Uncertainty Study of RPV Failure and Operator Actions in an MBLOCA Scenario of the OPR1000

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1. Introduction

Severe accident uncertainty refers to the inherent limitations in precisely predicting the progression of a severe accident in a nuclear power plant. This uncertainty arises from complex physical and chemical phenomena, lack of experimental data, and constraints in modeling and simulation capabilities. Also, in a severe accident environment, significant uncertainties exist in mitigation operations due to limited equipment functionality under harsh conditions and unpredictable human actions.

To address these uncertainties, analyzing various accident progression scenarios is essential for developing robust accident management strategies that remain effective under uncertain conditions. This study investigates the impact of parametric uncertainty and operator interventions to identify major factors influencing Reactor Pressure Vessel (RPV) failure, thereby contributing to the improvement of accident management strategies and enhancing the understanding of severe accident progression.

2. Modelling

2.1 Accident Scenario Selection

A medium-break loss-of-coolant accident (MB LOCA) scenario, one of the scenarios derived from Probabilistic Safety Assessment (PSA), was selected to investigate RPV failure. The scenario involves a 6-inch rupture in the cold-leg, combined with safety injection system failure, thereby leading to a severe accident. The reason for selecting this accident scenario is that, from the perspective of RPV failure prevention, the available time for operator actions is relatively limited, thus providing insights into relation with RPV failure and the impact of operator interventions. The base case scenario results without mitigation strategies are presented in Table I.

Table I: Base case scenario without mitigation operation

Time	Events
0 sec	Initiation of MBLOCA
12 sec	Reactor Scram
172 sec (2.86 min)	RCP Trip
4,901 sec (1.36 hr)	Core Uncover
6,696 sec (1.86 hr)	CET exceeds 1200 F (SAMG entrance)
10,007 sec (2.8 hr)	Relocation of Corium to Lower Head
15,129 sec (4.2 hr)	RPV Failure

※ *SAMG: Severe Accident Management Guideline*

2.2 Parametric Uncertainty in RPV Failure

For the analysis, the MAAP5 code, a widely used for simulating severe accident progression in nuclear power plants, was utilized. The MAAP5 includes various modeling parameters that introduce uncertainties in predicting severe accident behavior.

Based on a literature research, 49 variables were selected from the uncertain input parameters identified in the MAAP5, focusing on those that could introduce uncertainties in the RPV failure. The selected variables were categorized according to phenomena and are presented in Table II. The range and distribution of each parameter were determined based on Reference [1], [2] and engineering judgment.

Table II: Selected uncertain input model parameters

P/M	Uncertain Input Parameter	Num.
TH-PP	FCHFCR, FFRICX, TJBRN, XSTIA, FGBYPA, TAUTO, FWHR, FROUPZ	8
SA-CR	FUPOOL, FDPOOL, FSPOOL, TCLMAX, LMCOL0, LMCOL1, LMCOL2, LMCOL3, EPSCUT, EPSCU2, FZORUP, FACT, FCRDR, FDDP, ENT0, FSGBEN, VFCRCO, FGPOOL, FMOVE, FAOX, IOXIDE, FASSOXID	22
SA-CS	TSPFAL, FPEEL, XDJETO, XLAFALS, FOXBJ, VFENT	6
SA-LP	XGAP0, XGAPLH, IQDPB, XLFALS, FZGAPTOPLH, IOXIDHT, IOCHF	7
SA-LH	ECREPF, ECREPP, EPSPB, FEMISD, FEMISP, FQUEN	6

2.3 Operator Action Modeling

In extreme conditions such as severe accidents, operator action timing contains substantial uncertainties, making it nearly impossible to realistically model. Therefore, operator action timing and its distribution were simply assumed, ensuring that both RPV failure and success cases could be evenly distributed in the dataset to gain insights through the simulation results.

In the selected severe accident scenario, the available mitigation measures to protect the RPV failure include Safety Depressurization System (SDS) operation, primary and secondary system external cooling water injection. The ranges and distributions of these actions assumed for the simulation are presented in Table III.

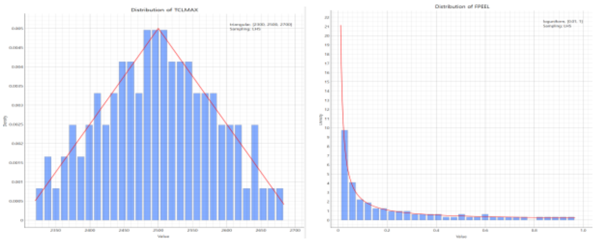
Table III: Assumed Operator Action

Operator Action	Range	Distribution.
Primary system External Injection	30 min ~ 3 hr. 30 min after SMAG entrance	uniform
Secondary system External Injection	30 min ~ 3 hr. 30 min after SMAG entrance	uniform
SDS operation 30 min after SAMG	Success (0.7) / Fail (0.3)	discrete

2.4 Sampling Methodology

The Latin Hypercube Sampling (LHS) method was selected because it effectively samples a broader range of parameter variations, ensuring a more comprehensive representation of uncertainty. For the typical uncertainty analysis, 59 samples are required for bound conditions and 92 samples for interval conditions to achieve a 95/95 confidence and probability level according to the Wilks formula.

However, this analysis differs in purpose with typical uncertainty analyses that evaluate whether simulation results within established confidence intervals meet safety margin requirements. Therefore, adherence to these statistically-derived sample sizes is not relevant for our purpose, which is to broadly examine accident progression uncertainties and gain insights by considering a diverse range of uncertainty-inducing variables. Nevertheless, 100 samples were generated to simulate a wide range of accident progression scenarios. Fig. 1 presents the sampling results of selected parameters with their theoretical distributions.



(a) TCLMAX (b) FPEEL

Fig. 1. Examples of Sampling Result from Uncertain Input Parameters (MAAP5)

3. Simulation Results

3.1 Main Results

A total of 100 simulations were conducted by combining the sampled variables. Of these, 6 simulations encountered computational errors. From the 94 successfully completed, 55 maintained reactor vessel integrity, while the remaining 39 resulted in RPV failure. The Fig. 2 shows a histogram that depicts the distribution of RPV failure times across all simulations. RPV failures predominantly occur within a two-hour period spanning from 2 to 4 hours after severe accident entrance. Notably, one outlier case exhibits significantly delayed failure about 6 hours after severe accident entrance, indicating a different RPV failure progression under specific conditions.

The Fig. 3 presents the total mass of corium accumulated in the lower plenum over time. A clear trend is observed where, upon RPV failure, the corium mass in the lower plenum decreases as molten material is released outside the vessel. However, even after the release, some cases exhibit remaining corium within the lower plenum, with variations in the retained mass.

For RPV intact cases, cooling the corium in the lower plenum is maintained through external water injection, leading to a stabilization of corium mass at a certain value. However, some cases show a continued increase in corium mass in the lower plenum, implying ongoing core degradation or material relocation.

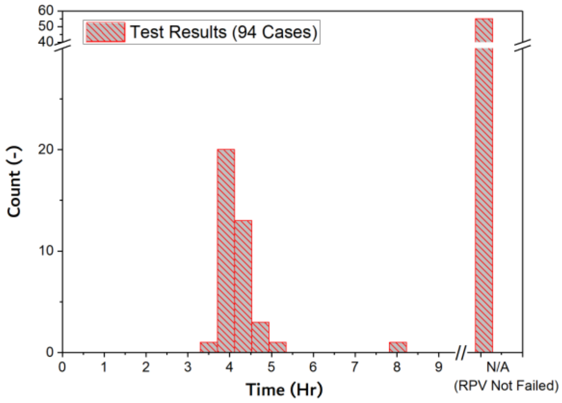


Fig. 2. Histogram of the distribution of RPV Failure times

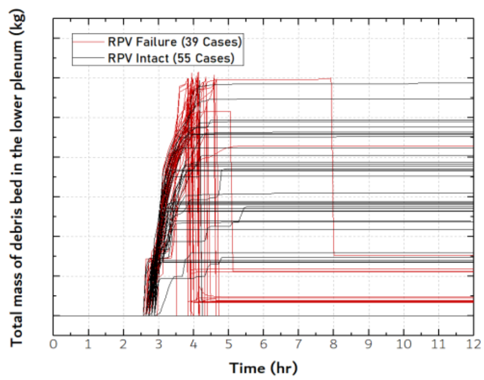


Fig. 3. The variations in total mass of corium accumulated in the lower plenum for the entire simulations

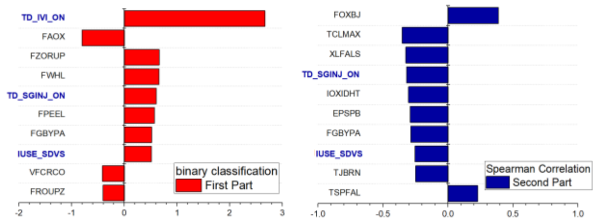
3.2 Key Parameters influencing RPV Failure

Since the variable of interest as a dependent variable for the analysis is RPV failure time, which includes many zero values (indicating cases where the reactor vessel does not fail), a two-part model was applied.

In the first part, a binary classification model determines whether the RPV fails or remains intact (RPV failure time is available or not available), identifying major factors that influence vessel integrity. In the second part, for cases where RPV failure occurs (RPV failure time is available), a continuous regression model analyzes failure timing, providing insights into the factors affecting the progression and timing of vessel failure.

The Fig. 4 displays the 10 most influential variables of the 52 uncertainty parameters considered in the simulation. The key factor preventing RPV failure was identified as the timing of primary system external cooling water injection, while secondary system external water injection and SDS operation had comparatively lesser influence as shown in Fig. 4(a).

However, the analysis of RPV failure timing faces significant limitations due to the imbalance in the data sets as refer to Fig. 4(b). For instance, only one of the 39 vessel failure cases received primary system external cooling water injection prior to RPV failure, which resulted in substantially delayed vessel fail. In the remaining 38 cases, injections were implemented after vessel failure had already occurred, rendering the operator action ineffective as a preventive measure. This skewed distribution prevents drawing statistically meaningful conclusions about the factors influencing failure timing in the second part.



(a) First Part (b) Second Part

Fig. 4. The Top 10 parameters influencing RPV failure

4. Summary

This study analyzed uncertainty of RPV failure under an MBLOCA scenario in OPR1000 nuclear power plants, considering both operator action and input model uncertainties.

Despite accounting for uncertain input model parameters, the results demonstrated that primary system external cooling water injection is the most effective strategy for preventing RPV failure. However, delayed external water injection, even if initiated before vessel failure, may cause crust formation on the upper surface of corium in the lower plenum, potentially reducing cooling efficiency and leading to eventual vessel failure after a significant time lag. Given the limited simulations of the current analysis, extensive sensitivity studies are required to identify boundary cases, which would contribute to establishing more robust and optimized strategies with technical backgrounds.

REFERENCES

[1] EPRI, Severe Accident Uncertainty Quantification and Analysis Using the Modular Accident Analysis Program (MAAP), 2021 Technical Report, 2021

[2] EPRI, Computer Code Manual for MAAP5 – Modular Accident Analysis Program for LWR Power Plants, 2021