Uncertainty and Sensitivity Analysis in Large-LOCA Scenarios Using MAAP and WinMACCS

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Abstract: Implementation of Level 3 Probabilistic Risk Assessment (PRA) is accompanied by various uncertainties. Understanding the magnitude of these uncertainties and identifying the parameters that significantly contribute to the assessment outcomes are crucial for the accuracy and reliability of Level 3 PRA. This study focuses on a Large Loss of Coolant Accident (Large-LOCA) sequence and conducts uncertainty and sensitivity analyses on parameters from both the Level 2 PRA accident progression code MAAP and the Level 3 PRA calculation code WinMACCS, particularly in relation to the latent cancer fatality (LCF) risk. Results indicate that, even for the same accident sequence, uncertainties associated with Level 2 PRA are significant in their impact on the LCF risk. Furthermore, the timing of source term release and parameters related to evacuation significantly influence the LCF risk. These findings underscore the importance of considering both Level 2 and Level 3 PRA uncertainties, even when considering the same severe accident sequence.:

Keywords: Level 3 PRA, WinMACCS, MAAP, Sensitivity Analysis

1. INTRODUCTION

In light of the Fukushima Daiichi Nuclear Power Plant accident, comprehensive and quantitative risk assessment of nuclear power plants using Probabilistic Risk Assessment (PRA) has received attention. PRA is divided into three levels: Level 1, Level 2, and Level 3. Among these, Level 3 PRA, which evaluates the impact on the public, is rarely conducted, highlighting the need for domestic knowledge accumulation. Consequently, CRIEPI is promoting a Level 3 PRA project, developing methodologies for Level 3 PRA implementation in Japan.

PRA allows for the quantification of risks, including the effects of aleatory uncertainty. However, it is also crucial to consider the impact of epistemic uncertainty, which arises from insufficient understanding of phenomena. In Level 3 PRA, epistemic uncertainties include uncertainties in the parameters related to the behavior of radioactive material dispersion and deposition, as well as protective measures for evacuees. Additionally, uncertainties propagated from Level 1 and Level 2 PRA should be considered.

The objective of this study is to assess the extent to which uncertainties in Level 2 PRA parameters influence the uncertainties in Level 3 PRA outputs for a specific accident sequence, thereby gaining insights into Level 3 PRA. This study employs the MAAP code developed by The Electric Power Research Institute (EPRI), conducting accident progression analysis for a large LOCA sequence with uncertainty settings applied to MAAP parameters. Furthermore, the source term obtained from this analysis is used for uncertainty analysis with the WinMACCS code developed by Sandia National Laboratories (SNL). Finally, a global sensitivity analysis is performed using the input parameter values of MAAP and WinMACCS, and the output results of WinMACCS. The following section discusses these results.

2. MATERIALS AND METHODS

2.1. MAAP Analysis

A severe accident analysis using MAAP was performed for large-LOCA sequence, which is a typical accident sequence in Level 1/2 PRA. The version of MAAP used was 5.04. The target plant was Peach Bottom, and the analysis was based on the default values in the sample parameter file provided with MAAP. Two release paths to the environment were considered: a small-scale release path from design leakage and a large-scale release path from containment failure. Since MAAP and WinMACCS handle the chemical forms and group characteristics of radioactive nuclides differently, the release fractions of MAAP's Fission Products (FP) groups were converted to the release fractions of WinMACCS's chemical groups (Table 1). Additionally, deposition velocity and particle size distribution corresponding to the aerosol particle size required for calculations in WinMACCS, as well as the release rate and density for the buoyancy effect of the radioactive cloud, were translated from MAAP output to WinMACCS input parameters.

As for the uncertainty analysis target parameters, seven parameters that affect the start time and amount of FP release and are representative of major event physical phenomena were selected from those indicated in EPRI's report [1], as shown in Table 2. For these parameters, 1,000 datasets were created using Monte Carlo sampling, and these datasets were used for analysis by MAAP.

Table 1. WinMACCS Chemical Groups

WinMACCS Chemical Group	**Element Member**
Xe	Xe, Kr
Cs	Cs
Rb	Rb
Ba	Ba
Sr	Sr
I	I
Te	Te
Ru	Ru
Rh	Rh, Tc
Mo	Mo
Ce	Ce, Np
La	La, Nd, Pr, Y, Nb, Zr, Am, Cm
Pu	Pu

Table 2. Uncertainty MAAP Parameters (Modified from D Luxat et al. [1])

Parameter	**Description**	**Sampling Type**	**Distribution**				
			min	**5th**	**50th**	**95th**	**max**
TCLRUP	Temperature at which fuel cladding fails if it has not already failed by ballooning for fission product release	linear	1000	1050	-	1350	2300
FAOX	Multiplier for cladding surface area for oxidation	linear	1	-	1.25	-	2
LMCOL	Criteria for time-at-temperature correlations for core node collapse	linear	47	48	-	53	54
EPSCUT	Porosity below which the node is blocked	logarithmic	0.0001	0.05	0.1	0.2	0.25
ENT0	Entrainment coefficient for a corium jet entering the water in the RPV lower plenum	linear	0.025	0.03	-	0.055	0.06
ECREPP	Maximum lower head penetration weld strain at failure	logarithmic	0.001	0.01	-	0.3	1
Leakage Area	Containment leakage area	linear	3.0E-07	8.0E-07	1.0E-06	1.2E-06	3.0E-06

2.2. WinMACCS Analysis

Using the 1,000 source terms generated by MAAP, the latent cancer fatality (LCF) risks per distance grid were calculated with WinMACCS. The version of WinMACCS used was 4.0. The LCF risk calculated from each source term is obtained by calculating the number of latent cancer fatalities within a region and dividing this number by the total population of the region. In this report, the LCF risk value was taken as the average of the values derived from 1,013 samples by meteorological sampling method. Site data included population distribution and meteorological data around a hypothetical nuclear power plant in Japan. Calculation conditions and parameter values were taken from the published literature on Level 3 PRA conducted by the U.S. NRC [2]. The project property was set as shown below.

- Atmospheric dispersion model: Gaussian plume, power law, time-based.
- Plume meander: none.
- Weather sampling: Nonuniform bin sampling.
- Plume source: Area source.
- Plume rise: Power model.
- Dose model: Linear no threshold without KI model.
- Segment model: Wind shift without rotation.
- Speed multiplier model: none.
- Keyhole evacuation model: none.
- Food Model: none.

WinMACCS outputs were calculated for the five emergency phase cohorts as indicated in the NRA Guide for Emergency Preparedness and Response [3], and for the long-term phase cohort (CHRONC). It was assumed that evacuees would not be exposed once they reached grids beyond the 30 km radius.

Cohort 1: General public within 5 km (PAZ: Precautionary Action Zone) who evacuate 71 minutes after the occurrence of a GE (General Emergency). 75.03% of the PAZ population falls into this cohort.
Cohort 2: Evacuation support recipients in PAZ who evacuate 71 minutes after the occurrence of an SE (Site Area Emergency). 4.47% of the PAZ population falls into this cohort.
Cohort 3: General public within 5-30 km (UPZ: Urgent Protection action planning Zone) who implement sheltering immediately. Only regions with a projected dose exceeding 0.05 Sv within a week will conduct temporary relocation beyond 30 km, 12 hours after the plume arrival. 79.5% of the population within 5-30 km falls into this cohort.
Cohort 4: Residents within UPZ who do not follow evacuation instructions and take similar evacuation actions as Cohort 2. 20% of the population within 30 km of the source falls into this cohort.
Cohort 5: General public within UPZ who do not evacuate. Only regions with a projected dose exceeding 0.05 Sv within a week will conduct temporary relocation beyond 30 km, 12 hours after the plume arrival. 0.5% of the population within 30 km of the source falls into this cohort.

The evacuation delay times for each cohort were set to include the following four delays:

- Delay from a decision of Emergency Action Level to the notification [4].
- Delay from receipt of the operator's notification to contact with local government [5].
- Delay from receipt of the notification from the Cabinet Office and others to the issuance of instructions to residents [5].
- Delay from the issuance of evacuation instructions to the start of evacuation [6].

The target parameters for uncertainty analysis were selected from those with indicated uncertainty ranges in the U.S. NRC guidance [2], as shown in Table 3. No correlations between parameters were set in this calculation. The evacuation speed settings are based on the Evacuation Time Estimate (ETE) results, which have been conducted and published under various conditions in the siting areas of nuclear power plants across Japan. Although these estimates assumed evacuation by vehicle, there was considerable variation in 90% evacuation times for PAZ residents outside the UPZ, ranging from 1.3 to 39.5 hours, depending on the site and the conditions. For this analysis, it was assumed that evacuation across 30 km would be completed in an average of 9.05 hours. The mode value for the evacuation speed was set at 0.92 m/s, with a minimum value of 0.46 m/s (half of the mode value), and a maximum value of 2.3 m/s (2.5 times the mode value). 1,000 datasets were created for these parameters using Monte Carlo sampling with each dataset using one source term for calculations in WinMACCS.

2.3. Sensitivity Analysis

Using the parameter datasets from MAAP and WinMACCS obtained in Sections 2.1 and 2.2, along with the logarithmic outputs of WinMACCS, surrogate models were created. The surrogate models were created using

LightGBM [7] in Python, targeting each cohort and distance grid. Hyperparameter tuning was performed utilizing 5-fold cross-validation and the Optuna library to optimize the performance of the surrogate models. These surrogate models were used to perform global sensitivity analysis to identify parameters with relatively large contributions to LCF risk. Sobol' indices, which are based on the relative proportions of the variance of each parameter term and interaction term to the total variance [8,9], were used as sensitivity measures for parameter contributions. These indices were calculated using the SALib library in Python.

3. RESULTS AND DISCUSSIONS

The time variation of the release fractions of source terms created using 1,000 MAAP parameter sets is shown in Figure 1, and the statistical values of the release fractions are presented in Table 4. The release fractions of the Cs, Rb, I, and Te groups had uncertainties of approximately 2-3 times, while those of the Ba, Ru, Rh and Mo groups had uncertainties exceeding 2 orders of magnitude. Additionally, the release timing for the large-scale release path due to containment failure ranged from a minimum of 1.08 hours to a maximum of 6.17 hours, with an uncertainty range of about 5 hours.

The results of the LCF risk, calculated using WinMACCS, are shown in Figure 2. The uncertainties for cohorts 1, 2, and 4 were more than 2-3 orders of magnitude, while the uncertainties for cohorts 3, 5, and CHRONC were less than 1 order of magnitude. Cohort 4, the only cohort to evacuate in the UPZ, showed increasing uncertainty in LCF risk as the distance grid increased. Although the uncertainty for cohort 5, which does not implement protective measures such as evacuation, was relatively small, the LCF risk in the PAZ tended to be higher than that of other cohorts.

The global sensitivity analysis using surrogate models identified parameters with relatively large contributions to LCF risk (Figure 3). For cohorts 1, 2, and 4, which perform evacuation, ESPEED was found to be the parameter that contributed the most to LCF risk. Additionally, BRRATE, CFRISK and MAAP parameters LMCOL were also significant contributors to LCF risk. For cohorts 3 and 5, which do not evacuate, CFRISK, BRRATE, and PROTIN were significant contributors to LCF risk. In CHRONC, CFRISK, DDREFA, and LGSHFAC were significant parameters contributing to LCF risk.

Table 3. Uncertainty WinMACCS Parameters

Parameter	**Distribution**	**Description**	**Note**
CYCOEF	TRIANGULAR	Linear Coefficient for Time-Based Crosswind Dispersion	
CYSIGA	TRIANGULAR	Linear and Exponential Coefficients for Sigma-y	Set for atmospheric stability levels A-F.
CZSIGA	TRIANGULAR	Linear and Exponential Coefficients for Sigma-z	
SCLCRW	UNIFORM	Scaling Factor for Critical Wind Speed	
SCLEFP	UNIFORM	Scaling Factor for E–F (Stable) Plume Rise	
VDEPOS	TRIANGULAR	Dry Deposition Velocities	Set for particle size bins 1-10.
CWASH1	LOGUNIFORM	Linear Coefficient for Washout	
CSFACT	UNIFORM	Cloudshine Shielding Factors	Set for each cohort for normal (NOR.), evacuation (EVA.), and sheltering (SHE.) activities.
PROTIN	CONTINUOUS LINEAR	Inhalation Protection Factor	
BRRATE	CONTINUOUS LINEAR	Breathing Rate	
SKPFAC	CONTINUOUS LINEAR	Skin Deposition Protection Factor	
GSHFAC	CONTINUOUS LINEAR	Groundshine Shielding Factors	
LPROTIN	CONTINUOUS LINEAR	Long-Term Inhalation Protection Factor	
LBRRATE	CONTINUOUS LINEAR	Long-Term Breathing Rate	
LGSHFAC	CONTINUOUS LINEAR	Long-Term Groundshine Protection Factor	
RESHAF	UNIFORM	Emergency Phase Resuspension Concentration Half-Life	
RWCOEF	LOGNORMAL-N	Long-Term Resuspension Factor Coefficients	
ESPEED	TRIANGULAR	Evacuation Speed	
DOSHOT	TRIANGULAR	Hot-Spot Relocation Dose Threshold	
EFFTHR	UNIFORM	Threshold Dose to Target Organ	Set for Hematopoietic Syndrome, Pulmonary Syndrome, Gastrointestinal Syndrome
EFFACA	UNIFORM	LD50 for Early Fatality	
EFFACB	UNIFORM	Shape Factor for Early Fatality	
EITHRE	UNIFORM	Early Injury Dose Threshold	Set for Pneumonitis, Prodromal Vomiting, Prodromal Diarrhea
EIFACA	UNIFORM	D50 For Early Injuries	
EIFACB	UNIFORM	Shape Factor for Early Injuries	Set for Pneumonitis.
CFRISK	TRUNCATED LOGNORMAL-N	Lifetime Cancer Fatality Risk Factors	Set for 8 cancer types (LEUKEMIA, BONE, BREAST, LUNG, THYROID, LIVER, COLON, OTHER)
DDREFA	CONTINUOUS LINEAR	Dose-Dependent Reduction Factor	

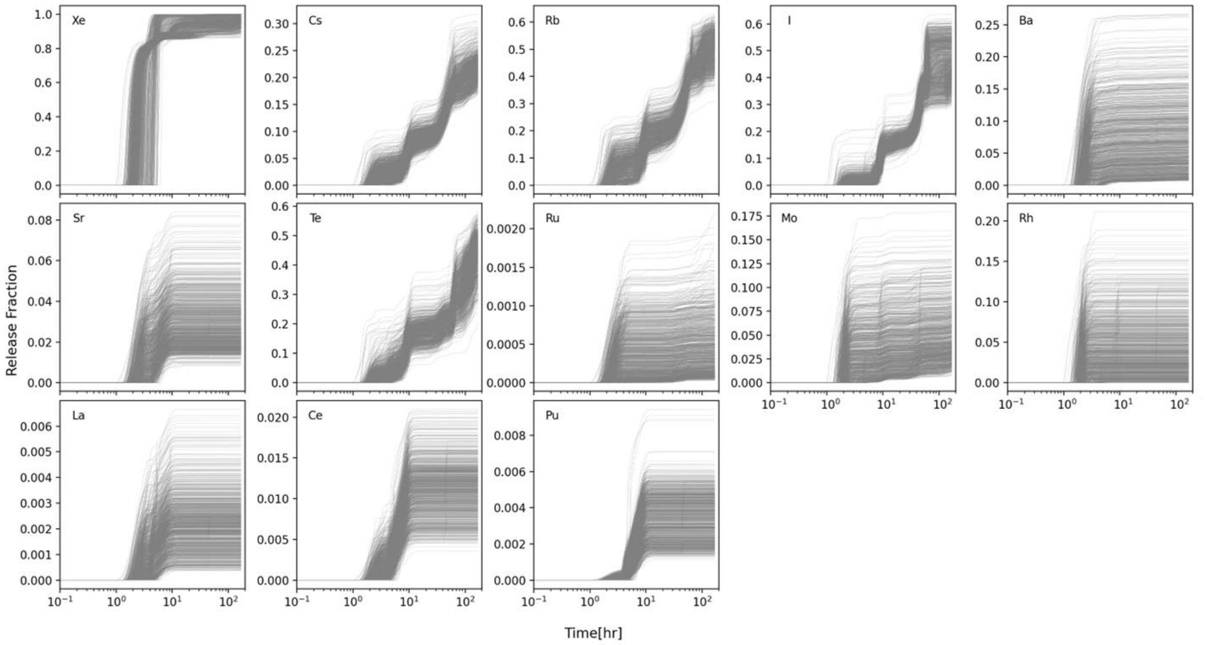

Figure 1. Release Fraction for Each Chemical Group from 1000 Source Terms

Table 4. Total Release Fraction

	Chemical Group						
	Xe	**Cs**	**Rb**	**I**	**Ba**	**Sr**	**Te**
Min	8.62E-01	1.70E-01	3.07E-01	2.86E-01	6.08E-03	8.37E-03	2.04E-01
5th	9.09E-01	1.87E-01	4.12E-01	3.66E-01	1.06E-02	1.44E-02	3.31E-01
50th	9.75E-01	2.24E-01	5.17E-01	4.77E-01	6.28E-02	2.62E-02	4.62E-01
95th	1.00E+00	2.59E-01	5.88E-01	5.81E-01	1.71E-01	5.44E-02	5.29E-01
Max	1.00E+00	3.18E-01	6.29E-01	6.36E-01	2.67E-01	8.41E-02	5.81E-01

	Chemical Group					
	Ru	**Mo**	**Rh**	**La**	**Ce**	**Pu**
Min	2.85E-05	7.64E-03	1.14E-04	3.70E-04	3.59E-03	1.14E-03
5th	7.12E-05	1.56E-02	9.16E-04	6.44E-04	5.91E-03	1.66E-03
50th	3.76E-04	4.05E-02	3.47E-02	2.13E-03	1.11E-02	3.44E-03
95th	1.13E-03	1.07E-01	1.18E-01	4.28E-03	1.67E-02	5.43E-03
Max	2.22E-03	1.80E-01	2.12E-01	6.66E-03	2.10E-02	9.44E-03

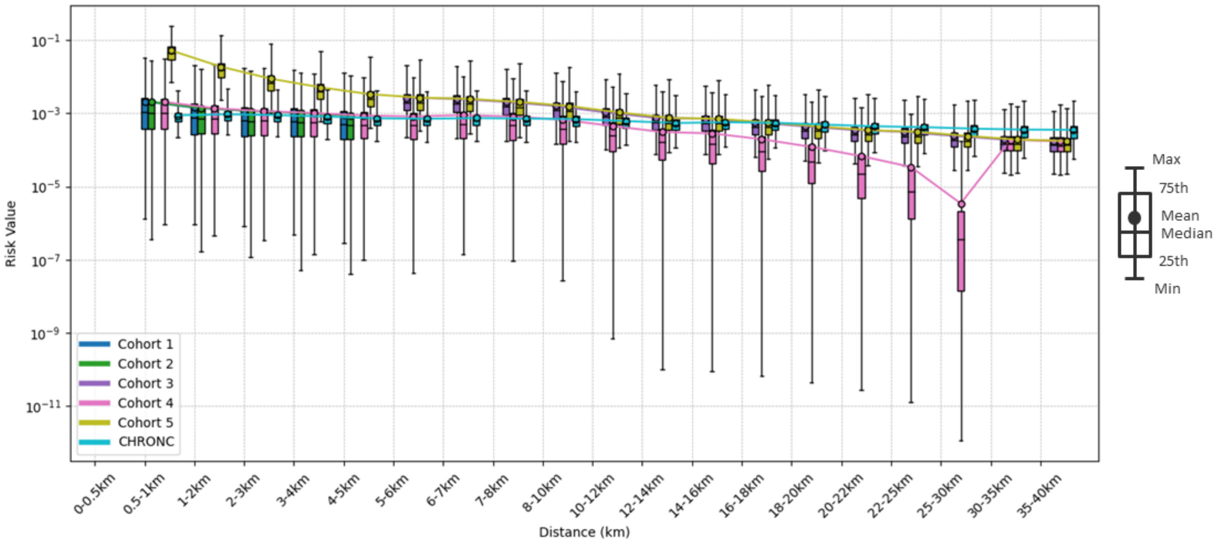

Figure 2. Latent Cancer Fatality Risk

The uncertainties in LCF risk for cohorts 1, 2, and 4 were larger compared to other cohorts, and it was found that most of these uncertainties were due to evacuation speed. In a SOARCA report [10], which used source terms with relatively late release timing, ESPEED was not identified as a significant parameter. However, in the analysis using source terms with early release timing, evacuation-related parameter settings were found to be important.

It was confirmed that MAAP parameter LMCOL is a significant parameter for LCF risk. Among the uncertainties in source terms, the uncertainties in the release amounts of major nuclides were relatively small, suggesting that the uncertainty in the release timing contributes significantly to the uncertainty in LCF risk. The later the release timing, the more time residents have to complete evacuation, resulting in lower LCF risk. Therefore, it was found that the impact of the uncertainties in MAAP parameters on the uncertainties in WinMACCS outputs cannot be ignored, even for the same accident sequence. When evaluating uncertainties in Level 3 PRA, it is especially important to appropriately assess the uncertainties in parameters that affect the release timing in Level 2 PRA, particularly for source terms with early release timing.

In Level 3 PRA, source terms selected for each release category classified in Level 2 PRA are generally used. However, the above results indicate that the results of Level 3 PRA can vary significantly due to uncertainties in Level 2 PRA parameters, even for the same sequence. Therefore, it is necessary to carefully consider the source terms passed on to Level 3 PRA to ensure that they retain their representativeness of the release category.

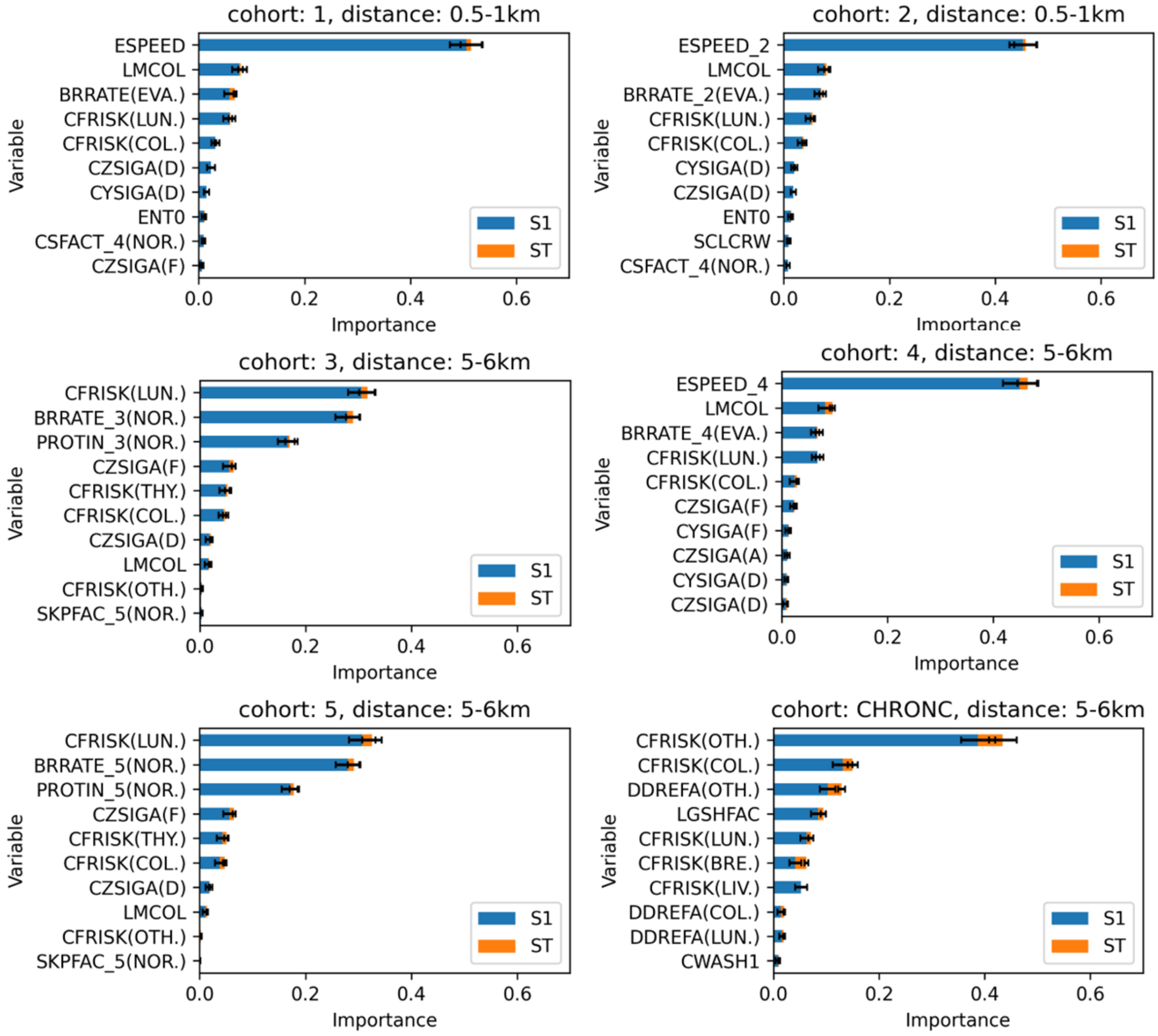

Figure 3. Top 10 parameters that contributed to latent cancer fatality risk. S1 and ST represent sensitivity indices considering a single parameter variance only and considering variance for interactions among parameters, respectively. Error bars indicate 95% credibility intervals. Results for Cohorts 1 and 2 are shown for the 0.5-1 km grid, while the results for the other cohorts are shown for the 5-6 km grid. The number after the underscore in a parameter name represents the cohort number.

4. CONCLUSION

This study conducted sensitivity analysis for accident sequences with early release timings, such as the AE sequence, to assess the impact of MAAP and WinMACCS parameters on the Late Cancer Fatality (LCF) risk. The results demonstrated that uncertainties associated with Level 2 PRA are significant in their impact on the LCF risk, even for the same accident sequence. This particularly underscores the importance of accurately assessing the uncertainties in parameters that influence the release timing.

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