

Development of a Pre-operational Thermal-Hydraulic Performance Test Scenario for the SMART100 PRHRS Using System Analysis and Robustness Assessment

Jehee Lee^{a*}, Seong-Su Jeon^a, Ju-Yeop Park^b

^a FNC Tech., Heungdeok IT Valley, Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 446-908, Korea

^b Korea Institute of Nuclear Safety, 62 Kwahak-ro, Yuseong, Daejeon, Korea

*Corresponding author: capable91@fnctech.com

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1. Introduction

Passive Safety Systems (PSSs) operate based on natural phenomena such as natural circulation, gravity and density differences, and therefore have the advantage of not relying on external power or active components such as pumps. However, due to their inherently small driving force, PSSs are sensitive to various performance degradation factors such as pressure drop in flow path, heat exchanger performance, heat sink conditions and performance degradation due to non-condensable gases.

In previous studies, Korea Institute of Nuclear Safety (KINS) developed a Robustness Assessment Methodology for PSSs[1] and systematically evaluated the impact of performance degradation factors under accident conditions using the system code MARS-KS[2]. Based on this methodology, a pre-operational test evaluation strategy for the SMART100 Passive Residual Heat Removal System (PRHRS) was proposed, in which a heat exchanger performance reduced to 75% of its nominal capacity was suggested as the most limiting credible test condition [3].

However, the existing verification chain of separate effect test, integral effect test, system code validation and plant accident analysis does not directly confirm whether the as-built PRHRS installed in a constructed plant behaves consistently with the plant analysis model. The final fabrication geometry, installed piping, valve characteristics, train-to-train flow resistance and actual heat exchanger performance are reflected only in the real plant. In addition, an artificially degraded heat exchanger condition cannot be physically implemented during pre-operational testing, and cooling down the plant from hot conditions with the full accident actuation logic may impose excessive thermal and mechanical loads on plant components.

Accordingly, in this study the robustness assessment is used not to degrade the actual test condition, but to establish minimum, reference and maximum cooling prediction bounds for the PRHRS. System analysis is then used to explore the plant

configurations that can realistically be implemented before fuel loading. The objective is to identify which configurations allow the intrinsic thermal-hydraulic behavior of the PRHRS to be observed and to derive the considerations that govern the selection of the final test scenario.

2. Proposed Analysis Approach Using the SMART100 Research Input Model

2.1 Target System and SMART100 Research Input Model

The SMART100 PRHRS consists of four independent trains, each connected to one steam generator (SG). Steam generated on the SG secondary side is condensed in the heat exchanger submerged in the emergency cooldown tank (ECT), and the condensate returns to the SG by gravity; the density head between the steam line and the return line forms the driving force of the two-phase natural circulation loop.

The analysis is based on the SMART100 research input model for MARS-KS provided by KINS (Fig. 1). This research-purpose plant model reflects the modelling experience accumulated in the separate and integral effect test analyses of the SMART100 passive safety systems, and is used here as the best-estimate reference model of the present study rather than as a licensing input. It includes the reactor vessel, reactor coolant pumps (RCPs), pressurizer, SGs, PRHRS, Passive Safety Injection System (PSIS) and ECT, and allows each PRHRS train and the PSIS to be actuated or isolated independently.

2.2 Minimum, Reference and Maximum Cooling Models

The robustness assessment identified pipe heat loss, fire, non-condensable gas, ECT conditions, heat exchanger aging and blockage, and heat transfer model uncertainty as the major performance issues of the PRHRS [1,4]. Most of these conditions cannot, and should not, be intentionally reproduced in an actual plant test.

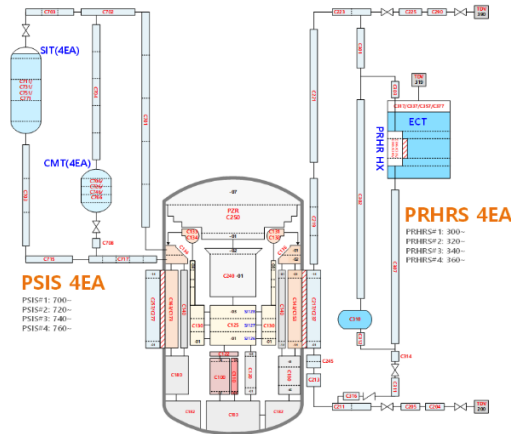


Fig. 1. Nodalization of the SMART100 MARS-KS input model.

In this study, the influence paths of these issues were represented by three equivalent parameters: the effective heat transfer performance of the PRHRS heat exchanger, the effective flow resistance of the steam and return lines, and the ECT heat sink condition (Table 1). In the minimum cooling model the heat transfer performance is reduced by 25%, the flow resistance is increased by 15% and the initial ECT temperature is raised to 40 °C; the maximum cooling model applies the opposite direction of each parameter. These ranges were determined from fabrication and installation tolerances, the uncertainty of the condensation and pressure drop models, and the range of ECT temperature that can realistically occur at the site.

Table 1. Equivalent parameters of the bounding input models.

Parameter	Min. cooling	Reference	Max. cooling
HX heat transfer	-25%	Nominal	+25%
Flow resistance	+15%	Nominal	-15%
ECT heat sink	40°C	Nominal	5°C

2.3 Analysis Case Matrix

All virtual tests start from identical thermal-hydraulic initial conditions corresponding to the 100% power hot operating state. Because they represent the pre-fuel-loading condition, no core fission or decay heat is applied after transient initiation; the available heat is the sensible heat stored in the coolant and structures, plus the pump heat when the RCPs continue to run.

Series A stops the RCPs after transient initiation, so no sustained heat source exists. Series B keeps four RCPs running and supplies a quantified total pump heat of 1 MW while maintaining forced circulation in the reactor coolant system (RCS). Each series consists of four system configurations combining four or one PRHRS train with PSIS actuation or non-actuation (Table 2), and each configuration is to be analyzed with the minimum, reference and maximum cooling models, giving 12 cases per series. Together with three

Total Loss of Flow (TLOF) pre-analysis cases, in which the core decay heat is removed by four PRHRS trains after the RCPs coast down, the full analysis matrix consists of 27 cases.

At the present stage the three TLOF pre-analyses and the eight Series A and B configurations calculated with the reference input model have been completed. The results presented here are therefore used to examine which configuration is adequate as a pre-operational test; the minimum and maximum cooling analyses of the candidate configurations will be performed subsequently to establish the pre-test prediction band.

Table 2. Analysis case matrix

Case	RCP heat	PRHRS	PSIS
TLOF-1/2/3	Decay heat	4 trains	Actuated
A-1 / B-1	No / 1 MW	4 trains	Actuated
A-2 / B-2	No / 1 MW	4 trains	Not act.
A-3 / B-3	No / 1 MW	1 train	Actuated
A-4 / B-4	No / 1 MW	1 train	Not act.

3. Analysis Results

3.1 TLOF Pre-analysis

The TLOF analysis was performed not to re-demonstrate accident safety, but to confirm that the bounding input models are physically credible. As shown in Fig. 2, the RCS reached the safe shutdown temperature of 488 K at 20,100 s with the reference model, at 45,000 s with the minimum cooling model and at 14,900 s with the maximum cooling model. In the minimum cooling case the reduced heat exchanger performance and the increased flow resistance lowered the PRHRS natural circulation flow rate and heat removal rate and delayed the safe shutdown time by about 6.9 hours, but the safe shutdown temperature was still reached well within 36 hours. The maximum cooling case advanced it by about 1.4 hours, and its cooling rate remained below the design limit of 55.6 °C/h. The reference result lies between the two bounds, which confirms that the three input models form a consistent and physically credible prediction band.

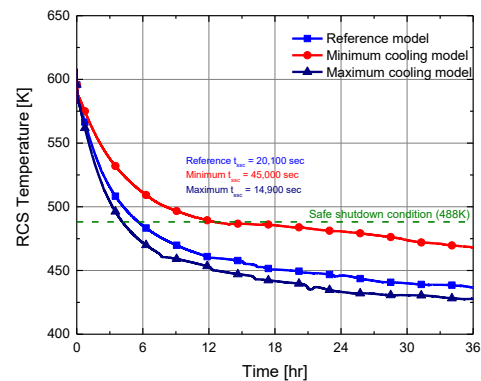


Fig. 2. RCS temperature of the TLOF pre-analysis cases.

3.2 Series A: No Sustained Heat Source

Series A was analyzed with the reference input model to compare the four configurations without a sustained heat source. As shown in Fig. 3, the RCS temperature decreased monotonically in every configuration and no equilibrium was established within 36 hours. In A-1, where four PRHRS trains and the PSIS are actuated, the RCS passed 488 K in about 2.5 hours and fell to approximately 383 K at 36 hours, so the plant is cooled far below the range of interest before the long-term natural circulation behavior can be observed. A-2 removes the PSIS effect, but because the heat removal capacity of four trains is dominant the cooldown was only slightly moderated.

Reducing the number of operating trains had a larger effect. In A-3 the safe shutdown temperature was reached in about 6.5 hours and the RCS temperature was approximately 420 K at 36 hours, whereas in A-4, with a single train and no PSIS, it crossed 488 K only after about 18 hours and was still decreasing at 440 K. A-4 therefore isolates the effect of a single train most clearly, and the large difference between A-3 and A-4 shows that this intrinsic performance cannot be separated when the PSIS is actuated. However, since only the stored sensible heat is available in Series A, the test heat source decreases continuously and no quasi-steady observation window is formed.

3.3 Series B: RCP Heat Applied

Series B repeats the same four configurations with four RCPs in operation, which supplies a quantified pump heat of 1 MW and maintains forced heat transport from the RCS to the SGs. As shown in Fig. 4, the RCS temperature in every configuration approaches a quasi-steady value at which the PRHRS heat removal is balanced by the pump heat and the plant heat loss, in contrast with the monotonic decrease of Series A. The equilibrium temperature is governed mainly by the number of operating trains: approximately 408 K in B-1 and 410 K in B-2 with four trains, and 471 K in B-3 with a single train and the PSIS.

In B-4, in which only one PRHRS train operates and the PSIS is not actuated, the cooldown was the mildest of all configurations. The RCS temperature decreased gradually and approached about 498 K at 36 hours, so that the plant stays close to the safe shutdown temperature instead of being cooled far below it. Because the temperature gradient is small over a long period, the PRHRS start-up, the establishment of the two-phase natural circulation and the heat removal rate can be observed for a sufficient duration without imposing a large cooling transient on the plant, and once the stored sensible heat has been released the heat removal rate can be compared directly with the quantified 1 MW pump heat.

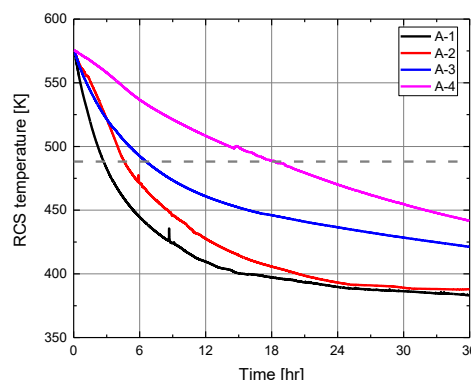


Fig. 3. RCS temperature of the Series A configurations (reference input model).

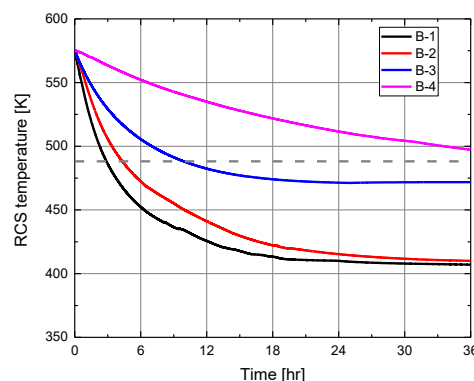


Fig. 4. RCS temperature of the Series B configurations (reference input model).

4. Considerations for the Test Scenario

4.1 Selection of the Test Configuration

The eight configurations calculated with the reference input model do not by themselves determine the test scenario; they rather identify the trade-offs that have to be resolved. First, from the viewpoint of uncertainty it is preferable to keep the RCPs running during the test, because the pump heat provides a quantified and sustained heat source and maintains forced heat transport between the RCS and the SGs, so that the PRHRS heat removal can be evaluated against a known energy input. Series A, in which the stored sensible heat is the only heat source and decreases continuously, is therefore excluded. Second, the PSIS should not be actuated, since its injection changes both the RCS temperature and the inventory and the resulting response cannot be separated from the PRHRS heat removal. B-1 and B-3 are therefore excluded as well.

The remaining question is the number of trains to be actuated. When all four trains operate (B-2), the PRHRS performance can be evaluated within a short time, which is attractive for test operation, but the cooldown is fast enough that the pressurizer level may be depleted and the RCS temperature may decrease before the operator can take the required actions, and the simultaneous operation of four trains imposes a

larger thermal load on the plant components. When only a single train operates (B-4), the cooldown is slow and the test becomes long; on the other hand the pressurizer level decreases slowly, the plant behaves gradually enough for the operator to act at the appropriate time, and the burden on the components is small.

For these reasons a single test scenario is not concluded in the present work. B-2 and B-4 remain the candidate configurations, and the final selection requires the minimum and maximum cooling analyses of both, together with an evaluation of the pressurizer level behavior, the RCS cooling rate, the time available for operator action, the thermal load on the components and the test duration that is acceptable in the commissioning schedule. More generally, as various SMRs and passive safety systems are being developed, the pre-operational performance test scheme has to be derived for each system in accordance with its own design performance and characteristics, rather than applying a single scenario uniformly.

4.2 Pre-test Prediction and Post-test Comparison

Whichever configuration is finally chosen, the test should be evaluated against a prediction band rather than a single calculated curve. The minimum, reference and maximum cooling predictions are produced in advance using the actual planned initial conditions and the bounding models of Table 1, and the comparison variables and the expected behavior are fixed before the test. The measured result is then evaluated against this band with the measured initial conditions and the instrument uncertainty taken into account. Adjusting the analysis input after the results are known must be avoided so that the meaning of model verification is preserved.

5. Conclusions

In this study, virtual pre-operational test scenarios for the SMART100 PRHRS were analyzed with MARS-KS using the SMART100 research input model together with bounding models derived from the robustness assessment. The following conclusions were derived:

- Credible minimum, reference and maximum cooling input models were constructed from the robustness assessment, with the heat exchanger performance varied by $\pm 25\%$, the flow path resistance by $\pm 15\%$ and the initial ECT temperature between $5\text{ }^{\circ}\text{C}$ and $40\text{ }^{\circ}\text{C}$, instead of imposing an artificial degradation condition on the plant test.
- The TLOF pre-analysis confirmed that these models form a credible prediction band; the safe shutdown temperature was reached at 45,000 s, 20,100 s and 14,900 s with the minimum, reference and maximum cooling models, all well within 36 hours.
- Continuous RCP operation and PSIS non-actuation are preferable for the test, because they provide a quantified heat source and remove the

uncertainty introduced by the injection. The number of PRHRS trains to be actuated remains a trade-off between the test duration and the burden imposed on the plant.

- A single test scenario is therefore not concluded at this stage. The final selection will be made after the minimum and maximum cooling analyses of the candidate configurations, taking the pressurizer level behavior, the RCS cooling rate, the time available for operator action and the component thermal load into account.

Future work will complete these analyses and specify the pump heat measurement, the plant heat loss, the instrumentation and its uncertainty and the test termination criteria using actual plant data. As various SMRs and passive safety systems are being developed, the approach also has to be extended so that a test scheme suited to the characteristics of each system can be derived.

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