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Effectiveness of MACST in the Extended Loss of AC Power Scenario of the OPR-1000

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1. Introduction

The Fukushima Daiichi accident led to the development of numerous preparedness strategies to prevent or mitigate severe accidents.[1] In 2019, the accident management plan (AMP) for all operating nuclear power plants (NPPs) was submitted, and the improvement of uncertainties in the accident management plan was required. This study evaluates the AMP by considering severe accident uncertainties and analyzes the effectiveness of strategies using Multi-barrier Accident Coping Strategy (MACST) equipment in the event of extended loss of AC power (ELAP). Through uncertainty and sensitivity analyses, it assesses the effectiveness of reactor coolant system and steam generator injection strategies, considering execution reliability and mobile equipment performance.

2. Accident Management Plan of OPR-1000

OPR-1000, Korea's domestic NPP has implemented equipment and facilities to prevent and mitigate accidents, even in extreme conditions caused by severe natural disasters or human factors. As part of these measures, an injection line was installed to enable external water supply to the steam generator (SG) and reactor coolant system, along with the introduction of a mobile pump for water injection.

2.1 MACST injection strategies in ELAP scenario

If the Alternative AC Diesel Generator fails to restore power after a station blackout (SBO) event, the plant enters an ELAP state and attempts AC power recovery using a mobile generator. If this also fails, internal equipment cannot support accident mitigation, requiring the use of mobile pumps. In such cases, water is injected into the SG via an external injection line for heat removal, and depending on conditions, reactor coolant system (RCS) depressurization and injection may also be performed. Fig. 1 presents the Simplified Plant Damage State Event Tree (PDS-ET), which incorporates mobile equipment accident mitigation strategies for the initiating event for SBO. Fig. 2 illustrates the execution process of external injection strategies after the declaration of ELAP.

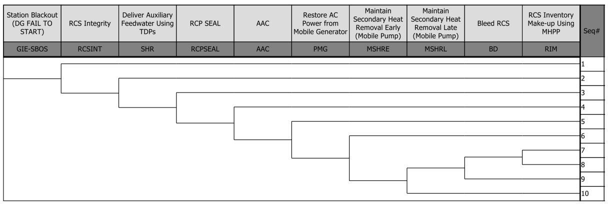


Fig 1. Simplified PDS-ET with MACST mitigation strategy

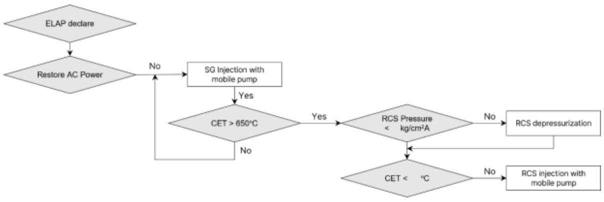


Fig 2. External injection strategies in Extended SBO scenario

To assess the effectiveness of the strategy utilizing a portable pump, accident scenarios were analyzed under conditions where secondary heat removal (SHR) via the turbine-driven auxiliary feed water (TDAFW) pump is unavailable, and AC power restoration remains unsuccessful:

1. The SG injection strategy is executed using a mobile pump within the appropriate timeframe, without implementing the RCS inventory make-up strategy
2. The SG injection strategy is applied with a delay due to time constraints, without carrying out additional strategies
3. A combined approach involving both the SG injection strategy and the RCS inventory make-up strategy is implemented when the SG injection strategy is delayed

2.2 Time delay of accident management strategies

After an initiating event, a time delay occurs before accident diagnosis and the implementation of preventive or mitigation strategies. From an accident management perspective, delays arise in diagnosing the accident and deciding on strategies in the Main Control Room (MCR) or Technical Support Center (TSC). From the Emergency Plan (EP) perspective, delays occur between the radiation emergency declaration and the Emergency Response Organization's (ERO) response, including personnel and equipment deployment. This study identifies key delay factors:

1. SG injection strategy diagnosis/decision (30 min)
2. Mobile pump movement/installation for SG injection (20 min)
3. ERO call-up/ready (90 min)
4. RCS depressurization (25 min after SG injection)
5. RCS injection strategy diagnosis/decision with mobile pump installation (15 min after RCS depressurization)

To analyze realistic accident scenarios, research on time delay phenomena was conducted using Table-top Exercise (TTX) data and experimental data from former MCR and TSC personnel, considering portable equipment scenarios.[2] The identified time delay factors and their corresponding delay times were derived from this study.

2.2.1 Time delay scenario of SG injection strategy

Severe Accident analysis differs from Design Basis Accident analysis by incorporating more realistic assumptions. This study defines three time-delay scenarios for applying the SG injection strategy while maintaining conservatism and considering realistic accident conditions. The time delay scenarios for the SG injection strategy are presented in Fig. 3.

Case 1:
Represents an optimal scenario where, following the initiating event, ELAP is promptly declared by the initial ERO, and SG injection is successfully performed using a mobile pump. The total time from the initiating event to strategy execution is 50 minutes.

Case 2:
Describes a situation where ELAP is not immediately declared by the initial ERO. Instead, after the regular ERO is summoned, SG injection is performed using a mobile pump. This process takes 140 minutes from the initiating event to execution.

Case 3:
This scenario occurs when ELAP remains undeclared even after the regular ERO is summoned. SG injection begins only after the SAMG condition (CET>650°C), followed by diagnosis, assessment, and strategy application.

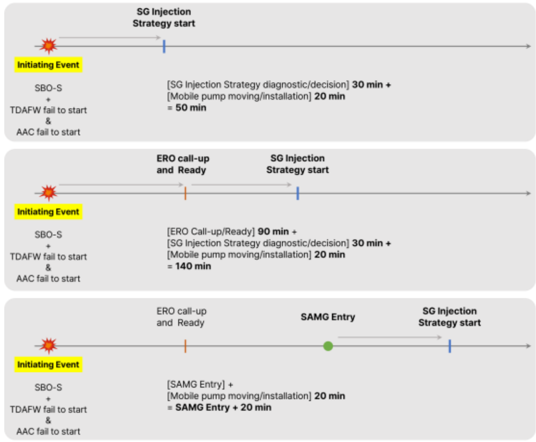


Fig. 3. Time latency case scenario set-up of SG injection strategy

2.2.2 Time delay scenario of SG and RCS injection combine strategy

When the plant shifts from its normal state, accident prevention and mitigation strategies are put into action. If SG injection alone is insufficient to prevent or mitigate the accident, additional strategies are incorporated. The combined scenario setup, which integrates the RCS injection strategy with each SG injection case outlined in Section 2.2.1 and shown in Fig. 4, accounts for a 25-minute delay for RCS depressurization and a 15-minute delay for RCS injection.

Fig. 4. Time latency case scenario set-up of SG and RCS injection Combine strategy

3. MAAP Simulation for Effectiveness Evaluation of ELAP Scenario

The FAUSKE MAAP5 code, utilized to examine the progression of severe accidents, contains packages designed to simulate severe accident scenarios in the OPR1000, including decay heat, oxidation, thermal hydraulics, core material relocation, and rupture models.

3.1 Study on the Effectiveness Evaluation

As a nuclear power plant moves away from normal operation, uncertainty increases, particularly due to limited experimental data and accident experience. The 2020 accident management plan review sought to reduce this uncertainty by incorporating recent research.[4] Various uncertainty sources exist, but this study focused on model parameter uncertainties. Following KHNP's accident management plan, the analysis aimed to mitigate damage progression and contain molten core material within the reactor vessel, assessing uncertainty factors influencing reactor vessel failure. Using the MOSAIQUE program and Monte Carlo sampling, 124 files were generated for uncertainty analysis based on MAAP code parameters.[5]

3.1.1 SG Injection Strategy

A sensitivity analysis of the injection rate was conducted to analyze how the performance of the mobile pump could impact the success of accident mitigation measures, with the feedwater injection rate increasing from 0 kg/s to 35 kg/s in 5 kg/s increments. SG injection rate sensitivity and uncertainty analysis were conducted for each case in Section 2.2.1

3.1.2 SG and RCS Combine Strategy

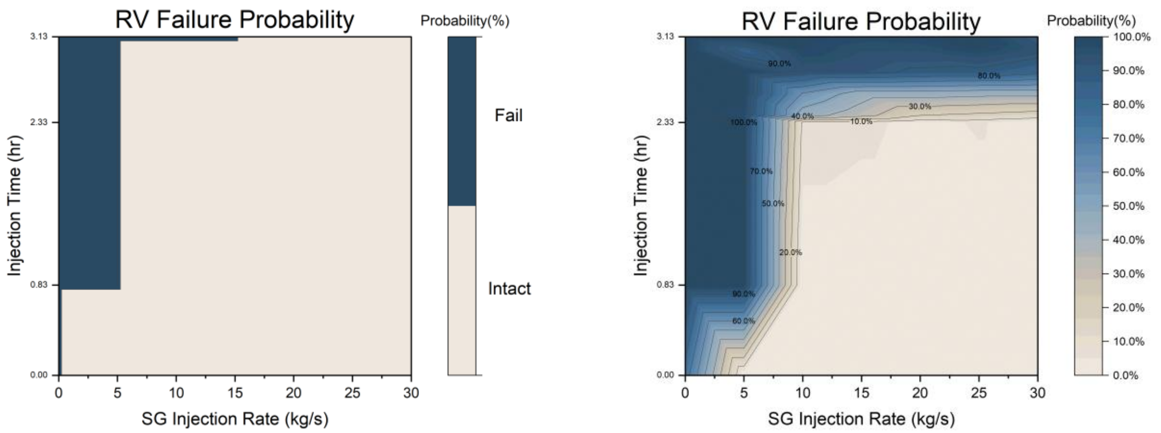
Sensitivity analysis of SG and RCS injection rates, along with an uncertainty analysis, was conducted for the combined strategy. Sensitivity of RCS injection rate was varied from 0 kg/s to 25 kg/s in increments of 5 kg/s.

4. Result and Discussion

To assess whether severe accident uncertainty impacts the effectiveness of accident management strategies, the results were compared with those obtained by executing the strategy without assigning distributions to the uncertainty parameters, which were kept at their default values. Effectiveness of each strategy were evaluated by examining the RV failure, a key target of severe accident management. This was done based on the uncertainty and sensitivity analysis results for each case and visualizing the RV failure probability for each case using equation 1, presented in Fig. 5.

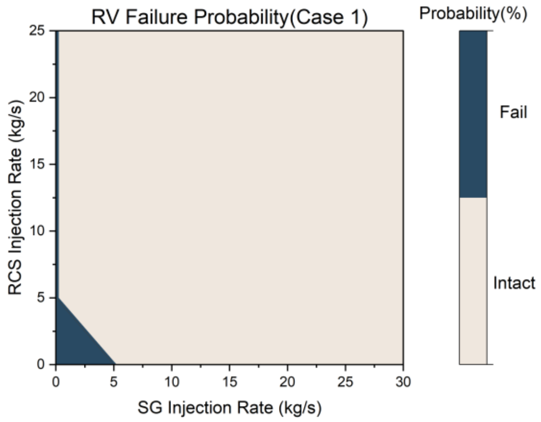
$$P_{RV\ Fail} = \frac{(\#\ of\ total\ RV\ Fail\ case)}{(\#\ of\ Total\ case)} \times 100(\%) \quad (1)$$

When the uncertainty of severe accident phenomena is considered, more conservative results are obtained compared to when this uncertainty is not considered. The effect of uncertainty is most evident in case 2, where the SG injection strategy is delayed by about 90 minutes compared to the ideal scenario. In case 3, where the strategy begins after the SAMG entry condition (CET>650°C) is reached, the RV failure probability stays high due to uncertainty, despite the SG injection rate increasing by more than 15kg/s.

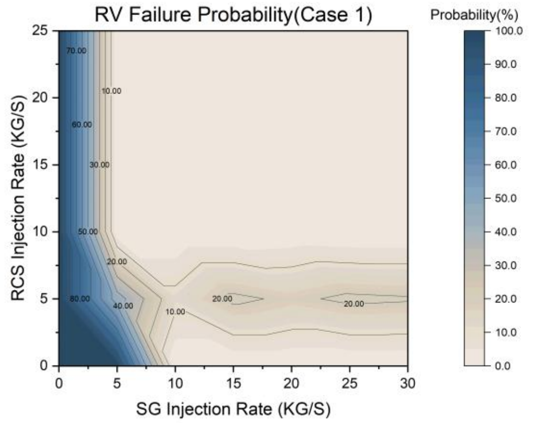


(a) Without Uncertainty (b) With Uncertainty

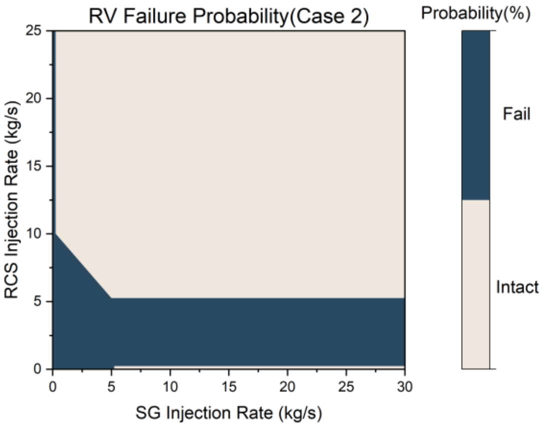
Fig. 5. Effectiveness evaluation of the SG Injection strategy



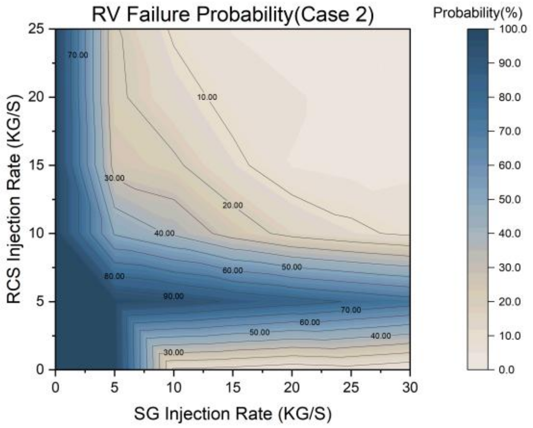
(a) Case 1 Without Uncertainty



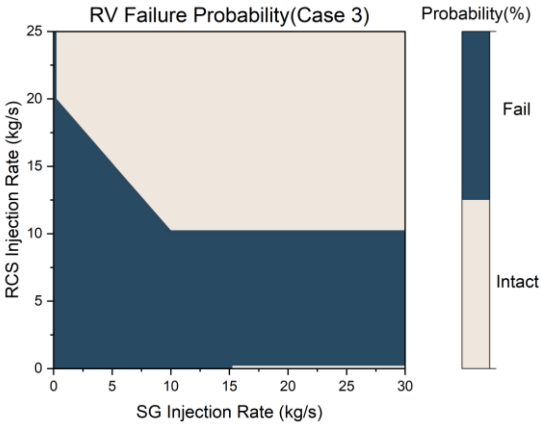
(b) Case 1 With Uncertainty



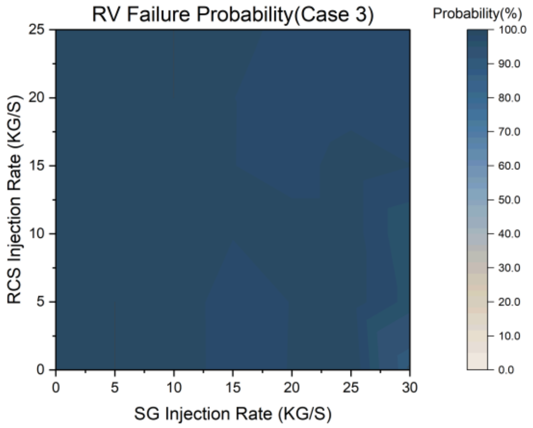
(c) Case 2 Without Uncertainty



(d) Case 2 With Uncertainty



(e) Case 3 Without Uncertainty



(f) Case 3 With Uncertainty

Fig. 6. Effectiveness evaluation of the SG and RCS Injection combine strategy

In Fig. 6, when the SG injection rate is 0 kg/s, neither the SG injection strategy nor the RCS depressurization /injection strategy is executed. However, when the RCS injection rate is 0, the SG injection strategy is implemented, but the RCS depressurization and injection strategies are not. As seen in Fig. 6 - (a), (c), (e), when uncertainty is not considered, if both the SG and RCS injection rates exceed a certain threshold, the RV protection strategy is successful. However, when uncertainty is included, maintaining the RV's integrity becomes challenging. In the combined SG/RCS injection strategy, issues arise if the operator opens the manway of the safety depressurization valve before starting the RCS injection. This situation occurs when, even after reaching the appropriate pressure level for RCS injection, the coolant injection rate is less than the discharge rate at the safety valve, causing a decrease in RCS inventory. This issue is also visible when considering uncertainty, as shown in Fig. 6 (b) and (d) at an RCS injection rate of 5 kg/s. Moreover, in case 3, where there is the longest delay before the SG injection strategy is applied, the gap between results considering and not considering uncertainty is substantial. Even when the SG and RCS injection rates are maximized using a mobile pump, the probability of RV rupture remains high due to uncertainty. The analysis of AMP effectiveness with uncertainty suggests that, in cases of significant time delays, alternative strategies to protect other multi-barrier systems should be prepared, rather than focusing on RV protection.

5. Conclusion

The evaluation of AMP requires considering the uncertainties associated with severe accident phenomena. This study examined the effectiveness of accident management strategies for an Extended SBO scenario, with a particular focus on the impact of external water injection into the SG and RCS via mobile pumps. The findings show that SG and RCS injection using mobile equipment can prevent RV failure under ideal conditions. Specifically, the RV protection strategy proves effective when the SG and RCS injection rates are sufficiently high. However, when uncertainty is considered, the likelihood of RV failure increases, especially in cases where there are significant delays before the SG injection strategy is implemented. Moreover, if the safety depressurization valve is opened prior to RCS injection and the RCS injection rate falls below 10 kg/s, excessive coolant loss may occur, compromising the strategy's effectiveness. Therefore, the ERO must exercise caution in its decision-making.

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