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Performance Analysis of Passive Safety System of the SMART in SBLOCA Situation using MARS-KS Code

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1. Introduction

Passive safety system has been adopted in newly developed nuclear reactor concepts for its characteristic of reducing the cost for the production of electricity and enhancing the operational safety of the reactor. However, in the passive safety system, because the driving force for flow is not supplied by external input but only generated by natural phenomena like circulation or gravity, its performance can be degraded significantly by operating condition changes. Therefore, the detailed analysis would be essential to guarantee that the expected function would be performed properly in accident conditions.

When Small Break Loss of Coolant Accident (SBLOCA) occurs in SMART, the Passive Safety Injection System (PSIS) injects water into the reactor coolant system and the Passive Residual Heat Removal System (PRHRS) removes the heat transferred from the primary side by natural circulation flow. PSIS and PRHRS are composed of 4 independent trains. Each train of PSIS contains of one Core Makeup Tank (CMT) and one Safety Injection Tank (SIT). PRHRS includes heat exchanger and Emergency Cooldown Tank (ECT).

There are several studies for evaluating the performance of the passive systems. Jafari *et al.* (2003) developed and applied REPAS method for evaluating reliability of Isolation Condenser System. Marques *et al.* (2005) developed RMPS (Reliability Methods for Passive Safety Function) for the assessment of thermal hydraulic passive system performance. Nayak *et al.* (2008) applied APSRA (Assessment of Passive System Reliability) to the natural circulation system.

In this study, the performance of PSIS and PRHRS of SMART is evaluated under SBLOCA has analyzed. Performance assessment method is developed by consulting previous studies. The MARS-KS model has been used for simulating the thermal-hydraulic behaviors. As a result, the success criteria for PSIS were derived.

2. Procedure for Performance Analysis for the Passive Safety System

Analysis procedure for evaluating the performance of the passive system is demonstrated Figure 1. Firstly, the accident condition needs to be determined. Then, the relevant physical phenomena and the mechanisms should be addressed and the parameters which can influence the cooling performance should be collected. The importance of those parameters can be evaluated with respect to the system failure. Some parameters have significant impact compared to the others. Screening the less influential parameters and focusing only on key parameters would help to conduct the performance evaluation efficiently and enable the detailed analyses. For evaluation, the numerical simulation would be essential.

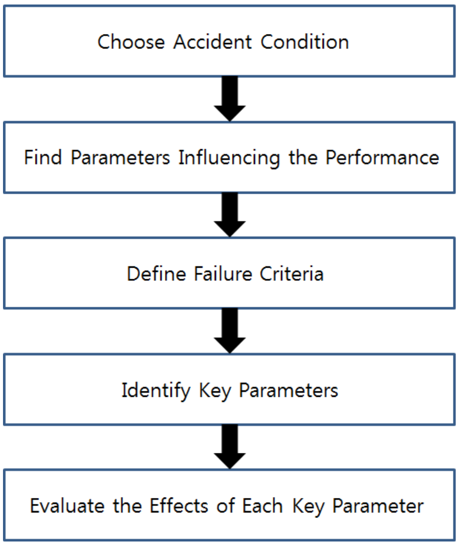

Fig. 1 Analysis Methodology

3. Applying Methodology to SMART Under SBLOCA

In this study, SMART (System-integrated Modular Advanced ReacTor) has been modeled by MARS-KS and used for performance analysis of passive system. Note that the SMART is now under development and its design is not completed. Therefore, the system description and the results of this paper should not be considered as the final one.

It has been assumed that Small Break Loss of Coolant Accident (SBLOCA) occurs at Passive Safety Injection Line (PSIS). Break occurs at safety injection nozzle in one passive safety system train. Thus, there are 3 available PSIS trains and 4 PRHRS trains. Break area was assumed to 0.00223m^2. Once accident occurs, coolant flows from the primary side of the reactor, which includes reactor vessel, pressurizer and primary steam generator, Pressure of primary side decreases simultaneously. Decreasing of the pressure causes Low Pressurizer Pressure (LPP) signal, which triggers the reactor shutdown and the turbine trip. Flow in secondary side of the reactor is also congested.

Passive safety system of the SMART cools the reactor in the accident situation. Core Makeup Tank (CMT) injects coolant into the reactor induced by pressure difference. PRHRS actuation signal arise by LPP and make flow in the secondary side. When the pressure decreases by about 2 MPa, SIT starts to cool down the reactor. The passive safety system is required to maintain the heat removal for 3 days under accident situations.

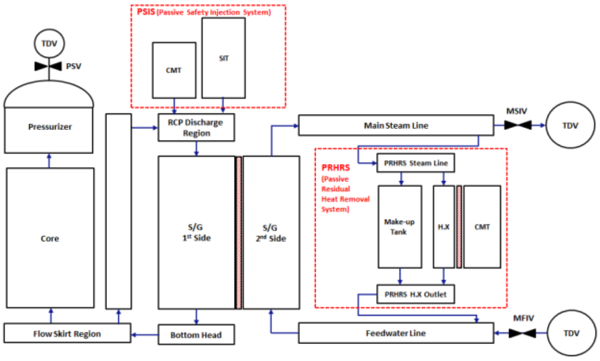

Fig. 2 MARS Modelling of SMART

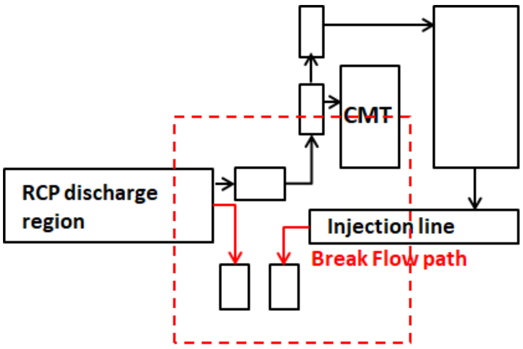

Fig. 3 Break Location of SBLOCA

Parameters which can influence the cooling performance have been collected as follows:

- The number of the PSIS train
- The number of the PRHRS train
- Initial reactor vessel water level
- Initial ECT temperature
- Initial CMT, SIT water volume
- Valve open criteria
- Property of orifice in the PSIS

Peak cladding temperature (PCT) 2200F has been used for the failure criteria. Failure caused by SBLOCA occurs from the excessive coolant loss and coolant boiling. Thus injected coolant from PSIS trains and PRHRS trains is the most important parameter for safety at SBLOCA situation as shown in Fig. 4.

Therefore, the focus has been given to the sensitivity of the number of the PSIS/PRHRS trains. 8 cases of the numerical simulation performed.

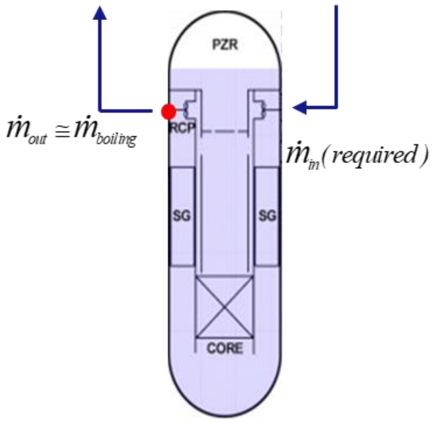

Fig. 4 Schematic Diagram for Heat Removal

4. Analysis Results

In case with no safety injection (i.e., no CMT and no SIT) and no PRHRS, the cladding temperature has been increased due to the lack of the decay heat removal as can be seen in Fig. 4, which means the core would be damaged.

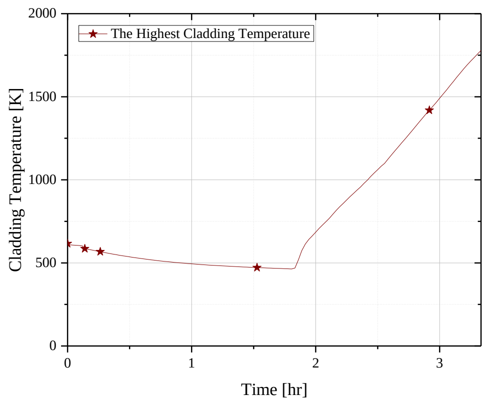

Fig. 5 Cladding Temperature (no PSIS / no PRHRS)

Without PSIS operation, the core would not be cooled as can be seen in Fig. 5. The core water level would be decreased quickly in early stage of the accident. It would take 60 to 90 minutes until the water level reduced to the top of the core. As the core is exposed, the peak cladding temperature starts to rise and exceed the failure criteria as in Fig. 6.

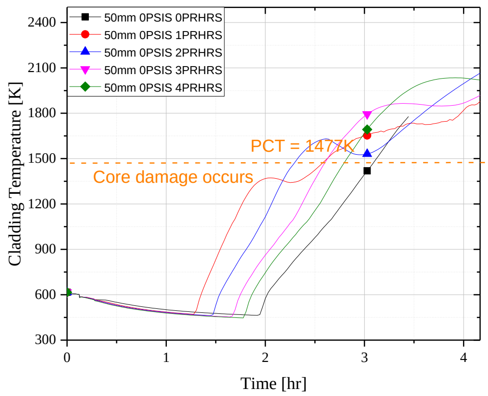

Fig. 6 Highest Cladding Temperature (no PSIS)

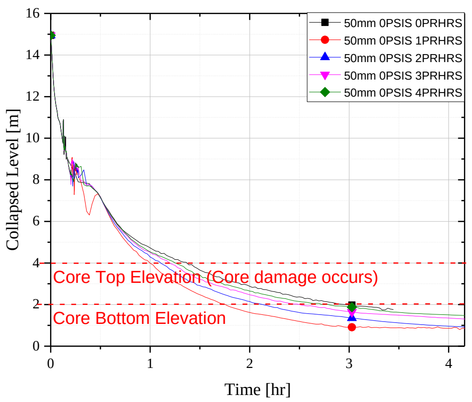

Fig. 7 RPV Water Level (no PSIS)

Figure 8 and 9 show the comparison for the cases with PSIS injection. Cases with 2 PSIS trains / 2 PRHRS trains and 3 PSIS train without PRHRS have been successful to cool the core. However, in case of using 2 PSIS trains, the peak cladding temperature would be maintained below 1477K however, the core would be exposed and the cladding temperature would be increased as in Fig. 8.

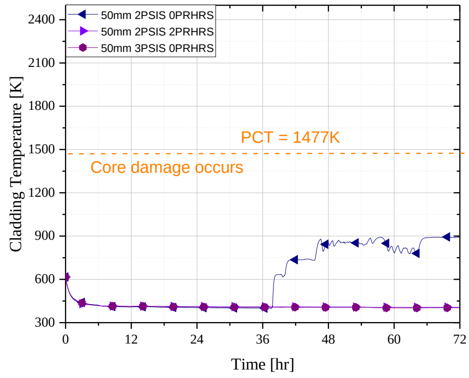

Fig. 8 Highest Cladding Temperature

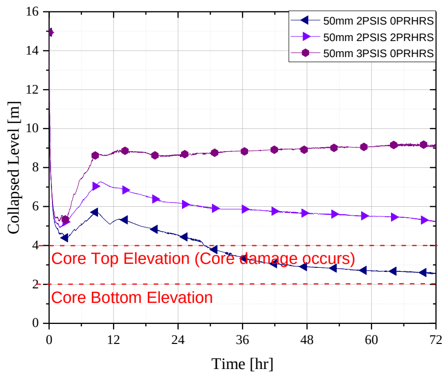

Fig. 9 RPV Water Level

Figure 10 shows the heat transfer rate to secondary side with the various numbers of PRHRS trains. In case with 2 PRHRS trains, 0.5MW of core heat would be transferred through natural convection. Figure 11 shows injection rate by SIT in 3 PSIS case. CMT depleted in the early stage of the accident, thus SIT plays a crucial role in the cooling process. Injection flow rate decreases as time elapsed due to decay heat reduction. In using 2 PSIS trains, coolant is injected with 0.70kg per second which is 2 out of 3 PSIS case. From this result, it is obtained that more than 1.1kg per second of coolant is needed when PRHRS doesn't operate under SBLOCA.

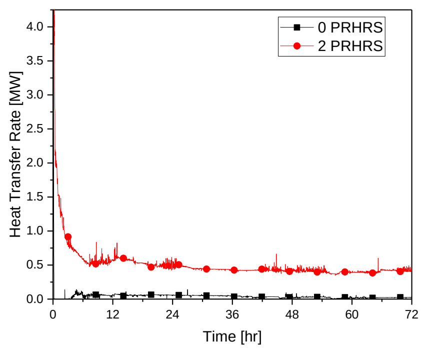

Fig. 10 Heat Transfer Rate for PRHRS trains

Qualitative analysis is performed to evaluate result. Fig. 12 shows that decay heat along with the time. Minimum requirement of coolant is calculated from decay heat graph. It is assumed that the reactor reaches quasi-steady state about 20 hours (71000 sec) later from the accident. Decay heat of this time is about 2897kJ/s. Required injected mass can be calculated from the following equation.

$$\dot{m}_{boiling} = \frac{Q_{decay}}{H_g - H_f} = \frac{2897kJ/s}{(2674.94 - 417.43)kJ/kg} = 1.283kg/s$$

Only if PSIS trains are participate in cooling process, only SITs inject the coolant at assumed quasi-steady state. As stated previously, the amount of coolant is about 0.70 kg/s and 1.1 kg/s in case of 2 PSIS trains or 3 PSIS trains respectively. Though it is not accurately matched because of heat removal from the coolant which is initially exist in RPV, which decreases constantly as shown in Fig. 9, the obtained requirement from the equation can be used to evaluate the amount of coolant.

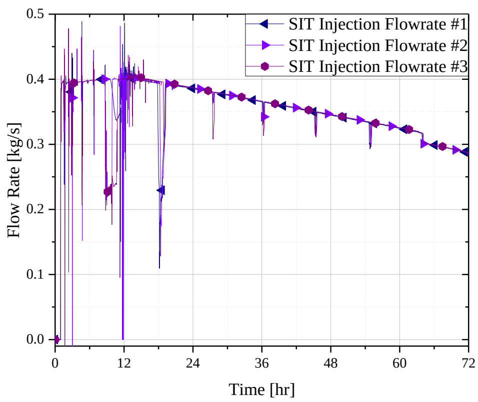

Fig. 11 SIT Injection Rate

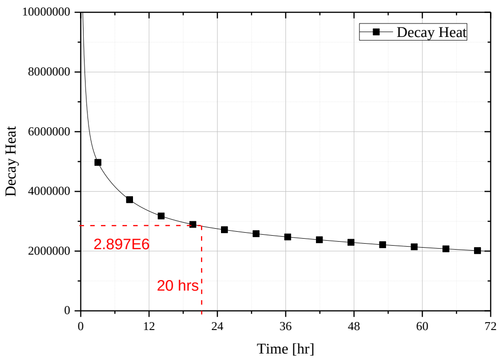

Fig. 12 Decay Heat

5. Conclusion

Performance analysis of the passive safety system in SMART was conducted by using MARS code under small loss of coolant accident at safety injection nozzle. Performance analysis methodology is used for assessing each related parameters and selecting key parameters**.** The number of available trains in PSIS and PRHRS was varied to examine the effect of their injection to the reactor. The simulation results are summarized in Table 1.

Table 1. Summary of results

Accident	Location / Size	Analysis Condition	Core damage	Core damage time
SBLOCA	PSIS Injection Line Break (50mm)	0 PSIS / 0 PRHRS	O	4,500 sec
		0 PSIS / 1 PRHRS	O	3,800 sec
		0 PSIS / 2 PRHRS	O	4,100 sec
		0 PSIS / 3 PRHRS	O	4,400 sec
		0 PSIS / 4 PRHRS	O	4,800 sec
		2 PSIS / 0 PRHRS	O	100,000 sec
		2 PSIS / 2 PRHRS	X	-
		3 PSIS / 0 PRHRS	X	-

In conclusion, 2 PSIS with 2 PRHRS trains or 3 PSIS trains are minimum requirements for SBLOCA. PRHRS cools down the core when coolant from PSIS trains is insufficient. 2 Trains of PRHRS induce deduction heat energy by 0.5MW. It is important to note that if the injection from PSIS is sufficient, additional heat removal via secondary side (e.g., Passive Residual Heat Removal System) would not be necessary in case of using more than 3 trains. Specifically, reactor maintains safety during 3 days in the condition of more than about 1.1kg/s coolant. This feature is analyzed qualitatively by using heat equation. However, the design of the SMART is changing even now thus these results should not be considered as final one.

6. References

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