Effectiveness and Practicality of Severe Accident Mitigation Strategies with Uncertainty Considerations

Jemo Ryu[1], Jaehyun Cho[2]

[1]Chung-Ang University, Heukseok-ro 84, Dongjak-gu, Seoul, 06974, Republic of Korea, jemo2000@cau.ac.kr
[2] Chung-Ang University, Heukseok-ro 84, Dongjak-gu, Seoul, 06974, Republic of Korea, jcho@cau.ac.kr

ABSTRACT

Following the Fukushima Daiichi nuclear accident, nuclear power plants (NPPs) in Korea have undergone significant changes in their severe accident management plan. The updated Accident Management Plans (AMP) systematically integrates the specific procedures for Korean NPPs, such as emergency operation procedure, multi-barrier accident coping strategy, and severe accident management guidelines, to effectively respond to design basis accident scenarios. As NPPs deviate from normal operational conditions, the level of uncertainty in our predictions increases. In particular, severe accidents are characterized by limited experimental and empirical data, leading to greater predictive uncertainty. During the accident progression, diagnosing the NPP's state and applying mitigation strategies rely on human judgment, inevitably leading to time delays. This study proposes an evaluation framework that incorporates human reliability analysis (HRA) and the uncertainties associated with severe accident phenomena. Parametric uncertainty analyses were conducted using MAAP5, a severe accident analysis code, and the proposed framework was applied to the OPR1000, a domestic NPP in Korea. The framework, demonstrated through the external steam generator injection strategy in an extended loss of AC power accident, produced visual profiles by evaluating uncertainty, mitigation strategy time delays, and equipment performance. These profiles serve as decision-making indicators for the technical support center in diagnosing NPP status and determining appropriate mitigation strategies during severe accidents. By evaluating the effectiveness of MACST while considering uncertainties and reflecting these uncertainties in the AMP, this study is expected to improve the Severe Accident Management Guideline (SAMG) and thereby enhance the safety of nuclear power plants (NPPs) against severe accident scenarios.

Keywords: severe accident, MAAP5, accident management plan, accident management plans, OPR1000

I. Severe Accident and Multi-barrier Coping Strategy

After the Fukushima Daiichi incident, the OPR-1000 nuclear power plants in Korea have adopted a range of new systems and protocols to both prevent and mitigate accidents, even under extreme circumstances such as severe natural disasters or intentional human actions. Among these enhancements, an external injection line was established to facilitate the supply of water to the steam generator(SG) from outside the plant, and mobile pumps were procured to enable flexible water injection capabilities. Should the Alternative AC(AAC) Diesel Generator fail to restore power after an initial station blackout(SBO), the plant is anticipated to remain in a prolonged power loss condition. Under such circumstances, the plant formally declares an Extended Loss of AC Power(ELAP) and proceeds to implement measures aimed at restoring AC power and removing residual heat. The initial response to ELAP involves attempting to reestablish AC power using a portable generator. If these strategies are unsuccessful, reliance on internal plant equipment is no longer viable for prevention and mitigation, necessitating the deployment of mobile pumps. When restoration of AC power using the mobile generator is not achieved, the next step is to depressurize the SG via the atmospheric dump valve, after which a mobile pump is connected to the external injection line to supply water and sustain secondary side heat removal. The criterion for determining a severe accident is continuously monitoring whether the CET(Core Exit Temperature) exceeds 650°C, and repeatedly performing SG (Steam Generator) depressurization and injection as necessary. Depending on the evolving status of the plant, additional actions such as depressurizing the reactor coolant system(RCS) and injecting water into the RCS using a mobile pump may also be implemented. Figure 1 shows a simplified Plant Damage State Event Tree(PDS-ET) that incorporates accident mitigation strategies utilizing mobile equipment during an initial SBO scenario. Extended loss of all AC power refers to a situation where all alternating current (AC) power sources are lost, making rapid recovery of AC power and the use of on-site fixed equipment malfunctioned. In this scenario, as indicated by all headings up to the AAC heading in Figure 1 being marked as Fail, mobile equipment is used to ensure the safety of the power plant. Figure 2 outlines the sequence for executing external injection strategies following the declaration of ELAP.

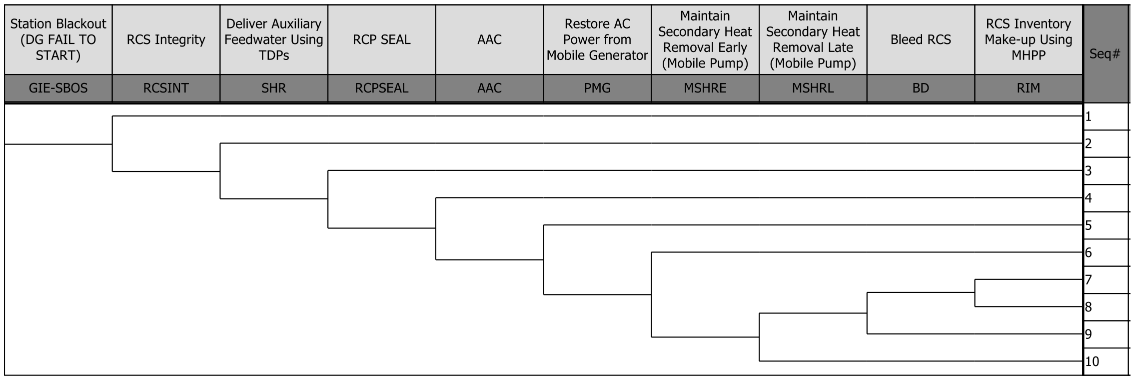


Figure 1. Simplified PDS-ET with Multi-barrier Accident Coping Strategy

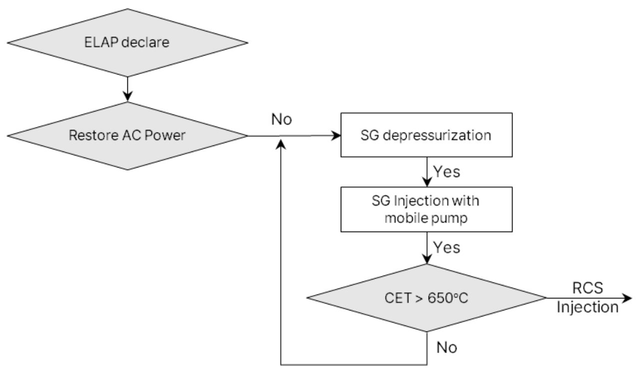


Figure 2. SG External injection strategies in Extended SBO scenario

I.A. SG Injection with Multi-barrier Coping Strategy

To quantify the efficacy of portable pump deployment strategies, three accident sequences were evaluated under sustained failure conditions of both secondary heat removal by turbine-driven auxiliary feedwater and AC power restoration:

1. Timely SG Injection: Mobile pump implementation for steam generator water injection within optimal response windows, absent RCS inventory replenishment measures.
2. Delayed SG Injection: SG injection strategy execution postponed due to operational time lags, without supplementary countermeasures.
3. Combined SG/RCS Make-up: Concurrent SG injection and RCS inventory restoration when SG injection initiation is delayed.

   Notably, Scenario 3 (integrated SG/RCS strategy) falls outside the analytical scope of this study.

II. Time delay of accident management with MACST strategies

After the initiating event occurs, there is inevitably a time delay before the accident diagnosis and the implementation of the preventive/mitigation strategies determined by the operators. When a severe accident such as significant fuel damage or core meltdown occurs, the SAMG(Severe Accident Management Guideline) systematically presents measures to suppress the progression of the accident and minimize the release of radioactive materials to the outside. SAMG is applied in severe accident situations where response is not possible even with Emergency Operating Procedure. From an accident management perspective, there are time delay factors in diagnosing the accident and deciding on the application of preventive/mitigation strategies by the Main Control Room(MCR) or the Technical Support Center(TSC). From the Emergency Plan(EP) perspective, there is a time delay from the radiation emergency declaration to the response of the Emergency Response Organization(ERO) to the plant, and the deployment of personnel and equipment to the site for mission execution. In this study, the major time delay factors were identified as SG injection strategy diagnostic/decision, RCS depressurization, RCS injection strategies diagnostic/decision, ERO ready, and MACST(portable equipment) moving/installation was considered. To consider realistic severe accident scenarios, research on time delay phenomena was conducted[1], and each time delay factors were based on

Table-top Exercise(TTX) data[2], based on experimental data from former MCR and TSC personnel considering portable equipment scenarios. The time delay factors and with each delay time based on the TTX data are as follows:

1. SG injection strategy diagnostic/decision: 30 min(from Initiating Event)
2. mobile pump moving/installation for SG injection: 20 min(from decision)
3. ERO call-up/ready: 90 min(from Initiating Event)
4. RCS depressurization: 25min(after SG injection or CET > 650°C)
5. RCS injection strategy diagnostic/decision and mobile pump moving/installation: 15 min (after RCS depressurization)

Severe accident progression modeling fundamentally diverges from design basis accident assessments through its explicit integration of operational realism. This investigation establishes three temporally distinct implementation pathways for the steam generator (SG) injection protocol, preserving conservative safety margins while reflecting plausible emergency response conditions. The schematic representation of these temporal frameworks is provided in Figure 3.

Case 1: Optimized Response Sequence

Characterizes an ideal emergency protocol execution where:

- ELAP declaration occurs immediately upon incident initiation
- First-responder emergency team deploys mobile pumping systems without delay
- SG injection strategy implementation completes within 50 minutes of ELAP

Case 2: Delayed Organizational Activation

Represents suboptimal organizational response where:

- Initial emergency crew fails to declare ELAP promptly
- Full emergency response organization (ERO) mobilization precedes action
- Mobile pump deployment and SG injection commence 140 minutes of ELAP

Case 3: SAMG-Triggered Intervention

Depicts worst case procedural delay:

- ELAP remains undeclared despite full ERO mobilization
- Strategy initiation requires meeting SAMG entry criteria (CET > 650°C)
- Implementation follows diagnostic confirmation and procedural validation

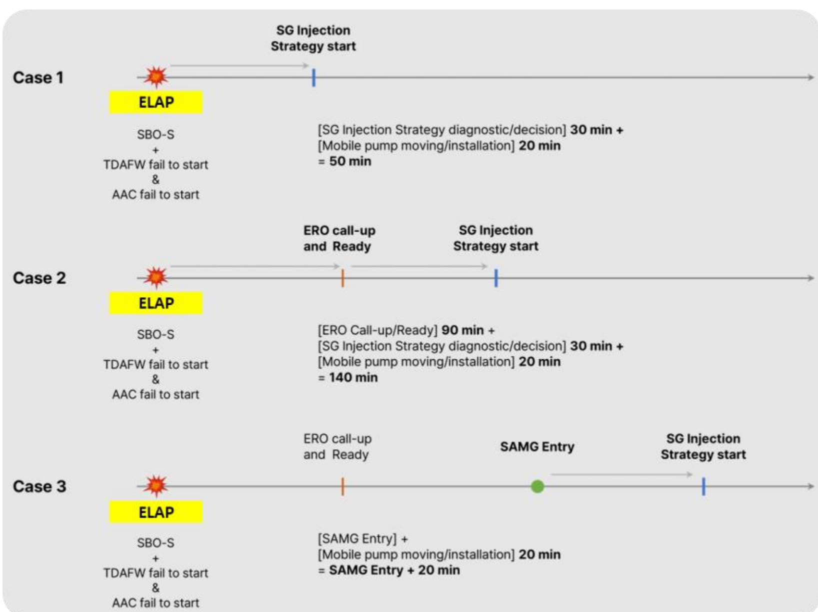


Figure 3. MAAP Simulation for Effectiveness Evaluation of ELAP Cases

III. Effectiveness Assessment of MACST strategies

As nuclear power plants transition from normal operating states to accident conditions, the degree of uncertainty in predicting accident progression increases significantly. This heightened uncertainty is largely attributable to the scarcity of empirical data and limited precedent for severe accident scenarios. Recognizing these challenges, the 2020 revision of the accident management plan in Korea incorporated the latest scientific findings to better address knowledge gaps and improve the reliability of severe accident response strategies.[3]

In the present study, the primary focus was placed on uncertainties arising from model parameters, which are known to exert a substantial influence on accident outcome predictions. The analysis was structured in accordance with the accident management strategy outlined by Korea Hydro & Nuclear Power Co. (KHNP), with the overarching objective of minimizing core damage and ensuring that molten core materials remain confined within the reactor vessel. To systematically explore the impact of parameter uncertainty on reactor vessel failure, a probabilistic approach was adopted.

A set of 27 distinct input parameter combinations was generated for each scenario using Monte Carlo sampling, with each set representing a plausible variation in the key variables that govern RV failure in the MAAP code.[4] Alongside the uncertainty assessment, a sensitivity analysis was performed to determine how variations in mobile pump performance could affect the overall effectiveness of accident mitigation strategies. In this analysis, the feedwater injection rate, a key parameter for maintaining adequate secondary cooling, was systematically adjusted from 0kg/s to 35 kg/s, increasing in steps of 5 kg/s. This approach enabled a detailed evaluation of how changes in injection capacity directly influence the probability of preventing reactor vessel failure.

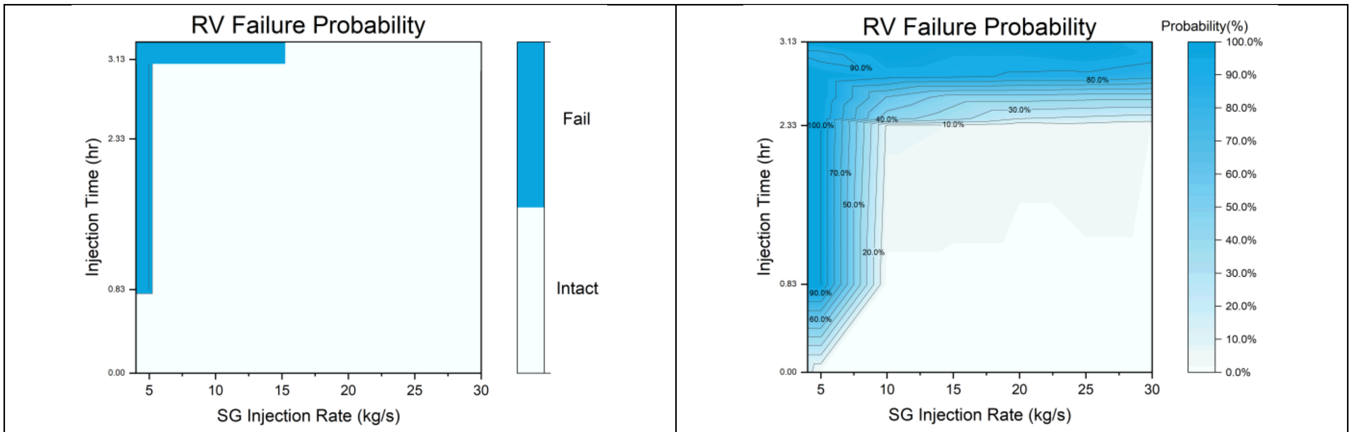
By integrating the outcomes of both the uncertainty and sensitivity analyses, a comprehensive picture of the MACST strategy's robustness was developed. The study mapped the relationships among parameter variability, equipment performance, and accident progression, thereby highlighting the strengths and limitations of current severe accident management protocols under realistic operational challenges. Furthermore, the results for each time-delay scenario, underscore that both prompt implementation and maintaining injection rates above critical thresholds are essential for the successful mitigation of severe accident consequences.

IV. Result and Discussion

To determine how uncertainty in severe accident phenomena affects the performance of accident management strategies, a comparative analysis was performed. This involved contrasting the results of probabilistic simulations, where key model parameters were treated as distributions, with those from deterministic calculations that held all parameters at their default values. The primary criterion for evaluating each strategy was the likelihood of RV failure, which serves as a central indicator of severe accident management effectiveness. For each scenario, the RV failure probability was quantified and visualized using the results of the uncertainty and sensitivity analyses, as illustrated by Equation 1 in Figure 4.

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

The inclusion of uncertainty consistently led to more conservative estimates, with higher projected probabilities of RV failure compared to the deterministic baseline. This effect was particularly pronounced in the scenario where the SG injection strategy was delayed by approximately 90 minutes(Case 2), highlighting how time delays can amplify the impact of RV Failure. In the scenario where mitigation measures were initiated after the SAMG entry threshold(CET > 650°C) was reached(Case 3), the probability of RV failure remained high, even when the SG injection rate exceeded 15 kg/s. In the deterministic results shown in Figure 4(a), the RV Fail Probability is simply divided into fail/intact. However, in Figure 4(b), which reflects code and HRA uncertainties, there is high uncertainty observed in the portions evaluated as intact in the dichotomized results of Figure 4(a). In particular, for Case 3 where the injection time is significantly delayed high probability uncertainty occurs even though a sufficient injection flow rate is achieved. These findings underscore that accounting for uncertainty is essential for realistic and robust assessment of accident management strategies, especially in situations where response actions are not implemented promptly. The purpose of quantification and visualization is to clearly understand the effectiveness of accident management strategies and the impact of uncertainties, and to intuitively provide this information to decision-makers and stakeholders. By presenting how changes in variables affect accident outcomes through numerical data and graphical representations, it enables operators to intuitively recognize critical information during an accident.



(a)Without Uncertainty | (b)With Uncertainty

Figure 4. Effectiveness of the SG Injection strategy

V. CONCLUSIONS

A thorough evaluation of accident management strategies must explicitly address the inherent unpredictability of severe accident phenomena. In this research, the focus was placed on extended loss of AC power scenarios, examining how different mitigation actions, especially those involving external water delivery to the steam generator via mobile pumps, influence overall plant safety. The findings indicate that prompt deployment of mobile injection equipment, coupled with adequate flow rates, is highly effective in safeguarding the reactor vessel from failure. The analysis demonstrated that, while the use of portable equipment for steam generator injection can help prevent reactor vessel failure under optimal conditions, there remains significant uncertainty in the outcome when the injection rates are near the threshold values required for effective mitigation. The results of this study offer valuable insights that can directly inform the revision and enhancement of both the SAMG and the AMP for nuclear power plants in Korea. By systematically analyzing the uncertainties inherent in severe accident phenomena and quantifying the impact of human response delays and equipment performance, the proposed evaluation framework identifies critical factors that influence the effectiveness of accident mitigation strategies. These findings can be leveraged to refine the structure and content of the SAMG, particularly by improving its clarity and visibility for plant operators and emergency response teams. Enhanced clarity in the SAMG will enable more rapid and accurate diagnosis of plant conditions and selection of appropriate mitigation actions during severe accidents. Furthermore, the integration of uncertainty analysis into the AMP ensures that accident management procedures are robust and adaptable to a wide range of unpredictable scenarios. Ultimately, the application of this research will support the continuous improvement of accident management strategies, contributing to the overall safety and resilience of nuclear power plants in the face of severe accident risks.

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