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Analysis on the Performance of SMART Steam Generator using SMART-ITL Data

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1. Introduction

SMART-ITL is an integral test loop facility that has been constructed by the Korean Atomic Energy Research Institute (KAERI) in 2009 and finished its commission tests in 2012, to observe and understand the thermal hydraulic phenomena that occur in the systems of SMART during the normal operation or transients [1]. Recently three types of tests have been performed with SMART-ITL, which are design basis accident tests, system performance tests and operation and maintenance tests. Therefore, SMART-ITL [2] could be a powerful tool to verify the integral performance and response of each system and component of the reference reactor during these different types of tests.

The main objective of this paper is to evaluate and analyze the performance of SG for the design concept verification with SMART-ITL through three tests with different assumptions as follows [3]:

- 25% of full scaled SG flow rate with 4-trains.
- 50% of full scaled SG flow rate with 2-trains.
- 100% of full scaled SG flow rate with 1-train.

2. Methodology

2.1 Overview of SMART-ITL

In SMART-ITL, the primary system consist of a reactor pressure vessel, pressurizer, four reactor coolant pumps, four steam generators, and core heater bundles. The maximum power of core heater in SMART-ITL is 30% of scaled full power for the volume scale ratio. The secondary system in SMART-ITL consists of feedwater supply system, steam supply system, vapor condensation system, and cooling system. Therefore, SMART-ITL has the same integral features of all systems and components as SMART except the external installation of steam generators.

SMART-ITL was basically designed following a volume scaling methodology and during the scaling analysis of each component, three-level of scaling methodology have been applied which consists of integral scaling, boundary flow scaling, and local phenomena scaling. In addition, SMART-ITL has been designed to reserve and represent the same height ratio, time scale, pump head and pressure drop of the prototype plant of SMART. While the diameter has been scaled down to 1/7 and each of the area, volume, core power and flow-rate have been scaled down to 1/49 compared with the prototype plant of SMART. Table I shows that the major scaling ratio parameters of SMART-ITL.

Table I: The Major Scaling Ratio Parameters of SMART-ITL

Design Parameter	Ratio (SMART/ITL)
Length	1/1
Time	1/1
Pump head	1/1
Pressure drop	1/1
Diameter	1/7
Area	1/49
Volume	1/49
Core power	1/49
Flow-rate	1/49

2.2 Overview of SG

The steam generator of SMART-ITL for the reference reactor is reduced by length ratio, total area ratio, and volume ratio of 1:1, 1:49, and 1:49, respectively. Also the reference reactor has eight steam generators, and each steam generator has 376 heat exchanger pipes. But SMART-ITL has four steam generators with a total of 15 heat exchanger pipes for each. The area and volume ratio of a single actual SMART-ITL steam generator is 2:49 because the ratio is 1:49 for two generators of reference reactor.

In SMART, the steam generator is installed inside the reactor pressure vessel, while in SMART-ITL, the steam generator is separated from the RPV for several reasons, firstly the inner diameter of RPV scaled down is very small, secondly it's easier to measure the flow of RCS because it's easy to install the instrumentations, finally it's easier for operation and maintenance. In SMART-ITL, the SG is connected to the upper and bottom hemispheres parts of RPV through a cylindrical pipe as shown in Figure 1.

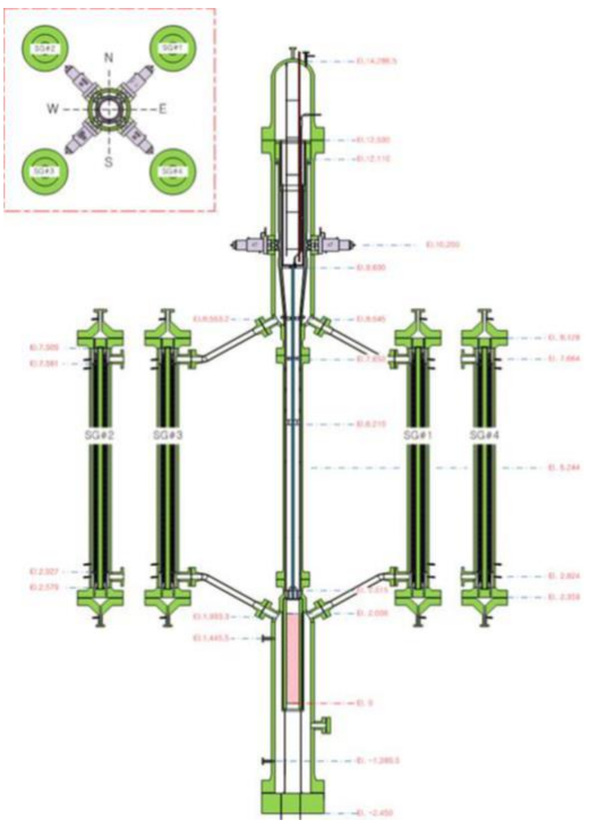

Fig. 1. Setup between the Steam Generators and the Reactor Pressure Vessel in SMART-ITL

2.3 Steady State Conditions

The steady state conditions of these SG performance tests have been applied on 25% of full scaled thermal core power of SMART-ITL, the full thermal core power in SMART PPE design equals 365 (MWth). So, the thermal core power in these tests with SMART-ITL was equal:

$$\frac{365}{49}(25\%) = 1.862\ (MWth)$$

In addition, the total primary flow-rate in SMART PPE design equals 2,507 (Kg/s). So, the total RCS flow-rate in these tests with SMART-ITL was equal:

$$\frac{2{,}507}{49}(25\%) = 12.791\ (\frac{kg}{s})$$

And the bypass flow rate through the core equals 0.51 (kg/s), almost 4% of the total flow rate. Thus, the actual core flow rate is 12.281 (kg/s). Also, the bypass flow rate of SG primary side equals 0.77 (kg/s). Which means the total flow rate of SG in primary side is 12.021 (kg/s). Thus, Table II shows the primary flow rate of SG trains for each test.

Table II: The Primary Flow Rate of SG Trains for Each Test.

Test No.	Ratio (SMART/ITL)
1 (4-Trains)	1/4
2 (2-Trains)	1/2
3 (1-Train)	1/1

For the secondary feedwater flow-rate, in SMART PPE design equals 190.61 (Kg/s). So, the total secondary feedwater flow-rate in these tests with SMART-ITL was equal:

$$\frac{190.4}{49}(25\%) = 0.97\ (\frac{kg}{s})$$

Thus, Table III shows the secondary flow rate of SG trains for each test.

Table III: The Secondary Flow Rate of SG Trains for Each Test.

Test No.	Ratio (SMART/ITL)
1 (4-Trains)	1/4
2 (2-Trains)	1/2
3 (1-Train)	1/1

In the primary system, the operation pressure and temperature of core inlet and outlet for SMART-ITL are the same as SMART PPE design. Also, in the secondary system the pressure and temperature of feedwater and main steam lines have the same values between SMART-ITL and SMART PPE design. Table IV shows that steady-state conditions of 25% thermal core power and flow rate with SMART PPE design and SMART-ITL PPE target value for the primary system. Table V shows that steady-state conditions of 25% thermal core power and flow rate with SMART PPE design and SMART-ITL PPE target value for the secondary system.

Table IV: Steady-State Conditions Steady-state Condition of 25% Core Power between SMART PPE Design and SMART-ITL PPE Target Value for the primary system.

Parameter	Ratio (SMART/ITL)
Core power (MWth)	1/196
Operation pressure (MPa)	1/1
Flow-rate (Kg/s)	1/196
Core inlet temp. (^{0}C)	1/1
Core outlet temp. (^{0}C)	1/1

Table V: Steady-State Conditions Steady-state Condition of 25% Core Power between SMART PPE Design and SMART-ITL PPE Target Value for the secondary system.

Parameter	Ratio (SMART/ITL)
Flow-rate (Kg/s)	1/196
Feedwater pressure (MPa)	1/1
Feedwater temp. (^{0}C)	1/1
Main steam pressure (MPa)	1/1
Main steam temp. (^{0}C)	1/1

2.4 Sequence of Events

In these tests we had to reach the steady state conditions of 25% as have been mentioned in Table IV and Table V. Then the data was acquired during 15 minutes. Table VI shows the sequence of event for SG performance tests.

Table VI: The sequence of event for SG performance tests (25% of thermal core power and flow rate)

Event	Remark
Reach the steady state	Steady state conditions for 25% in Table IV and V
Acquire the test data	15 (minutes)
End of event	

3. Results and Discussion

A highlight of the main results will be presented in this section. Fig. 2 shows the Core Power for the SG performance tests. Firstly, as we know that in these experimental tests we are trying to maintain the total flow rate of RCS at 12.79 (kg/s). So, in case of using 1-train of SG the needed thermal power was 2.005 (MWth). And in case of using 2-trains and 4-trains of SGs, the needed thermal power were 2.049 and 2.067 (MWth) respectively. Fig 3 shows the Primary SG flow rate for SG tests. Firstly, as we know there are several reasons of the fluctuation of mass flow rate such as the pressure of RCS, or the speed signal reference from the Programmable Logic Controller (PLC) or external Proportional Integral Derivative (PID) to a Variable Frequency Drive (VFD) analog. Secondly, in our test results the acceptance fluctuation of mass flow rate during normal operation or even in transient is related to the PZR Level Control System (PLCS). Finally, in our tests the total of mass flow rate of primary side of SG should be 12.79 (kg/s) including the bypass flow rate which equals 0.77 (kg/s). Due to the results and calculations the actual flow rate of the primary side of SG in case of using 1-train was 12.11 (kg/s). And in case of using 2-trains and 4-trains of SGs, the actual flow rate were 11.28 and 11.85 (kg/s) respectively. So, in this figure we can see that in case of using 1-train we needed higher flow rate because the leakage flow to inactive SGs trains which was around 0.55 (kg/s) for each train.

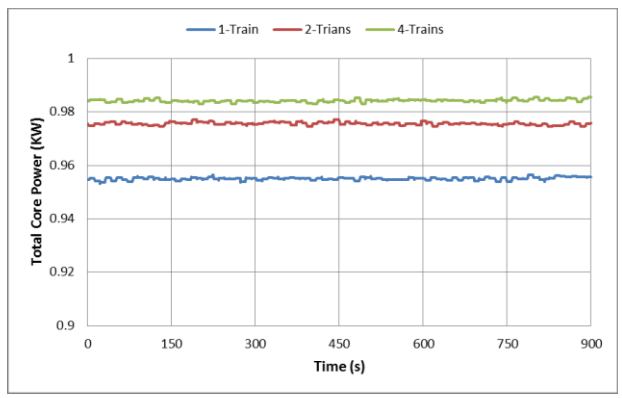

Fig. 2. Core Power of the SG Trains for Each Test (Normalized)

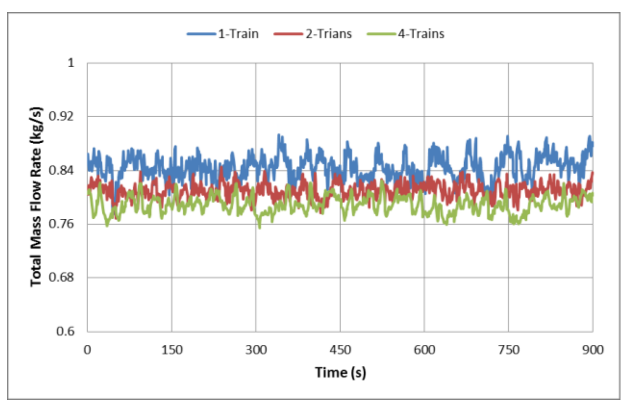

Fig. 3. Primary SG Flow Rate of the SG Trains for Each test (Normalized)

For calculating the heat removal rate of RCS and the secondary side of SG, we had to apply the following Equation (1):

$$Q\ (kW) = \dot{m}\ \left(\frac{kg}{s}\right)\ \ \Delta h\ \left(\frac{kJ}{kg}\right) \qquad (1)$$

Table VII shows the input core thermal power and the calculated heat removal by the RCS and SGs trains. Due to Table VII and the results of test, there were a specific and required number of SGs trains to handle and carry out the core thermal power during the steady state. The maximum capacity of core thermal power that can be maintained during the steady state by 1 SG in SMART-ITL was 2.005 (MWth), which equals 98.245 (MWth) in the reference reactor. So, the maximum core thermal power can be reached during the steady state by 1 SG of SMART is 49.123 (MWth). Fig 4 shows that the needed number of SGs to maintain the steady state at certain demand of core thermal power.

One of the main results and objective of this experimental test is to validate the “ONCE-SG Code” and Fig 5 shows that a comparison between the experimental and code results of the SG secondary side pressure.

Table VII: Input Core Thermal Power and the Calculated Heat Removal Rates by the RCS and SGs Trains

	1-train	2-trains	4-trains
q_{CORE} (MWth)	2.005	2.049	2.067
q_{RCS} (MWth)	2.003	1.890	1.885
q_{SGtot} (MWth)	1.810	1.851	1.875

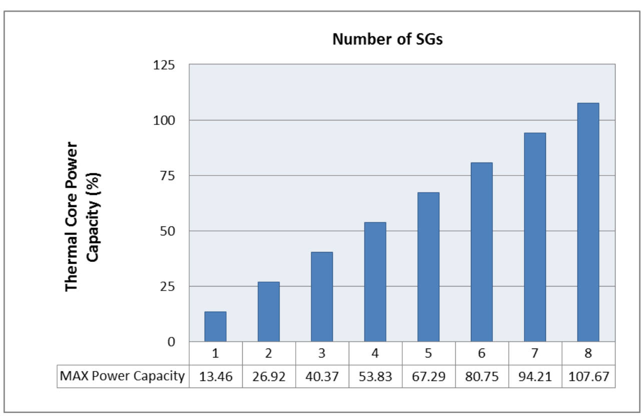

Fig. 4. Needed Number of SGs to Maintain the Steady State at Certain Demand of Core Thermal Power

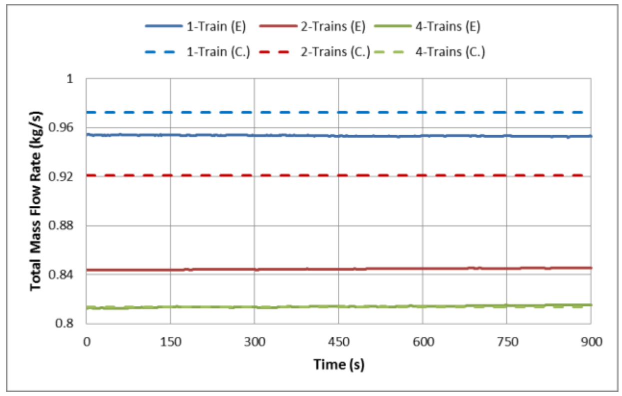

Fig. 5. Comparison between the Experimental and ONCE-SG Code Results of the SG Secondary Side Pressure (Normalized)

4. Conclusion

In this paper, the system performance of SMART steam generator has been evaluated with SMART-ITL during the steady state through three different test assumptions as have been mentioned. Due to the results, the eight SGs of SMART can maintain the core thermal power demand up to 107% and satisfy the steady state during normal operation. Finally, the results of the experimental tests were matched up with the results of the ONCE-SG code for the design concept verification of SMART SG.

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