

For the Level 2 analysis, varying every MAAP5 model and control input is impractical. The uncertainty set was therefore selected following the OPR1000 source-term uncertainty procedure previously applied in Level 2 PSA [5] and the MAAP5 uncertainty-analysis guidance and candidate parameter groups recommended by Fauske & Associates (FAI). Parameters were retained when they could influence severe-accident progression or radionuclide release. The selected groups cover core-melt progression, lower-vessel accident progression, molten-core-concrete interaction, fission-product and aerosol behavior, and selected accident-sequence assumptions. Distribution forms were assigned according to the available information: triangular distributions were used

when a preferred value and lower and upper bounds were available, uniform distributions when only a defensible range was available, and discrete distributions for alternative model choices. A total of 124 Level 2 parameter sets were sampled and propagated through MAAP5.

For the Level 3 analysis, the MACCS uncertainty set was selected with reference to the SOARCA Surry uncertainty analysis, particularly NUREG/CR-7262 Table 4-16 [4]. Rather than varying all MACCS inputs, the sampled set was limited to parameter groups that can affect the 30-day L-TEDE consequence calculation, including atmospheric dispersion, wet and dry deposition, shielding and protection, and other dose-related consequence-model inputs. The probability distributions were adopted or adapted from the corresponding SOARCA characterizations. Emergency-response parameters were excluded because the present calculation takes no evacuation or relocation credit. Meteorology was not included in the epistemic parameter sample; the full-year site weather record is evaluated internally by MACCS as 8,760 meteorological sequences and is treated as a separate aleatory layer.

Table II. Uncertainty parameter groups and treatment.

Analysis stage	Uncertainty group	Selection basis	Treatment
Level 2 / MAAP5	Core-melt and lower-vessel progression	FAI guidance and previous OPR1000 UA [5]	Triangular / uniform / discrete
Level 2 / MAAP5	MCCI and fission-product/aerosol behavior	FAI guidance and previous OPR1000 UA [5]	Triangular / uniform / discrete
Level 2 / MAAP5	Accident-sequence/input assumptions	Representative-STC input uncertainty	Parameter-specific
Level 3 / MACCS	Dispersion, deposition, shielding/protection, and dose-related inputs	NUREG/CR-7262 Table 4-16 [4]	NUREG-based probability distributions
Level 3 / MACCS	Emergency response	No evacuation or relocation credit	Excluded
Meteorology	Full-year site weather	Hanul site data	8,760 internal MACCS sequences

2.3 Sampling and Level 2-Level 3 Coupling

The 124 MACCS parameter vectors were generated by simple random sampling (SRS) from the distributions described above. The Level 2 source-term samples and Level 3 parameter samples were generated independently. Because no cross-level correlation was prescribed, the Level 3 sample indices were randomly permuted and paired one-to-one, without replacement, with the 124 Level 2 source terms. The resulting set contains 124 paired cases, each with one MAAP5-derived source term and one MACCS parameter vector. This random 124-to-124 coupling uses every marginal sample once, avoids an artificial rank-to-rank correspondence, and provides a computationally efficient Monte Carlo representation of the independent Level 2-Level 3 input space without performing the full 124 x 124 cross-combination. Each paired case was assigned an equal outer weight of 1/124.

For each paired case, the sampled source term and MACCS model parameters were fixed before the meteorological calculation. MACCS then evaluated 8,760 meteorological sequences from the same full-year Hanul

site data. Meteorology is therefore treated as a nested aleatory layer rather than as another outer SRS parameter. For each paired case, MACCS produces a weather-dependent consequence distribution represented in the output by 33 dose-exceedance-probability points; these conditional distributions are retained for the integration in Section 2.4.

2.4 Weather-Integrated Consequence Distribution

For paired case i , the conditional complementary cumulative distribution function (CCDF) is defined as

$$G_i(d) = P_W(D > d | S_i, \theta_i) \quad (1)$$

In Eq. (1) D is the consequence dose, d is a specified dose level, and P_W denotes probability over the meteorological sequences evaluated internally by MACCS. Here, S_i denotes the MAAP5-derived Level 2 source term input for paired case i , and θ_i denotes the corresponding Level 3 MACCS consequence model parameter vector.

The corresponding cumulative distribution is $F_i(d) = 1 - G_i(d)$. Because the 33 native dose coordinates differ among the paired cases, the conditional distributions cannot be averaged by point index. A common dose support is constructed from the sorted union of all native dose coordinates, and each conditional CDF is evaluated at those common dose locations before probability averaging.

For a common dose d located between adjacent native points $d_{i,k}$ and $d_{i,k+1}$, the cumulative probability is evaluated using piecewise linear interpolation

$$\tilde{F}_i(d) = F_{i,k} + \frac{d - d_{i,k}}{d_{i,k+1} - d_{i,k}} (F_{i,k+1} - F_{i,k}) \quad (2)$$

Linear interpolation was selected because no additional information is available on the distribution shape between the reported points. This preserves the native probabilities and CDF monotonicity without imposing a parametric form. If a common dose coincides with a native point, the original probability is retained. For doses below the first native point, the CDF is anchored at $F_i(0) = 1 - P_i(D > 0)$ and linearly connected to the first native point. For doses above the case-specific maximum consequence, $F_i(d) = 1$ is assigned.

With equal outer weights, the integrated consequence distribution is obtained by averaging probabilities at the same dose level,

$$F_{mix}(d) = \frac{1}{N} \sum_{i=1}^N \tilde{F}_i(d), \quad N = 124 \quad (3)$$

Equation (3) is a mixture of the conditional weather distributions: dose values are not averaged, and percentiles are not averaged across cases. Instead, the cumulative probability at each fixed dose is averaged over the Level 2-Level 3 epistemic cases. The resulting consequence percentiles are then obtained from the integrated distribution itself,

$$C_p = F_{mix}^{-1}(p), \quad p = 0.05, 0.95 \quad (4)$$

while the mixture mean is calculated independently by averaging the MACCS-reported weather mean over the 124 coupled cases. A parallel calculation using interpolation in log-dose space changed the principal consequence quantiles by less than 0.3%, indicating that the final P05-P95 characterization is not materially controlled by the interpolation coordinate.

3. Application and Results for OPR1000

3.1 Level 2 Source-Term Uncertainty

Table III summarizes the Level 2 Cs release-fraction results for the two selected STCs. The release fraction is used as a normalized measure of source-term magnitude, allowing the two release regimes to be compared independently of the initial Cs inventory. STC-02 shows a broad relative spread at small release fractions, whereas STC-20 remains in a high-release range because of the containment-bypass pathway.

Table III. Level 2 Cs release-fraction results.

STC	Base RF	Mean RF	Wilks 95/95 upper
STC-02	8.498E-04	1.774E-03	4.045E-03
STC-20	6.694E-01	7.865E-01	9.354E-01

RF denotes the Cs release fraction. The Wilks value is the third-order one-sided 95/95 upper tolerance estimator for the Level 2 sample.

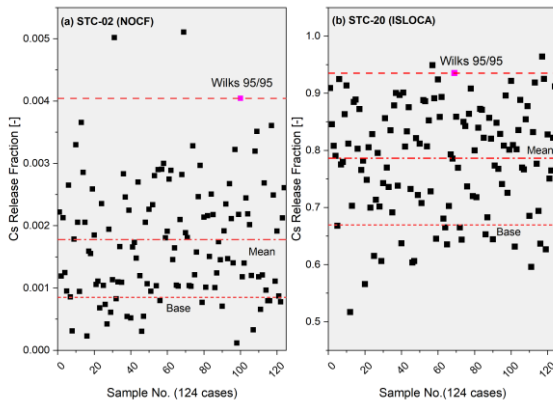


Fig. 2. Level 2 Cs release-fraction distributions.

Figure 2 shows all 124 MAAP5 source-term samples together with the base value, sample mean, and the third-order one-sided Wilks 95/95 upper tolerance estimator. The Level 2 Wilks marker is distinct from the P95 consequence reported in Section 3.2: the former is an order-statistic tolerance estimate of source-term uncertainty, whereas the latter is a quantile of the integrated Level 2-Level 3-weather consequence distribution.

3.2 Integrated Consequence Uncertainty

The consequence endpoint is the 30-day L-TEDE (lifetime total effective dose equivalent) at the exclusion area boundary (EAB). The same full-year Hanul meteorological data were used for every paired case, and

no evacuation or relocation credit was applied. In Fig. 3, each thin curve is the conditional weather CCDF for one paired Level 2-Level 3 case, the dashed curve is the nominal base-case weather distribution, and the thick curve is the integrated mixture from Eq. (3).

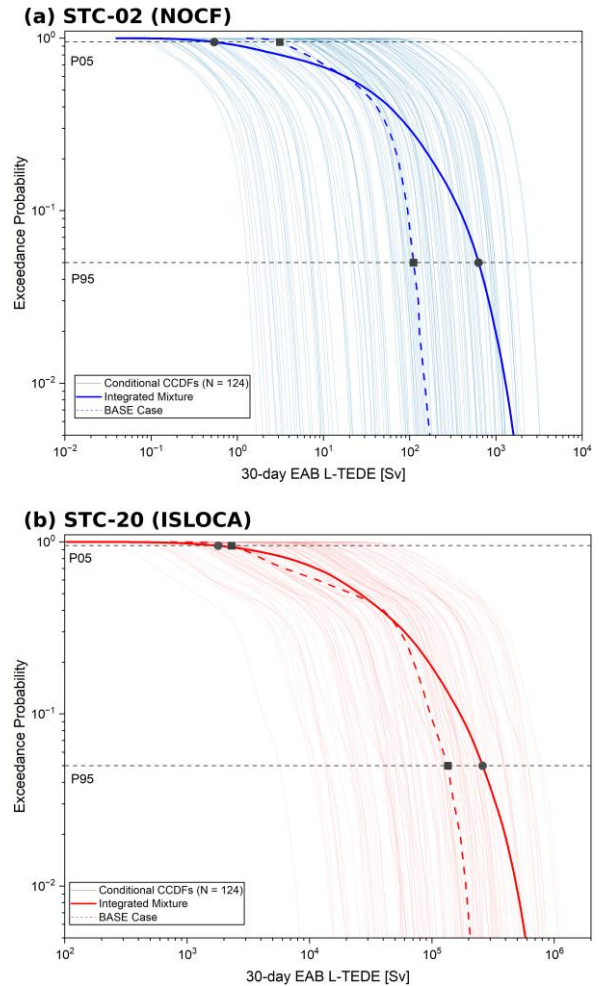


Fig. 3. Integrated consequence CCDFs

Table IV. 30-day EAB L-TEDE results [Sv].

STC	Distribution	P05	Mean	P95
STC-02	Base case	3.11	40.1	111
	Integrated mixture	0.542	132.2	630.4
STC-20	Base case	2.306E+03	3.990E+04	1.350E+05
	Integrated mixture	1.793E+03	6.372E+04	2.603E+05

The integrated mixture broadens the consequence characterization relative to the nominal base case. For STC-02, the mean increases from 40.1 to 132.2 Sv and the P95 increases from 111 to 630.4 Sv, approximately factors of 3.3 and 5.7, respectively. For STC-20, the corresponding increases are from 3.990E+04 to 6.372E+04 Sv for the mean and from 1.350E+05 to 2.603E+05 Sv for P95, approximately factors of 1.6 and 1.9. The P05 decreases in both cases, showing that the propagated epistemic variability broadens both sides of the weather-dependent consequence distribution rather than shifting only the upper tail.

The base-case CCDF already contains meteorological variability because it is evaluated over the same 8,760 sequences. Therefore, the additional spread between the

base-case and integrated distributions reflects the combined Level 2 source-term and Level 3 model variability superimposed on the meteorological distribution. The stronger relative broadening for STC-02 indicates that uncertainty treatment can materially change the horizontal consequence location of a high-frequency, low-release category on an F-C plot.

4. Discussion and Conclusions

This study developed the consequence-axis component of uncertainty-informed F-C characterization by integrating Level 2 source-term uncertainty, Level 3 consequence-model uncertainty, and meteorological variability for two OPR1000 source-term categories. Independently generated Level 2 and Level 3 samples were coupled by one-to-one random pairing, and MACCS internally evaluated 8,760 meteorological sequences for each paired case.

The conditional MACCS weather CCDFs were retained rather than reduced to single weather-mean doses. After mapping the distributions to a common dose support, probabilities were averaged at identical dose levels to obtain an integrated mixture characterized by P05, mean, and P95. The resulting broadening, particularly in the upper consequence range, shows that the choice of consequence representation can materially change the horizontal location and margin of an STC on the F-C plane. Thus, the present results provide a consequence-axis basis for representing an STC by a mean value with P05-P95 uncertainty bounds before frequency uncertainty is introduced.

The present application is limited to two representative STCs and assumes statistical independence between the Level 2 and Level 3 samples during random pairing; known cross-level dependencies would require joint sampling. The reported consequence P05 and P95 are quantiles of the integrated mixture and are distinct from Wilks 95/95 tolerance limits. Although demonstrated for OPR1000, the integration procedure is not specific to large-LWR geometry and can be applied to light-water SMRs using reactor-specific source-term categories, uncertainty models, and site meteorology. Future work will extend the method to additional STCs, propagate STC frequency uncertainty, and compare point-based, quantile-based, and full distribution-preserving F-C representations.

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REFERENCES

- [1] S. Hwang and J. Cho, "Uncertainty Quantification Framework for Systematic Source Term Assessment," Transactions of the Korean Nuclear Society Spring Meeting, 2025.
- [2] Nuclear Energy Institute, "Risk-Informed Performance-Based Technology Inclusive Guidance for

Non-Light Water Reactor Licensing Basis Development," NEI 18-04, Rev. 1, 2019.

[3] U.S. Nuclear Regulatory Commission, Safety Evaluation for the Kemmerer Power Station Unit 1 (Natrium) Construction Permit Application, ADAMS No. ML26026A333, 2025.

[4] U.S. Nuclear Regulatory Commission, State-of-the-Art Reactor Consequence Analyses Project: Uncertainty Analysis of the Unmitigated Short-Term Station Blackout for the Surry Power Station, NUREG/CR-7262, 2022.

[5] S. Hwang and J. Cho, "Uncertainty Analysis for Cs-137 Quantification for Risk Safety Goal Assessment," Transactions of the Korean Nuclear Society Autumn Meeting, 2024.

[6] Nuclear Energy Institute, "Technology Inclusive Guidance for Non-Light Water Reactors: Safety Analysis Report Content for Applicants Using the NEI 18-04 Methodology," NEI 21-07, Rev. 0, 2021.