

# SOARCA Peach Bottom Atomic Power Station Long-Term Station Blackout Uncertainty Analysis: Contributions to Overall Uncertainty

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**Abstract:** This paper describes an uncertainty analysis based on a MELCOR Accident Consequence Code System (MACCS) evaluation of the offsite consequences for the State-of-the-Art Reactor Consequence Analyses (SOARCA) unmitigated long-term station blackout scenario at the Peach Bottom Atomic Power Station. Four types of uncertainty are characterized in this analysis: that from the source term itself (radiological release, or Level-2 epistemic uncertainty); that from the influence of source term on offsite health risk (the influence of Level-2 epistemic uncertainties on Level-3 risk); that from a set of offsite consequence parameters reflecting state-of-knowledge uncertainties (Level-3 epistemic uncertainty); and that from the stochastic variability related to weather (Level-3 aleatory uncertainty). Each of these uncertainties contributes to the overall uncertainty in the estimation of health risk to the population surrounding the nuclear power plant. An important question is how much of the overall uncertainty comes from each of these sources. A second question is how the individual sources of uncertainty combine to form the whole. The answers to these two questions are evaluated in this paper. The paper also discusses the most important of the uncertain input parameters in terms of their influence on offsite health risk.

**Keywords:** SOARCA, Uncertainty Analysis, Level-2 and Level-3 Analysis, Severe Accident Analysis

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## 1. INTRODUCTION

The purpose of the State-of-the-Art Reactor Consequence Analyses (SOARCA) project, NUREG-1935 [1], is to develop a body of knowledge on the realistic outcomes of severe accidents that might result in a release of radioactive material into the environment. Major objectives of the SOARCA Peach Bottom uncertainty analysis are to assess the robustness of the SOARCA deterministic, “best estimate,” results and conclusions with respect to the results of an integrated evaluation of uncertainty in accident progression and source term release into the environment (using MELCOR) and offsite health effects (using the MELCOR Accident Consequence Code System, MACCS), and to develop insights into the overall sensitivity of the SOARCA results to uncertainties in key modeling inputs. As this is a first-of-a-kind analysis in its integrated look at uncertainties in both MELCOR and MACCS analyses, an additional objective is to develop and demonstrate an uncertainty analysis methodology that can be used in future combined Level 2/3 probabilistic risk assessment (PRA) and consequence studies. Assessing key MELCOR and MACCS modeling uncertainties in an integrated fashion provides an understanding of the relative importance of each uncertain input on the potential consequences.

A detailed uncertainty analysis (documented in draft NUREG/CR-7155 [2]) is performed for a single accident scenario, the SOARCA Peach Bottom boiling-water reactor (BWR) pilot plant unmitigated long-term station blackout (LTSBO) scenario [3]. The detailed uncertainty analysis does not include uncertainty in the scenario frequency from the Level-1 analysis. While one scenario cannot provide a complete exploration of all possible effects of uncertainties in analyses for the two SOARCA pilot plants, it can be used to provide initial insights into the overall sensitivity of SOARCA results and conclusions to input uncertainty. In addition, since station blackouts (SBOs) are an important class of events for BWRs, the phenomenological insights gained on accident progression and radionuclide releases may prove useful for BWRs in general. A companion paper at this conference, “SOARCA

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Peach Bottom Atomic Power Station Long-Term Station Blackout Uncertainty Analysis: Overview,” provides an overview of methodology and results of this uncertainty analysis.

In the primary SOARCA Peach Bottom uncertainty analysis documented in draft NUREG/CR-7155, 865 source terms were calculated for a set of uncertain input parameters to the MELCOR (Level-2) analysis for the SOARCA Peach Bottom LTSBO scenario. These source term results were used as input combined with additional epistemic parameter uncertainties in the MACCS (Level-3) parameters to create a set of 865 realizations (as discussed in the companion overview paper). This is a reasonable process because both the uncertainties in the source term and in the Level-3 parameters are epistemic in nature. Each of the 865 realization results includes 984 individual weather trials, performed to evaluate the aleatory variability from weather. While regional and seasonal climate is considered in the analysis through site-specific weather inputs, weather is inherently unknowable because, even if weather prediction were perfect, the exact month or time of day of an accident is unknowable. Furthermore, because weather can have a significant impact on predicted consequences, a statistically significant set of weather samples needs to be considered to characterize weather variability. Final results for this analysis are presented as complementary cumulative distribution functions (CCDFs) of mean (over weather variability), latent-cancer-fatality (LCF) risks to the population residing within 10, 20, 30, 40, and 50 miles of the plant, conditional on the postulated accident occurring. In this paper, the focus is on the LCF risks within 50 miles from the plant. These results are representative of the results at shorter distances, with the exception of the area within 10 miles where most of the population evacuates rapidly and does not receive significant exposure during the emergency phase. Early fatality risks are also considered in draft NUREG/CR-7155 [2] but these risks are determined to be considerably lower than the LCF risks because, among other things, the MELCOR (Level-2) model results project there is plenty of time for the public to evacuate before the release begins. Because the early-fatality risks are so small, essentially zero, they are not evaluated in this paper.

The SOARCA study [3] and the SOARCA Peach Bottom uncertainty analysis [2] consider three alternative dose-response models for LCF risk. These are (1) the linear, no-threshold (LNT) model; (2) a linear, dose-with-threshold model that excludes annual doses below average US background radiation plus average medical radiation, which sum to 620 mrem/yr, from contributing to LCF risk; and (3) a linear, dose-with-threshold model based on the Health Physics Society Position Statement that health effects should not be estimated for annual doses below 5 rem unless the lifetime contribution exceeds 10 rem. To simplify and focus the discussion, results in this paper are only presented for the LNT model; however, draft NUREG/CR-7155 [2] also contains results for the other two dose-response models that were used in the SOARCA study.

In this supplemental analysis of the relative contributions of different sources of uncertainty, the uncertainty in the source term is characterized by the distribution in isotopic releases (e.g., Cs-137 release, which is the dominant contributor to long-term LCF risk). To isolate the influence of source term on LCF risk, a set of 865 realizations was evaluated in which the epistemic Level-3 parameters were held constant at their point-estimate values (i.e., the values used in the original SOARCA project) and only the source term was varied. To isolate the influence of the Level-3 epistemic parameters, three representative source terms were selected and a set of 1000 realizations was generated by varying just the Level-3 epistemic parameters for each source term. Weather variability was also characterized by evaluating the uncertainty of the three representative source terms.

In addition to the isolated influence of each type of uncertainty, it is also useful to examine how the uncertainties from multiple sources combine. This is done in section 4 below in sequential fashion as follows:

1. The influence of source term on offsite LCF risk is shown for the 865 source terms as a CCDF. Level-3 parameters are held constant at their point-estimate values. Weather variability is characterized by the means.

2. The influence of source term *and* epistemic Level-3 parameters on offsite LCF risk is shown for the 865 realizations as a CCDF. Weather variability is characterized by the means. This is the primary result reported in the Peach Bottom uncertainty analysis [2].
3. The influence of all three sources of uncertainty, Level-2/MELCOR source term, Level-3/MACCS epistemic input parameters, and weather, are shown in a single CCDF.

## 2. MACCS PARAMETERS

The MACCS consequence model (Version 2.5.0.0) was used in the SOARCA analysis to calculate offsite doses and their effects on members of the public. Epistemic uncertainty was considered for the uncertainty analysis to evaluate the principal phenomena in MACCS, including atmospheric transport using a straight-line, Gaussian plume segment model of short-term and long-term dose accumulation through several pathways, including cloudshine, groundshine, and inhalation. The ingestion pathway was not treated in the SOARCA analyses based on the reasoning that abundant supplies of food and water are available in the United States and can be distributed to areas affected by a reactor accident [1]. The parameter uncertainty in the MACCS consequence model affects the following dose pathways included in the SOARCA reported risk metrics:

- cloudshine during plume passage
- groundshine during the emergency and long-term phases from deposited aerosols
- inhalation during plume passage and following plume passage from resuspension of deposited aerosols. Resuspension is treated during both the emergency and long-term phases.

Development of the emergency-planning-related parameters for MACCS input required establishing an emergency-response timeline. The timeline includes actions described in the onsite and offsite emergency-response plans. The emergency-response plans are tested and exercised often and there is a high confidence in the interactions between onsite and offsite agencies. Research of actual evacuations provided information regarding movement of the public in response to an emergency and has shown that emergency-response actions are routinely implemented and successful [4,5]. Although there is high confidence in response actions, an emergency response is a dynamic event with uncertainties in elements of the response.

All of the emergency-planning parameters used in MACCS were reviewed to determine the most appropriate parameters for the uncertainty analysis. The following three<sup>1</sup> emergency-planning parameter sets were selected:

- hotspot and normal relocation timing,
- evacuation delay, and
- evacuation speed.

In addition, the best-estimate offsite consequence results presented in the SOARCA study [1, 3] include the aleatory uncertainty associated with weather conditions at the time of the accident scenario. The best-estimate offsite consequence values represent the expected (mean) value of the probability distribution obtained from a large number of weather trials. The uncertainty analysis is consistent with the weather-sampling strategy adopted for SOARCA and uses the same non-uniform weather-binning approach in MACCS used in the SOARCA calculation [1]. Weather binning is an approach used in MACCS to categorize similar sets of weather data based on wind speed, stability class, and the occurrence of precipitation. For the non-uniform weather sampling strategy approach used in SOARCA, the number of trials selected from each bin is the maximum of 12 trials and 10% of the number of trials in the bin. Some bins contain fewer than 12 trials. In those cases, all of the trials within the bin are used for sampling. This strategy results in 984 weather trials from the possible 8760 hours of data in a 365-day year for the Peach Bottom accident scenario [1].

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<sup>1</sup> The habitability criterion is also considered to be an important potentially uncertain parameter, but is not included as part of the integrated uncertainty analysis because it would be decided by state or local authorities in the aftermath of an accident. The Peach Bottom pilot plant is in Pennsylvania, and the Pennsylvania State guideline is used as the fixed value.

Several of the parameter distributions selected for this analysis are based on expert elicitation data captured in the report, *Synthesis of Distributions Representing Important Non-Site-Specific Parameters in Off-Site Consequence Analysis* [6]. The United States and the Commission of European Communities conducted a series of expert elicitations to obtain distributions for uncertain variables used in health consequence analyses related to accidental release of nuclear material. The distributions reflect degrees of belief for non-site specific parameters that are uncertain and are likely to have significant or moderate influence on the results. The referenced report presents the effort to develop ranges of values and degrees of belief that fairly represent the divergent opinions of the experts while maintaining the resulting parameters within physical limits, specifically with the MACCS code in mind. The methodology used a resampling of the experts' values and was based on the assumption of equal weights of the experts' opinions.

For the SOARCA Peach Bottom uncertainty analysis [2], a set of 21 epistemic MELCOR parameters, 20 independent MACCS epistemic parameters (parameter sets), and one MACCS aleatory parameter (weather) were selected. Table 1 lists all of the MACCS parameter sets used to represent epistemic uncertainty. However, some of the MACCS parameter sets listed in Table 1 contain multiple sub-parameters and are too extensive to list in this paper (there are 350 individual epistemic input parameter distributions).

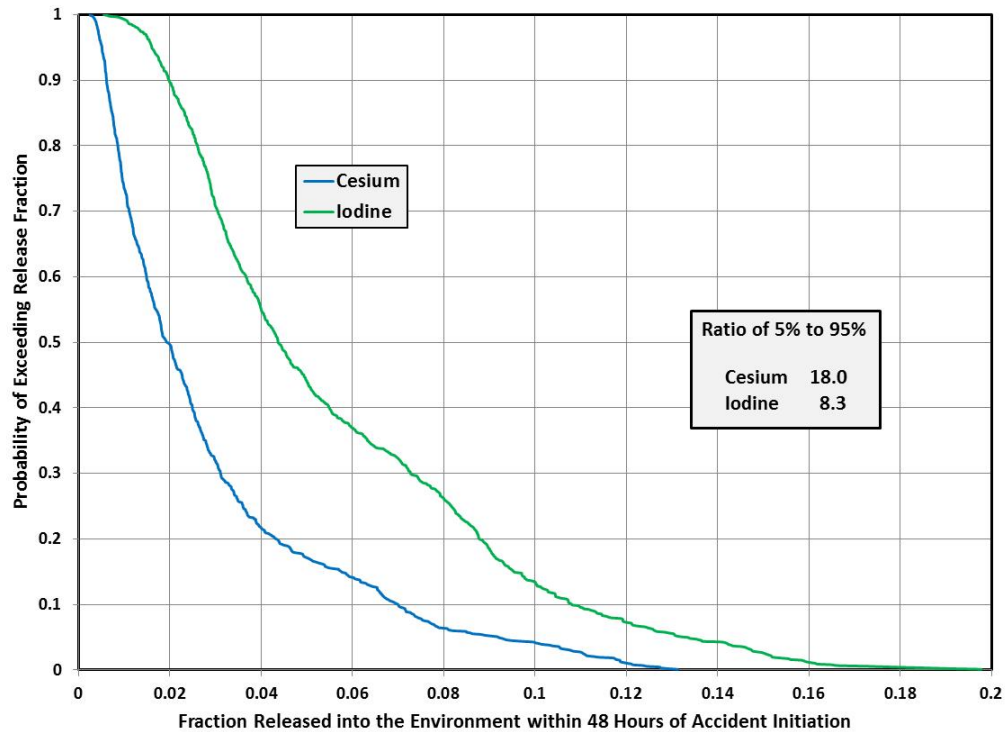
**Table 1: MACCS Uncertainty Parameter Sets**

<b><i>Deposition</i></b>	<b><i>Dispersion Parameters</i></b>
Wet deposition model (CWASH1)	Crosswind dispersion coefficients (CYSIGA)
Dry deposition velocities (VDEPOS)	Vertical dispersion coefficients (CZSIGA)
<b><i>Shielding Factors</i></b>	<b><i>Early Health Effects</i></b>
Shielding factors (CSFACT, GSFAC, PROTIN)	Early health effects (EFFACA, EFFACB, EFFTHR)
<b><i>Relocation Parameters</i></b>	<b><i>Evacuation Parameters</i></b>
Hotspot relocation (DOSHOT, TIMHOT)	Evacuation delay (DLTEVA)
Normal relocation (DOSNRM, TIMNRM)	Evacuation speed (ESPEED)
<b><i>Latent health effects</i></b>	
Groundshine (GSHFAC)	Mortality risk coefficient (CFRISK)
Dose and dose rate effectiveness factor (DDREFA)	Inhalation dose coefficients (radionuclide specific)

### 3. SOURCE TERM UNCERTAINTIES

Source term uncertainties were calculated by running the MELCOR model repeatedly in a Monte Carlo simulation using simple random sampling. The input uncertainty for the Level-2 analyses included 21 input parameters that were expected to have a significant or moderate influence on the estimated source term results [2]. The Monte Carlo process resulted in 865 equally probable source terms. Figure 1 shows the distributions obtained from the set of MELCOR calculations. The figure contains complementary cumulative distribution functions (CCDFs) of the final fractions of cesium and iodine release (the release at 48 hours after accident initiation, the duration of MELCOR simulations, as explained in [1].)

The CCDFs in Figure 1 show that iodine release is larger than cesium release, by about a factor of two. However, the range of uncertainty for cesium is larger than that for iodine. The range of the distribution is captured here and in subsequent results by taking the ratio of the 5<sup>th</sup> percentile from the CCDF to the 95<sup>th</sup> percentile. For cesium, the ratio is 18; for iodine it is 8. In terms of influence on LCF risk, cesium release is more important than iodine release, as demonstrated in NUREG/CR-7110 Vol. 1 [3]. So the range of uncertainty introduced purely by the source term uncertainty is close to 18, but possibly somewhat less than 18 due to the influence of the other chemical groups.



**Figure 1. Complementary Cumulative Distribution Function of Final Cesium and Iodine Release Fractions for the 865 MELCOR Realizations Used in the Uncertainty Analysis.**

#### 4. RISK UNCERTAINTIES

Figure 2 shows the influence of source term uncertainty, one type of epistemic uncertainty, on the consequence results for mean (over weather variability), individual, LCF risk. The range of LCF risk is significantly reduced from the range shown for the source term in Figure 1. This is because the consequence analysis accounts for protective countermeasures (such as relocation of affected populations and return dose-rate criterion) that diminish the effects of a radioactive release on the public. Generally speaking, the larger the release, the greater the countermeasures to protect the public. This results in a sublinear relationship between the magnitude of a source term and the predicted LCF risks.

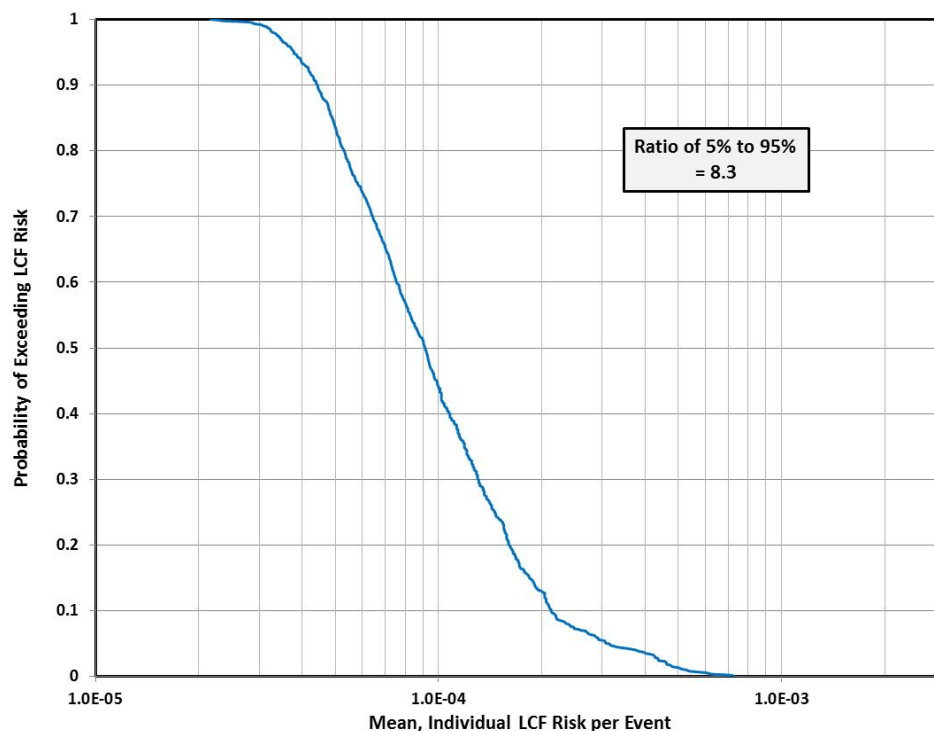
The set of countermeasures considered by MACCS are sheltering and evacuation, ingestion of potassium iodide to reduce thyroid dose, relocation for the nonevacuees during the emergency phase, and long-term relocation while property is being decontaminated and possibly interdicted beyond the period of decontamination. Permanent relocation is invoked when property is condemned because it cannot be economically restored to a dose level that is acceptable for human habitation. These countermeasures are employed over larger regions and to a larger extent, i.e., higher levels of decontamination, when release magnitudes are larger. Of these countermeasure, only evacuation is independent of the magnitude of the release; both emergency-phase and long-term-phase relocation are directly related to the magnitude of the release.

Figure 3 shows the influence of the second source of epistemic uncertainty (due to uncertain MACCS/Level-3 parameters) considered in the uncertainty analysis on health effect risks. Results are shown in this figure for the three separate source terms that were selected to characterize the range of source terms from the MELCOR uncertainty analysis. This was done to account for the fact that the magnitude and characteristics of the source term might influence the importance of some of the Level-3 parameters. The three source terms were selected to represent the lower, middle, and higher third of the probability range of the 865 realization analysis.

For the selection process, the following set of 11 metrics was used:

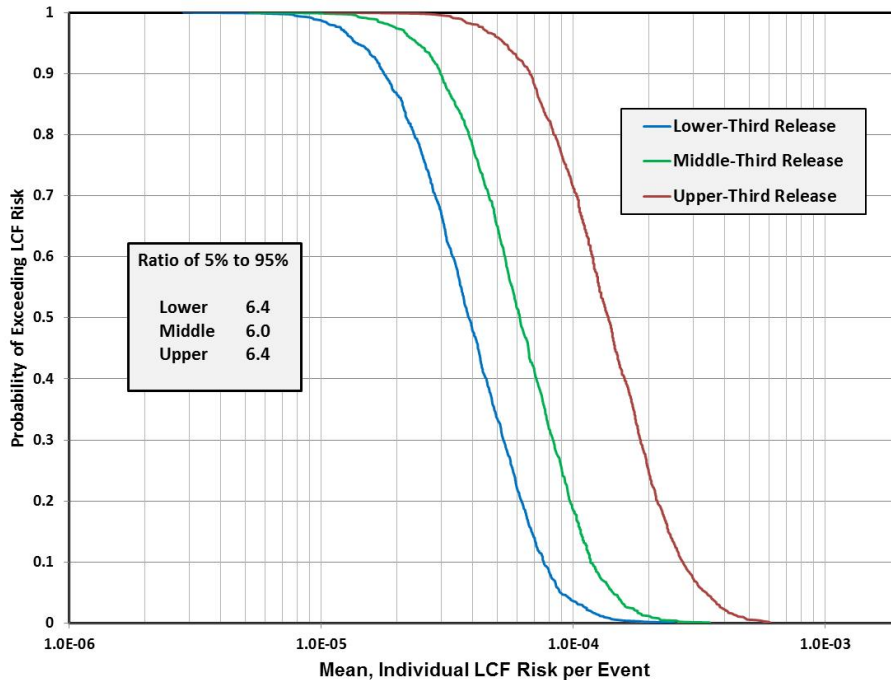
- LCF risk at five different locations (10, 20, 30, 40 and 50 miles),
- fraction of inventory released for five important radionuclides (Cs, I, Ba, Ce, and Te), and
- release time.

Three source terms were selected by minimizing the weighted sum over the 11 metrics of the squares of the difference between the rank of a realization and the desired rank. Weightings were used to reflect the relative importance of each of the metrics. For example, LCF risk results are considered more important (LCF risk is the final result of interest) than the individual fraction of inventory released for each radionuclide, and release time is considered the least important parameter because all of the releases were relatively late. A companion paper at this conference, “SOARCA Peach Bottom Atomic Power Station Long-Term Station Blackout Uncertainty Analysis: Convergence of the Uncertainty Results,” provides further details of this process and analysis.



**Figure 2. Complementary Cumulative Distributions of Mean (Over Weather Variability) LCF Risk Within 50 Miles of the Site, Conditional on a LTSBO Event Occurring at Peach Bottom. Distributions Are Based on All 865 MELCOR Source Terms and Use Best-Estimate Values for All Other Parameters in the MACCS Analysis.**

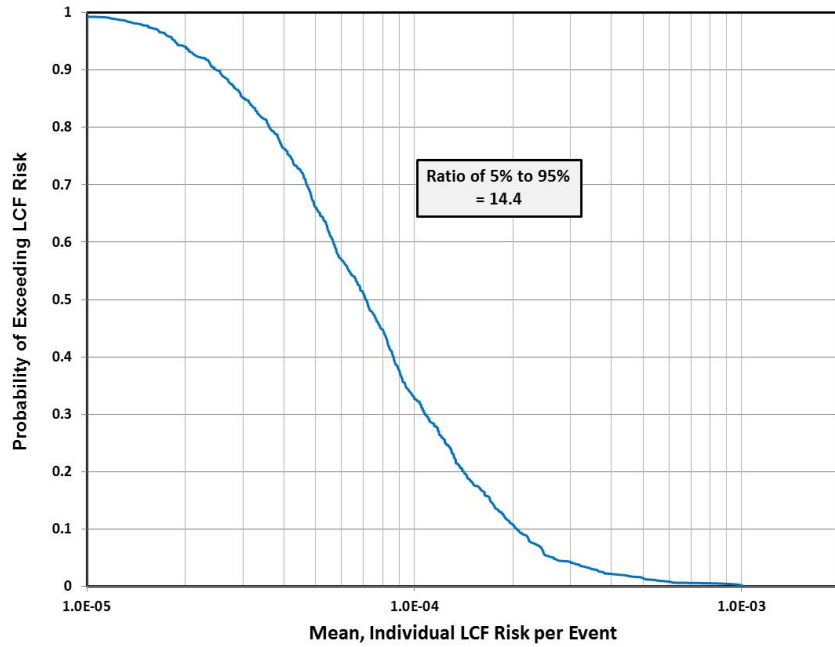
The uncertainties shown in Figure 3 are from uncertainty in MACCS input parameters listed in Table 1 and show the distributions for each of the three selected source terms described above. The range of uncertainty in LCF risk resulting from epistemic uncertainty in the MACCS analysis, excluding the influence of source term, is between ~6. Comparing Figures 2 and 3 shows that the range of uncertainty in LCF risk stemming from uncertainty in the source term epistemic inputs is greater than the uncertainty stemming from the Level-3 epistemic inputs that influence LCF risk (~8 compared with ~6).



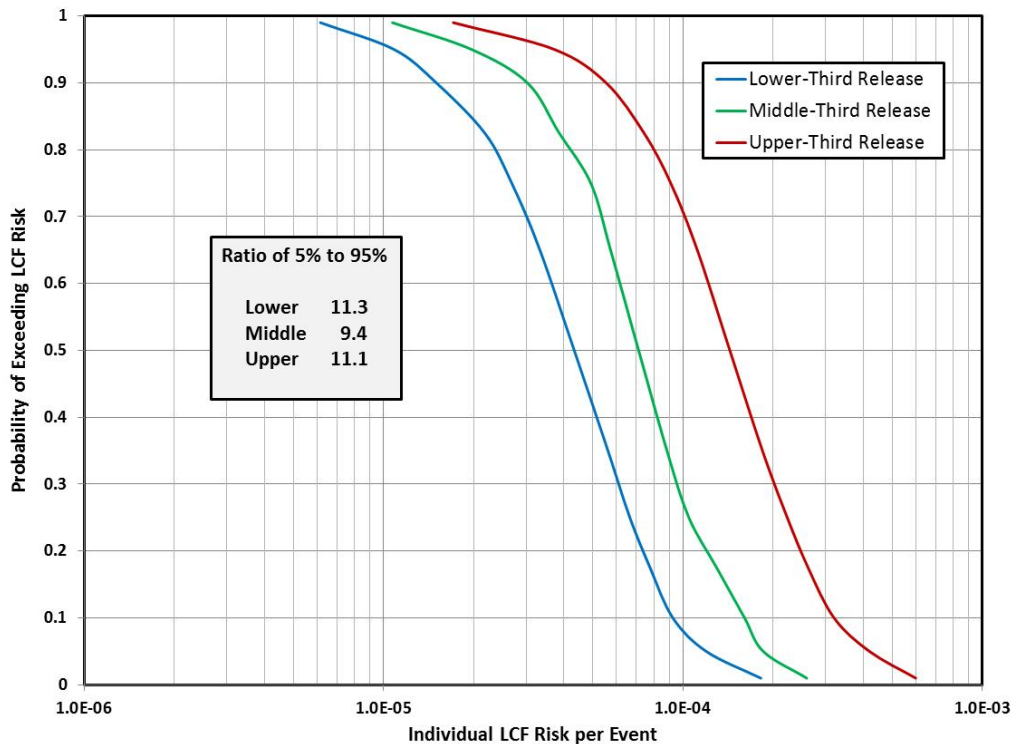
**Figure 3. Complementary Cumulative Distributions of Mean (Over Weather Variability) LCF Risk within 50 Miles of the Site, Conditional on a LTSBO Event Occurring at Peach Bottom. Distributions Are for Three Source Terms Representing the Lower, Middle, and Upper Third of the Distribution and Show Epistemic Uncertainties for the Non-Source-Term Parameters in the MACCS Analysis.**

Figure 4 combines all of the epistemic uncertainties together into one CCDF. This result was created by simultaneously sampling the source term and uncertain MACCS/Level-3 input variables in a single Monte Carlo simulation. Considering the ratio of the 5<sup>th</sup> percentile from the CCDF to the 95<sup>th</sup> percentile, the resulting range in results for the mean (over weather conditions) individual LCF risk considering all epistemic uncertainties combined is slightly more than 14.

Figure 5 shows the effect of aleatory weather variability on LCF risk. Weather variability captures the effects of wind direction, wind speed, stability class, and precipitation on the projected consequences. Weather data for a site, in this case the Peach Bottom plant, are captured in the form of a set of hourly averages for each hour of a 365-day year. Weather sampling is performed by randomly selecting a starting hour using the weather binning approach described above. Using that starting hour, calculations are performed by pairing the evolving weather with the evolving source term on an hour-by-hour basis. Over the set of hours for which release occurs, weather conditions are allowed to change each hour and, at the same time, release rates and other release characteristics change each hour. In this way, the time dependence of the weather and source term is evaluated in a realistic way.



**Figure 4. Complementary Cumulative Distribution of Mean (Over Weather Variability) LCF Risk within 50 Miles of the Site, Conditional on a LTSBO Event Occurring at Peach Bottom. Distributions Are for Source Term and Other Epistemic Uncertainties in the MACCS Analysis.**

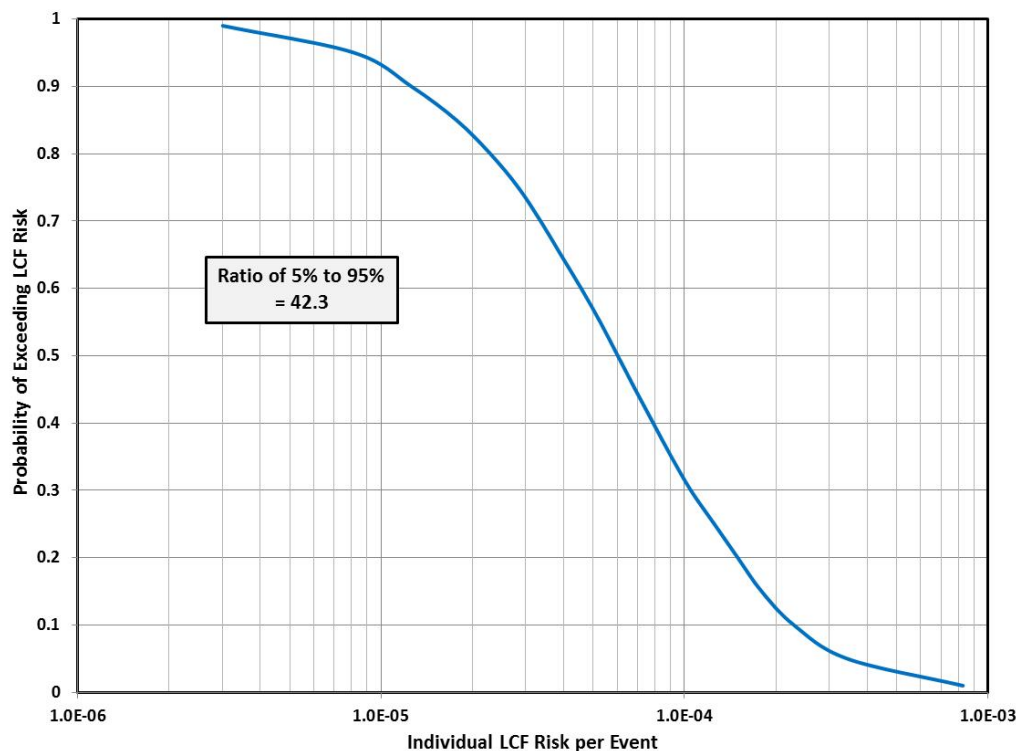


**Figure 5. Complementary Cumulative Distribution Showing the Effect of Weather Variability on LCF Risk Within 50 Miles of the Site, Conditional on a LTSBO Event Occurring at Peach Bottom. Distributions Are for Three Source Terms Representing the Lower, Middle, and Upper Third of the Distribution and Use Best-Estimate Values for the Other Parameters in the MACCS Analysis.**



Considering the ratio of the 5<sup>th</sup> percentile from the CCDF to the 95<sup>th</sup> percentile, Figure 5 shows that the uncertainty in LCF risk due to weather variability, a type of aleatory uncertainty, introduces a range of between about 9 and 11, depending on the characteristics of the release. The influence of uncertain weather is slightly greater than either source of epistemic uncertainty alone, from source term or from Level-3 uncertain MACCS input parameters, but slightly less than the combined epistemic uncertainty from both. This can be seen by comparing the results in Figure 5 with those in Figures 2, 3, and 4. Figure 5 is one of the primary results reported in the SOARCA Peach Bottom uncertainty analysis report, draft NUREG/CR-7155 [2].

Figure 6 shows the combined effects of all three sources of uncertainty included in this study on LCF risks. Those are from epistemic uncertainty in the source term, from epistemic uncertainty in the other MACCS input variables, and from weather variability. The overall uncertainty range, as estimated by the ratio of the 5<sup>th</sup> to the 95<sup>th</sup> percentile values, is about 42. Of the three individual contributions, weather variability has the greatest contribution to overall uncertainty, source term uncertainty has an intermediate contribution, and other uncertain MACCS epistemic input variables have the smallest contribution.



**Figure 6. Complementary Cumulative Distribution Showing the Effect of All Uncertainty, Including Weather Variability, Source Term, and Level-3 Epistemic Uncertainties on LCF Risk within 50 miles of the Site, Conditional on a LTSBO Event Occurring at Peach Bottom.**

## 5. REGRESSION ANALYSIS RESULTS

Table 2 shows the results of four separate regression analyses, ranging from simple rank regression to multivariate regression techniques. Regression analyses were performed for circular areas with radii of 10, 20, 30, 40, and 50 miles, but only the 50-mile results are shown in this paper. The results show the influence of the most important MELCOR and MACCS input parameters on mean (over weather variability), individual LCF risk within 50 miles of the Peach Bottom plant.

The MACCS dry deposition velocity (VDEPOS) input is the most important of the input variables. For the 50-mile LCF risk, VDEPOS is ranked first in the simple linear rank regression analysis,

accounts for 9% of the variance alone with a  $T_i^2$  of 0.18 using the quadratic regression analysis, 19% of the variance alone with a  $T_i$  of 0.39 using the multivariate adaptive regression splines (MARS) method, and 16% of the variance alone with a  $T_i$  of 0.46 using the recursive partitioning regression analysis. Dry deposition is characterized in MACCS with a set of deposition velocities corresponding to a set of aerosol size bins. All of the deposition velocities are correlated, so VDEPOS corresponds to the deposition velocities for the entire set of aerosol bins. Currently, MACCS uses a fixed deposition velocity that is independent of wind speed and other conditions.

VDEPOS is expected to be important to LCF risk because the long-term dose with the LNT model is driven by dry deposition velocity since long-term dose results mainly from groundshine. Wet deposition also contributes to groundshine dose, but its contribution is smaller on average due to the fact that rain only occurs about 7% of the time at Peach Bottom. A larger value of dry deposition velocity results in larger long-term doses at shorter distances and smaller doses at longer distances.

The MELCOR input variables are shaded in Table 2, and three (SRVLAM, fuel failure criterion, FL904A) show up as important to LCF risk. The  $T_i$  values indicate greater influence in conjunction with other variables. These MELCOR input variables are expected to be important because they account for much of the variance in cesium release fractions and ultimately correlate with much of the uncertainty contribution of the source term to LCF risk. The MELCOR regression analyses indicate CHEMFORM and SRV open area fraction (SRVOAFRAC) also to be important variables for release magnitude, but these two parameters do not appear among the most important variables in the regression analyses for the 50-mile area consequences results. A companion paper at this conference, "SOARCA Peach Bottom Atomic Power Station Long-Term Station Blackout Uncertainty Analysis: Knowledge Advancement," provides further details on parameters and phenomena identified to be important in the SOARCA Peach Bottom uncertainty analysis.

**Table 2: Results of Four Regression Analyses for Mean, Individual LCF Risk within a 50-Mile Circular Area Surrounding the Peach Bottom Site**

	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R <sup>2</sup>	0.52			0.57			0.71			0.54		
Input	R <sup>2</sup> inc.	R <sup>2</sup> cont.	SRRC	S <sub>i</sub>	T <sub>i</sub>	p-val	S <sub>i</sub>	T <sub>i</sub>	p-val	S <sub>i</sub>	T <sub>i</sub>	p-val
VDEPOS	0.18	0.18	-0.43	0.09	0.18	0	0.16	0.46	0	0.19	0.39	0
SRVLAM	0.25	0.07	0.26	0.12	0.31	0	0.05	0.29	0	0.05	0.16	0.06
Fuel failure criteria	0.45	0.03	0.16	---	---	---	0	0.05	0.07	0	0.01	0.38
FL904A	0.48	0.02	-0.14	0.04	0.08	0	0.05	0.28	0	0.02	0	1
DDREFA Residual	0.30	0.05	0.24	0.05	0.09	0.07	---	---	---	0.09	0.09	0.29
CFRISK Residual	---	---	---	0	0.04	0.33	0	0.12	0	0.02	0.01	0.37
GSHFAC Normal	0.34	0.04	0.18	---	---	---	0	0.03	0.45	0.06	0.05	0.14
CFRISK Lung	0.37	0.03	0.19	0.01	0.12	0.01	0.04	0.22	0	0.03	0.07	0.28
DDREFA Lung	0.40	0.03	0.26	0	0.13	0	---	---	---	0.02	0.11	0
GSHFAC Evacuation	0.43	0.03	0.16	0.06	0.15	0	0.01	0.23	0	0.04	0.08	0
BATTDUR	---	---	---	0.03	0.02	0.46	---	---	---	0	0.01	0.34

<sup>2</sup>  $T_i$  is a measure that accounts for the interaction effects with other variables.

The most important of the remaining variables in Table 2 are the MACCS parameters CFRISK-residual, and DDREFA-residual. The  $T_i$  values indicate greater influence in conjunction with other variables. The mortality risk coefficients (CFRISK) for each of the organs included in the SOARCA analyses for latent health effects are assumed to be uncorrelated. The dose and dose rate effectiveness factor (DDREFA) is based on BEIR V risk factors for estimating health effects to account for observed differences between low and high dose rates. Doses received during the emergency phase are divided by DDREFA when they are less than 0.2 Gy (20 rad) in the calculation of latent health effects; they are not divided by DDREFA when emergency-phase doses exceed 0.2 Gy. Doses received during the long-term phase are generally controlled by the habitability criterion to be well below 0.2 Gy, so these doses are always divided by DDREFA in the calculation of latent health effects. Since DDREFA is in the denominator, it is negatively correlated with LCF risk.

The MACCS latent-cancer parameters, CFRISK-residual and DDREFA-residual, are used for estimating residual cancers not related to the seven organ-specific cancers that were used in SOARCA: leukemia, bone cancer, breast cancer, lung cancer, thyroid cancer, liver cancer, and colon cancer. It is reasonable that the CFRISK and DDREFA factors for the “residual” category are important because they account for multiple organs that are not modeled separately (as explained in more detail in the forthcoming NUREG/CR-7155 report).

Other input parameters that have a measurable but lesser influence on mean, individual LCF risk are cancer induction parameter corresponding to lung cancer (analogous to the ones described above for residual cancers) and groundshine shielding factors for normal activity and for evacuation.

## 6. CONCLUSIONS

This uncertainty analysis for the Peach Bottom unmitigated long-term station blackout scenario produced distributions of results for conditional LCF risk and conditional early fatality risk to members of the public. This paper focuses on the LCF risks. The SOARCA point estimates [1, 3] fall within the distribution of results from this analysis.

The contributions of each of the sources of uncertainty to the overall uncertainty in LCF risk, combining MELCOR (Level-2) and MACCS (Level-3) uncertainties for a LTSBO event occurring at the Peach Bottom site, have been evaluated. If considering separately the epistemic uncertainty from the Level-2 parameters, the epistemic uncertainty from the Level-3 parameters, and uncertainty due to weather, the largest contribution to uncertainty is from weather variability, which is a type of aleatory or stochastic uncertainty. The smallest contributor is the epistemic uncertainty from the Level-3 input parameters, i.e., those not related to source term uncertainty. The intermediate contributor to the overall uncertainty is from Level-2 uncertainties that influence the source terms. However, the total effect of epistemic uncertainty stemming from Level-2 and Level-3 parameters together is greater than the effect of weather uncertainty.

In this uncertainty analysis, all regression methods consistently rank the MACCS dry deposition velocity, the MELCOR SRV stochastic failure probability, and the MACCS residual cancer risk factors, respectively, as the most important input parameters for the mean, individual LCF risk using the LNT dose-response model.

The results and insights from this uncertainty analysis are expected to be useful for on-going and future work, such as informing the technical bases for post-Fukushima regulatory activities and the NRC’s Site Level 3 PRA project. This uncertainty study adds to the body of knowledge created by the SOARCA project, through the generation of 865 variations of how an LTSBO scenario may evolve at a BWR, and an investigation into the relative contributions of aleatory uncertainty (from weather) and epistemic uncertainty (from uncertain model parameters) to severe accident consequence results. One example use of this work is to identify key sources of uncertainty (per NUREG-1855 [7] guidance on

treatment of uncertainty) for the Level 3 portion of PRA studies for light-water reactor severe accidents.

### **Acknowledgements**

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The U.S. Nuclear Regulatory Commission sponsored and participated in this work.

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