Sensitivity Analysis of PECCS Success Criteria and Operator Manual Depressurization Time Windows for i-SMR MMPS LOCA Using MARS-KS

Jiwoo Choi, Yunseok Lee, Taewan Kim*
Department of Safety Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea
**Corresponding author: taewan.kim@inu.ac.kr*

***Keywords :** i-SMR, MARS-KS, SBLOCA, MMPS, PECCS*

1. Introduction

In the i-SMR, the major reactor coolant system components are integrated within a single reactor pressure vessel (RPV), eliminating the large-diameter piping used in conventional commercial reactors. Consequently, large-break loss-of-coolant accidents (LBLOCAs) are excluded from the design basis. Instead, a break in the charging line of the Modular Makeup and Purification System (MMPS) has been identified as the most conservative representative scenario. This event corresponds to a small-break LOCA (SBLOCA) involving a pipe break with a diameter of less than 2 inches [1].

As shown in Fig. 1, the i-SMR employs a Passive Emergency Core Cooling System (PECCS). The PECCS comprises Emergency Depressurization Valves (EDVs) installed at the top of the RPV and connected to the pressurizer, as well as Emergency Recirculation Valves (ERVs) connected to the upper core region. During an accident, these valves facilitate core cooling through the natural circulation of coolant within the containment vessel (CV) [2]. In this study, a sensitivity analysis was performed to establish the success criteria for PECCS valve operation. For the most limiting cases, in which core uncovery occurred exceeding design limits, a time-window analysis was conducted to determine the available time for operator manual depressurization actions.

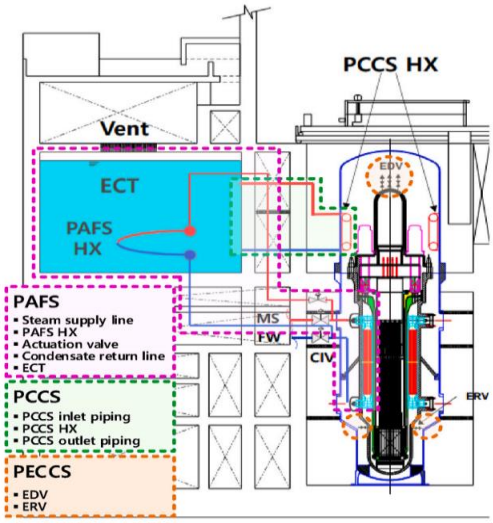

Fig. 1. Passive Safety System in i-SMR [2].

2. Methods and Results

2.1 Methods and assumptions

Although the i-SMR adopts passive safety systems that do not require operator action, the MMPS is provided as a severe accident mitigation measure in the event that all passive safety system functions are lost. However, because the accident scenario considered in this study involves a break in the MMPS charging line, the MMPS cannot be credited as a mitigation measure. Since manual actuation of an EDV is proposed as an accident mitigation measure, this study selected the opening of an EDV as the operator manual intervention. The PECCS consists of three EDVs and two ERVs, which are modeled as trip valves [2]. The following additional assumptions were applied to the accident scenarios:

- An EDV failure is assumed to be a failure of valve actuation only; the mechanical integrity of the valve is maintained, and it remains available for manual operator action.
- When an operator actuates an EDV, only one EDV is assumed to open as the most conservative assumption.
- All passive safety systems other than the PECCS are assumed to operate normally.
- A loss of offsite power (LOOP) is assumed to occur without delay immediately after the turbine trip.

To quantitatively evaluate the time limit for manual operator intervention, the time-window concept defined in the IJS-HRA methodology was applied [3–5]. The additional available time for the operator action (T_a), is defined in Eq. (1):

$$T_a = T_w - T_p \quad (1)$$

The time window of the action (T_w) corresponds to the success criterion for the operator manual action. In this study, it was derived from the MARS-KS calculation results. The time required to perform the action (T_p) is the actual time taken by the operator to perform the manual action. T_p for manual operation in the main control room was reported as 1 to 10 minutes on the basis of simulator measurements [5]. This value, however, was measured on a Westinghouse two-loop PWR simulator and is not i-SMR data. Thus, in this study, the upper bound of 10 minutes was applied conservatively.

2.2 Success criteria for PECCS valve operation

The representative event chronology for the MMPS charging line break accident was summarized in Table I. The peak cladding temperature (PCT) behavior was analyzed for a total of nine cases representing full operation, partial operation, and complete failure of the PECCS components. The results are presented in Fig. 2. Table II summarizes normalized peak cladding temperature for each case. The results clearly showed that the PCT exceeded the design limits (1477.6K) in cases 8 and 9. Furthermore, regardless of ERV availability, no core uncovery occurred when more than one EDV was successfully opened.

Table I: Main event timeline of the SBLOCA

Time [s]	Main Event timeline
0.002	MMPS SBLOCA occurrence
5.698	CV high pressure trip occurrence
6.801	Reactor trip signal occurrence
6.803	Turbine trip and LOOP occurrence MSIV and MFIV begin to close Control rod insertion begins
7.303	PAFS occurrence
2092.72	PECCS occurrence
18000	End of calculation

Table II: Normalized maximum PCT and its occurrence time for each case

Case	ERV on	EDV on	Normalized max PCT time [hr]	Normalized max PCT [-]	Time of first exceedance [hr]
1	2	3	0.6553	0.1801	-
2	2	2	0.6803	0.2149	-
3	2	1	0.7344	0.3186	-
4	1	3	0.6642	0.1870	-
5	1	2	0.6836	0.2298	-
6	1	1	0.7519	0.3263	-
7	0	1	0.7831	0.3524	-
8	1	0	1.0089	0.6054	0.8972
9	0	0	1.1614	0.5809	1.0964

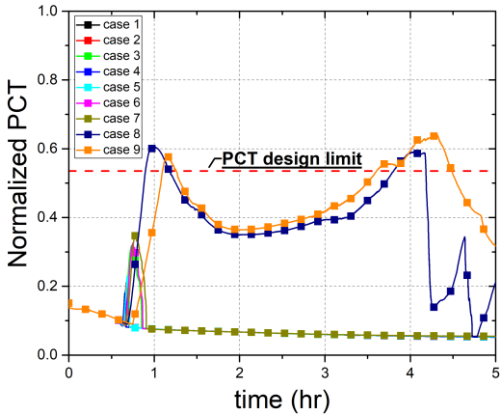

Fig. 2. Normalized PCT behavior for the PECCS valve failure combinations under the SBLOCA with LOOP.

2.3 Time Window Analysis for case 9 (All valves fail)

Using the PECCS actuation time of 2,092.72 s as the reference point, cases were analyzed in which the operator was assumed to recognize PECCS actuation failure upon initiation of the actuation signal and manually open a single EDV at 0, 5, 10, 20, 25, or 30 min after the signal. The PCT behavior is presented in Fig. 3, and the time of peak temperature occurrence and the normalized peak temperature for each case are summarized in Table III. When the operator manually intervened to open one EDV at 0, 5, 10, 20, 25, or 30 min after the alarm, the PCT remained below the design limit. In contrast, for the corresponding case without operator intervention, as discussed in Section 2.2, the PCT exceeded the design limit 30.91 min after the alarm, indicating that the safety criteria were not satisfied. Based on the PCT behavior analyzed using MARS-KS, the maximum task time window, T_w, was evaluated to be 30 min. Since the preparation time, T_p, was assumed to be 10 min, the time available for the operator action, T_a, was calculated as 20 min. Therefore, because T_a exceeds 10 min, operator errors can be recovered.

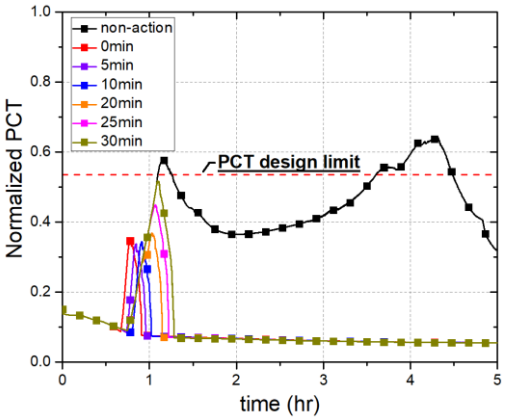

Fig. 3 Normalized PCT for the manual EDV operation with all PECCS valves failed.

Table III: Normalized maximum PCT for the manual operation with all PECCS valves failed

Action time	Time of PCT Occurrence [hr]	Normalized max PCT [-]
0 min	0.7819	0.3506
5 min	0.8478	0.3370
10 min	0.9108	0.3434
20 min	1.0256	0.3680
25 min	1.0725	0.4481
30 min	1.0925	0.5173

2.4 Time Window Analysis for case 8 (1 ERV operation)

Assuming that the operator recognizes PECCS actuation failure upon initiation of the actuation signal, cases were analyzed in which a single EDV was manually opened at 0, 5, 10, 15, or 18 min after the signal. The PCT behavior is presented in Fig. 4, and the time of peak temperature occurrence and the normalized peak temperature for each case are summarized in Table IV. When the operator manually intervened to open a single EDV at 0, 5, 10, 15, or 18 min after the alarm, the PCT remained below the design limit. In contrast, for the corresponding case without operator intervention, as discussed in Section 2.2, the PCT exceeded the design limit 18.95 min after the alarm. Based on the PCT behavior analyzed using MARS-KS, the maximum task time window, T_w, was evaluated to be 18 min. Since the preparation time, T_p, was assumed to be 10 min, the time available for operator action, T_a, was evaluated to be 8 min. Therefore, because T_a is less than 10 min, recovery from an operator error is not feasible.

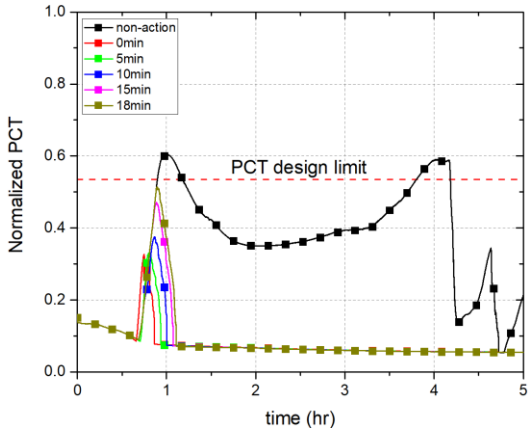

Fig. 4. Normalized PCT for the manual EDV operation with only one ERV available in PECCS.

Table V: Normalized maximum PCT for the manual operation with only one ERV available in PECCS

Action time	Time of PCT Occurrence [hr]	Normalized max PCT [-]
0 min	0.7475	0.3266
5 min	0.8067	0.3317
10 min	0.8644	0.3755
15 min	0.8867	0.4711
18 min	0.8883	0.5134

3. Conclusion

In this study, a sensitivity analysis was performed using MARS-KS to establish the success criteria for PECCS valve operation. Furthermore, time window analysis was performed for the most limiting cases to determine the available time for operator manual depressurization actions. The main findings are as follows:

- Sufficient core cooling was achieved whenever EDV opening was successful, regardless of ERV availability. In addition, the PCT exceeded the design limit in cases, in which one ERV was available while all EDVs failed to open, and all PECCS valves failed.
- For the case that all PECCS valves failed, the operator intervention time was evaluated from the alarm initiation time. Without operator action, the PCT reached the design limit 30.89 min after the alarm. Because manual EDV actuation performed within 30 min prevented the PCT from reaching the design limit, the maximum task time window, T_w, was evaluated as 30 min. With the preparation time, T_p, assumed to be 10 min, the available operator action time, T_a, was 20 min. Therefore, recovery from an erroneous operator action is considered feasible.
- For the case with 1 ERV available, the operator intervention time was likewise evaluated from the alarm initiation time. Without operator action, the PCT reached the design limit 18.95 min after the alarm. Because manual EDV actuation performed within 18 min prevented the PCT from reaching the design limit, the maximum task time window, T_w, was evaluated as 18 min. With T_p assumed to be 10 min, T_a was 8 min. Therefore, recovery from an erroneous operator action is not considered feasible.

REFERENCES

[1] Sang Gyu Lim, Hyun Suk Nam, Do Hwan Lee, Sang Won Lee*, Design characteristics of nuclear steam supply system and passive safety system for Innovative Small Modular Reactor (i-SMR), Nuclear Engineering and Technology 57 (2025) 103697

[2] Seong-Su Jeon a,* , Youngjae Park a , Sang Gyun Nam a , Seokjong Yoon b , Jisu Kim b , Sukho Lee b , Hyunsuk Nam b , Sang Gyu Lim. Design characteristics and preliminary performance analysis on passive safety systems of i-SMR. Nuclear Engineering and Technology. Volume 58, Issue 9, September 2026, 104574

[3] A. Prošek and M. Čepin, Success Criteria Time Windows of Operator Actions Using RELAP5/MOD3.3 within Human Reliability Analysis, Journal of Loss Prevention in the Process Industries, Vol.21, pp.260-267, 2008.

[4] M. Čepin, Importance of Human Contribution within the Human Reliability Analysis (IJS-HRA), Journal of Loss Prevention in the Process Industries, Vol.21, pp.268-276, 2008.

[5] A. Prošek, B. Mavko and M. Čepin, Estimation of Operator Action Time Windows by RELAP5/MOD3.3, NUREG/IA-0219, U.S. Nuclear Regulatory Commission, 2009.