Analysis of Uncertainty Parameter Effects on RPV Failure in an MBLOCA Scenario

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***Keywords :** Severe Accident, Uncertainty, RPV Failure, MBLOCA, OPR1000, MAAP5

1. Introduction

Severe accidents at nuclear power plants involve highly complex physical phenomena that occur during the various stages of accident progression. Due to the inherent complexity of the phenomena and the limited availability of experimental data, substantial phenomenological uncertainties exist in the modeling and prediction of severe accident progression. In severe accident analysis, a conservative approach may not be adequate, since an assumption that is conservative for a phenomenon can yield non-conservative outcomes for others. Therefore, severe accident analysis relies on a best-estimate approach that accounts for associated uncertainties, complemented by bounding analyses [1].

Integral severe accident analysis codes such as MAAP and MELCOR employ parametric models to represent complex accident phenomena through user-defined parameters rather than mechanistic descriptions. As a result, predicted accident progression and key output variables may vary significantly depending on parameter selection. Evaluation of uncertainty parameters is therefore essential to characterize the range of possible accident consequences and enhance the reliability of safety assessments and accident management strategies.

A critical implication of these uncertainties is that the effectiveness of accident management strategies themselves may be subject to phenomenological uncertainty, and their protective efficacy may be inherently variable. Accordingly, this study investigates key phenomenological uncertainty parameters affecting reactor pressure vessel (RPV) failure and evaluates how these uncertainties govern the reliability of operator intervention strategies under a representative severe accident scenario.

2. Modelling

The severe accident analysis code MAAP 5.06 was employed in this study. The reference plant is the OPR1000 pressurized water reactor, and the postulated initiating event is a medium-break loss-of-coolant accident (MBLOCA) caused by a 6-inch cold leg rupture. Based on a comprehensive review of relevant literature [2], [3], a total of 49 uncertainty parameters that may influence RPV failure were selected for analysis. The uncertainty parameters used in the modeling are listed in Table I, with their distributions and ranges defined based on values reported in the referenced literature. The number of uncertainty samples was determined based on the Wilks formula. To satisfy the 95%/95% criterion under the second-order Wilks formula, which requires a minimum of 93 samples for a one-sided lower bound, a total of 100 samples were applied in this study to ensure statistical conservatism. Detailed descriptions of the accident scenario are provided in the referenced prior study [4].

Table I: Selected Uncertain Input Model Parameters

Group	Uncertain Input Parameter	Num.
TH	FCHFCR, FFRICX, TJBRN, XSTIA, TAUTO, FGBYPA, FWHL, FROUPZ	8
CR	FUPOOL, FDPOOL, FSPOOL, TCLMAX, LMCOL0, LMCOL1, LMCOL2, LMCOL3, EPSCUT, EPSCU2, FZORUP, FACT, FSGBEN, VFCRCO, FGPOOL, FMOVE, FAOX, IOXIDE, FASSOXID, FPEEL	20
CL	FCRDR, FDDP, ENT0, TSPFAL, XDJETO, XLFALS, FOXBJ, VFENT,	8
LP	XGAP0, XGAPLH, XGAPTOPLH, IQDPB, FZGAPTOPLH, IOXIDHT, IOCHF, EPSPB, FEMISD, FEMISP, FQUEN	11
LH	ECREPF, ECREPP	2
Total		49

TH: Plant thermal hydraulic response
CR: Core melt progression inside the core-region
CL: Core debris relocation dynamics
LP: Core melt progression in the lower plenum
LH: RPV lower head failure modes

Uncertainty analyses were performed under two conditions: (1) without operator intervention, and (2) with operator intervention.

The unmitigated and mitigated cases were evaluated using different figures of merit (FOMs). For the unmitigated case, the FOM was defined as the RPV failure time. For the mitigated case, the FOM was defined as the critical injection timing—the latest time at which primary-side external water injection could be initiated to prevent RPV failure.

In the mitigated case, primary-side external water injection was assumed as the operator action, while other operator actions, such as secondary external water injection and primary-side depressurization, were not considered. For each sampled case, 10 injection initiation times were considered, ranging from 30 minutes to 3 hours and 30 minutes after SAMG entry, in 20-minute intervals. Accordingly, ten injection timing conditions were applied to each of the 100 unmitigated samples, resulting in a total of 1,000 mitigated calculations. This approach allows the critical injection timing for RPV protection in each sampled case.

3. Calculation Results

3.1 Unmitigated Case

Fig. 1 presents the results of the uncertainty analysis, showing the timing of three key events—the onset of severe accident, the relocation of corium to the lower head, and RPV failure—across the sampled cases. The results indicate that uncertainties accumulate and amplify as the accident progresses, resulting in increased dispersion in the predicted timing of successive events. From the results, it is observed that RPV failure may occur up to one hour earlier than the best-estimate prediction.

A sensitivity analysis was performed on the uncertainty parameters affecting RPV failure time in the unmitigated case. The analysis was conducted by varying one parameter at a time while fixing all others at their best-estimate values, thereby isolating the direct effect of each individual input parameter on RPV failure time. Fig. 2 shows the results, excluding the 11 variables that have no effect on the outcome. The horizontal axis represents the degree of linearity between the input and output; a large positive value indicates a strong positive linear relationship, while a large negative value indicates a strong negative linear relationship. The vertical axis represents the normalized magnitude of output variation in response to changes in the input, with larger values indicating a greater relative influence on the RPV failure time. The results indicate that several parameters that strongly influence RPV failure exhibit a high degree of nonlinearity in their relationship with the output. This suggests that RPV failure behavior is governed not by a single dominant phenomenon, but by the complex interaction of multiple severe accident processes. Parameters with a high degree of linearity are relatively predictable and more amenable to straightforward conservative bounding. In contrast, parameters that are both highly influential and highly nonlinear may cause abrupt changes in the output over specific input ranges, making them more difficult to interpret and bound conservatively.

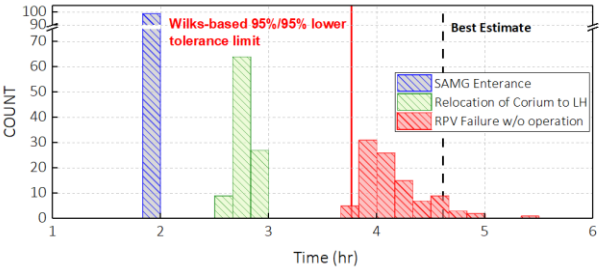

Fig. 1. Uncertainty Analysis Results for RPV Failure Time in the Unmitigated Case

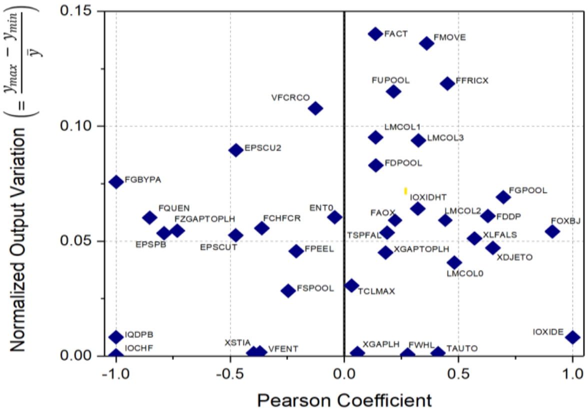

Fig. 2. Sensitivity Analysis Result: Affecting RPV Failure Time in the Unmitigated Case

3.2 Mitigated Case

In the mitigated case, the feasibility of RPV protection was evaluated as a function of the injection initiation time. For each sampled case, 10 injection times were applied at 20-minute intervals starting from 30 minutes after SAMG entry, and the critical injection timing for RPV protection was determined. An example illustrating how the critical injection timing for RPV protection was determined is presented in Table II.

Table II: Example of Critical Injection Timing

No.	Injection Time after SAMG Entry (min)										Critical Timing (min)
	30	50	70	90	110	130	150	170	190	210	
Case 1	O	O	O	O	X	X	X	X	X	X	90
Case 2	O	O	O	O	O	O	X	X	X	X	130
Case 3	O	O	O	O	O	X	X	X	X	X	110
Case 4	O	O	O	O	O	O	O	X	X	X	150
… (Case 100)											

(O: RPV Prevented, X: RPV Failed)

As shown in Fig. 3, when best-estimate parameter values are applied, RPV protection is achievable if operator action is taken within approximately 2 hours of SAMG entry. However, when uncertainties are considered, the allowable time window is reduced to approximately 80 minutes after SAMG entry. This indicates that consideration of phenomenological uncertainties can lead to a meaningful reduction in the permissible time for operator intervention.

The RPV failure probability as a function of injection timing across all sampled cases is presented in Fig. 4. The shaded region in the figure represents the uncertain region in which prevention of RPV failure by operator action cannot be guaranteed. Within this region, a later injection initiation time corresponds to an increasing probability of RPV failure, implying that as corium resides longer in the lower plenum, maintaining vessel integrity becomes increasingly difficult.

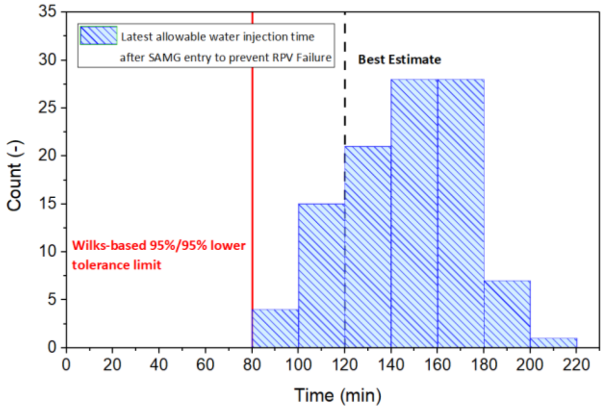

Fig. 3. Critical Injection Timing for RPV Protection Considering Uncertainty

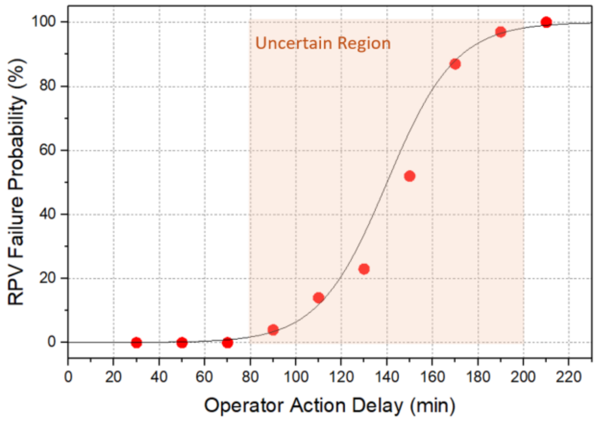

Fig. 4. RPV Failure Probability as a Function of Injection Timing after SAMG Entry

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4. Conclusions

This study evaluated the influence of phenomenological uncertainty parameters on RPV failure and operator intervention under an OPR1000 MBLOCA scenario using MAAP 5.06. In the unmitigated case, uncertainty consideration revealed that RPV failure may occur approximately one hour earlier than the best-estimate prediction. Sensitivity analysis further identified that certain parameters exert a large influence on RPV failure while exhibiting a high degree of nonlinearity, suggesting that RPV failure behavior arises from the complex interaction of multiple severe accident phenomena and cannot be adequately characterized by linear sensitivity alone.

In the mitigated case, the critical timing of primary-side external water injection for RPV protection was evaluated. The results demonstrate that the allowable time for operator action may be significantly reduced when phenomenological uncertainties are considered, compared to the margin estimated from a single best-estimate calculation. These findings highlight the importance of uncertainty-aware accident management strategies and provide a more robust and reliability-informed basis for defining operator action timing under severe accident conditions.

It should be noted that these results are specific to the accident scenario analyzed herein and may differ under alternative initiating events or accident sequences.

REFERENCES

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