Sensitivity Analyses of Passive Safety Systems for SMART Natural Circulation Cooldown using MARS-KS

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1. Introduction

The SMART (System integrated Modular Advanced ReacTor) is an integral reactor which includes reactor core, pressurizer, reactor coolant pumps (RCPs) and steam generators inside the reactor pressure vessel. Thus, the coolant circulation loops (e.g. cold legs and hot legs) are removed and the large break loss of coolant accident (LBLOCA) is inherently eliminated.

SMART standard design received standard design approval from the nuclear safety and security commission (NSSC) in 2012 [1]. The SMART standard design [2] was initially designed with active cooling system such as the high pressure safety injection pump (HPSIP). But the design has been improved for fully passive safety system to inherently enhance its safety. Improved passive safety design includes four train passive safety injection systems (PSISs) in the primary side in addition to the four train passive residual heat removal systems (PRHRSs) in the secondary side. Each passive system is designed four electrically and mechanically independent trains and two valves are implemented on parallel lines in each train to eliminate the single train failure.

In the previous study, natural circulation cooldown of SMART with four trains of passive safety systems is evaluated during 72 hours after the loss of off-site power (LOOP) [3]. In this study, sensitivity analysis for the natural circulation cooldown performance is performed during the LOOP. The cooldown capability of each passive safety system and the sensitivity study for the main thermal hydraulic parameters are performed in this study.

2. Analysis Methods

2.1 Analysis Methodology

A best-estimate safety analysis code, Multi-dimensional Analysis of Reactor Safety (MARS-KS) [4], is used for the sensitivity analyses. MARS-KS is regulatory safety analysis code of Korea Institute of Nuclear Safety (KINS).

SMART passive safety system has parallel design of the actuation valves to prevent the single failures. However, the single failure sensitivity studies are performed for the natural circulation cooldown due to regulatory issues of the single failures in the passive safety system [5]. The single failures of the PSIS or PRHRS are evaluated for the natural circulation cooldown performance. Also, parametric sensitivity analyses are performed for the PRHRS. The PRHRS is designed to remove decay heat from the primary system by natural circulation after the reactor trip when the normal steam extraction or feedwater supply is not available. It is designed to cool the reactor and make reactor safe shutdown at least 72 hours of operator grace time after the LOOP. Thus, sensitivity studies for the temperature and level of the emergency cooldown tank (ECT), a heat sink of PRHRS, are performed.

The analysis is performed up to 72 hours of operator grace time for the long term cooling.

2.2 Nodalization

Figure 1 shows MARS-KS nodalization of the SMART standard design. The pressurizer is located at upper part of the reactor vessel and 8 steam generators

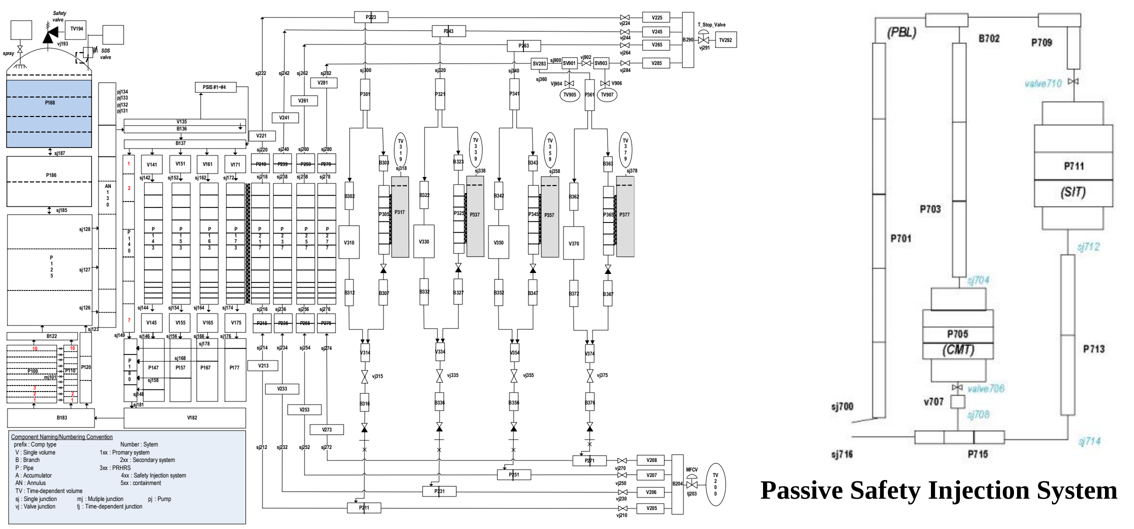

Figure 1. SMART MARS-KS Nodalization

are modeled with 4 pipe components. The PRHRS is connected to main steam line (MSL) and feedwater line (FL), and consists of PRHRS make up tank, ECT, heat exchanger and connecting pipes. On the other hand, PSIS is connected to RCP discharge region of the primary side. Figure 1 also shows SMART PSIS nodalization. Each train of the PSIS consists of pressure balance line (PBL), core makeup tank (CMT), safety injection tank (SIT) and safety injection line (SIL).

2.3 Initial and Boundary conditions

As design basis event of the long term cooling, LOOP is assumed as an initiating event. Limiting conditions for operation (LCO) are conservatively used in the natural circulation cooldown performance analysis [3] as initial and boundary conditions as follows;

- Core power
- RCS flow rate
- Pressurizer level
- Core coolant temperature
- Pressurizer pressure

The actuation signals used for the PSIS and PRHRS are as follows [6];

- CMT : Passive residual heat removal actuation
- SIT : Low-Low PZR pressure
- PRHRS : Low feedwater flow rate

Among the actuation signals designed for the PSIS and PRHRS, only the selected signals are use in this study from the reference design [6]. The initial ECT temperature and water level are 40℃ and 8.2m [6], respectively. Thermal hydraulic conditions of the ECT are changed depending on the sensitivity cases.

3. Sensitivity Analysis Results

3.1 PSIS single failure

The PSIS is connected to the RCP discharge region. When the CMT and SIT isolation valves are opened, the steam from the RCS discharges to CMT through the PBL. And then it is condensed and flows into the RCS again through the SIL. The PSIS provides safety injection water for the core make up. Figures 3 through 7 are the behaviors of main parameters of the PSIS single failure case compared with the default case of the no single failure during the transient. Even one train of PSIS is not actuated due to assumed single failure, pressure is not much different as shown in Figure 3, and the safe shutdown condition is reached after 4 hours in the transient and maintained for 72 hours after the event as shown in Figure 4. Although the PSIS flow rate decreases in Figure 5, the PRHRS flow rate slightly increases, and more core decay heat is removed to the secondary side by the PRHRSs as shown in Figure 6. The ECT water level decreases as sown in Figure 7.

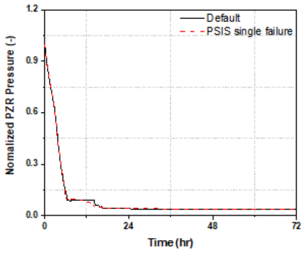

Figure 3. PZR pressure, PSIS single failure

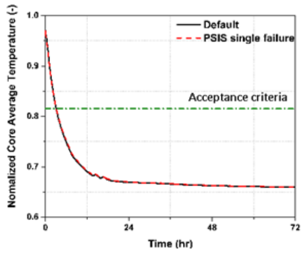

Figure 4. Avg. Core Temp., PSIS single failure

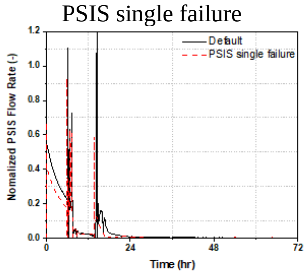

Figure 5. PSIS Flow rate, PSIS single failure

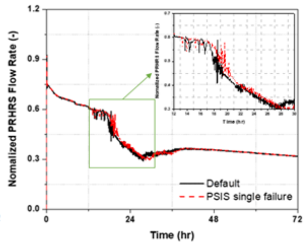

Figure 6. PRHRS Flow rate, PSIS single failure

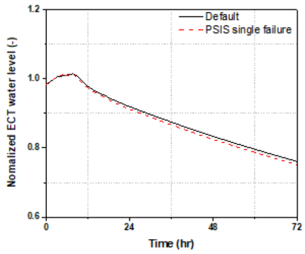

Figure 7. ECT water level, PSIS single failure

3.2 PRHRS single failure

The PRHRS is connected between MSL and FL in the secondary side. When the feedwater isolation valves (FIVs) and main steam isolation valves (MSIVs) are closed, PRHRS actuation valves are opened and natural circulation in the secondary side starts to remove residual heat from the primary side. Figures 8 through 12 are the results of the PRHRS single failure analysis. During the transient after the LOOP, pressurizer pressure and core temperature decrease slightly later than the default case of no PRHRS single failure as shown in Figure 8 and 9, but the core is successfully cooled down even the PRHRS single failure occurs. This is because the PSIS flow rate increases slightly but the heat removal rate of unit PRHRS decreases due to decreased PRHRS flow rate as shown in Figures 10 and 11. The ECT water level decreases rapidly, but it remains around 60% of initial inventory after 72 hours of the LOOP. According to the PRHRS single failure sensitivity analysis, PRHRSs cooled down the reactor core enough to reach safe shutdown condition at 6 hours after the LOOP and maintained safe shutdown condition for 72 hours in the transient satisfying the long term cooling (LTC) acceptance criteria.

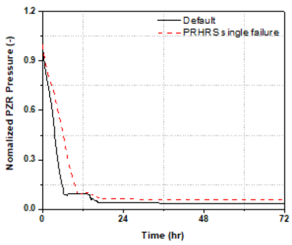

Figure 8. PZR pressure, PRHRS single failure

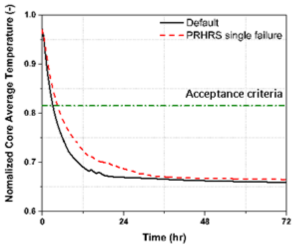

Figure 9. Avg. Core Temp., PRHRS single failure

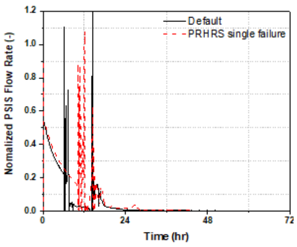

Figure 10. PSIS Flow rate, PRHRS single failure

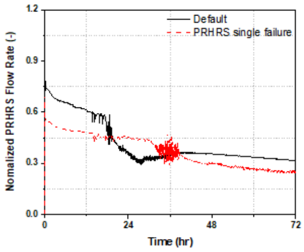

Figure 11. PRHRS Flow rate, PRHRS single failure

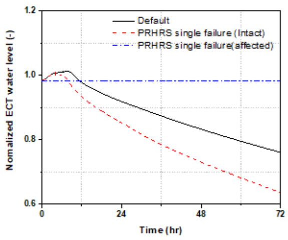

Figure 12. ECT water level, PRHRS single failure

3.3 ECT water level and ECT temperature sensitivity

According to the previous single failure sensitivity results, it shows that the PRHRS single failure more affects the core cooling down after the LOOP than the PSIS single failure. Therefore it is evaluated whether the cooling margin of the PRHRS is enough even for the PRHRS single failure. The ECT is a ultimate heat sink of the PRHRS which is major heat removal mechanism in the secondary side. ECT is designed to prevent heat exchanger uncovery for 72 hours after the accident. In sensitivity analysis, ECT temperature sensitivity evaluates its performance whether heat exchanger is uncovered, while water level sensitivity evaluates cooldown capacity. Thus, it is needed to evaluate the PRHRS cooldown margin for long term cooling natural circulation safe shutdown for 72hours after the design base event, LOOP.

The ECT water level and ECT temperature sensitivity is performed for the case of the conservative ECT water temperature. Most conservative condition of ECT water temperature is assumed as saturation temperature at initial state of the LOOP. Figures 13 and 14 show ECT water level and average core temperature, respectively.

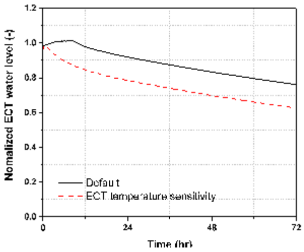

Figure 13. ECT water level, ECT temp. sensitivity

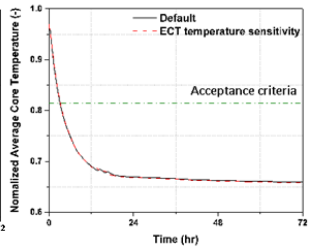

Figure 14. Avg. Core Temp., ECT temp. sensitivity

The ECT water level decreases rapidly at initial state due to bulk boiling of the ECT water. But the water inventory still remains above 60% at 72 hours after the transient. Thus average core temperature successfully reaches safe shutdown acceptance criteria at 4 hours after the transient and maintained until 72 hours.

ECT water level sensitivity analysis is also performed for 60% of nominal ECT water level. Figures 15 and 16 show ECT water level and average core temperature, respectively.

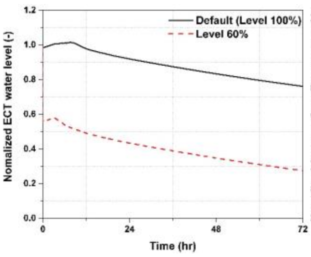

Figure 15. ECT water level, ECT level sensitivity

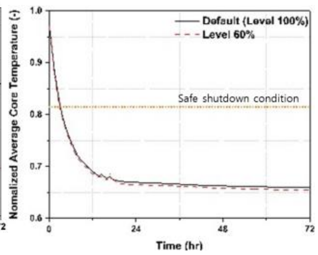

Figure 16. Avg. Core Temp., ECT level sensitivity

Even the initial ECT water level is about 60% of the nominal ECT water level, ECT maintains its water level around heat exchanger bottom level after 72 hours. It means core can be cooled down sufficiently even with almost half of the ECT water inventory.

4. Conclusions

Sensitivity studies are performed for the evaluation of the natural circulation cooldown capacity of the SMART passive safety systems during LTC design basis event of the LOOP. The sensitivity analyses are carried out using MARS-KS which is a regulatory best estimate safety analysis code of the KINS.

According to the analysis results, PRHRS single failure more impacts the core cooling during the LTC design basis event of the LOOP than the PSIS single failure. In both cases of the single failure analysis, the results show that the average core temperature reaches safe shutdown condition in early stage of the transient. Even the single failure is occurred, the cooling capability of remaining 3 trains of the PRHRS or PSIS is evaluated to be sufficient and satisfies the long term cooling safe shutdown regulatory acceptance criteria.

On the other hand, even the initial ECT water temperature is saturated or ECT water level is 60%

initially, ECT water inventory remains over heat exchanger bottom level even after 72 hours after the transient and reactor can be cooldown sufficiently to be maintained at safe shutdown condition for 72 hours after the transient.

Through the sensitivity studies, both PSIS and PRHRS are verified for the design basis event of LTC to cool down the reactor and maintain the core in the safe shutdown condition for 72 hours even if system single failure is occurred. Thus the improved SMART passive safety system design satisfies the long term cooling safe shutdown acceptance criteria of the passive safety system.

REFERENCES

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