Sensitivity Analysis of Branch Probabilities in Level 2 PSA

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1. Introduction

Level 2 probabilistic safety assessment (PSA) quantifies the occurrence frequencies of source term categories (STCs) by modeling severe accident progression and changes in containment integrity following core damage. Decomposition event trees (DETs) represent alternative branches and conditional probabilities of Level 2 phenomena and are important factors governing the STC distribution. Therefore, examining and verifying the effects of DET branch probabilities is important.

In this study, the base Level 2 PSA model for Reference Plant A was quantified using AIMS-L2, and single-variable sensitivity analyses were performed for the branch probabilities associated with three model variables: MELTSTOP, CFC, and DBCOOL. Their individual effects and the resulting redistribution of accident frequencies among the STCs were compared.

2. Methods

2.1 Base-Case Quantification

The base model for Reference Plant A comprised 111 plant damage states (PDSs), 160 containment event tree (CET) end states, 18 STCs, and 11 DETs. AIMS-L2 input checks confirmed that there were no anomalies in the PDS/STC logic definitions or CET-DET linkages before quantification. The total core damage frequency (CDF) was calculated to be 1.597E-5/yr. Because only Level 2 DET branch probabilities were varied, the total CDF and PDS frequencies remained unchanged in all sensitivity cases.

2.2 Sensitivity Analysis Conditions

Based on the base-case STC distribution and the branching structures of the DETs, MELTSTOP, CFC, and DBCOOL were selected because they are linked to the dominant STCs and represent distinct accident-progression pathways. STC-1 and STC-2 together account for 82.8567% of the base CDF. MELTSTOP redistributes frequency between STC-1 and STC-2, CFC between STC-2 and STC-5, STC-6, STC-8, and STC-9, and DBCOOL between STC-2 and STC-11. These variables therefore enable comparison of changes in the dominant STCs and frequency redistribution to different downstream STCs.

To isolate the effect of each variable, all other inputs were held at their base values, and the failure-branch probabilities associated with one analysis variable at a time were scaled by the same factor. The cases in which the base failure probabilities were multiplied by 0.1 and 10 were defined as the 0.1× and 10× cases, respectively; the complementary branch probabilities were adjusted so that the probabilities summed to 1. These hypothetical conditions were established to examine changes in the STC distribution in response to order-of-magnitude variations and do not represent statistical confidence intervals. Depending on the initial condition, the base MELTSTOP failure probabilities were 1.0E-3 and 1.7E-2. The base failure probabilities for CFC and DBCOOL were 1.0E-2 and 1.0E-3, respectively. The analysis conditions are summarized in Table 1.

Table 1. Sensitivity Analysis Inputs

DET	Base Case	0.1× Case	10× Case
MELTSTOP G1	1.0E-3	1.0E-4	1.0E-2
MELTSTOP G3	1.7E-2	1.7E-3	1.7E-1
CFC	1.0E-2	1.0E-3	1.0E-1
DBCOOL G1/G2	1.0E-3	1.0E-4	1.0E-2

3. Results

3.1 Base-Case STC Distribution

STC-2, STC-1, and STC-12 accounted for 60.3267%, 22.5300%, and 7.6910%, respectively, with a combined contribution of 90.5477%. The RVFAIL-NO CF and MELTSTOP pathways following containment isolation were dominant, followed by the RBCM- and SGTR-related end states. The major base-case STC results are summarized in Table 2.

Table 2. Base-Case STC Results

STC	Representative Path	Frequency (/yr)	Fraction (%)
2	ISOL-RVFAIL-NO CF	9.636E-6	60.3267
1	ISOL-MELTSTOP	3.599E-6	22.5300
12	NO BYP-RBCM	1.228E-6	7.6910
18	SGTR	1.143E-6	7.1527
9	ISOL-RVFAIL-LCF-RUP-WET	1.299E-7	0.8131
Others	13 STCs	2.341E-7	1.4865

3.2 Sensitivity of Branch Probabilities

Because the sum of the STC frequencies and the PDS frequencies remained unchanged from the base case, the observed differences represent redistribution of the fixed CDF among the STCs rather than changes in CDF. The STCs showing concentrated changes under the 0.1× and 10× conditions are presented in Table 3. The change column reports the difference between the 10× and base cases.

Table 3. STC Sensitivity Results

Parameter	STC	0.1× Case	Base Case	10× Case	Change (pp)
MELTSTOP	1	22.5722	22.5300	22.1086	-0.4214
	2	60.2853	60.3267	60.7405	+0.4138
CFC	2	60.8656	60.3267	54.9383	-5.3884
	5,6, 8,9	1.4544	1.9936	7.3875	+5.3939
DBCOOL	2	60.3811	60.3267	59.7832	-0.5435
	11	0.0060	0.0604	0.6039	+0.5435

Increasing the MELTSTOP failure probability by a factor of 10 decreased STC-1 by 0.4214 percentage points and increased STC-2 by 0.4138 percentage points. Under the 10× DBCOOL condition, STC-2 decreased by 0.5435 percentage points and STC-11 increased by the same amount. In particular, STC-11 increased from 0.0604% to 0.6039%, showing a large relative change, although its contribution to the total CDF remained limited.

Under the 10× CFC condition, STC-2 decreased from 60.3267% to 54.9383%, a change of 5.3884 percentage points, whereas the combined fraction of STC-5, STC-6, STC-8, and STC-9 increased from 1.9936% to 7.3875%, a change of 5.3939 percentage points. The opposite trend was observed under the 0.1× condition. Based on the maximum absolute change in STC fraction, the order of influence was CFC, DBCOOL, and MELTSTOP.

3.3 CET Pathway-Based Interpretation

To identify the direction of the STC changes, the frequencies of representative CETs showing notable changes under the 10× conditions were traced, and the results are presented in Table 4. Under the MELTSTOP condition, the frequency of CET-77 decreased, whereas that of CET-86, which leads to STC-2 within the same accident progression, increased. Under the CFC condition, CET-10 decreased, whereas CET-25 and other CETs associated with STC-5, STC-6, STC-8, and STC-9 increased. Under the DBCOOL condition, part of the CET-10 frequency shifted to CET-11, which has the basemat melt-through (BMT) end state.

Table 4. CET Frequency Changes

Parameter	CET/ STC	Base Case (/yr)	10× Case (/yr)	Change (/yr)
MELTSTOP	77/1	2.380E-7	2.009E-7	-3.71E-8
	86/2	3.415E-6	3.450E-6	+3.50E-8
CFC	10/2	5.921E-6	5.383E-6	-5.38E-7
	25/5	2.377E-8	2.247E-7	+2.009E-7
DBCOOL	10/2	5.921E-6	5.868E-6	-5.30E-8
	11/11	5.927E-9	5.927E-8	+5.334E-8

Changes in branch probabilities redistributed the fixed PDS frequencies among CETs and STCs without changing the total CDF. CFC shifted frequency from STC-2 to several alternative STCs, DBCOOL produced complementary changes between STC-2 and STC-11, and MELTSTOP resulted in only a small redistribution between the two major STCs.

4. Conclusions

In the AIMS-L2-based Level 2 PSA for Reference Plant A, the base CDF was 1.597E-5/yr, and the top five STCs accounted for 98.5135% of the total. The single-variable sensitivity analyses of the three variables showed that CFC produced the largest redistribution between STC-2 and several alternative STCs. DBCOOL produced a large relative increase in STC-11, but its overall effect was limited, whereas MELTSTOP had the smallest effect among the three variables. These results provide a screening basis for identifying severe accident branch probabilities that warrant priority review in Level 2 PSA. Future work should quantify uncertainty intervals for the STC distribution by accounting for the probability distributions and correlations of the input variables. In addition, representative accident sequences showing high sensitivity should be analyzed using MELCOR to assess severe accident progression and fission product behavior and to quantify sequence-specific source terms.

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