Impact Evaluation on Performance issues of V-SMART's Passive Safety Systems during a TLOF

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1. Introduction

Various types of passive safety systems(PSSs) are being developed and introduced to improve the safety and economics of advanced nuclear power plants. PSSs operate without the use of pumps and rely on heat conduction, density differences, and gravity. This allows the safety system to operate even when external power is lost, and has the advantage of performing safety functions without operator interaction. However, the driving force using natural phenomena is relatively small, and the counter force (friction and pressure drop in pipes, environmental changes inside and outside the system, etc.). In the event of a nuclear power plant accident, the operating environment of the safety system varies greatly, so it is necessary to evaluate whether the system can adequately perform safety functions in various environments. For this purpose, KINS has proposed various performance issues that can affect the passive safety system [1], and this study aims to analyze the impact of performance issues on the performance of the PSSs through code analysis. To select the evaluation target, we developed a research analysis model, V-SMART (Virtual SMART), with SMART100[2] as a reference nuclear power plant, which is an SMR with many PSSs. The TLOF accident of V-SMART was selected as the accident scenario, and the analysis was performed using the system analysis code, MARS-KS 2.0. This study analyzed the impact of performance issues in the PSS on the performance of PRHRS (Passive Heat Removal System) and PSIS (Passive Safety Injection System), and analyzed the changes in accident mitigation behavior due to these issues.

2. Impact Evaluation on Performance Issues of PSS in V-SMART

2.1 Development of V-SMART

To analyze the impact of performance issues on PSSs in plant accident mitigation behavior, a research analysis model, V-SMART, was developed with SMART100 as the reference plant. V-SMART is a virtual analysis model that integrates the eight steam generators and four PRHRS and PSIS of the reference plant into a single unit, while preserving the volume, flow area, and heat transfer area of the system. It was developed to stably analyze the effects of performance issues for symmetric accidents such as TLOF and PSV-LOCA. The MARS-KS 2.0 nodalization of V-SMART is shown in Figure 1, and the steady state for TLOF analysis is shown in Table 1.

The event sequence of the TLOF reference input model is shown in Table 2, and the RCS temperature result is shown in Figure 2. In the TLOF accident, it was confirmed that the accident was mitigated by stably cool down the system to the safe shutdown temperature through the operation of the PSS without loss of the coolant. Therefore, in this study, the time to reach the safety shutdown temperature was used as the performance analysis index of the PSSs.

2.2 Essential performance issues for PSSs

The essential performance issues that affect the performance of each PSS were derived from existing studies [3, 4], and the following performance issues were analyzed in this study.

<u>PRHRS</u>

- Non-condensable gases in the system

In this study, it is assumed that the non-condensable gas is dissolved in 1~4kg (within 0.02w/o), and the analysis is performed by assuming that it slowly extrudes based on the point where the secondary pressure becomes lower than the steady state pressure.

- Change of the ambient temperature

The heat transfer coefficient outside the ECT is assumed to be 2~10 W/m^{2}K, and the outside air temperature is assumed to change from 40℃ → 10℃ → 40℃ in 24 hours.

- Heat loss of the system

This study assumes a heat loss coefficient of 2~10 W/m^{2}K for PRHRS pipes and performs an impact evaluation.

- Fire in the containment building

This impact evaluation assumes fire heat fluxes of 2 to 10 kW/m^2 over the analysis period to determine the impact of fire on PRHRS performance.

- Aging of the pipe and heat exchanger

In this study, the impact of the aging issue was evaluated by analyzing the performance change of the system when the area and heat transfer area of the pipes decreased by 5-20% due to the aging of the system.

- Model and correlation uncertainty of the analysis code

This study aims to evaluate the uncertainty of condensation heat transfer in heat exchangers. Therefore, the heat transfer of the PRHRS heat exchanger was varied from -50% to 20% to evaluate the impact of performance issues.

<u>PSIS</u>

- Fire in the containment building

Same with PRHRS

- Aging of the pipe

Same with PRHRS

- Pipe deformation due to seismic event

In this study, it is assumed that the safety injection piping of PSIS is deformed by 30° to 90° due to the impact of the seismic event, and the impact assessment is performed by reflecting the change in the length and area of the piping.

- Operability of the check valve

In this study, the cracking pressure (minimum pressure required to open the check valve) of the check valve was set from 0 to 40 kPa (reference input: 3 kPa) to evaluate the impact.

2.3 Evaluation results

The impact of the performance issues on the PSSs and the accident mitigation process was evaluated with the issues suggested in 2.2, and the evaluation results are shown in Tables 3 ~ 5.

<u>Impact evaluation results of PRHRS performance issues</u>

- Non-condensable gases accumulate at the bottom of the heat exchanger, affecting system performance.
- Change of the ambient temperature does not have a significant impact on performance.
- Heat loss in the system reduces the temperature of the return line, which removes heat from the system more efficiently. Natural circulation flow is reduced due to heat loss, but the impact is not significant.
- The heat from the fire injected into the system, slowing the RCS cooling rate. The heat added by the fire can be removed with the current performance of the PRHRS.
- Aging of the pipe and heat exchanger directly affects the heat removal performance of the PRHRS, reducing RCS cooling rates.
- Model and correlation uncertainty directly affects the performance of the PRHRS, resulting in different RCS cooling rates depending on the uncertainty.

<u>Impact evaluation results of PSIS performance issues</u>

- In the event of a fire, the cooling rate of the RCS decreases as the temperature of the coolant injected from the PSIS increases.
- When the area of the pipe decreases due to aging, the flow rate of the safety injection water decreases due to the increase in pressure drop. This reduces the cooling rate of the RCS.
- Pipe deformation due to seismic event increases the pressure drop in the pipe and decreases the flow rate of the safety injection water. This reduces the cooling rate of the RCS.
- In the case of a TLOF event, the water level in the CMT is kept at the full level during the analysis, and the pressure difference between the front and back of the check valve remains high due to the water head. Therefore, the effect of the operability of the check valve is not shown.

<u>Impact evaluation results of PRHRS + PSIS performance issues</u>

- In the event of a fire in the containment building, the temperature of the coolant in the PRHRS return line and the PSIS safety injection water increases. This reduces the RCS cooling rate.
- Aging of the pipe and heat exchanger directly reduces the heat removal performance of the PRHRS and the PSIS injection performance. This has been identified as a performance issue that reduces the cooling rate of the RCS.

3. Conclusions

Due to the small driving force, the performance of the PSS can change significantly due to various internal and external factors. Therefore, this study evaluated the impact of various performance issues on the performance and accident mitigation characteristics of the PSS through the V-SMART model. In this study, a TLOF accident was selected as the accident scenario, and the effects of essential performance issues of PRHRS and PSIS on the accident development were identified. In a TLOF accident, since there is no outflow of coolant through a break, it is important to remove the residual heat from the core rather than supplement the coolant. Therefore, the accident is mitigated by cooling the RCS through the PRHRS and PSIS. Therefore, issues affecting the heat removal performance of the PRHRS and the temperature of the return line affected the accident mitigation, and issues affecting the injection flow rate and safe injection water temperature of the PSIS affected the accident mitigation performance.

The findings of this study are expected to have a similar impact on various Passive Heat Removal Systems(PHRSs) and Passive Emergency Core Cooling Systems(PECCSs). The analysis of the performance changes of the PSS through these performance issues is expected to improve the reliability of the performance and stable operation of the PSS and suggest considerations to improve the performance of the system. It is also expected to help provide guidelines for safety analysis of the PSSs.

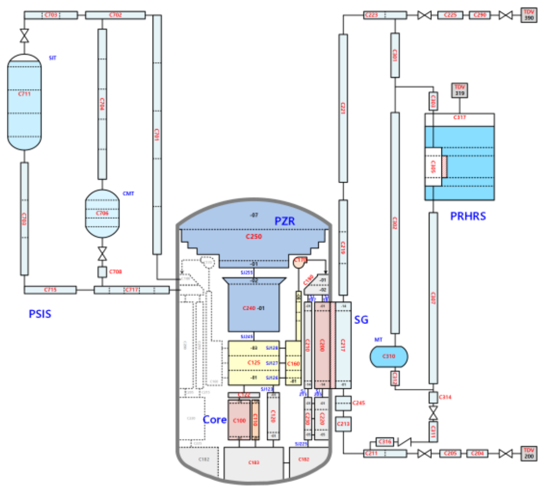

Fig. 1. MARS-KS Nodalization for V-SMART model

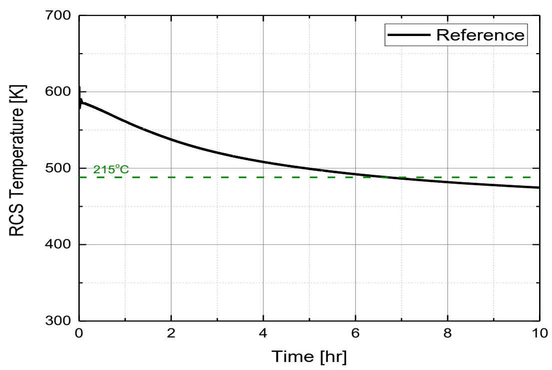

Fig. 2. RCS Temperature results – reference model

Table 1. V-SMART steady state result

Power	376 MW_{th}
Core outlet Temp.	594K
Mass flow rate	2430 kg/s
PZR Pressure	157 bar
PZR level	75%
SG Pressure	49 bar
SG flow rate	193 kg/s
CMT pressure	158 bar
CMT temperature	313K
SIT pressure	1 bar
SIT temperature	313K

Table 2. TLOF event sequence (reference model)

LOOP	0.0s
Low feedwater signal	0.4s
Low RCP speed signal	0.5s
Reactor trip	1.6s
PRHRS actuation signal CMT actuation signal	1.9s
Shutdown CRA insert	2.0s
RCS safe shutdown temperature	~24,000s

Table 3. Impact of performance issue evaluation results (PRHRS)

Performance issue		Time (Safety shutdown Temp.)	Difference
NC gas	1 kg	24,090s	0%
	2 kg	24,270s	0.7%
	4 kg	25,800s	7.1%
Ambient Temp.	2 W/m^2K	24,090s	0%
	5 W/m^2K	24,090s	0%
	10 W/m^2K	24,080s	-0%
Heat loss	2 W/m^2K	23,870s	-0.9%
	5 W/m^2K	23,430s	-2.7%
	10 W/m^2K	23,000s	-4.5%
Fire	2 kW/m^2	25,080s	4.1%
	5 kW/m^2	26,940s	11.8%
	10 kW/m^2	30,400s	26.2%
Aging	-5%	25,490s	5.8%
	-10%	27,200s	12.9%
	-20%	30,870s	28.1%
Code uncertainty	-50%	Fail	-
	-20%	31,240s	29.7%
	+20%	20,420s	-15.2%

Table 4. Impact of performance issue evaluation results (PSIS)

Performance issue		Time (Safety shutdown Temp.)	Difference
Fire	2 kW/m²	24,850s	3.2%
	2 kW/m²	26,450s	9.8%
	2 kW/m²	30,500s	26.6%
Aging	-5%	24,510s	1.7%
	-10%	24,900s	3.4%
	-20%	25,960s	7.8%
Seismic event	30°	24,550s	1.9%
	60°	24,770s	2.8%
	90°	25,780s	7.0%
Check valve	0 kPa	24,090s	0%
	10 kPa	24,090s	0%
	40 kPa	24,090s	0%

Table 5. Impact of performance issue evaluation results (PRHRS+PSIS)

Performance issue		Time (Safety shutdown Temp.)	Difference
Fire	2 kW/m²	26,060s	8.2%
	2 kW/m²	30,640s	2.72%
	2 kW/m²	Fail	-
Aging	-5%	25,940s	7.7%
	-10%	28,290s	17.4%
	-20%	33,150s	37.6%

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