

Development of Level 2 PSA Model for Severe Accident Risk Evaluation of i-SMR

Sein Hong ^a, Jin Hee Park ^b, Sung Min Shin ^b, Jaehyun Cho ^{a*}

^aChung-Ang Univ., 84 Heukseok-ro, Dongjak-gu, Seoul, 06974, Republic of Korea

^bKorea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea

*Corresponding author: jcho@cau.ac.kr

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1. Introduction

Severe accident risk assessment provides a quantitative basis for identifying dominant accident progression paths and evaluating measures to reduce their risk significance. In particular, Level 2 probabilistic safety assessment (PSA) can be used to assess changes in containment response and source term categories (STCs) resulting from additional accident mitigation strategies.

In this study, a simplified Level 2 PSA model is developed for the i-SMR based on core damage sequences derived from Level 1 PSA. Dominant contributors to severe accident risk are identified from the base model, and additional mitigation strategies, including operator action for pressurizer safety relief valve (PSRV) opening and external makeup to the emergency cooling tank (ECT), are incorporated into the model to evaluate their potential risk reduction. The effectiveness of each strategy is quantitatively evaluated by comparing changes in STC fractions before and after strategy implementation. The developed framework provides a basis for risk-informed identification and prioritization of severe accident mitigation measures.

2. Level 2 PSA Base Model for i-SMR

A simplified Level 2 PSA base model was developed for the i-SMR to represent the major accident progression paths affecting reactor vessel (RV) and containment vessel (CV) integrity. The model was quantified to characterize the source term category (STC) distribution and identify dominant accident sequences and risk-significant contributors.

2.1 Development of the Base Model

The Level 2 PSA base model was developed using core damage sequences identified from the i-SMR Level 1 PSA. The sequences were grouped into plant damage states (PDSs) according to relevant characteristics at the time of core damage and subsequent severe accident progression was represented using a containment event tree (CET). The resulting severe accident scenarios were finally classified into STCs according to CV integrity and radioactive release characteristics.

The base model was simplified to retain the major safety functions and severe accident phenomena that

significantly affect the final accident outcome. The principal considerations include reactor coolant system (RCS) depressurization, coolant inventory and core cooling, RV integrity, long-term decay heat removal, and CV integrity. Branch probabilities associated with major severe accident phenomena were quantified through expert elicitation.

The simplified STC logic diagram is shown in Fig. 1.

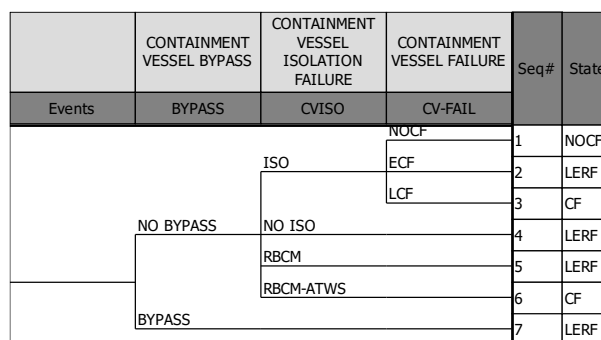


Fig. 1. Simplified STC logic diagram of the i-SMR Level 2 PSA base model.

2.2 STC Results of the Base Model

The developed Level 2 PSA model was quantified using the frequencies of the core damage sequences derived from Level 1 PSA. As shown in Fig. 2, STC-1 was the dominant category, accounting for 62.46% of the total, followed by STC-6 at 32.12%. The remaining STCs showed relatively small contribution. The quantified STC distribution was subsequently used to identify dominant accident progression paths associated with CV failure and large early release conditions.

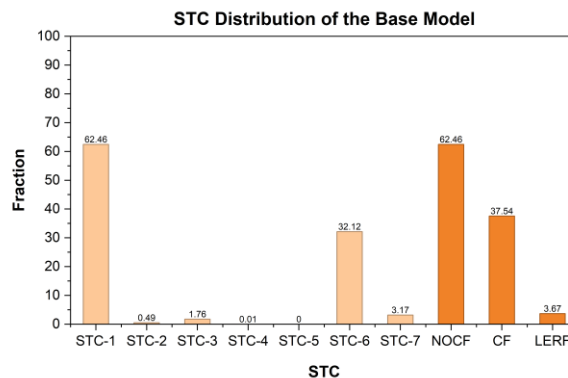


Fig. 2. STC distribution of the Level 2 PSA base model.

2.3 Dominant Contributors to Severe Accident Risk

The contribution of individual accident progression paths was evaluated to identify dominant contributors to severe accident risk. The analysis indicated that the major contributors were associated with 1) high-pressure RV failure due to PSRV opening failure and 2) loss of long-term heat removal following ECT depletion after anticipated transient without scram (ATWS).

One risk-significant accident pathway was associated with failure of RCS depressurization. In the corresponding ATWS sequence, failure of automatic PSRV opening maintains the RCS at high pressure. If sufficient depressurization is not achieved, the RCS pressure may reach RV design pressure, resulting in high-pressure RV failure and subsequent challenge to CV integrity.

Another dominant pathway was associated with long-term loss of heat removal. Following the corresponding ATWS sequence, decay heat is initially removed by the passive auxiliary feedwater system (PAFS) and the passive containment cooling system (PCCS). However, prolonged operation results in depletion of emergency cooling tank (ECT), which serves as the ultimate heat sink for these passive systems. Loss of the ECT ultimately leads to loss of long-term heat removal and an increase in CV pressure, resulting in overpressure. This sequence accounted for approximately 32% of the total CDF and was identified as a dominant contributor in the base model.

3. Evaluation of Additional Accident Mitigation Strategies

Based on the dominant accident sequences identified from the base model, two additional mitigation strategies were selected: (1) manual PSRV opening for RCS depressurization and (2) external water makeup to the ECT for long-term heat removal. Each strategy was incorporated into the corresponding PDS-ET model, and its effectiveness was evaluated based on changes in STC fractions.

3.1 PSRV Operator Action for RCS Depressurization

The first mitigation strategy considered in this study is manual opening of the PSRV by operator action. In the base model, failure of automatic PSRV opening prevents sufficient RCS depressurization and may eventually lead to high-pressure RV failure.

The passive emergency core cooling system (PECCS) provides core cooling through depressurization and recirculation using the emergency depressurization valve (EDV) and emergency recirculation valve (ERV). However, operation of the EDV and ERV is restricted by the spurious opening protection module (SOPM) until the differential pressure between the RV and CV decreases below the specified setpoint of approximately 2MPa. Therefore, manual PSRV opening was considered

as an additional operator action to provide prompt RCS depressurization following failure of automatic PSRV opening and to establish the pressure condition required for subsequent PECCS operation. The modified PDS-ET incorporating this operator action is shown in Fig. 3.

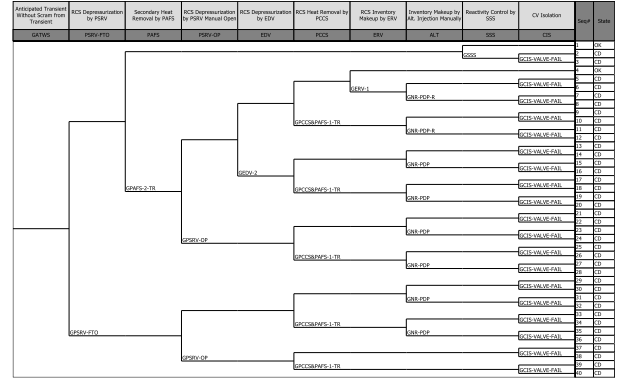


Fig. 3. Simplified PDS-ET with PSRV manual opening strategy.

Thermal-hydraulic analysis using MARS-KS was performed for the target ATWS sequence to determine the success criteria for the operator action. The analysis was used to evaluate the available response time before the RV pressure reaches its limiting condition and the subsequent depressurization behavior required for RV integrity. Based on the calculated transient response, the success criteria include an operator action time of 193s, a maximum RV pressure of 17.7MPa, and achievement of PECCS actuation condition at approximately 4,584s.

Table I. Success criteria for PSRV manual opening.

Strategy	Success Criteria	Assumed/ Required Value
PSRV manual opening	Latest operator action time	193 s
	Maximum RV Pressure	17.7 MPa
	Time to satisfy PECCS actuation condition	4,584 s

Fig. 4 compares the RV pressure before and after implementation of the PSRV manual opening strategy.

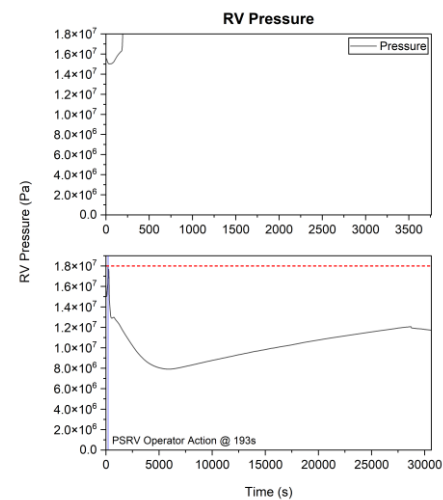


Fig. 4. RV pressure response before and after PSRV manual opening.

3.2 External Makeup to ECT

The second mitigation strategy addresses long-term depletion of ECT, which provides the heat sink required for continued operation of PAFS and PCCS. Prolonged operation of these passive systems gradually reduces the ECT inventory and long-term decay heat removal through PAFS and PCCS eventually becomes unavailable. As a result, decay heat continues to accumulate within the system and can lead to gradual increase in CV pressure. In the base model, this progression can ultimately result in containment overpressure and contribute significantly to unfavorable STCs.

External water makeup to the ECT was therefore considered to maintain sufficient water inventory and extend the operating duration of PAFS and PCCS. The modified PDS-ET incorporating the ECT makeup strategy is shown in Fig. 5.

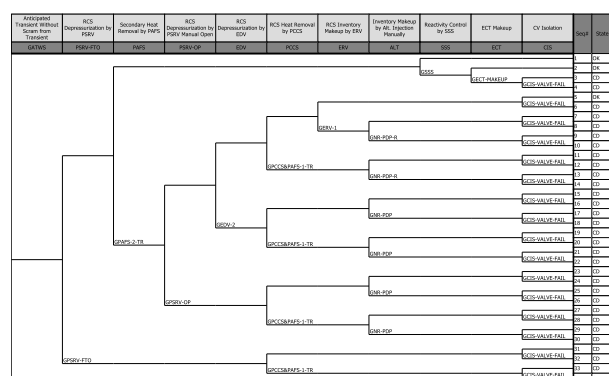


Fig. 5. Simplified PDS-ET with ECT makeup strategy.

MARS-KS analyses were performed to determine the success criteria for the ECT makeup strategy. The calculated ECT inventory behavior was used to estimate the depletion time and the required makeup conditions. Under the analyzed limiting condition, the ECT water level reached the minimum PAFS operating level at approximately 49 h. A makeup initiation time of 24 h and a minimum flow rate of 3.6 kg/s were therefore adopted for the present evaluation.

Table II. Success criteria for external ECT makeup.

Strategy	Success Criteria	Assumed/ Required Value
External ECT makeup	ECT depletion time	~ 49 h
	Makeup initiation time	24 h
	Minimum makeup flow rate	3.6 kg/s
	External water source	Fire Truck (assumption)

Fig. 6 compares the ECT water level before and after implementation of the makeup strategy.

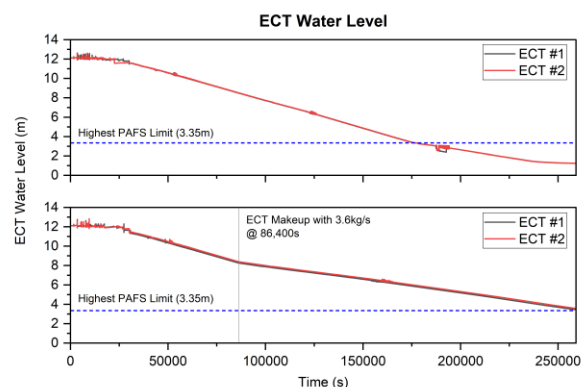


Fig. 6. ECT water level before and after external makeup.

3.3 Effect on Severe Accident Risk

The Level 2 PSA model was requantified after incorporating each mitigation strategy, and the resulting STC fractions were then compared with those of the base model to quantify the risk reduction effectiveness of the proposed strategies, as shown in Fig. 7.

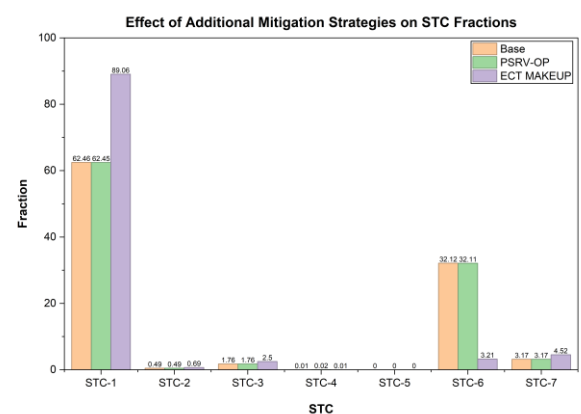


Fig. 7. Effect of additional mitigation strategies on STC fractions.

The PSRV operator action showed only a minor effect on the overall STC distribution. In contrast, external ECT makeup significantly altered the accident progression by maintaining long-term heat removal. STC-6 decreased from 32.12% to 3.21%, while STC-1 increased from 62.46% to 89.06%. As a result, the total containment failure fraction decreased substantially from 33.87% to 5.72%. These results indicate that mitigation strategies targeting dominant accident pathways can substantially reduce the contribution of unfavorable accident outcomes.

These results demonstrate the importance of targeting dominant risk contributors when selecting additional accident mitigation measures. While mitigation of a low-contribution sequence may have only a limited influence on the overall risk profile, mitigation of the dominant ECT depletion sequence results in a substantial redistribution of the STC fractions toward the CV-intact condition.

4. Conclusions

A simplified Level 2 PSA model was developed for the i-SMR based on core damage sequences derived from Level 1 PSA, and dominant contributors to severe accident risk were identified. Two additional mitigation strategies were considered in this study: 1) manual PSRV opening for RCS depressurization and 2) external makeup to the ECT for maintaining long-term heat removal. By incorporating the success conditions of these strategies into the Level 2 PSA model, their effectiveness was quantitatively evaluated based on changes in STC fractions.

The PSRV operator action changed the high-pressure accident progression path, while its influence on the overall STC distribution was limited due to the relatively small contribution of the corresponding sequences. In contrast, external ECT makeup substantially reduced the dominant long-term CV overpressure pathway, decreasing STC-6 from 32.12% to 3.21% and increasing the CV intact STC from 62.46% to 89.06%. However, the quantitative effectiveness of the ECT makeup strategy remains subject to uncertainty in the reliability parameters of the external makeup system, which will be refined in future work.

The results demonstrate that the developed Level 2 PSA model can be used not only to quantify severe accident risk but also to identify dominant vulnerabilities and evaluate the risk reduction potential of additional mitigation strategies. Further refinement of the model will incorporate expert judgement on severe accident phenomenological probabilities and uncertainties to improve the completeness of the Level 2 PSA model.

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