Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Development of Robustness Assessment Methodology for Performance Issue on Passive Safety System

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Keywords : Passive Safety System, Performance issue, Robustness assessment methodology, Impact evaluation

1. Introduction

With the increasing adoption of nuclear power plants around the world and the development of various new types of reactors, passive safety systems (PSS) are being developed and introduced in various configurations. PSS utilizes natural phenomena to mitigate accidents and keep the plant safe without the use of external power. With the development of various types of PSS, there is a demand for performance evaluation of the capability of PSS to perform accident mitigation in various conditions. Especially, since PSSs have weaker driving forces and less driving experience than conventional safety systems, there are various uncertainties in the event of an accident. In addition, since the system analysis code used for safety system performance evaluation was mainly developed for the existing Active Safety System, it is necessary to demonstrate the applicability of the safety analysis code to the introduction of PSS.

This study was conducted to develop a robustness assessment methodology to demonstrate the applicability of existing system analysis code for PSS analysis and evaluate its impact on various performance issues using MARS-KS v 2.0[1] among the existing system analysis codes. For this purpose, previous studies have verified that MARS-KS can adequately predict experimental devices using natural circulation [2] and evaluated the impact of performance issues on two representative PSSs, the Passive Heat Removal System (PHRS) [3] and the Passive Emergency Core Cooling System (PECCS) [4].

In this paper, the development of robustness assessment methodology is summarized. In addition, it is briefly described the application of the developed methodology and presented the results of its application to Virtual SMART (V-SMART) [5], a research reactor developed with reference to SMART.

2. Robustness assessment methodology

Lee et al. developed an evaluation methodology consisting of seven steps, as shown in Fig. 1, to assess the robustness of a PSS to performance issues [3, 4].

1) Review of Target PSS Design
2) Identification of the Major Thermal-Hydraulic (TH) Phenomena of PSS
3) Assessment of Prediction Capability of System Analysis Code for PSS TH Phenomena
4) Development of Reference Analysis Model for Target PSS
5) Identification of Major Performance Issues for Target PSS
6) Nuclear Steam Supply System (NSSS) coupled PSS Performance Evaluation
7) Derivation of Considerations for Design Improvement and Safety Analysis Guidelines for PSS

A detailed description of each step of the methodology can be found in the References [3, 4].

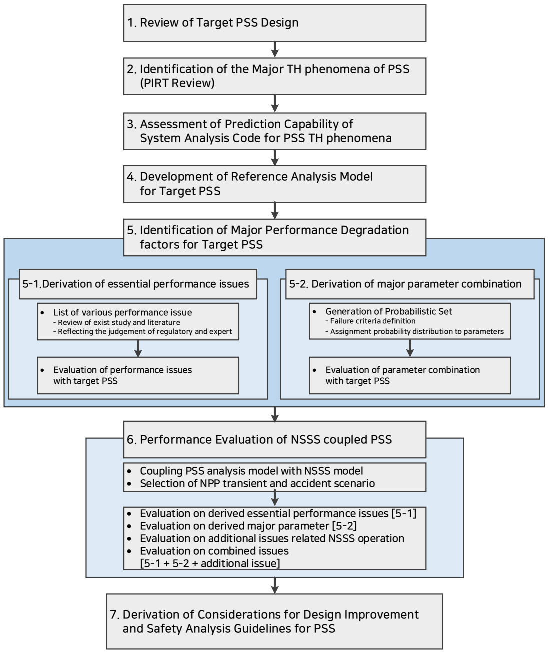


Fig. 1. Robustness Assessment Methodology for PSS

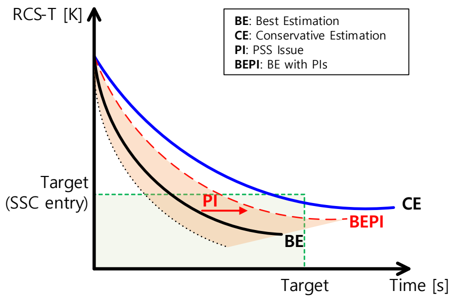


Fig. 2. Example of robustness assessment result – PRHRS

In this study, the robustness assessment methodology developed for the PRHRS and PSIS of SMART[6] was applied to validate the methodology and derive guidelines for PSS modeling and safety analysis. Fig. 2 shows an example of robustness assessment results for Passive Residual Heat Removal System(PRHRS). The PRHRS shall cool the reactor so that the Reactor Coolant System (RCS) temperature reaches the safety shutdown condition (215℃) within 36 hours of the accident and maintain the RCS temperature below 215℃ for the next 36 hours. As shown in the figure, the traditional Conservative Estimation (CE) analysis reaches the safety shutdown temperature slower than the Best-estimation (BE) analysis due to conservative assumptions. In this study, the performance degradation issue (PI) of PSS is applied to the BE analysis to check the changes in the analysis results and to show that the best-estimation with performance degradation issues (BEPI) is included in the CE analysis results.

3. Impact evaluation on separate PSS model

In order to identify the performance degradation issues (PIs) that have a major impact on the representative PSSs PHRS and PECCS, the impact assessment of performance issues and parameter uncertainties was conducted, and this paper presents the results for PHRS. The impact assessment was performed on the PHRS separate input model shown in Fig. 3. A detailed description of the separate input model is presented in reference [3].

3.1 Derivation of major performance issues

The PHRS can be degraded in its accident mitigation capabilities by PIs that affect heat removal performance or natural circulation flow. The PIs derived as shown in Table 1 were applied to the PHRS separate model to assess the impact, and the major performance issues with the most significant impact were identified. The impact assessment results are shown in Fig. 4 and the detailed analysis results are provided in the Reference [3]. The derived essential performance issues are shown in Table 2. In addition, the essential performance issues are also derived from the separate input model of PECCS [4] and derived issues are shown in Table 2.

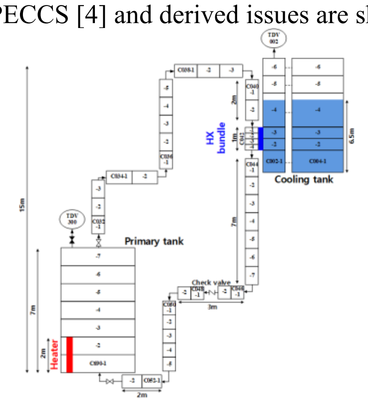


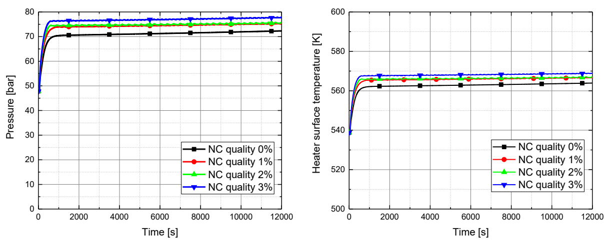
Fig. 3. Nodalization of PHRS separate input model

Table. 1. PHRS performance issues

Performance issue for PHRS		
Distortion of pressure distribution	Leakage	$A_{leakage} < 0.5\%$ of A_{pipe}
	Aging/Blockage (Flow path)	$A_{blockage} \leq 20\%$ of A_{pipe}
	Pipe deformation	Injection line (Preserving volume)
	Operability of check valve	$P_{crack} \leq 40$ kPa
Distortion of temperature distribution	Heat loss	$HTC_{pipe} \leq 20$ W/m^{2}K
	Fire	Heat flux ≤ 10 kW/m^2
Change of heat transfer rate	NC gas	$m_{NC}/m_{steam} \leq$ 3%
	Ambient Temp	ECT heat loss multiplier: 10, 50
	Aging/Blockage	$A_{blockage} \leq 20\%$ of A_{pipe}
	Model uncertainty	Fouling factor: 0.9

Table. 2. Derived essential performance issues

Derived Major Performance Issue for PRHRS	
Distortion of temperature distribution	Heat loss
	Fire
Change of heat transfer rate	NC gas
	Ambient Temp
	Aging/Blockage (HX)
	Model uncertainty (heat transfer)
Derived Major Performance Issue for PSIS	
Distortion of temperature distribution	Heat loss
	Fire
Distortion of pressure distribution	Aging/Blockage (Flow path)
	Pipe deformation
	Operability of check valve
	Model uncertainty (CMT)



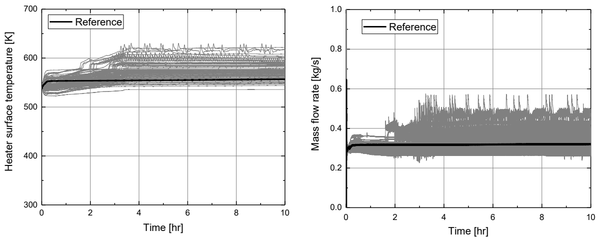
(a) Pressure (b) Heater surface temperature

Fig. 4. Impact evaluation on PHRS -NC gas in system

3.2 Derivation of major uncertainty parameter

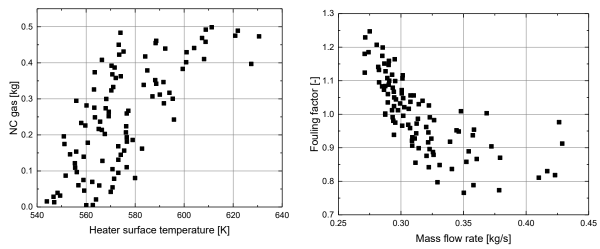
When analyzing a system, uncertainty of PSS-related input parameters can have a major impact on the results of the analysis, which can lead to different evaluations of the system's performance. Therefore, to evaluate the impact of parameter uncertainty, the parameters that consider uncertainty in conventional safety analysis and PSS-related uncertainty parameters were derived. Considering the probability distribution of the derived parameters, the probability set was generated using the DAKOTA[7] program and the input for the impact evaluation was generated.

To select the variables that have a major impact on PHRS performance, correlation coefficients were analyzed between MARS-KS analysis results and parameters, and the results are shown in Figs. 5 and 6. The correlation coefficient analysis showed that the mass of non-condensable gas in the system and the fouling factor of the heat exchanger had a significant impact on the system performance. The same parameter uncertainty impact assessment was performed for PECCS, and the main parameters that collectively have a major impact on both systems are shown in Table 3



(a) Heater surface temperature (b) Mass flow rate

Fig. 5. Impact evaluation on PHRS – parameter combinations



(a) NC gas vs. Heater surface Temp. (Correlation coefficient: 0.71) (b) Fouling factor vs. Mass flow rate (Correlation coefficient: -0.71)

Fig. 6. Correlation coefficient between parameters and results

Table. 3. Derived major uncertainty parameter combinations

Derived Major Uncertainty Parameter		
Parameter	**Nominal value**	**Uncertainty**
Core power	1.0	0.03 (Uniform)
Discharge coefficient	0.8	0.12 (Normal)
Fouling factor	1.0	0.125 (Normal)
Area (PRHRS)	1.0	0.1 (Normal)
Area (PSIS)	1.0	0.1 (Normal)
ECT Temp.	298.15 K	15.0 (Uniform)
Ambient Temp.	298.15 K	15.0 (Uniform)
PSIS pipe HTC_{loss}	5.0 W/m^2K	5.0 (Uniform)
PSIS tank HTC_{loss}	5.0 W/m^2K	5.0 (Uniform)
NC gas	0.25 kg	0.25 (Uniform)
PSIS form loss	1.0	0.15 (Normal)

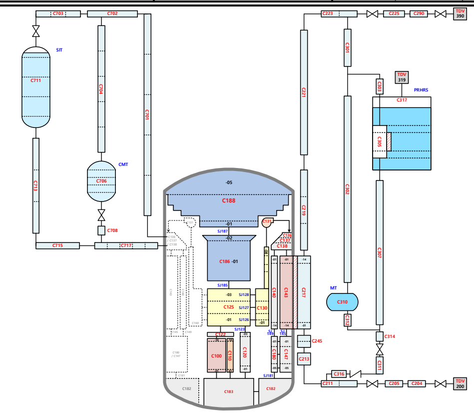


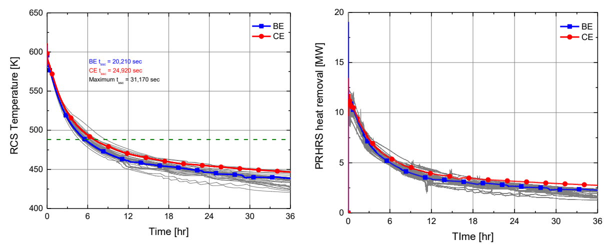
Fig. 7. MARS-KS nodalization for V-SMART [5]

4. Plant application of performance evaluation methodology

To apply the developed robustness assessment methodology to the entire power plant system, the impact of the major PIs (essential performance issues and parameter combinations) identified in Chapter 3 were evaluated using the V-SMART [5] input model. The V-SMART input model (Fig. 7) is a virtual research reactor using SMART as a reference reactor and introducing PRHRS and Passive Safety Injection System (PSIS) as the primary system. In this paper, the impact of major PIs in the event of a Total Loss of Reactor Coolant Flow (TLOF) accident on V-SMART was evaluated. Detailed information about the V-SMART and sequence of TLOF accident are described in Reference [5].

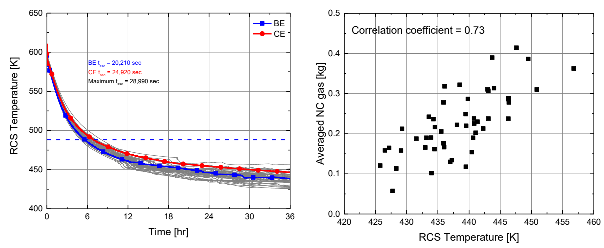
4.1 Impact evaluation with essential performance issues

To evaluate the impact of essential performance issues, performance issues were applied to the BE input model of V-SMART, and the analysis results are shown in Fig. 8. Some issues severely degraded the performance of the system, resulting in heat rejection performance similar to the CE analysis. The main issues affecting the RCS temperature and PRHRS heat exchanger were identified as NC gas in system, fire in containment building, aging of heat exchanger, and uncertainty of heat transfer model. Most of these PIs are issues that degrade the heat removal performance of the PRHRS heat exchanger, and PHRSs such as PRHRS have found that the performance of the heat exchanger has a major impact on the overall system performance rather than the pressure drop in the system.



(a) RCS temperature (b) Heater removal rate

Fig. 8. Impact evaluation with TLOF accident – essential performance issues



(a) RCS temperature (b) Correlation coefficient (NC gas vs. RCS Temp.)

Fig. 9. Impact evaluation with TLOF accident – major uncertainty parameters

4.2 Impact evaluation with major uncertainty parameters

The combinations of parameters that have a significant impact on PRHRS were applied to V-SMART to evaluate their impact, and the results are shown in Fig. 9. As shown in the figure, some parameters have an effect on the results, resulting in a more conservative analysis than CE. Especially, the correlation coefficient between the amount of NC gas and RCS temperature was the highest at about 0.73, confirming that the effect of NC gas has the most significant impact on PRRHS degradation. And when the amount of NC gas is more than 0.1 w/o, BEPI is more conservative than CE. In practice, the coolant injected into the reactor system is used after removing the NC gas, so it is unlikely that the degradation due to NC gas would result in a more conservative analysis than CE.

5. Conclusion

In this study, the robustness evaluation methodology is developed to evaluate the performance of the PSS considering its performance characteristics. In addition, a robustness assessment was performed on the V-SMART's passive safety system to verify the applicability of the developed methodology. Through this study, the impact of various performance issues that may occur when introducing a passive safety system was analyzed, and the existing conservative safety analysis methodology was confirmed to be valid for evaluating PSSs. By applying this methodology, it is expected that modeling and safety analysis guidelines for the evaluation of PSSs could be derived and derived guidelines are expected to contribute to the safety evaluation of PSSs in the future. In addition, this study is expected to contribute to securing regulatory verification technology for the extended application of the passive concept of safety systems.

ACKNOWLEDGEMENT

We acknowledge that this research has been conducted with a support from the national nuclear safety research titled “Study on Validation of Consolidated safety Analysis Platform for Applications of Enhanced Safety Criteria and New Nuclear Fuels (Contract No. 2106002)” funded by Nuclear Safety and Security Commission of KOREA.

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