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Preliminary Study of the Passive Steam Generator Cooling System Operation in WH 3-Loop NPPs

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1. Introduction

In nuclear power plants (NPPs), Design Basis Accidents (DBAs) can generally be classified into two categories: loss of coolant accidents (LOCA) and non-loss of coolant accidents (Non-LOCA). Beyond these DBA categories, there are Beyond Design Basis Accidents (BDBAs), such as Extended Loss of all AC Power (ELAP) and the Total Loss of Feedwater (TLOFW) accident, which involve more severe scenarios. NPPs are equipped with various accident response strategies and facilities to manage these accidents effectively. Active equipment, which requires resources like electricity to operate, is predominantly employed in currently operational commercial PWRs for responding to accidents. For instance, Feed Water (FW) pumps powered either electrically or by steam pressure are used to supply feedwater to steam generators in pressurized water reactors (PWRs). And Korean nuclear power plants are prepared to cope with beyond-design-basis accidents through a strategy called MACST (Multi-barrier Accident Coping Strategy). However, the availability of active equipment cannot be trusted if extremely significant seismic activity exceeds the design scope or if the drive power supply is interrupted, potentially leading to issues in accident response.

To address this issue, our study proposes a Passive Emergency Cooling System (PECS) utilizing steam generators, applicable to operational PWRs, and assesses the functionality of this system in scenarios like ELAP or TLOFW within a Westinghouse 3-loop type PWR [1].

2. Methods and Results

2.1 Design of Passive Emergency Cooling System for SG

The PECS comprises the steam generator for cooling (SG1), the steam generators for pressurization (SG2, SG3), the Condensate Storage Tank (CST), and associated valves/piping. The system is designed to extract steam from the pressurizing steam generators (SG2, SG3) to pressurize the CST located on-site. The PECS utilize the pressurized water from the CST to inject feedwater into the cooling steam generator (SG1), thus cooling the primary side. The coolant source for the PECS of the steam generator is the CST, currently used as an Auxiliary Feed Water (AFW) source during accidents, with piping and valves installed to supply feedwater from the feed pump. The shape, diameter, height, and volume of the tank were iteratively determined. Among the variables influencing the analysis results, the tank volume was assumed to be approximately 1,700 m^3.

2.2 RELAP5 code modeling

Figure 1 illustrates the nodalization of the PECS for secondary side of the steam generators. The Steam is extracted from the top of the pressurizing steam generators (SG2, SG3) and injected into the top of the CST to pressurize it, allowing the condensate stored in the CST to be fed into the feedline. To pressurize the CST, steam is drawn from the top of the steam generator and introduced into the top of the CST.

Connecting the upper part of the steam generators (SG2, SG3) and the CST are pipes, with a feedwater Pressure Isolation Valve (PIV) installed in-between to transmit steam pressure inside the SG2 and SG3 to the top of the CST through the opening and closing of the PIVs.

A By-pass Valve (BV) is included in the piping linking the bottom of the CST to the SG1, enabling pressurized cooling water within the CST to be supplied to the SG1 upon BV opening. Both PIV and BV are modeled as trip valves, with their operational logic designed considering factors such as the SG pressure, CST pressure, SG water level, among others, related to the water injection operation. Connections between the SG and the CST incorporate considerations of the CST height and the SG feed water intake height. Given the purpose of pressure transmission, the pipe sizing is modeled based on the diameter of the SG Power Operated Relief Valve (SG PORV). The CST encompasses 10 control volumes, whereas the piping connecting the CST to the SG comprises 4 control volumes each for the lower segment and the connection between the SG FW pipe.

2.3 . Assumption

The operational conditions for the PECS of the SG assume the ELAP and TLOFW. It is anticipated that a power loss situation will result in control rods dropping, thereby shutting down the reactor, stopping all RCPs, tripping the turbine, and closing the main steam isolation valves. However, it is assumed that leakage through the RCP seals due to the shutdown of charging pumps caused by power loss is not taken into account to confirm the cooling and depressurization effects through the injection of CST cooling water.

The decay heat curve used in the analysis employs the ANSI/ANS-5.1-1979 [2] model embedded within the RELAP5/MOD3.3 code. [3]

Without opening the SG PORV for CST pressurization, the pressurizing steam generators (SG2, SG3) are assumed, while the cooling steam generator (SG1) opens its SG PORV after 15 minutes post-accident for RCS cooling. The PIV is assumed to open about 45 minutes after the accident when considering the SG1 water depletion point. It is assumed that the steam in SG2 and SG3 pressurizes the CST to supply feedwater to SG1.

The BV is set to open only when both the CST pressure is higher than the SG1 pressure and the SG1 water level is below a certain threshold. Considering the PIV pressurization timing, the BV is also set to open around 45 minutes after the accident. The BVs opening and closing are adjusted according to the CST pressure, SG1 pressure, and water level to maintain a certain range of levels.

Initially, the temperature of the cooling water in the CST is assumed to be at atmospheric temperature (23°C), and pressure (1.03 kg/cm²). The initial capacity of the CST is assumed to be about 75% of the total capacity. The CST and piping between the CST and the SG were assumed to be adiabatic.

2.4 Analysis results

When ELAP and TLOFW occur simultaneously, the key events related to the accident analyzed are shown in Table 1.

For RCS cooling, the SG PORV opens at 30 minutes, and before operator action, the Main Steam Safety Valve (MSSV) repeatedly opens and closes to maintain the valve set pressure, displaying a fluctuating pressure pattern until the operator actions.

With the opening of the SG PORV, the pressure in SG1 decreases, followed by the decrease in pressure in the SG2 and SG3 due to the subsequent opening of PIV1 and PIV2. Particularly, the pressure in SG1 rapidly decreases initially, showing fluctuations depending on the presence or absence of feedwater injection but generally trends downward over time. Approximately 3.5 hours later, SG1/2/3 exhibits similar pressure behavior patterns (see Figure 2).

In the early stages of the accident, the pressure in the CST remains below 10 kg/cm^2 due to the opening and closing of SG2, SG3, and PIV (as seen in Figure 3). As the accident progresses, however, the pressure gradually declines because the inventory of feedwater in the pressurizing steam generators depletes, leading to reduced pressure in the pressurizing steam. After the opening of the BV, continuous feeding from the CST occurs. Initially, significant amounts of coolant are injected due to the high pressure in the CST, but this amount reduces over time as the CST pressure lowers relative to SG2 and SG3 pressures (refer to Figure 4).

Following the accident, the water level in SG1 gradually decreases, reducing sharply after the SG PORV opens, reaching depletion in about 0.5 hr. During the initial stages of the accident, the SG1 water level changes seem to be influenced by the opening and closing of the MSSV valves, impacting the SG pressure behaviors. Although temporarily recovered by the supply from the CST, the water level eventually depletes again, mostly exhausted after about 4.2 hours. Around 2.8 hours post-accident, the water levels in SG2 and SG3 also deplete, interpreting further pressurization of the CST through SG3 impossible (see Figure 5).

After roughly 4.4 hours following the depletion of feedwater in the cooling steam generator (SG1), the temperatures and pressures in the RCS begin to rise. Post-accident, since SG1 acts as a cooling steam generator and SG2/SG3 serve a pressurizing role, natural convection causes temperature differences across loops (refer to Figures 6 and 7).

3. Conclusions

The purpose of this paper is to review the concept of the Passive Emergency Cooling System (PECS) of the steam generator (SG) in cases where ELAP and TLOFW occur simultaneously. The findings of this study are summarized as follows:

- We modeled and analyzed the injection system of the passive cooling system to examine its operability.
- Sensitivity analysis on the area of SG PORV showed that if the operator's action time is assumed to be 30 minutes, it is possible to depressurize within 10 minutes with the current SG PORV.
- Limiting the pressure of CST below 10 kg/cm² allows supplying approximately 189 m³ of feedwater for about 3.5 hours; however, the temperature and pressure of RCS rise to their limits due to the depletion of feedwater inside the SG.
- While the PECS is operation was confirmed, continuous operation is not feasible; however additional system modifications are necessary to ensure safe long-term operation of the plant.

For long-term cooling operations, follow-up research is currently underway to investigate additional upper-side pressurization methods for the CST. Future studies aim to demonstrate the feasibility of extending feedwater supply times by additional systems.

ACKNOWLEDGMENTS

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REFERENCES

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[2] "American National Standard for Decay Heat Power in Light Water Reactors," ANSI/ANS-5.1-1979, ANS, 1979.

[3] "RELAP5/MOD3.3" Code Manual," NUREG/CR-5535, Rev.1, December, 2001.

Table 1. Major sequence of LUHS event

Time (sec)	Event
0	Initiating event (ELAP+TLOFW)
0	Feed Water (FW) Sys. trip
	Rx. trip
	Turbine trip
	RCP trip
	Charging Pump (CP) trip
	Letdown HX isolation
	RCP seal leak isolation
~30	Main Steam Safety Valves (MSSVs) open
1,800	RCS Cooling initiation
1,800	- SG1 SG PORV & BV open - FW injection standby - CST pressurization start - PIV1 & 2 open - FW injection initiation - SG1 water level recovery
~2,000	Depletion of SG1 water level
~10,000	Depletion of SG2,3 water level
~15,000	Loss of FW injection
~16,000	RCS Temp. & Press. Increase

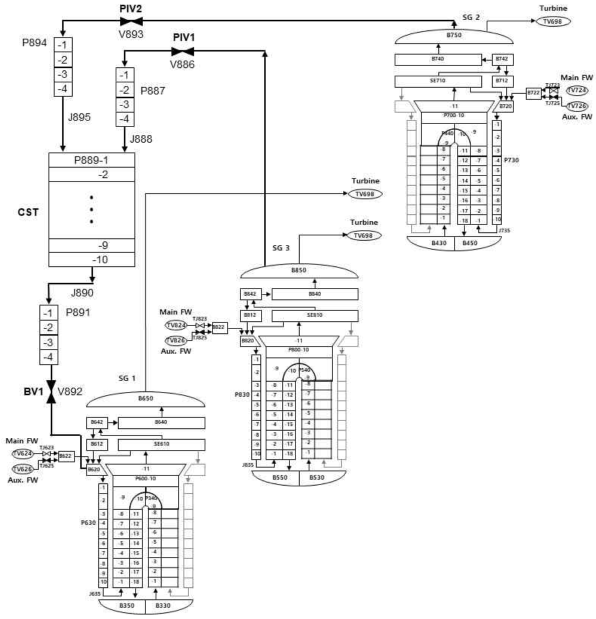

Fig. 1 Nodalization of Passive Emergency Cooling System (PECS)

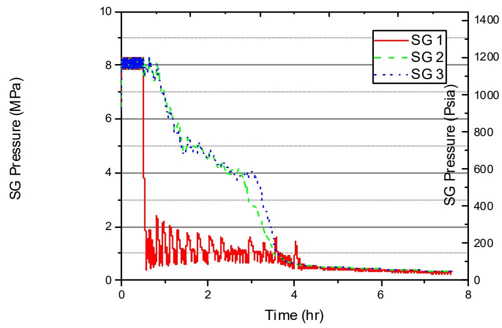

Fig. 2 Pressurizer Pressure

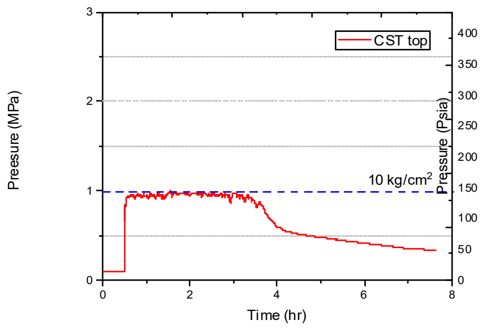

Fig. 3 CST Pressure (upper side)

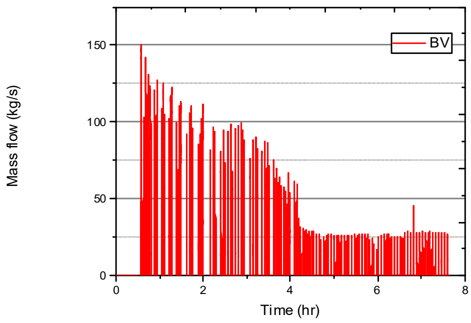

Fig. 4 FW injection mass flow (SG1)

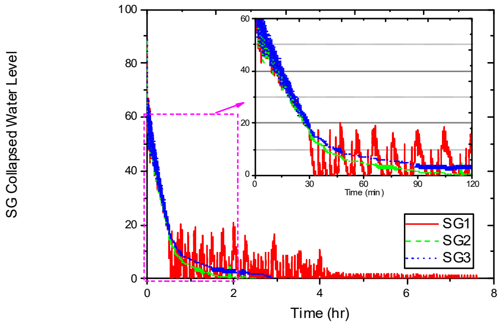

Fig. 5 SG water level

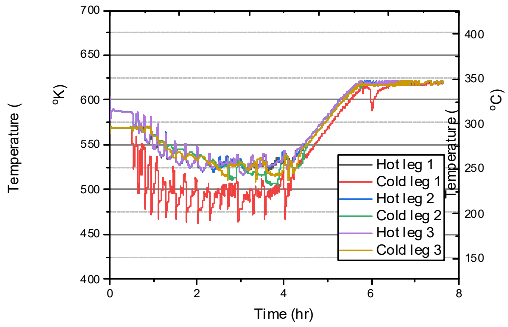

Fig. 6 RCS temperature

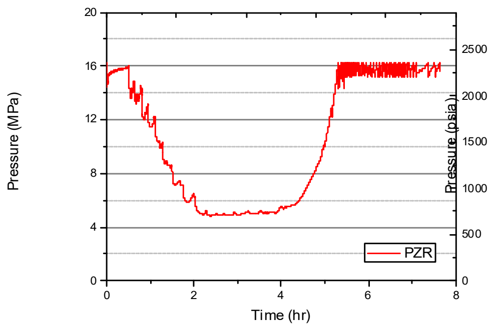

Fig. 7 RCS pressure

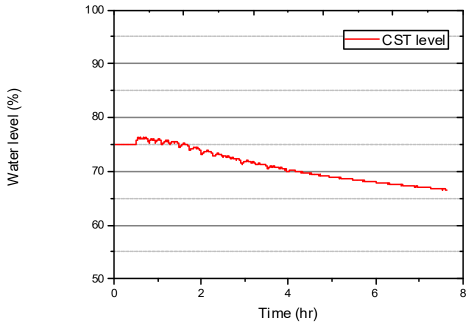

Fig. 8 CST water level