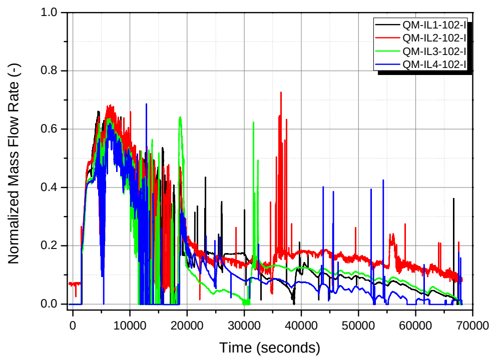

Fig. 6. Flow Rate of CMT and SIT Injection Line.

The pressure and the water level of the reactor coolant system are simultaneously decreased by the SGTR. Because the reactor trip signal can occur due to the pressurizer low pressure (LPP) and the pressurizer low water level (LPL), the accident scenario should be prepared for both. In this test, reactor coolant addition by CVCS was performed with the start of the SGTR accident simulation, but the pressurizer low water level (LPL) reached earlier than the pressurizer low pressure (LPP). The reactor trip signal was generated by the LPL, and the core decay heat began to be simulated as a table value set in the control logic. With PRHRAS and CVCSIAS by the LPL, the PRHRS was connected to the secondary system to start natural circulation and the core decay heat was removed. The CVCS charging pump was stopped by the CVCSIAS.

The CMTAS was generated by the PRHRAS and the CMT was activated, and reactor coolant inventory began to recover. The reactor coolant system was cooled by depressurization as well as by natural circulation of PRHRS (Fig. 5) and CMT injection (Fig. 6), and reached a safe shutdown point. Subsequently, the pressurizer pressure reached the setpoint of the SITAS (pressurizer low-low pressure) and the SIT was activated. Data were collected up to 68,128 seconds until the reactor coolant pump operated.

Reactor trip, core decay heat simulation, passive safety injection, water / steam pipe isolation valve close, and passive residual heat removal system operation that occurred after reaching the reactor trip setpoint by the LPL were performed according to preset automatic control logic. The results of the SGTR test conducted to evaluate the stability of the SMART reactor in the SGTR accident were analyzed based on the important parameters in terms of initial and boundary conditions [8].

3. Conclusions

An SGTR test has been performed to simulate a postulate accident in which the RCS inventory is reduced as a result of a single tube rupture of the steam generator tube and it is mixed with the secondary cooling water. The steam generator tube rupture, reactor trip, core residual heat simulation, passive residual heat removal system operation, main steam / feedwater pipe isolation, feedwater supply pump stop, CMT and SIT injection were simulated according to sequence of event. 4 trains of passive safety injection system were operated to prevent the core uncover in the early stage of the accident. The thermal property behavior of the train with the ruptured tube was affected by the RCS during PRHRS operation. Residual heat removal of core by PRHRS natural circulation was sufficient to cool down the RCS to the safety shutdown temperature.

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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] H. K. Kim, "Analysis Methodology for Steam Generator Tube Rupture Accident in SMART," 911-TH474-002, Rev02, 2011.
[3] H. K. Kim, "Analysis Methodology for Steam Generator Tube Rupture Accident in SMART with Fully Passive Safety System," SER-911-NS474-005, Rev00, 2016.
[4] B. D. Chung, et al., "Development and Assessment of Multi-Dimensional Flow Models in the Thermal-Hydraulic System Analysis Code MARS," KAERI/TR-3011/2005, 2005.
[5] H. S. Park, S. J. Yi, and C. H. Song, SMR Accident Simulation in Experimental Test Loop, Nuclear Engineering International, November 2013, 12-15.
[6] 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, May 2013. pp. 30-31, Gwangju, Korea.
[7] H. Bae, "Test procedure for steam generator tube rupture (SGTR)," TESTA-TP-17-01, Rev00, 2017.
[8] H. Bae, et al., "Quick-Look Report on steam generator tube rupture test using SMART-ITL (SGTR-04)", FESTA-TR-17-01, Rev00, 2017.