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Analysis on the System Performance Test of Passive Residual Heat Removal System (SP-PRHRS) with SMART-ITL

Sharaf F. Alsharif [a*], Eslam Bali [a,b], Jin-Hwa Yang[b], Hyun-Sik Park[b]
[a]*King Abdullah City for Atomic and Renewable Energy, Riyadh 12244, Saudi Arabia*
[b]*Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 305-353, Korea*
**Corresponding author: s.sharif@energy.gov.sa*

1. Introduction

SMART-ITL is an integral test loop facility that has been constructed by the Korean Atomic Energy Research Institute (KAERI) and finished its commissioning tests in 2012, to observe and understand the thermal hydraulic phenomena that occur in the systems of SMART during normal operation or transients [1]. There are three types of tests that can be simulated with SMART-ITL; namely, design basis accident simulation tests, system performance tests, and operation and maintenance tests. SMART-ITL therefore provides a powerful means to verify the integral performance and the response of each system and component under various types of test scenarios and conditions.

To achieve national and international goals of nuclear safety enhancement, three Passive Safety Systems (PSS) have been designed and added to the SMART, and these have accordingly been added to SMART-ITL, maintaining the relevant scaling ratios. These PSSs are the Passive Residual Heat Removal System (PRHRS), the Passive Safety Injection System (PSIS) and the Automatic Depressurization System (ADS). Each one of these systems has a specific function and design requirements.

The main objective of the experimental test presently analyzed in this work is to evaluate the system performance of the PRHRS. The main focus is to measure the steady state heat removal capacity of the system when the temperature of core outlet of the Reactor Coolant System (RCS) is to be maintained constant at 300 ^{o}C.

2. Methodology

2.1 Overview of SMART-ITL

In SMART-ITL the primary system consist of a rector pressure vessel, a pressurizer, four reactor coolant pumps, four steam generators, and core heater bundles. The maximum power of the core heater in SMART-ITL is 20% of the scaled full power based on the volume scale ratio. The secondary system in SMART-ITL consists of a feedwater supply system, steam supply system, vapor condensation system, and a cooling system. Therefore, SMART-ITL has the same integral features of all systems and components in SMART, except for the fact that, unlike SMART, the steam generators are installed externally to the reactor vessel in SMART-ITL.

SMART-ITL was designed following a volume scaling methodology and during the scaling analysis of each component, a three-level scaling methodology has been applied. This consists of integral scaling, boundary flow scaling, and local phenomena scaling. In addition, SMART-ITL has been designed to preserve and represent the same height ratio, time scale, pump head and pressure drop of the reference plant 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 reference plant [2]. Table I shows the major scaling ratio parameters of SMART-ITL.

Table I: 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 PRHRS

The PRHRS is composed of four trains, each train includes an Emergency Cool-down Tank (ECT), a Heat Exchanger (HX), a Makeup Tank (MT), several valves, and connecting pipes. In addition, several transmitters have been installed on each train to measure the water level, pressure, deferential pressure and fluid temperature through each component and line of PRHRS as shown in Fig. 1. The PRHRS is connected to feed-water and steam lines of the secondary system. The main function of this passive safety system is removing heat from the secondary side of the steam generator. The PRHRS of the SMART-ITL should have the capability to simulate the passive cooling of reference reactor. Therefore, the PRHRS must be capable of removing the core decay heat. During the PRHRS operation steam generated from the steam generator secondary side is injected into and condensed in the PRHRS heat exchangers which are submerged in the emergency cool-down tank, and the condensed water is drained through the PRHRS condensate line and returned to the feed water line of the secondary side of SGs to cool down the primary system [3].

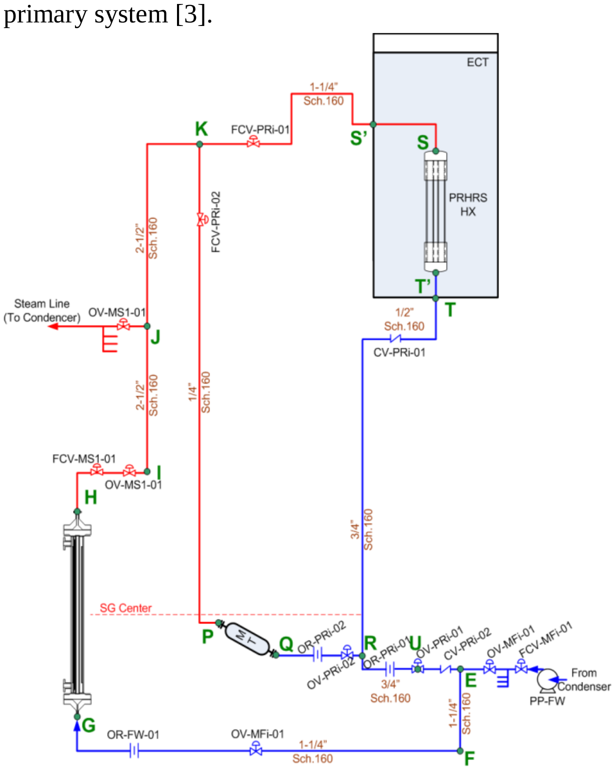

Fig. 1. Schematic of PRHRS

2.3 Steady State Conditions

The steady state conditions of this SP-PRHRS experimental test has been applied when the core outlet temperature of RCS equals 300 °C. Table II shows the steady-state conditions between SMART PPE design and SMART-ITL PPE reference and target values for the primary system. Table III shows the steady-state conditions when RCS equals 300°C between SMART PPE design and SMART-ITL PPE target values for the secondary system.

Table II: Steady-state reference and target ratios for the primary system for the 300° C RCS outlet temperature requirement.

Parameter	Ratio (SMART/ITL)
Core power (MW_{th})	1/245
Operating pressure (MPa)	1/1
Flow-rate (kg/s)	1/245
Core inlet temp. (°C)	1/1.08
Core outlet temp. (°C)	1/1.07

Table III: Steady-state reference and target ratios for the secondary system for the 300° C RCS outlet temperature requirement.

Parameter	Ratio (SMART/ITL)
Flow-rate (kg/s)	1/245
Feedwater pressure (MPa)	1/1.38
Feedwater temp. (°C)	1/1.004
Main steam pressure (MPa)	1/1.5
Main steam temp. (°C)	1/1.09

2.4 Sequence of Events

The initial phase of the test procedure was to adjust the input core thermal power in order to reach steady state conditions with the RCS core outlet temperature held at 300 °C. After this is achieved, the isolation valves (IV) of all 4 PRHRS were opened, and the water in the ECT was allowed to heat up until it reached boiling condition at 100 °C. Steady state conditions are then monitored and ensured to prevail for a minimum of 20 minutes. After the experimental data was recorded for at least 20 minutes with 4 PRHRS trains operating at steady state conditions, the isolation valve of PRHRS train number one was closed. Again steady state conditions are allowed to develop and then maintained for at least 20 minutes, with 3-trains of PRHRS. The same process steps were applied with 2 trains at steady-state, and finally with 1-train at steady-state. It is thus evident that in this sequence of events there are four steady state intervals. The first interval includes 4-trains, the second includes 3-trains, third includes 2-trains, and the fourth interval includes 1-train. Table IV shows that the sequence of events for SP-PRHRS test.

Table IV: Sequence of Events for SP-PRHRS Test

Event	Remark
Steady state condition	RCS = 300 ^{0}C
All PRHRS IV open	ECT = 100 ^{0}C
SS with 4-trains PRHRS	Data during 20 min
PRHRS IV #1 close	OV-PRI1-03 close
SS with 3-trains PRHRS	Data during 20 min
PRHRS IV #2 close	OV-PRI2-03 close
SS with 2-trains PRHRS	Data during 20 min
PRHRS IV #3 close	OV-PRI3-03 close
SS with 1-train PRHRS	Data during 20 min
End of event	

3. Results and Discussion

A highlight of the main results will be presented in this section. Fig. 2 shows a selection of the measured variables related to the PRHRS performance. The pressure in the secondary loop at the inlet to each of the PRHRS trains is shown in the top, followed by the inlet temperature. There is approximately a 20% difference between the highest and lowest inlet pressure, and correspondingly there is about 4% difference between the highest and lowest condensation temperatures. The third figure from the top shows the mass flow rates in the secondary loop, similarly to the previous variables, there is a slight variation in flow distribution among the trains within 9% (between train 3 and train 1). Finally, the bottom plot in Fig. 2 shows the level in the ECT of each train. In all plots the interval selected for data processing and steady state calculations is marked with two vertical lines (dash-dot).

Fig. 3 shows the input core thermal power (normalized) and the calculated heat removal by the RCS, steam generators, PRHRS, and ECT heat exchangers, respectively. The heat removal rates have been calculated according to

$$Q = \dot{m}\ \Delta h \qquad (1)$$

Also indicated in Figure 3 are the steady state intervals. The drop in steady state thermal power carried by each system moving from the core outwards indicates heat loss to the environment, allowing also for measurement uncertainty. The steady state values of thermal power, averaged over the intervals shown in the figure, are listed in Table V. The table additionally lists the calculated total rate of heat lost through evaporation form the ECTs, as determined from the slope of the ECT level curves in Fig. 2. When divided by the number of trains in each case, it can be seen that the evaporation heat removal is approximately 2% of maximum power per train.

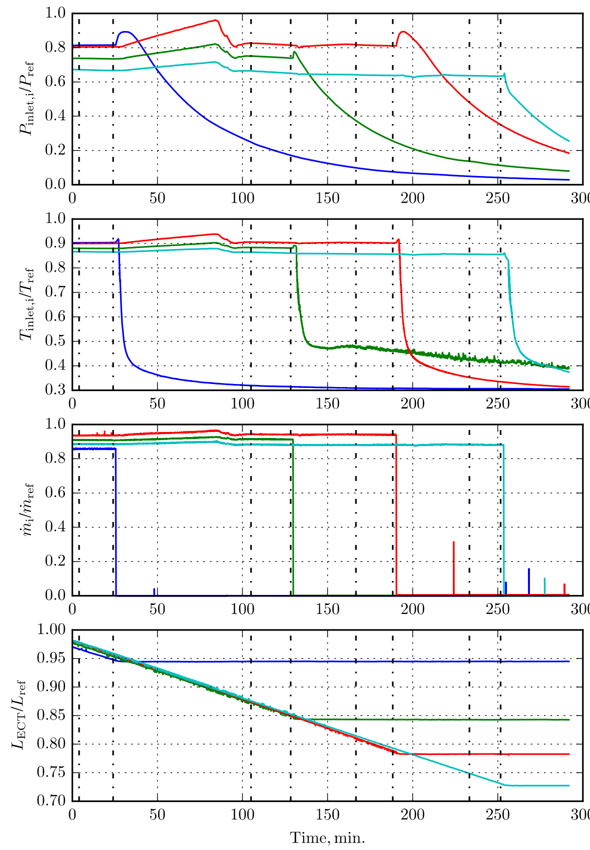

Fig. 2. Selected measured variables related to the PRHRS system performance. All variables normalized by a constant reference value.

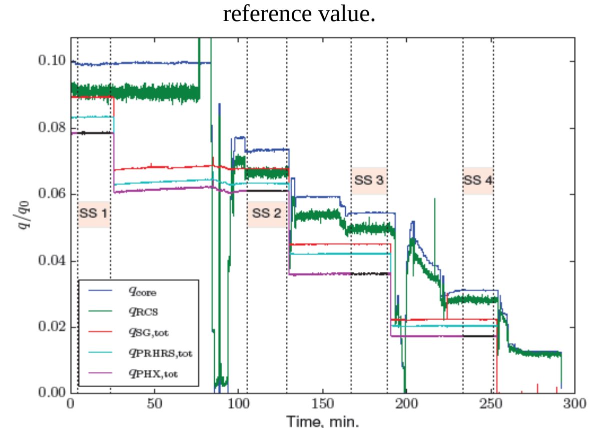

Fig. 3. Selection of the Measured Variables Related to the PRHRS System Performance

Table V: Steady-state core power and heat removal rates

	4-Trains	3-Trains	2-Trains	1-Train
q_{CORE}	0.099	0.073	0.054	0.031
q_{RCS}	0.091	0.067	0.050	0.028
$q_{SG,tot}$	0.089	0.068	0.045	0.022
$q_{PR,tot}$	0.083	0.063	0.042	0.020
$q_{PHX,tot}$	0.079	0.061	0.036	0.017
$q_{EVAP,tot}$	0.080	0.062	0.041	0.020

To give a sense of scale and reference, the observed steady state heat removal capacities are shown against a typical normalized decay heat curve in Fig. 4. The top figure shows the observed steady state core powers as horizontal lines on the decay heat curve, and the bottom figure plots the integrated decay heat and the steady state core heat removals for the cases of two trains and one train, respectively. The intersections of the steady state heat removal curves with the cumulative decay heat curve give an approximate sense of scale of the steady state heat removal capacities, under a hypothetical situation of constant rate of heat extraction at maximum capacity, for the conditions defined in the present test (RCS core outlet temperature maintained at 300 °C). It is important to note that this is not intended as a prediction of actual instantaneous performance, since that would require a transient analysis and is not the purpose or scope of the present test.

4. Conclusion

In this paper, the system performance of PRHRS has been evaluated with SMART-ITL under steady state conditions with the RCS outlet temperature held at 300 ^{0}C, and the ECT temperature at 100 ^{0}C. Based on the results of the experimental test, the heat removal capacity of each train of PRHRS, under the defined steady-state conditions, was approximately 2% of maximum power. The component heat losses, as the heat is transported from the core to PRHRS, ranged approximately from 10 to 15%. Finally, this experimental test was beneficial in evaluating the steady state performance of the PRHRS, and relating it to the decay heat.

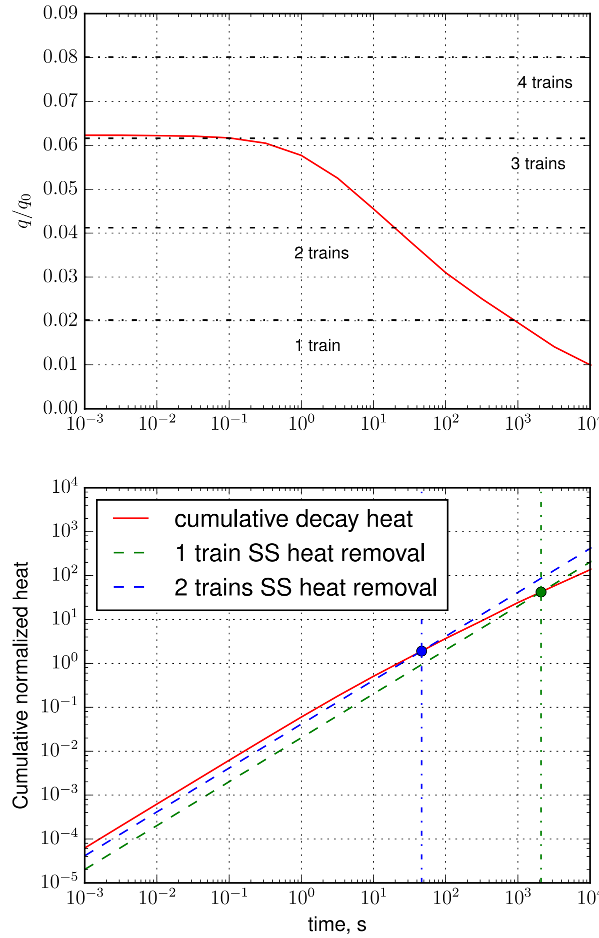

Fig. 4. Observed steady-state heat removal capacities compared to a typical normalized decay heat curve.

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