

Analysis of a TLOFW Accident with PAFS Failure in the i-SMR Using MARS-KS

Hyeonjo Kim^a, Changyong Jung^a, Yeon-Gun Lee^{a*}

^aDepartment of Quantum and Nuclear Engineering, Sejong University
209, Neungdong-ro, Gwangjin-gu, Seoul, Republic of Korea

*Corresponding author: yglee@sejong.ac.kr

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1. Introduction

The innovative small modular reactor (i-SMR) adopts passive safety systems to maintain core cooling and remove decay heat following reactor shutdown [1]. During a total loss of feedwater (TLOFW) accident, the normal secondary-side heat sink is lost and reactor coolant system (RCS) pressure increases rapidly. Under this condition, the passive auxiliary feedwater system (PAFS) is designed to provide an alternative secondary-side decay-heat removal path without alternating-current power or operator intervention [1]. The availability of PAFS therefore plays an important role in controlling the pressure response and removing decay heat during a TLOFW transient.

If all PAFS trains fail, however, steam-generator cooling remains unavailable and the transient is governed by reactor trip, pressurizer safety relief valve (PSRV) discharge, containment heat removal, and passive emergency core cooling system (PECCS) actuation. Repeated PSRV opening limits RCS pressure by discharging primary coolant mass and energy to the containment vessel (CV), while reducing reactor vessel (RV) coolant inventory and increasing CV pressure. Because PECCS is actuated when the RV-to-CV differential pressure decreases below its set point, PSRV operation also affects the timing of passive injection and the subsequent redistribution of coolant inventory. Manual PSRV opening may therefore accelerate RCS depressurization and influence the subsequent passive-system response.

Previous studies evaluated i-SMR passive safety performance under representative LOCA and non-LOCA conditions [2], and a recent MELCOR TLOFW analysis considered simultaneous PAFS and PECCS unavailability with PCCS functionality maintained [3]. This study uses MARS-KS to compare TLOFW transients with and without prescribed manual PSRV operation under complete PAFS failure. CV and RV pressures, RV downcomer and core-side water levels, and heat-transfer rates were evaluated. Partial PAFS-operation cases are also presented for pressure comparison. The objective is to clarify the effect of manual PSRV operation when secondary-side feedwater heat removal is unavailable.

2. Analysis Model and Scenario

2.1 System Model and Initial Conditions

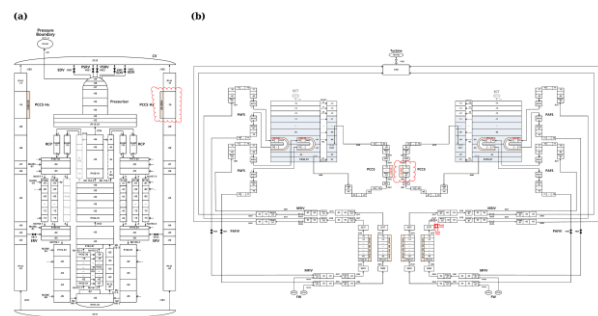


Fig. 1. MARS-KS nodalization of the i-SMR: (a) primary system and containment; (b) secondary-side and passive systems (adapted from slides 3 and 5 of Ref. [4]).

The MARS-KS input model represented a 520 MWt i-SMR and was initialized from a converged steady state. Four PAFS trains and two passive containment cooling system (PCCS) heat exchangers were modeled, and the ECT was modeled as the ultimate heat sink for both systems [1]. The principal initial conditions are summarized in Table I.

Table I: Principal initial conditions.

Parameter	Value
Core power (MWt) / RCS pressure (MPa)	520 / 15.5
Core inlet / outlet temperature (K)	562.1 / 597.7
PZR level (%) / feedwater flow per SG (kg/s)	66.0 / 64.75
SG secondary-side inlet (feedwater) pressure (MPa) / temperature (K)	5.75 / 483.14
SG secondary-side outlet (steam) pressure (MPa) / temperature (K)	5.04 / 565.36
ECT temperature (K) / water level (m)	303.15 / 12.3

The base MARS-KS input deck was adopted from the regulatory-verification model presented in Ref. [4], and its nodalization is shown in Fig. 1. The model included the RV, pressurizer, steam generators, PAFS, PECCS,

CV, PCCS heat exchangers, and ECT. The PSRV discharge path from the RV to the CV was also represented. Control functions implemented the protection and actuation logic for reactor and RCP trips, valve operation, and differential-pressure signals.

2.2 Protection and Actuation Conditions

The reactor protection logic included the applicable trip signals of the i-SMR design. In the present TLOFW transient, the pressurizer high-pressure signal actuated first and initiated reactor scram. The pressure reached its 16.45 MPa setpoint at 12.4 s, and the modeled 1.1 s signal delay yielded a scram time of 13.5 s. The RCPs tripped on the reactor-trip signal, and the PSRV cycled automatically at its opening and closing setpoints. The PECCS emergency depressurization valve (EDV) and emergency recirculation valve (ERV) actuated when the RV-to-CV differential pressure fell below 2.0 MPa.

2.3 Accident Sequence and Calculation Conditions

Complete loss of feedwater and PAFS failure were imposed simultaneously at 0 s, and the calculated sequence with manual PSRV operation is summarized in Table II. The high pressurizer-pressure signal occurred at 12.4 s, reactor scram and RCP trip at 13.5 s, and first automatic PSRV opening at 14.8 s. The PSRV was manually opened 30 min after reactor trip, at 1813.5 s, and PECCS actuated at 7609.1 s when the RV-to-CV differential pressure reached its setpoint. The 30-min timing was prescribed as a sensitivity assumption rather than derived from an operating procedure. The manual signal was latched, so the PSRV opening command remained active for the remainder of the calculation.

Table II: Calculated accident sequence for complete PAFS failure with manual PSRV operation.

Event	Time
TLOFW and PAFS failure	0 s
PZR high-pressure signal	12.4 s
Reactor scram / RCP trip	13.5 s
First automatic PSRV opening	14.8 s
Manual PSRV opening by operator	1813.5 s
PECCS actuation	7609.1 s

The calculation was continued to 260,000 s (approximately 72 h) to evaluate the long-term system response. Two principal cases were analyzed, differing only in whether prescribed manual PSRV operation was applied. Additional cases with one to four PAFS trains available were included only for pressure comparison.

3. Results and Discussion

3.1 PAFS Failure with Manual PSRV Operation

Fig. 2 shows the pressure response during PAFS failure with manual PSRV operation. RV pressure rose until PSRV actuation and then cycled between approximately 145 and 170 bar. PSRV discharge increased CV pressure to approximately 17 bar. After manual PSRV opening at 1813.5 s and subsequent PECCS actuation, RV pressure decreased below 20 bar near 10,000 s; both vessel pressures then approached a few bar. The principal event times are marked in Fig. 2.

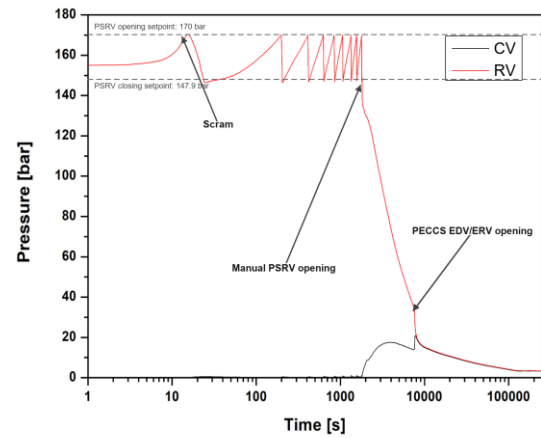


Fig. 2. CV and RV pressures during TLOFW with PAFS failure and manual PSRV operation.

The corresponding inventory response is presented in Fig. 3. The RV downcomer and core-side levels decreased from their initial values during the early discharge and redistribution period. Their minimum values were approximately 5-6 m, after which passive injection and pressure equalization produced a gradual recovery. The long-term levels stabilized at approximately 8-9 m and remained above the modeled core-region top elevation of about 6.2 m. The CV water level increased rapidly as coolant was discharged from the primary system and then changed slowly during the remainder of the calculation.

Fig. 4 shows the heat-transfer response. Core power decreased rapidly after scram and then followed the decay-power trend. Early PSRV discharge produced peaks in the CV- and RV-wall heat-transfer rates, while PCCS heat removal increased after energy was transferred to the CV. After approximately 10,000 s, the pronounced oscillations in the wall heat-transfer rates largely subsided.

Immediately after PECCS actuation, coolant flowed from the RV to the CV through both the EDV and ERV, temporarily lowering the RV water level below the modeled core-region top elevation. As the RV-to-CV differential pressure decreased, ERV flow reversed to the CV-to-RV direction while the EDV continued to support RV depressurization; the ERV return flow then restored

RV inventory. Compared with no manual action, this lower minimum RV level makes the manual-opening condition more limiting from an inventory and level-margin perspective, although it accelerates pressure reduction. The calculated peak cladding temperature (PCT), defined as the maximum over the 260,000 s transient of the modeled hot-rod cladding-surface temperature, was approximately 615 K. This value remained far below the 1477.6 K (1204 °C) criterion in 10 CFR 50.46 [5], confirming that the temporary inventory redistribution did not cause sustained loss of core cooling.

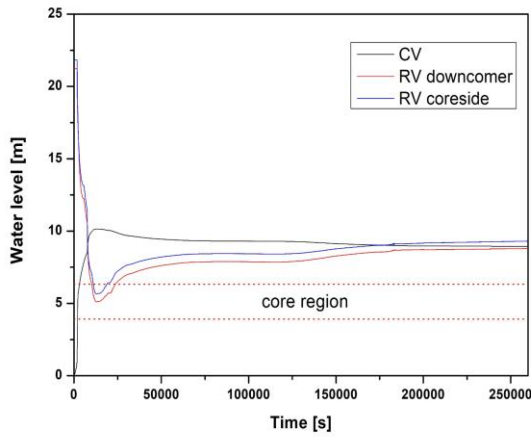


Fig. 3. CV and RV water levels during TLOFW with PAFS failure and manual PSRV operation.

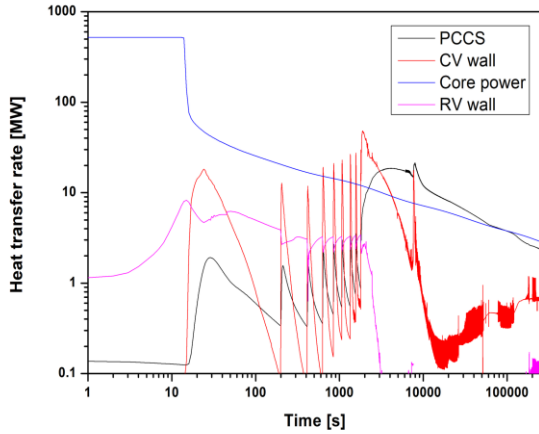


Fig. 4. Heat-transfer rates during complete PAFS failure with manual PSRV operation.

3.2 PAFS Failure without Manual PSRV Operation

Without manual PSRV operation, depressurization was delayed (Fig. 5). Repeated PSRV cycling kept the primary system near relief pressure, and RV pressure remained about 35 bar at 260,000 s, versus a few bar with manual operation. Relief discharge also caused repeated transient pressure peaks in the CV.

Fig. 6 shows that RV inventory remained above the modeled core region. After early oscillations, the downcomer and core-side levels stabilized near 11 and 12 m at 40,000-60,000 s. The higher levels reflect less cumulative discharge than in the case with manual PSRV operation.

Fig. 7 shows persistent RV-to-CV heat transfer through the RV wall. Together with intermittent PSRV discharge and PCCS heat removal, this several-MW heat transfer supported gradual depressurization without sustained core uncovering.

Overall, even without manual PSRV opening, intermittent PSRV discharge, PCCS heat removal, and RV-wall conduction to coolant accumulated in the CV gradually depressurized the RV. Despite the slower depressurization, the RV level remained above the modeled core region. Using the same hot-rod cladding-surface measure, the calculated PCT was approximately 623 K, slightly higher than the 615 K obtained with manual opening but still far below the 1477.6 K (1204 °C) criterion [5]. Core uncovering was therefore avoided in this case, and fuel integrity was maintained throughout the calculation.

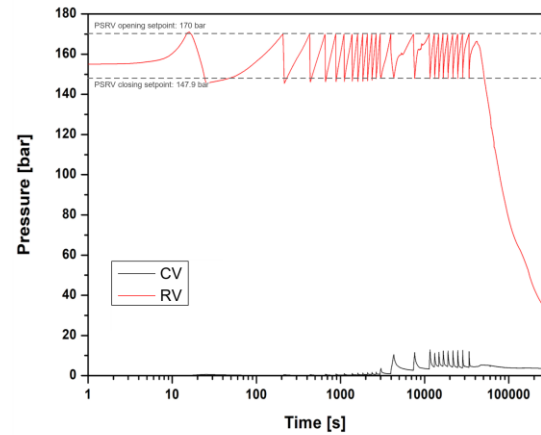


Fig. 5. CV and RV pressures during TLOFW with PAFS failure and without manual PSRV operation.

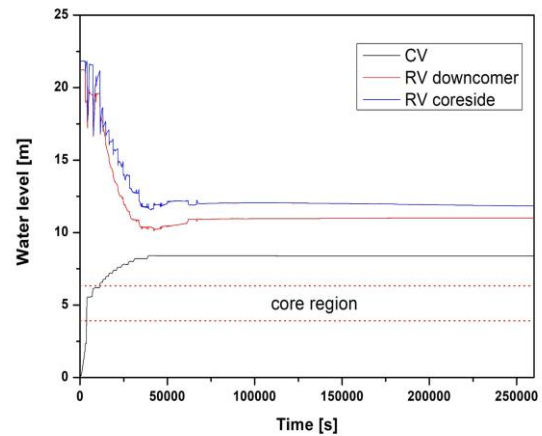


Fig. 6. CV and RV water levels during TLOFW with PAFS failure and without manual PSRV operation.

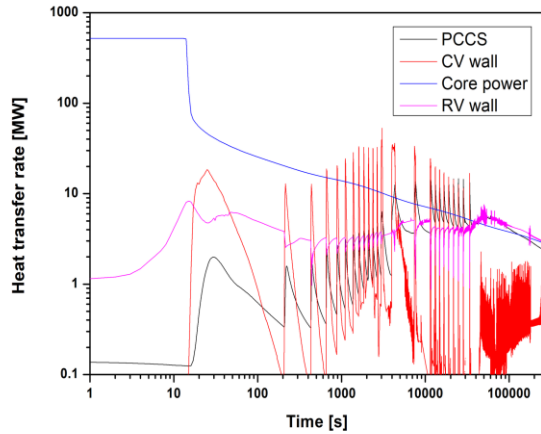


Fig. 7. Heat-transfer rates during complete PAFS failure without manual PSRV operation.

3.3 Effect of PAFS Availability

For comparison, Fig. 8 shows pressure responses for complete PAFS failure and for one to four available PAFS trains. The PSRV was manually opened 30 min after reactor trip in all cases. When two or more of the four PAFS trains were available, the RV began gradual depressurization before manual PSRV opening. Greater PAFS availability further accelerated depressurization, whereas complete PAFS failure produced the longest period of PSRV cycling.

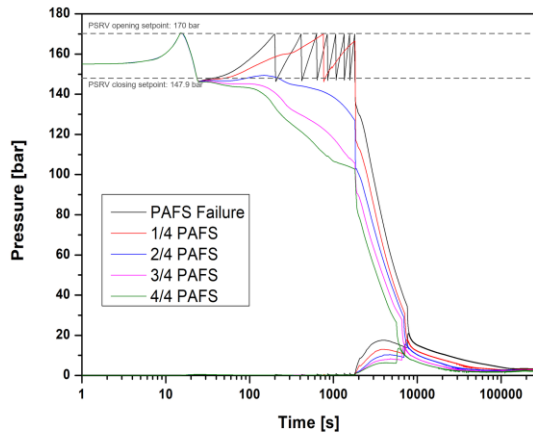


Fig. 8. Pressure responses for different numbers of available PAFS trains with manual PSRV operation.

4. Conclusions

The MARS-KS analysis of complete PAFS failure showed that manual PSRV operation reduced RV pressure below 20 bar near 10,000 s; without it, cycling persisted and RV pressure remained approximately 35 bar at 260,000 s. Combined EDV and ERV discharge temporarily lowered RV level below the modeled core-region top elevation, but differential-pressure-driven CV-to-RV flow through the ERV restored inventory while PCCS heat removal continued.

Manual PSRV operation accelerated depressurization but lowered long-term RV inventory through increased discharge. With two or more PAFS trains available, depressurization began before manual opening. Thus, manual PSRV operation governs both pressure and inventory responses under complete PAFS failure.

Without manual PSRV operation, late RV-wall heat transfer remained several megawatts, comparable to decay power. The calculated PCTs were approximately 615 K with manual PSRV opening and 623 K without it; both were far below the 1477.6 K (1204 °C) limit in 10 CFR 50.46 [5]. Thus, the manual-opening case was more limiting in RV inventory and level margin, whereas the no-manual-opening case was more limiting in long-term depressurization and produced the slightly higher PCT.

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