

Analysis of Model Parameter Uncertainty in MAAP5 Predictions of Reactor Vessel Failure for APR1400 In-Vessel Retention Assessment

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1. Introduction

In-vessel retention (IVR) aims to prevent the ex-vessel release of core melt by maintaining corium within the reactor vessel. Its feasibility depends on the thermal load and structural response of the lower head, but also on when and how the first vessel breach is predicted. The predicted time margin determines the window available for severe-accident management actions, while the breach mechanism determines the location and form of the loss of vessel integrity. Reactor-vessel failure predictions used to support IVR assessment should therefore be accompanied by a characterization of relevant modeling uncertainty [1].

MAAP5 is an integral severe-accident analysis code used to predict plant response, core degradation, lower-head debris behavior, and vessel failure [2]. Its lower-head models contain parameters for debris-bed porosity and quenching, crust geometry, gap formation, and heat transfer. Uncertainty in these parameters propagates to the calculated failure time and mode. An uncertainty analysis is therefore needed before a nominal parameter set is used to define the vessel-failure margin for an accident-management assessment [3].

This study characterizes the variability of MAAP5-predicted first vessel failure for APR1400 large loss-of-coolant accident (LLOCA) and station blackout (SBO) sequences. Twelve continuous model parameters and the binary gap-boiling option were sampled. All external water injection was disabled to quantify uncertainty in vessel-failure timing and mode without intervention by an IVR action. The resulting distributions provide a no-external-injection baseline for selecting candidate IVR injection times and evaluating the effect of the strategy in subsequent analyses.

2. Methods and Results

2.1. Uncertain Inputs and Sampling

The 12 continuous parameters were assigned triangular distributions defined by a minimum, mode, and maximum. The binary parameter IGCHF disables (0) or enables (1) the critical-heat-flux (CHF) gap-boiling model for in-vessel debris cooling. Table I lists

the assumed inputs. Latin hypercube sampling (LHS) was used to generate 100 cases for each IGCHF state in each accident sequence [4]. Thus, 200 calculations were evaluated for LLOCA and 200 for SBO. The adopted branch size of 100 exceeds 93, the sample count associated with a first-order, two-sided 95/95 Wilks tolerance statement [5].

Table I. Uncertain MAAP5 inputs. Continuous entries show minimum / mode / maximum of each trigonometric distribution. Modes are set as default parameter value of MAAP5. IGCHF is binary.

Parameter	Values	Unit
CDCMLP	1 / 2.75 / 100	—
EPSPB	0.26 / 0.40 / 0.53	—
FHTGAP	0 / 1 / 1	—
FQUEN	0 / 0.2 / 1	—
FZGAPTOPLH	0.3 / 0.5 / 0.7	—
XGAPLH	1e-6 / 1e-5 / 3e-4	m
XGAPPB	0.001 / 0.001 / 0.05	m
XGAPTOPLH	1e-6 / 0.004 / 0.02	m
XXPSML	0.01 / 0.1 / 0.5	m
XXPSMN	0.0001 / 0.0001 / 0.005	m
XXPSMU	0.01 / 0.1 / 0.5	m
HTFB	100 / 300 / 400	W/m ² .°C
IGCHF	0 or 1	—

The sampled inputs cover debris-pool and debris-bed heat transfer (CDCMLP, EPSPB, FQUEN, and HTFB), gap cooling and geometry (FHTGAP, IGCHF, FZGAPTOPLH, XGAPLH, XGAPPB, and XGAPTOPLH), and crust-thickness limits (XXPSML, XXPSMN, and XXPSMU).

2.2. First Vessel-Failure Criterion

MAAP internal event identifiers were interpreted according to the physical stage they represent. The first occurrence of a core-exit temperature above 1200°F (CET1200) marked the reference point for severe-accident entrance. Three vessel-related stages were then distinguished: an earlier gas or fission-product path through an in-core instrumentation (ICI) tube, the first loss of vessel pressure-boundary integrity, and

extensive vessel failure. The ICI-tube event was considered a precursor, not a vessel failure. The first loss of vessel integrity was used to determine when, where, and how the vessel first failed. Extensive vessel failure was treated as a later stage of damage. Therefore, the uncertainty analysis focused on the time to the first vessel failure after CET1200.

Three first-failure identifiers appeared in the analyzed results. TRPTN denotes melt-through of a guide-tube weld after reheating of a frozen debris plug, CRLH denotes lower-head wall creep rupture, and VBPT denotes a supported penetration-tube or gap breach after weld failure. The minimum, quartiles, median, maximum, and failure-mode counts were calculated for each 100-case branch.

2.3. Failure-Time and Failure-Mode Distributions

All 200 LLOCA calculations produced TRPTN as the first failure mode. The failures were highly localized among ICI-tube-bearing lower-head nodes: 191 of 200 occurred at the hottest such node, and the remaining nine at the immediately adjacent node below it. The elapsed-time ranges were 97.140–131.575 min for IGCHF = 0 and 98.581–135.476 min for IGCHF = 1, corresponding to sample spans of 34.435 and 36.895 min. The medians were 109.247 and 109.903 min, respectively; the 0.656-min difference was small relative to the within-branch spread. Figure 1 shows the two LLOCA distributions.

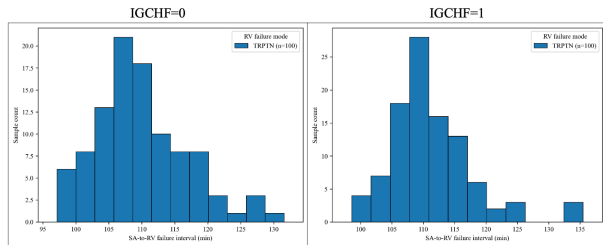


Fig. 1. Distributions of the time to the first reactor vessel failure after CET1200 in the LLOCA cases: (a) IGCHF = 0 and (b) IGCHF = 1 ($n = 100$ each). All first failures were TRPTN.

The SBO distributions were much wider. The elapsed-time ranges were 440.186–732.915 min for IGCHF = 0 and 471.004–737.214 min for IGCHF = 1, with medians of 584.826 and 596.908 min. Unlike LLOCA, SBO produced competing penetration and vessel-wall failures. For IGCHF = 0, the 100 cases comprised 68 TRPTN, 23 CRLH, and nine VBPT failures; for IGCHF = 1, the corresponding counts were 78, 17, and five. The branch medians were later when gap boiling was enabled, but the separately sampled branches are not paired one-factor calculations. Figure 2 and Tables II and III summarize the distributions and failure modes.

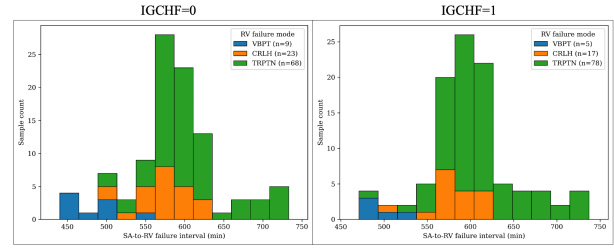


Fig. 2. Distributions of the time to the first reactor vessel failure after CET1200 in SBO: (a) IGCHF = 0 and (b) IGCHF = 1 ($n = 100$ each). Colors denote TRPTN, CRLH, and VBPT failure modes.

Table II. First-vessel-failure time statistics (min after CET1200).

Case	IGCHF	Range [min]	Median
LLOCA	0	97.140–131.575	109.247
LLOCA	1	98.581–135.476	109.903
SBO	0	440.186–732.915	584.826
SBO	1	471.004–737.214	596.908

Table III. Counts of first-vessel-failure modes ($n = 100$ per branch).

Case	IGCHF	First-failure modes
LLOCA	0	TRPTN 100
LLOCA	1	TRPTN 100
SBO	0	TRPTN 68; CRLH 23; VBPT 9
SBO	1	TRPTN 78; CRLH 17; VBPT 5

2.4. Parameter Correlation Analysis

Pearson correlation coefficients were calculated separately for each IGCHF branch between the 12 continuous inputs and the elapsed time from CET1200 to first vessel failure. Positive r indicates that larger parameter values tend to accompany later failure, whereas negative r indicates earlier failure. For $n = 100$, the threshold follows from $t = r\sqrt{(n-2)/(1-r^2)}$ with 98 degrees of freedom; the two-sided 5% critical t value of 1.984 gives $|r| = 0.197$. Therefore, coefficients exceeding this magnitude provide nominal evidence of a nonzero linear correlation, but the threshold does not measure effect size or establish causality. Table IV reports the parameters that met this criterion in at least one branch.

Table IV: Selected Pearson correlations with the CET1200-to-first-vessel-failure interval.

Sequence	Parameter	IGCHF = 0	IGCHF = 1
LLOCA	XXPSMU	−0.357*	−0.285*
LLOCA	XXPSMN	+0.114	+0.437*
LLOCA	EPSPB	+0.224*	+0.022
SBO	FQUEN	+0.362*	+0.281*

* Exceeds the nominal two-sided 5% threshold for $n = 100$ ($|r| = 0.197$); no multiple-comparison correction was applied. Positive r denotes a longer failure interval.

In LLOCA, XXPSMU, the allowable maximum upper-crust thickness, was negatively associated with

the failure interval in both branches ($r = -0.357$ and -0.285 for IGCHF = 0 and 1). XXPSMN, the minimum lower-crust thickness, showed its strongest positive association for IGCHF = 1 ($r = +0.437$), whereas EPSPB, the lower-head particulate-bed porosity, was positively associated only for IGCHF = 0 ($r = +0.224$). Because every LLOCA first failure was TRPTN at an ICI-tube location, these coefficients mainly screen the plug/weld thermal-failure path rather than lower-head wall creep. The correlation directions are physically consistent with changes in heat retention and the thermal-buffering role of the crust and debris bed. However, correlation alone cannot demonstrate that these were the mechanisms controlling failure.

For SBO, FQUEN was the only parameter above the nominal threshold in both branches ($r = +0.362$ and $+0.281$). FQUEN multiplies the critical heat flux used for quenching lower-head debris by overlying water; the positive coefficients therefore associate greater modeled quench capacity with later failure. The smaller r for IGCHF = 1 does not, by itself, show that gap boiling weakened the role of FQUEN, because the two IGCHF branches used different LHS parameter combinations. In addition, the SBO correlation pooled TRPTN, CRLH, and VBPT cases; it therefore cannot distinguish whether FQUEN delayed failure within a given mode, changed which mode occurred, or both.

The coefficients are univariate linear screening measures, not a global sensitivity ranking. Twelve correlations were tested per branch without a multiple-comparison correction, and the largest R^2 was 0.191; nonlinear responses and parameter interactions may therefore remain important. Each IGCHF branch was generated from an independent LHS ensemble, so an IGCHF = 0 case was not paired with an otherwise identical IGCHF = 1 case. Differences in medians or correlation coefficients therefore cannot be attributed solely to IGCHF; isolating its effect would require paired samples in which only IGCHF is changed.

3. Conclusions

This study quantified the effects of selected MAAP5 model-parameter uncertainties on the timing and mode of the first reactor vessel failure for APR1400 LLOCA and SBO sequences without external water injection. Twelve continuous parameters related to lower-head debris behavior and cooling were sampled together with the binary IGCHF option. For each accident sequence, 100 calculations were performed for IGCHF = 0 and another 100 for IGCHF = 1. The main response was the time to the first vessel failure after CET1200, together with the failure mode and location. The effects of the parameter uncertainties differed between the two accident sequences. In LLOCA, the time to first vessel failure after CET1200 ranged from approximately 97 to 135 min, and all 200 cases produced TRPTN as the first failure mode. Most failures occurred at the hottest ICI-tube-bearing lower-head node. In SBO, the corresponding time ranged from approximately 440 to

737 min, and TRPTN, CRLH, and VBPT failures were observed. The correlation analysis identified upper- and lower-crust thickness and debris-bed porosity as the main LLOCA-related parameters. FQUEN was the only parameter satisfying the nominal correlation criterion in both SBO branches. These results provide an uncertainty-informed baseline for reactor vessel failure without external water injection. The baseline can support the selection of candidate IVR injection times and comparison of mitigated calculations with the unmitigated accident progression. When subsequent IVR calculations use the same sampled parameter sets, the results can also help assess whether a predicted IVR success or failure remains consistent under MAAP5 parameter uncertainty rather than occurring only for a nominal input set. The reported ranges are conditional on the parameters, distributions, ranges, and accident conditions considered in this study. Nevertheless, they provide quantitative information on the uncertainty of vessel-failure timing and mode that can be used in subsequent IVR strategy assessments.

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