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SOARCA PEACH BOTTOM ATOMIC POWER STATION LONG-TERM STATION BLACKOUT UNCERTAINTY ANALYSIS MACCS2 PARAMETERS AND PROBABILISTIC RESULTS

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ABSTRACT

This paper describes the uncertainty analysis MELCOR Accident Consequence Code System, Version 2 (MACCS2) parameters and probabilistic results of offsite consequences for the State-of-the-Art Reactor Consequence Analyses unmitigated long-term station blackout accident scenario at the Peach Bottom Atomic Power Station. The results are presented in terms of risk to the public. All results are presented as conditional risk (i.e., assuming the accident occurs) and show risks to individuals as a result of the accident (i.e., latent-cancer-fatality (LCF) risk per event or prompt-fatality risk per event). For the mean, individual LCF risk, all regression methods at each of the circular areas around the plant (10-mile to 50-mile radii are considered) consistently rank the MACCS2 dry deposition velocity, the MELCOR safety relief valve (SRV) stochastic failure probability, and the MACCS2 residual cancer risk factor, respectively, as the most important input parameters. For mean, individual prompt-fatality risk within the circular areas less than 2-miles, the non-rank regression methods consistently rank the MACCS2 wet deposition parameter, the MELCOR SRV stochastic failure probability, the MELCOR SRV open area fraction, the MACCS2 early health effects threshold for red bone marrow, and the MACCS2 crosswind dispersion coefficient, respectively, as the most important input parameters. For mean, individual prompt-fatality risk within the circular areas between 2.5-miles and 3.5-miles, the regression methods consistently rank the MACCS2 crosswind dispersion coefficient, the MACCS2 early health effects threshold for red bone marrow, the MELCOR SRV stochastic failure probability, and the MELCOR SRV open area fraction, respectively, as the most important input parameters.

Key Words: SOARCA, Uncertainty, Peach Bottom, MACCS2

1 INTRODUCTION

The purpose of the State-of-the-Art Reactor Consequence Analyses (SOARCA), NUREG-1935 [1], was to evaluate the consequences of postulated severe reactor accident scenarios that might result in a release radioactive material into the environment. Toward that end, the objective of the SOARCA uncertainty analysis is 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 to the environment (MELCOR) and offsite health effects (MELCOR Accident Consequence Code System, Version 2 – MACCS2), and to develop insight into the overall sensitivity of the

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SOARCA results to uncertainty in key modeling inputs. As this is a first-of-a-kind analysis in its integrated look at uncertainties in MELCOR and MACCS2 analyses, an additional objective is to develop an uncertainty analysis methodology that could be used in future combined Level 2/3 probabilistic risk assessment (PRA) studies. Assessing key MELCOR and MACCS2 modeling uncertainties in an integrated fashion yields an understanding of the relative importance of each uncertain input on the potential consequences.

1.1 Background

The evaluation of accident phenomena and offsite consequences of severe reactor accidents has been the subject of considerable research by the U.S. Nuclear Regulatory Commission (NRC), the nuclear power industry, and the international nuclear energy research community. Most recently, with NRC guidance and as part of plant security assessments, updated analyses of severe accident progression and offsite consequences were completed. These analyses are detailed in terms of the fidelity of the representation of facilities and emergency response, realistic phenomenological models and procedures, and integrated in terms of the coupling between accident progression and offsite consequence models.

The results of those previous studies confirmed and quantified what was suspected but not well quantified; some past studies were sufficiently conservative to the point that predictions were not useful in characterizing results. The calculation of risk attributable to severe reactor accidents should consider realistic estimates of the more likely outcomes and should incorporate both the many improvements to nuclear power plants (NPPs) and improved understanding of severe accident behavior. Moreover, improvements in plant design and construction, better understanding of accidents and their consequences, and realistic modeling should be appropriately communicated.

In addition to the improved understanding and calculational capabilities that have resulted from these studies, many influential changes have occurred in the training of operating personnel and the increased use of plant-specific capabilities. These changes include the following:

- The transition from event-based to symptom-based emergency operating procedures for the boiling-water reactor (BWR) and pressurized-water reactor (PWR) designs.
- The performance and maintenance of plant-specific PRAs that include the spectrum of accident scenarios.
- The implementation of plant-specific, full-scope control room simulators to train operators.
- An industry wide, owners-group-specific guidance, and plant-specific implementation of the severe accident management guidelines.
- Additional safety enhancements, described in Title 10, Section 50.54(hh) of the Code of Federal Regulations (10 CFR 50.54(hh)). These enhancements are intended to be used to maintain or restore core cooling, containment integrity, and spent fuel pool cooling capabilities under the conditions associated with the loss of large areas of the plant due to explosions or fire and include strategies for use in the following areas: (i) firefighting; (ii) operations to mitigate fuel damage; and (iii) actions to minimize radiological release. Successful implementation of this equipment and associated procedures could possibly:

(i) prevent core damage or (ii) delay or prevent radiological release, which is reflected in the SOARCA scenarios.

- Improved understanding of the underlying phenomena that result in influential processes such as the following:
    - in-vessel steam explosions
    - Mark I containment drywell shell attack
    - dominant chemical forms for fission products
    - direct containment heating
    - hot-leg creep rupture
    - reactor pressure vessel failure and molten core-concrete interactions

Additional changes in plant operation have occurred over time, including the following:

- power uprates
- higher core burnups

The SOARCA project, conducted by the NRC and Sandia National Laboratories, is a research effort to realistically estimate the outcomes of postulated severe accident scenarios that might cause a NPP to release radioactive material into the environment.

SOARCA [1] conducted an in-depth analysis of two operating NPPs: Peach Bottom, a BWR, and Surry, a PWR. SOARCA used computer modeling techniques to understand how a reactor might behave under severe accident conditions, and how a release of radioactive material from the plant might impact the public. Specifically, SOARCA uses MELCOR (i.e., an integral severe accident analysis code) to model the severe accident scenarios within the plant, and MACCS2 (i.e., a radiological consequence assessment code) to model the offsite health consequences for atmospheric releases of radioactive material.

In determining realistic consequences of postulated severe accidents, SOARCA relies on many years of previous national and international reactor safety research. The NRC, the U.S. Department of Energy, the nuclear power industry, and international nuclear safety organizations have extensively researched plant responses to hypothetical scenarios that could damage the reactor core or the containment. This research has significantly improved the NRC's ability to analyze and predict how nuclear plant systems will respond to severe accidents, and how accidents progress. In addition, NPP owners have continually improved safety by enhancing their plant designs, emergency procedures, inspection programs, and operator training. Plant owners and local governments have also refined and improved emergency preparedness to further protect the public in the highly unlikely event of a severe accident. Finally, the NRC has incorporated insights from health physics organizations and employed both the linear-no-threshold (LNT) model and alternate dose truncation models for analyzing health effects.

SOARCA incorporated the accumulated research for plant operations and design enhancements into integrated computer models. These models consider onsite and offsite actions, including the implementation of mitigation measures and protective actions for the public such as evacuation and sheltering that may prevent or mitigate accident consequences.

These SOARCA calculations, results, and conclusions are documented in NUREG-1935 [1], and NUREG/CR-7110, Volume 1 [2].

1.2 Objectives of the Uncertainty Analysis

The purpose of SOARCA is to evaluate the consequences of postulated severe reactor accident scenarios that might cause a NPP to release radioactive material into the environment. Toward that end, the objective of the SOARCA Uncertainty Analysis is to evaluate the robustness of the SOARCA deterministic “best estimate” results and conclusions, and to develop insight into the overall sensitivity of the SOARCA results to uncertainty in key modeling inputs. As this is a first-of-a-kind analysis in its integrated look at uncertainties in MELCOR accident progression and MACCS2 offsite consequence analyses, an additional objective is to demonstrate uncertainty analysis methodology that could be used in future source term, consequence, and Level 3 PRA studies.

SOARCA included sensitivity studies to examine issues associated with accident progression, mitigation, and offsite consequences for the accident scenarios of interest. The objective of these sensitivity studies was to examine specific issues and ensure the robustness of the conclusions documented in NUREG-1935 [1]. Single sensitivity studies, however, do not form a complete picture of the uncertainty associated with accident progression and offsite consequence modeling. Such a picture requires a more comprehensive and integrated evaluation of modeling uncertainties.

In general terms, the SOARCA offsite consequence results presented in NUREG-1935 [1] incorporated only the uncertainty associated with weather conditions at the time of the accident scenario considered. The reported offsite consequence values represent the expected (i.e., mean) value of the probability distribution obtained from a large number of aleatory weather trials. The weather uncertainty is handled the same way in this uncertainty analysis. In addition, the impact of epistemic model parameter uncertainty (the focus of this analysis) is explored in detail by randomly sampling distributions for key model parameters that are considered to have a potentially important impact on the offsite consequences. The objective of this uncertainty analysis is to develop insight into the overall sensitivity of the SOARCA results and conclusions to the combined integrated uncertainty in accident progression (MELCOR) and offsite health effects (MACCS2). Assessing key MELCOR and MACCS2 modeling uncertainties in an integrated fashion, yields an understanding of the relative importance of each uncertain input on the potential consequences.

NRC guidance documents (i.e., Regulatory Guide 1.174 and NUREG-1855) discuss three types of epistemic uncertainty: parameter, model, and completeness. Completeness uncertainty is not treated in this study. This analysis leverages the existing SOARCA models and software, along with a representative set of key parameters. In other words, the uncertainty stemming from the choice of conceptual models and model implementation is not explicitly explored. It is worth noting, however, that many of the input parameters in the models are lumped parameters that can represent different mechanistic models. In that respect, the distributions assigned to some input parameters serve as a proxy for exploring mechanistic model uncertainty as well. The integrated uncertainty analysis is supplemented with limited sensitivity analyses which also explore some model uncertainties. In addition, not all possible uncertain input parameters were included in the analysis. Rather, a set of key parameters was carefully chosen to capture important influences on release and consequence results.

A detailed uncertainty analysis was performed for a single-accident scenario rather than all seven of the SOARCA scenarios documented in NUREG-1935. This work does not include uncertainty in the scenario frequency. The SOARCA Peach Bottom BWR Pilot Plant Unmitigated Long-Term Station Blackout (LTSBO) scenario [2] is analyzed. 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 black outs are an important class of events for BWRs in general, the phenomenological insights gained on accident progression and radionuclide releases may prove useful for BWRs in general.

2 MACCS2 PARAMETERS

The MACCS2 consequence model (Version 2.5.0.0) is used in the SOARCA analysis to calculate offsite doses and their effect on members of the public. Epistemic uncertainty was considered for the principal phenomena in MACCS2, including atmospheric transport using a straight-line Gaussian plume 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 because uncontaminated food and water supplies are abundant within the United States and it is unlikely that the public would eat radioactively contaminated food [3]. The parameter uncertainty in the MACCS2 consequence model will impact the following doses 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 uncertainty parameters for MACCS2 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 existing 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 MACCS2 were reviewed to determine the most appropriate parameters for the uncertainty analysis. The following three[2] emergency planning parameter sets were selected:

- Hotspot and normal relocation,

[2] The habitability criterion is also considered to be an important potentially uncertain parameter, but will not be included as part of the integrated uncertainty analysis.

- evacuation delay, and
- evacuation speed.

In addition, the best-estimate offsite consequence results presented in the SOARCA study include the aleatory uncertainty associated with weather conditions at the time of the accident scenario. These 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 MACCS2 used in the SOARCA calculation [1]. Weather binning is an approach used in MACCS2 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 for 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 roughly 1,000 weather trials for the Peach Bottom accident scenario.

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 MACCS2 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 this uncertainty analysis, a set of 21 epistemic MELCOR parameters, 20 independent MACCS2 epistemic parameters, and one MACCS2 aleatory parameter (weather) were selected. Table 1 lists all of the epistemic uncertainty MACCS2 parameters. However, some of the MACCS2 parameters listed in Table 1 contain multiple sub-parameters and are too extensive to list in this paper. Examples of the uncertainty data are shown in Figure 1, which shows the cumulative distributions for the dry deposition velocities and Figure 2 which shows the values used in this uncertainty analysis for groundshine (GSHFAC), inhalation (PROTIN), and cloudshine (CSFACT).

3 PROBABILISTIC RESULTS

The results of the consequence analyses are presented in terms of risk to the public for each of the probabilistic source terms analyzed using the Peach Bottom unmitigated LTSBO MELCOR model for the uncertainty analysis. All results are presented as conditional risk. Absolute risk is discussed in certain instances within the text. The conditional risks assume that the accident occurs and show the risks to individuals as a result of the accident (i.e., latent cancer fatality (LCF) risk per event or prompt-fatality risk per event). The absolute risk is the product of the core damage frequency for the accident sequence and the conditional risk for that sequence. The absolute risk is the likelihood of receiving a latent fatal cancer or prompt fatality for an average individual living within a specified radius of the plant per year of plant operation (i.e., LCF risk per reactor year (pry) or prompt-fatality risk pry).

The reported risk metrics are LCF and prompt-fatality risks to residents in circular regions surrounding the plant. They are averaged over the entire residential population within each circular region. The risk values represent the predicted number of fatalities divided by the population for the selected dose truncation level. These risk metrics account for the distribution of the population within the circular region and for the interplay between the population distribution and the wind rose probabilities.

Comparisons of LCF risks calculated for the SOARCA Uncertainty Analysis to the NRC Safety Goal are provided to give context that may help the reader to understand the contribution to cancer risks from this type of NPP accident scenario (i.e., Peach Bottom LTSBO). However, such comparisons have limitations for which the reader should be aware. The safety goal is intended to encompass all accident scenarios. The SOARCA Uncertainty Analysis examines only a single accident scenario and is less comprehensive than a full PRA. In fact, any analytical technique, including a PRA, has inherent limitations of scope and method.

As a result, comparison of the SOARCA Uncertainty Analysis scenario-specific LCF risks to the NRC Safety Goal is incomplete. However, it is intended to show this specific scenario has such a low risk, in the ~10^{-11} to 10^{-8} pry. This can be used to estimate a summary risk from all scenarios. The summary risk is also well below the NRC Safety Goal of 2×10^{-6} pry or two in one million per reactor year.

Table 1. MACCS2 uncertainty parameters

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

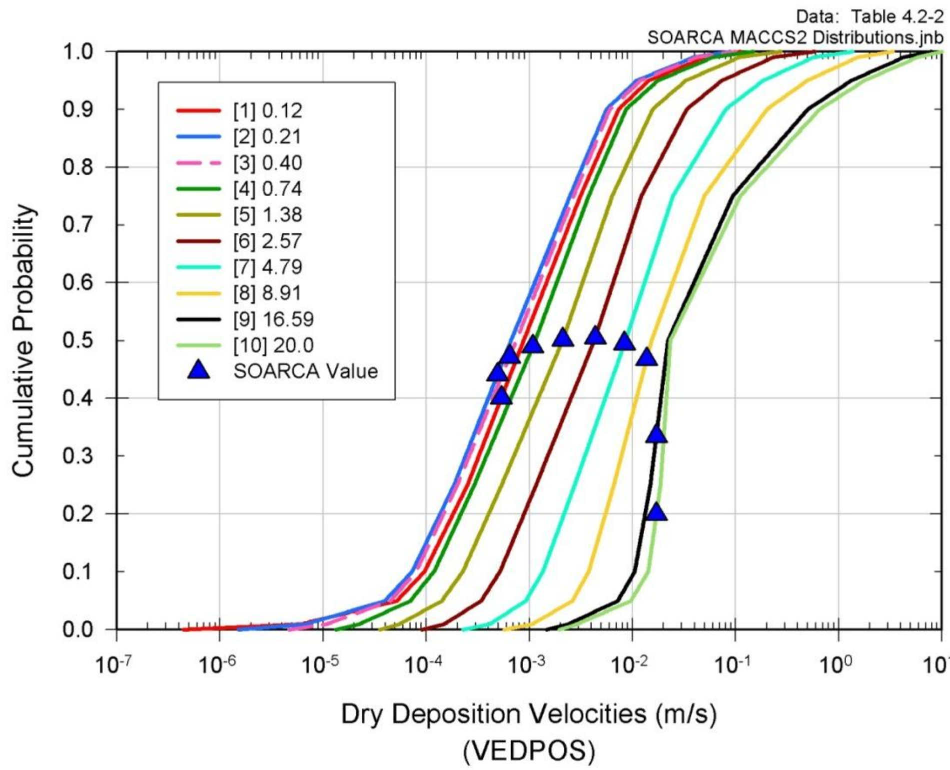

Figure 1. Cumulative distribution functions of dry deposition velocities for MACCS2 aerosol bins/aerosol mass median diameters

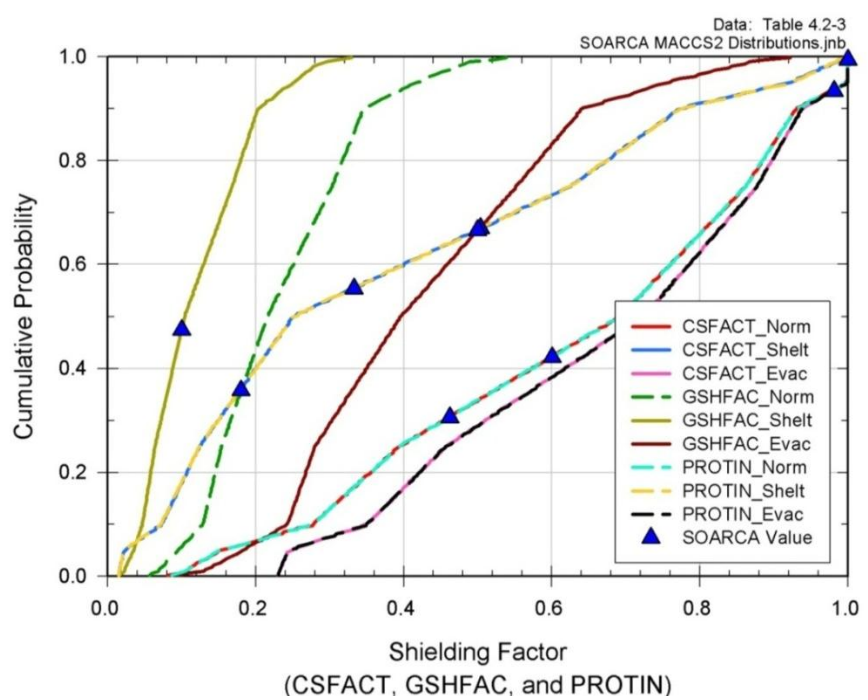

Figure 2. Cumulative distribution for shielding factors

The three separate replicates representing the uncertainty in the MELCOR source terms combined were used in a single MACCS2 uncertainty analysis to determine the conditional, mean, individual LCF risk (per event) and prompt-fatality risk per event complimentary cumulative distribution functions (CCDFs). Mean risk is for possible variations in weather using the weather sampling practice developed for SOARCA. The three MELCOR replicate analyses produced 284 (Replicate 1), 290 (Replicate 2), and 291 (Replicate 3) MELCOR source terms, respectively. Each MELCOR source term replicate was analyzed individually with a single WinMACCS run using Latin hypercube sampling (LHS) and include the 350 MACCS2 uncertain input variables. This WinMACCS run created a set of 865 MACCS2 realizations, each paired with one of the MELCOR source terms. Table 2 lists the MACCS2 probabilistic analyses and corresponding MELCOR source terms. The risk results presented use only the linear-no-threshold hypothesis dose-response model.

3.1 Latent Cancer Risk Fatality

Table 3 shows statistical results for conditional, mean, individual LCF risk (per event) from the MACCS2 uncertainty analysis at each specified circular area for the analysis using all three MELCOR source term replicates. Each statistic was estimated to evaluate the epistemic uncertainties resulting from the uncertain inputs to MACCS2. A t-distribution was used to determine the 5^{th} and 95^{th} confidence intervals.

For this work, the emergency phase is defined as the first seven days following the initial release to the environment. The long-term phase is defined as the time following the emergency phase (i.e., there is no intermediate phase). The long-term phase risk (i.e., the LCF risk contribution beyond the emergency phase) dominates the total risks (i.e., 100% of all realizations have a long-term risk contribution that is greater than 50% of the total risk) within the emergency planning zone (EPZ) for the uncertainty analysis when the LNT dose-response assumption is made. No realization resulted in an emergency phase risk contribution greater than 48% of the total risk. The emergency phase risk within the EPZ is entirely to the 0.5% of the population who are assumed not to evacuate. These results further emphasize the benefits of evacuating the EPZ. The long-term risks are controlled by the habitability (return) criterion, which is the dose rate at which residents are allowed to return to their homes following the emergency phase. For Peach Bottom, the habitability criterion is an annual dose rate of 500 mrem/yr. For comparison, only 55% of all realizations have a long-term risk contribution greater than 50% of the total risk within a 20-mile radius (i.e., 45% of the realizations have an emergency phase risk greater than 50% of the total risk).

As shown on Figure 3, the CCDF for the MACCS2 Uncertainty Analysis for the conditional, mean, individual LCF risk (per event) are very similar and are in good agreement with the three uncertainty analyses corresponding to the three sets of MELCOR results the 10-mile circular area. Also, Figure 3 shows a relatively small change within the 95^{th} percentile confidence interval between each analysis. This indicates that incorporation of all 865 MELCOR source terms into a single MACCS2 uncertainty analysis is reasonably well converged compared with smaller samples using the MELCOR Replicates 1, 2, and 3.

On Figure 3, the x-axis represents the distribution of possible LCF risk per event results within the 10-mile circular area and is generated by sorting (from smallest to largest) all the LCF risk results from the sample of size ‘N’ (i.e., N=865 samples for Figure 3). On Figure 3, the y-axis represents the likelihood of being higher or equal than the value read on the x-axis. When LHS is used, the likelihood of the outcome is estimated by a weight of 1/N and decreasing the y-value by this weight starting from one. The mean can be added on the curve (i.e., a dot for Figure 3) to the CCDF. Quantiles can be read directly by finding the corresponding y-value to the graph, or displayed for a selected quantile as a dot over the curve.

In risk analysis, it is traditional to plot CCDFs rather than cumulative distribution functions (CDFs) as a CCDF answers the question, "How likely it is to have such value or higher?"

As shown on Figure 4, the CCDF for the MACCS2 Uncertainty Analysis for conditional, mean, individual LCF risk (per event) at the 50-mile radial distance is very similar to Figure 3 and is in good agreement with the three uncertainty analyses corresponding to the three sets of MELCOR results. Also, Figure 3 shows a slight increase in the uncertainty within the 95^{th} confidence interval between each analysis. This increase in statistical differences between the MACCS2 Uncertainty Analysis and the MACCS2 Convergence Analyses is a result of a larger number of scenarios analyzed in the MACCS2 for the MACCS2 Uncertainty Analysis.

Table 2. MACCS2 probabilistic analyses

MACCS2 Analysis	Description	MELCOR Source Terms
UAS_CAP14v364_2509	**CAP14**. MACCS2 analysis for MELCOR Replicate #1, LNT Dose Threshold model.	UAS_STP08v1.8.6YV3780
UAS_CAP18v364_2509	**CAP18.** MACCS2 analysis for MELCOR Replicate #2, LNT Dose Threshold model.	UAS_STP09v1.8.6YV3780
UAS_CAP19v364_2509	**CAP19**. MACCS2 analysis for MELCOR Replicate #3, LNT Dose Threshold model.	UAS_STP010v1.8.6YV3780
UAS_CAP17v364_2509	**CAP17**. MACCS2 analysis for combined MELCOR Replicates #1, #2, & #3, LNT Dose Threshold model.	UAS_STP08v1.8.6YV3780; UAS_STP09v1.8.6YV3780; UAS_STP10v1.8.6YV3780

Table 3. Conditional, mean, individual LCF risk average statistics for the MACCS2 Uncertainty Analysis for five circular areas (using all three source term replicates)

	0-10 miles	0-20 miles	0-30 miles	0-40 miles	0-50 miles
Mean	$1.7x10^{-4}$	$2.8x10^{-4}$	2.0x10-[4]	$1.3x10^{-4}$	$1.0x10^{-4}$
Median	$1.3x10^{-4}$	$1.9x10^{-4}$	$1.3x10^{-4}$	$8.7x10^{-5}$	$7.1x10^{-5}$
5^{th} percentile	$3.1x10^{-5}$	$4.9x10^{-5}$	$3.4x10^{-5}$	$2.2x10^{-5}$	$1.9x10^{-5}$
95^{th} percentile	$4.2x10^{-4}$	$7.7x10^{-4}$	$5.3x10^{-4}$	$3.4x10^{-4}$	$2.7x10^{-4}$

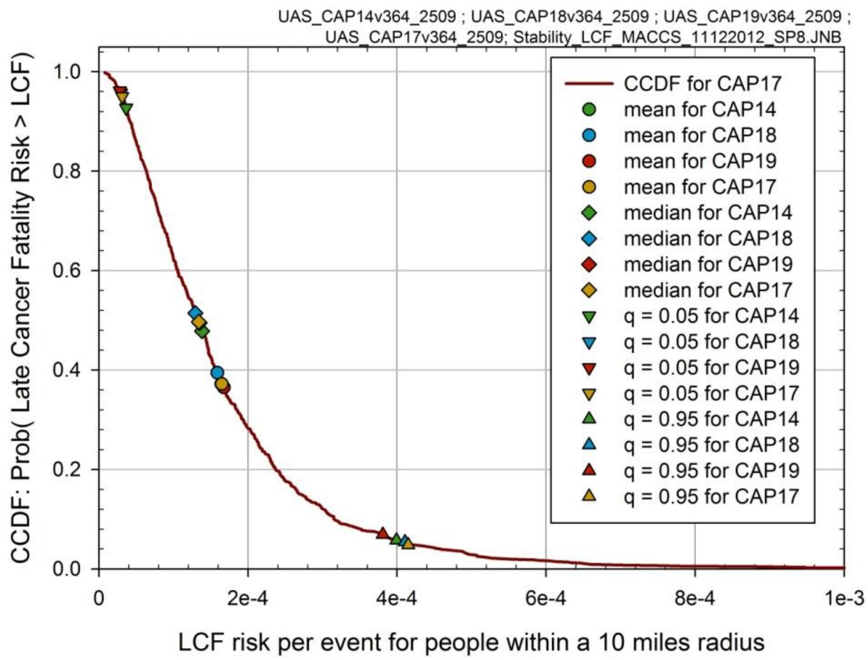

Figure 3. Complementary cumulative distribution function and statistical values for conditional, mean, individual LCF risk (per event) within a 10-mile radius

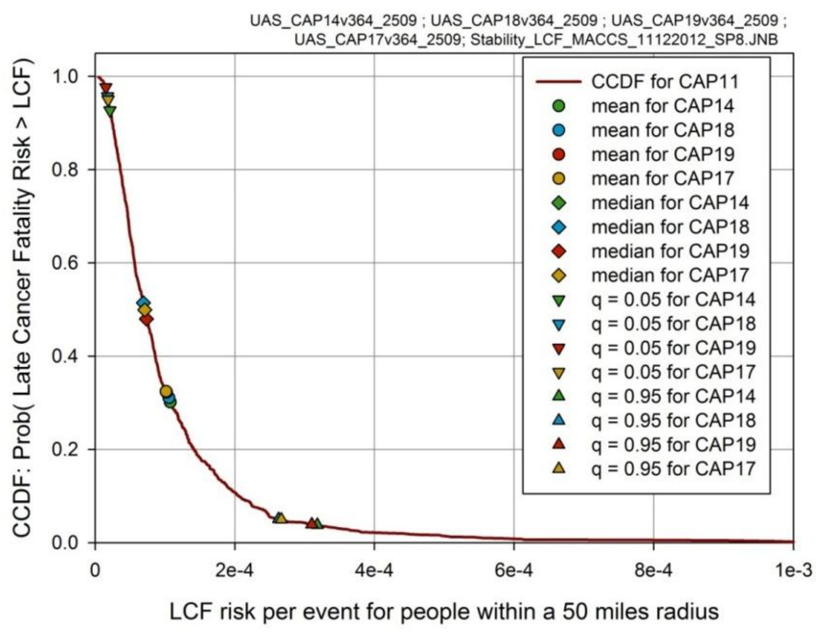

Figure 4. Complementary cumulative distribution function and statistical values for conditional, mean, individual LCF risk (per event) within a 50-mile radius

3.2 Latent Cancer Fatality Risk Regression

Table 4 shows an example of the results of the regression methods used to correlate the conditional, mean, individual LCF risk (per event) results from the MACCS2 uncertainty analysis (CAP17) for the 10-mile, 20-mile, 30-mile, 40-mile, and 50-mile circular areas. The table is a general indication of input parameter influence on the results. Rank regression is often an underestimate the true influence of a parameter since it captures only a monotonic relationship. A slightly non-monotonic relationship results in a smaller R^2 than when the relationship is purely monotonic.

The table is ordered by input variables with the highest rank regression results, and then is further grouped according to the type of input parameter (i.e., MACCS2 or MELCOR variables). The final R^2 determination for all four regression models are fairly high at the five specified circular areas and range from 0.42 for multivariate adaptive regression splines (MARS) at 30 miles to 0.85 for recursive partitioning at 10 miles (Table 4).

All regression methods for the specified circular areas consistently rank the MACCS2 dry deposition velocity (VDEPOS), the MELCOR safety relief valve (SRV) stochastic failure probability (SRVLAM), and the MACCS2 risk factor for cancer fatalities for the residual organ (CFRISK – Residual), respectively, as the most important input variables. The residual organ is represented by the pancreas and is used to define all latent cancers not specifically accounted for in the MACCS2 model. The pancreas is chosen to be a representative soft tissue.

Additional variables also consistently show some level of importance at all circular areas. These additional input variables include the following:

- The MELCOR fuel failure criterion,
- The MELCOR drywell liner melt-through open area flow path (FL904A),
- The MELCOR DC station battery duration (BATTDUR) and
- The MACCS2 dose and dose-rate effectiveness factor for the residual organ (DDREFA-Residual)

These seven variables (VDEPOS, SRVLAM, fuel failure criterion, FL904A, BATTDUR, CFRISK-residual and DDREFA-residual) account for at least 58% of the variance for the specified circular areas in the rank regression analysis, at least 55% of the variance for the specified circular areas in the quadratic regression analysis, at least 37% of the variance for the specified circular areas in the recursive partitioning analysis, and at least 69% of the variance for the specified circular areas in the MARS analysis.

Other input parameters indicate some importance at certain circular areas but not at other circular areas. Thus, the most important variable, VDEPOS, appears at the top of the table followed by the consistently important MELCOR variables, (i.e., SRVLAM, fuel failure criterion, BATTDUR, and FL904A), the LCF risk parameters for residual cancers (i.e., CFRISK-residual and DDREFA-residual), and finally other LCF risk parameters, dose conversion factors for inhalation, and MELCOR parameters (e.g., rail road doors open or closed – RRDOOR) that appear in only some of the tables.

The MACCS2 dry deposition velocity (VDEPOS) input accounts for at least 9% of the variance with a T_i of 0.18 using the quadratic regression analysis to at most 33% of the variance with a T_i of 0.37 using the MARS analysis at each of the circular areas for all regression methods and is the most important of the input variables. Dry deposition is characterized in MACCS2 with a set of deposition velocities corresponding to a set of aerosol size bins. All of the deposition velocities are correlated, so VDEPOS indicates the deposition velocity for each of the aerosol bins.

A larger value of dry deposition velocity results in larger long-term doses at shorter distances and smaller doses at longer distances. This explains why the correlation coefficient is positive at 10 miles and negative beyond 10 miles for the rank regression analysis. 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. Currently, MACCS2 uses a fixed deposition velocity that is independent of wind speed and other conditions. A potential improvement is to allow deposition velocity to vary with wind speed and even variations in surface roughness.

In a previous study [7], the amount of shielding between an individual and the source of groundshine, the groundshine shielding factor (GSHFAC), was determined to be an important variable. However, it is found to be of lesser importance in this study. The long-term GSHFAC was directly correlated with the emergency-phase GSHFAC during normal activities for the non-evacuated residents (GSHFAC-Normal). Table 4 shows GSHFAC-Normal as an important variable at the 10-mile circular area (i.e., 0-6% of the variance for all regression methods).

Unlike the previous study, this uncertainty analysis has varied source terms, a more detailed evacuation model, and approximately 300 more MACCS2 uncertainty variables. Of these differences, the varied source terms have the greatest overall effect on the GSHFAC variance with respect to importance.

The MELCOR input variables (SRVLAM, fuel failure criterion, BATTDUR, and FL904A) account for at least 7% of the variance with a T_i of 0.16 using the MARS analysis to at most 28% of the variance with a T_i of 0.31 using the MARS analysis at the specified circular areas for all regression methods. These MELCOR input variables account for most of the variance in iodine and cesium release fractions. CHEMFORM and SRV open area fraction (SRVOAFRAC) on the other hand, do not appear as variables of importance. Based on this uncertainty analysis, these four variables ultimately correlate with most of the uncertainty contribution of the source term to LCF risk. Further investigation of SRV failure probability, SRV failure modes, fuel failure criterion, DC station battery duration, and containment failure as a result of drywell liner melt-through may provide additional insights into reducing the uncertainty which results from the current state of knowledge of these phenomena.

Within 10 miles, SRVLAM is negatively correlated with LCF risk in the rank regression analysis. This is because longer SRV valve cycling results in a main steam line creep rupture, a higher degree of core degradation, and greater releases. The larger releases lead to greater LCF risk mainly from long-term doses since the 10-mile area is evacuated with the exception of the assumed 0.5% of the population that refuses to evacuate.

Table 4. Conditional, mean, individual LCF risk (per event) regression of the MACCS2 Uncertainty Analysis for the 10-mile circular area

	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	0.73			0.76			0.85			0.72		
Input	**R^2 inc.**	**R^2 cont.**	**SRRC**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**
VDEPOS	0.31	0.31	0.56	0.15	0.28	0	0.22	0.53	0	0.33	0.37	0
SRVLAM	0.43	0.12	-0.35	0.07	0.21	0	0.16	0.35	0	0.12	0.12	0.02
Fuel failure criterion	0.44	0.01	0.15	0.01	0.03	0.55	---	---	---	0.07	0.13	0
FL904A	0.45	0.01	0.12	---	---	---	---	---	---	0	0	1
BATTDUR	---	---	---	---	---	---	0	0.01	0.55	0	0	1
CFRISK Residual	0.54	0.09	0.31	0.16	0.27	0	0.15	0.48	0	0.18	0.25	0
DDREFA Residual	0.57	0.03	-0.18	0.03	0.19	0	0.01	0.05	0.05	0.05	0.16	0
GSHFAC Normal	0.63	0.06	0.24	0.05	0.22	0	---	---	---	0.04	0.09	0.01
CFRISK Colon	0.66	0.03	0.17	0.03	0.20	0	0	0.04	0.33	0.07	0.08	0.05
DDREFA Colon	0.67	0.01	-0.08	0.03	0.02	0.4	---	---	---	---	---	---
CFRISK Lung	0.70	0.03	0.17	0.03	0	1	0	0.10	0.11	0.05	0.02	0.35
DDREFA Lung	0.71	0.01	-0.08	---	---	---	0.01	0.05	0.09	0	0	1

Beyond 10 miles, SRVLAM is positively correlated in the rank regression analysis. Further statistical regression and sensitivity studies are required to understand the negative correlation beyond 10 miles. A possible explanation is the different dependence on SRVLAM of the release fractions for the chemical classes that results in emergency phase dose versus long-term phase dose.

Of the seven variables (VDEPOS, SRVLAM, fuel failure criterion, BATTDUR, FL904A, CFRISK-residual and DDREFA-residual) that are most important in the regression analysis, CFRISK-residual, and DDREFA-residual account for at least 0% of the variance with a T_i of 0.12 using the recursive partitioning regression analysis to at most 23% of the variance with a T_i of 0.25 using the MARS analysis at the specified circular areas for all regression methods. 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 MACCS2 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. Additional development to the MACCS2 model could potentially further improve the treatment of latent health effects by increasing the number of organ-specific cancers to more than 10.

3.3 Prompt Fatality Risk

The NRC quantitative health objective (QHO) for prompt-fatality risk ($5x10^{-7}$ pry) is generally interpreted as the absolute risk within one mile of the exclusion area boundary (EAB). For Peach Bottom, the EAB is 0.5 mile from the reactor building from which a release occurs, so the outer boundary of this one mile zone is at 1.5 miles. The closest MACCS2 grid boundary to 1.5 miles used in this set of calculations is at 1.3 miles. The Peach Bottom LTSBO scenario has a conditional, mean, individual prompt-fatality risk (per event) of 0.00.

Unlike the SOARCA analyses, prompt-fatality risk was estimated to occur beyond 2.5 miles (see Table 5). There are 11% of the 865 MACCS2 realizations investigated that resulted in a nonzero prompt-fatality risk per event out to 1.3 miles and 0.3% of the 865 realizations that resulted in a nonzero prompt-fatality risk per event out to 10 miles. In other words, a select few realizations result in a large enough source term that when combined with specific weather trials in the MACCS2 calculation result in prompt-fatality risks out to the boundary of the EPZ.

The prompt-fatality risks are zero for 87% of all realizations at all specified circular areas (e.g., 1.3% of the realizations result in a prompt-fatality risk at 2 miles but not at 1.3 miles due to specific sampled weather trial conditions, including wind directions, and the nearest location of residents in that direction). This is because the release fractions are too low to produce doses large enough to exceed the dose thresholds for early fatalities, even for the 0.5% of the population that are modeled as refusing to evacuate. The largest value of the mean, acute exposure for the closest resident (i.e., 1.6 to 2.1 kilometers from the plant) for many of these replicates is about 0.3 gray (Gy) to the red bone marrow, which is usually the most sensitive organ for prompt fatalities, but the minimum acute exposure that can cause a prompt fatality is about 2.3 Gy to the red bone marrow. The calculated exposures for these scenarios are all below this threshold.

Table 5 shows statistical results for conditional, mean, individual prompt-fatality risk (per event) from the MACCS2 Uncertainty Analysis at the specified circular areas. Each statistic was estimated to evaluate the epistemic uncertainties resulting from the uncertain inputs to MACCS2. A t-distribution was used to determine the 75th and 95th confidence intervals.

At 2.5 miles and beyond in Table 5 the mean result is greater than the 95th percentile. This is due to the few number of nonzero prompt-fatality risks (i.e., less than 6% of the realizations) at these distances. It is possible that the smallest nonzero values will be lower than the average of all values. In theory, a distribution can be skewed enough so that the mean is greater than the 95th percentile. An instance of this is an exponential of a value sample from a log-normal distribution. For these cases the mean may be higher than the 99th percentile, because it is driven by few nonzero values. This is the same thing that happens here for prompt-fatality risk beyond 2.5 miles.

As shown on Figure 5, the CCDF for the MACCS2 uncertainty analysis for the conditional, mean, individual prompt-fatality risk (per event) are very similar and are in good agreement when compared with the three uncertainty analyses conducted for MACCS2 convergence at the 1.3-mile circular area (i.e., within 1 mile of EAB). Also, Figure 5 shows a change within the 95^{th} percentile interval between the MACCS2 Uncertainty Analysis and the MACCS2 convergence analyses. This is a result of the limited number of prompt-fatality risks greater than zero. Only 11% of the total data of the MACCS2 results for the MACCS2 Uncertainty Analysis resulted in a nonzero prompt-fatality risk. However, the slight difference between the means indicates that the incorporation of all 865 MELCOR source terms into a single MACCS2 uncertainty analysis does not result in any significant change to the overall statistics with respect to the MACCS2 uncertainty inputs. No MELCOR source term combined with the MACCS2 LHS uncertainty inputs approached the NRC QHO for absolute prompt-fatality risk ($5x10^{-7}$ pry). The highest absolute prompt-fatality risk is $1.1x10^{-10}$ pry (i.e., the Peach Bottom LTSBO core damage frequency is $3x10^{-6}$ pry) at 1.3 miles.

Figure 6 shows the CCDFs for the MACCS2 Uncertainty Analysis for the conditional, mean, individual prompt-fatality risk (per event) for the 3.5-mile circular area. The results are similar to those discussed on Figure 5; however, the prompt-fatality risk results greater than zero for each subsequent circular area decreases. The nonzero prompt-fatality risk results decreases from 11% of the total prompt-fatality risk results at 1.3 miles to 4% of the total prompt-fatality risk results at 3.5 miles. Beyond the 3.5 mile circular area, the source terms that generate nonzero prompt-fatality risks drop below 2% and the plots convey little useful information. For distances beyond 2.5 miles, the 95^{th} percentile statistics are not well converged (i.e., greater than an order of magnitude difference). Even at a 2-mile radius, the 95^{th} percentiles differ up to 70%.

Table 5. Conditional, mean, individual prompt-fatality risk average statistics for the MACCS2 Uncertainty Analysis for specified circular areas using all three source term replicates

	0-1.3 miles	0-2 miles	0-2.5 miles	0-3 miles	0-3.5 miles	0-5 miles	0-7 miles	0-10 miles
Mean	$4.5x10^{-7}$	$1.8x10^{-7}$	$8.9x10^{-8}$	$6.4x10^{-8}$	$3.5x10^{-8}$	$1.4x10^{-8}$	$8.3x10^{-9}$	$4.8x10^{-9}$
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75^{th} percentile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95^{th} percentile	$1.9x10^{-6}$	$7.4x10^{-7}$	$3.5x10^{-8}$	$5.3x10^{-10}$	0.0	0.0	0.0	0.0

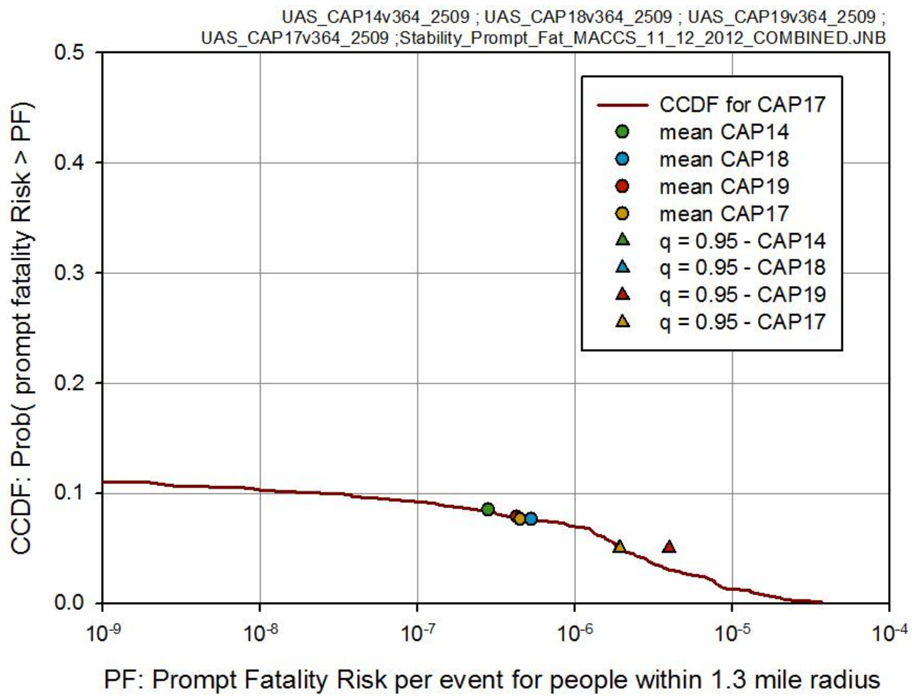

Figure 5. Complementary cumulative distribution function and statistical values for conditional, mean, individual prompt-fatality risk (per event) within a 1.3-mile radius

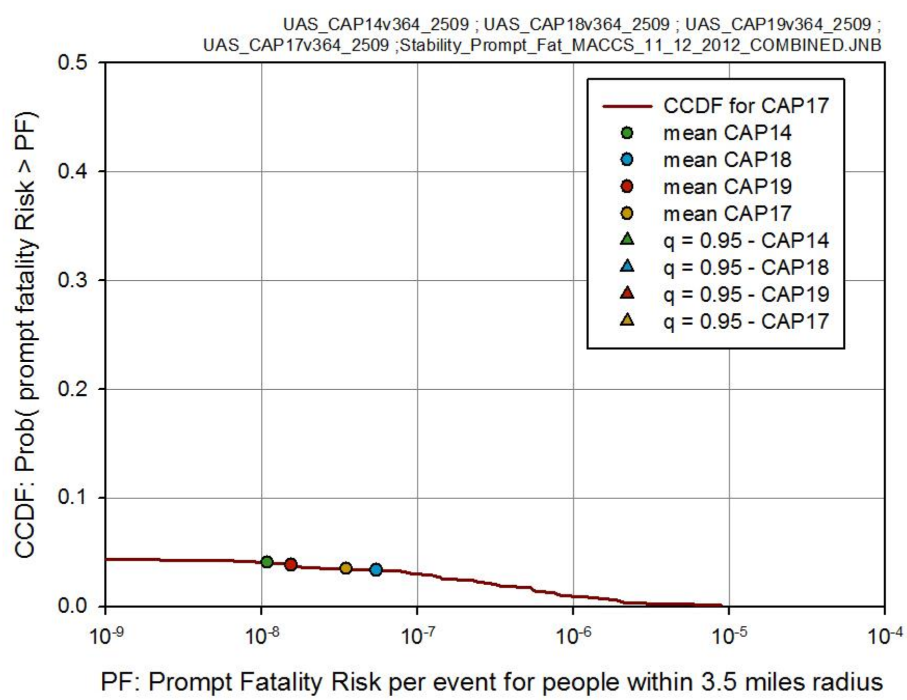

Figure 6. Complementary cumulative distribution function and statistical values for conditional, mean, individual prompt-fatality risk (per event) within a 3.5-mile radius

3.4 Prompt Fatality Regression

Table 6 shows an example of the results of the regression results obtained for conditional, mean, individual prompt-fatality risk (per event) for the MACCS2 Uncertainty Analysis (i.e., CAP17) for the 1.3-mile circular area. Since less than 2.5% of all the MACCS2 Uncertainty Analysis realizations resulted in a nonzero prompt-fatality risk for the 5-mile, 7-mile, and 10-mile circular areas, they are not included in the regression analysis results due to unreliable statistics regarding variable importance.

The table is a general indication of input parameter influence on the results. Rank regression is often an underestimate the true influence of a parameter since it captures only a monotonic relationship. A slightly non-monotonic relationship results in a smaller R^2 than when the relationship is purely monotonic. The tables are ordered by input variables with the highest rank for all regression results, and then are further grouped according to the type of input parameter (i.e., MACCS2 or MELCOR variables). There are two noticeable groupings when the important variables are examined. Those within 2 miles show the final R^2 for the non-rank regression models are fairly high and range from 0.58 for MARS to 0.75 for recursive partitioning. The rank regression shows that monotonic relationship for all variables are poor.

For the circular areas less than 2 miles, the non-rank regression methods consistently rank the MACCS2 wet deposition model (CWASH1), the MELCOR SRV stochastic failure probability (SRVLAM), the MELCOR SRV open area fraction (SRVOAFRAC), the MACCS2 early health effects threshold and beta (shape) factor for red bone marrow (EFFTHR-Red Marrow and EFFACB-Red Marrow), and the MACCS2 linear, crosswind dispersion coefficient (CYSIGA), in order, as the most important input variables. Additional variables also consistently show some level of importance for circular areas less than 2 miles. These additional input variables include the following:

- The MACCS2 amount of shielding between an individual and the source of groundshine during normal activities for the non-evacuated residents (GSHFRAC-Normal),
- The MACCS2 evacuation delay for Cohort 5 (DELTVA-Cohort 5), and
- The MELCOR DC station battery duration (BATTDUR)

These nine variables (CWASH1, SRVLAM, SRVOAFRAC, EFFTHR-red marrow, EFFACB-red marrow, CYSIGA, GSHFRAC-normal, DELTVA-cohort 5, and BATTDUR) account for at least 24% of the variance for the quadratic regression, at least 46% of the variance for the recursive partitioning, and at least 30% of the variance for MARS.

Other input parameters show a low importance at certain circular areas but not for other circular areas. Thus, the most important variable, CWASH1, appears at the top of Table 6 followed by the consistently important MELCOR variables, SRVLAM and SRVOAFRAC, and then the other five important variables, and finally a set of parameters not consistently seen in all the tables.

The MACCS2 wet deposition parameter (CWASH1) accounts for at least 4% of the variance with a T_i of 0.78 using the MARS analysis to at most 29% of the variance with a T_i of 0.76 using the quadratic regression analysis for circular areas less than 2 miles for all non-ranked regression methods and is the most important input variable. Also, CWASH1 consistently has the highest rank for interactions with other input variables (T_i). The wet deposition parameter shows that under heavy rains, wet deposition is very effective and rapidly depletes the plume. This process can produce concentrated deposits on the ground and create what is often referred to as a hot spot (i.e., an area of higher radioactivity than the surrounding areas). As seen in the non-ranked regression analysis, rain and its interactions with other input variables (e.g., see the T_i for recursive partition in Table 6) can significantly affect consequence calculations when it does occur. However, the prompt-fatality risk is driven more the crosswind dispersion (CYSIGA) beyond 2 miles.

The MELCOR input variables (SRVLAM, SRVOAFRAC, and BATTDUR) account for at least 1% of the variance with a T_i of 0.2 using the quadratic regression analysis to at most 17% of the variance with a T_i of 0.6 using the recursive partitioning regression analysis for circular areas less than 2 miles for all non-ranked regression methods. These MELCOR input variables account for the majority of the variance for iodine and cesium release. Based on this uncertainty analysis, these two variables and their interactions with other MELCOR input variables ultimately provide the majority of the uncertainty in the source term with respect to prompt dose for the consequence analysis. Further investigation of SRV failure probability, SRV failure modes, and DC station battery duration may provide additional insights into reducing the uncertainty which results from the current state of knowledge of these phenomena.

The crosswind dispersion coefficient (CYSIGA), early health effects threshold for red bone marrow (EFFTHR–Red Marrow), and other important variables also show a large non-monotonic interaction with other input variables. While the overall R^2 contribution from these input variables is low, their interactions with other variables do justify their consideration to prompt-fatality risk.

Table 7 shows an example of the results of the regression results obtained for conditional, mean, individual prompt-fatality risk (per event) for the MACCS2 Uncertainty Analysis (i.e., CAP17) for the 2.5-mile circular area. For the circular areas greater than 2 miles but less than 5 miles, the regression methods consistently rank the MACCS2 crosswind dispersion coefficient (CYSIGA), the early health effects threshold risk for red bone marrow (EFFTHR-Red Marrow), the early health effects beta (shape) factor for red bone marrow (EFFACB-Red Marrow), the MELCOR SRV stochastic failure probability (SRVLAM), and the MELCOR SRV open area fraction (SRVOAFRAC) as the most important input variables. However, additional variables also consistently show some level of importance for circular areas greater than two miles. These additional input variables include the following:

- The MACCS2 inhalation protection factor during sheltering activities for non-evacuated residents (PROTIN-Sheltering),
- The MELCOR DC station battery duration (BATTDUR), and
- The MELCOR railroad inner door open fraction (RRIDFRAC)

The final R^2 for non-rank regression models is reasonable for circular areas between 2.5 to 3.5 miles. They range from 0.44 for recursive partitioning at 3.5 miles to 0.82 for MARS at 3.5 miles. These eight variables (CYSIGA, EFFTHR-red marrow, EFFACB-red marrow, SRVLAM, SRVOAFRAC, PROTIN-sheltering, BATTDUR, and RRIDFRAC) account for at least 12% of the variance for the quadratic regression analysis, at least 96% of the variance for the recursive partitioning analysis, and at least 21% of the variance for the MARS analysis.

Table 6. Conditional, mean, individual prompt-fatality risk (per event) regression of the MACCS2 Uncertainty Analysis for the 1.3-mile circular area

	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	0.26			0.67			0.75			0.64		
Input	**R^2 inc.**	**R^2 cont.**	**SRRC**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**
CWASH1	0.03	0.03	0.10	0.12	0.88	0	0.29	0.77	0	0.11	0.94	0
SRVLAM	0.07	0.04	-0.10	0	0.03	0.56	0.15	0.60	0	0.01	0.17	0.19
SRVOAFRAC	0.10	0.03	-0.09	0.01	0.20	0.13	0.02	0.15	0.12	0.04	0.23	0.14
BATTDUR	---	---	---	---	---	---	0	0.29	0	---	---	---
GSHFAC Normal	0.12	0.02	0.08	0.01	0.60	0	0	0	1	0.01	0.13	0.59
EFFTHR Red Marrow	0.18	0.06	-0.14	0.01	0	1	0	0	1	0	0.04	0.43
EFFACB Red Marrow	0.19	0.01	-0.05	---	---	---	---	---	---	0	0.39	0
CYSIGA	0.22	0.03	-0.09	0	0	1	0.01	0.39	0	0.02	0.39	0
DLTEVA Cohort 5	0.23	0.01	0.01	0.01	0	1	---	---	---	0	0.13	0.30

The MACCS2 crosswind dispersion coefficient (CYSIGA) parameter accounts for at least 0% of the variance with a T_i of 0.16 using the quadratic regression analysis to at most 81% of the variance with a T_i of 0.25 using the recursive partitioning regression analysis for circular areas from 2.5 to 3.5 miles for all non-ranked regression methods and is the most important input variable (see Table 7). Also, CYSIGA consistently has one of the highest ranks for interactions with other input variables (T_i). Crosswind dispersion directly affects prompt doses to members of the population and resulting prompt health effects.

The MELCOR input variables (SRVLAM, SRVOAFRAC, BATTDUR, and RRIDFRAC) account for at least 0% of the variance with a T_i of 0.5 using the MARS analysis to at most 17% of the variance with a T_i of 0.52 using the recursive partitioning regression analysis for circular areas greater than 2 miles for all non-ranked regression methods and are the second most important group of input variables (see Table 7). These MELCOR input variables account for the majority of the variance for iodine and cesium release fractions. Based on this uncertainty analysis, these two variables and their interactions with other MELCOR input variables ultimately provide the majority of the uncertainty in the source term with respect to prompt dose for the consequence analysis. Further investigation of SRV failure probability, SRV failure modes, DC station battery duration, and failure modes of the railroad doors may provide additional insights into reducing the uncertainty associated with these parameters.

The early health effects threshold risk for red bone marrow (EFFTHR-Red Marrow) and the early health effects beta (shape) factor for red bone marrow (EFFACB-Red Marrow) inputs account for at least 0% of the variance with a T_i of 0.41 using the quadratic regression analysis to at most 16% of the variance with a T_i of 0.82 using the MARS analysis for circular areas of 2.5 to 3.5 miles for all non-ranked regression methods and are the third most important group of input variables. Also, EFFTHR-red marrow and EFFACB-red marrow consistently show interactions with other input variables. EFFTHR-red marrow and EFFACB-red marrow are important because the hematopoietic syndrome has the lowest threshold for an early fatality.

The amount of shielding between an individual and the source of groundshine for sheltering activities for the non-evacuees (GSHRAC-sheltering), the wet deposition parameter (CWASH1), and a few other important variables also show a significant non-monotonic interaction with other input variables. While the overall R^2 contribution from these input variables is low, with the exception of PROTIN-sheltering at the 2.5-mile circular area, their interactions with other variables do justify their consideration for prompt-fatality risk.

In the case of PROTIN-sheltering within the 2.5-mile circular area, this variable has the largest overall non-monotonic variance (i.e., 15-56% of the variance for the regression methods considered) and the highest rank for interactions with other input variables (T_i). Since this MACCS2 input variable does not consistently appear as an important variable at other distances, it is considered to be a minor overall variable.

Table 7. Conditional, mean, individual prompt-fatality risk (per event) regression of the MACCS2 Uncertainty Analysis for the 2.5-mile circular area

	Rank Regression			**Quadratic**			**Recursive Partitioning**			**MARS**		
Final R^2	0.18			0.52			0.50			0.66		
Input	**R^2 inc.**	**R^2 cont.**	**SRRC**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**
PROTIN Sheltering	0.01	0.01	0.04	0.28	0.78	0	0.28	0.41	0	0.10	0.74	0
CYSIGA	0.02	0.01	-0.04	0.05	0.21	0.03	0.17	0.28	0.01	0	0	1
SRVLAM	0.05	0.03	-0.06	0	0	1	0.01	0.31	0	0	0.12	0.28
SRVOAFRAC	0.07	0.02	-0.07	0.01	0	1	0.03	0	1	0.03	0.35	0.01
BATTDUR	0.07	0	0.02	---	---	---	---	---	---	---	---	---
RRIDFRAC	0.08	0.01	0.02	0	0.17	0.11	---	---	---	---	---	---
EFFTHR Red Marrow	0.14	0.06	-0.10	0	0	1	0.03	0.42	0	0.01	0.65	0
EFFACB Red Marrow	0.14	0	0.02	0	0.41	0	---	---	---	0	0	1
CWASH1	0.15	0.01	0.05	0	0.36	0	---	---	---	0	0	1
DLTEVA Cohort 3	0.17	0.02	-0.01	---	---	---	---	---	---	0.02	0.41	0

4 CONCLUSIONS

For this work, the mean, individual LCF risk, all regression methods at each of the circular areas around the plant (10-mile to 50-mile radii are considered) consistently rank the MACCS2 dry deposition velocity, the MELCOR SRV stochastic failure probability, and the MACCS2 residual cancer risk factor, respectively, as the most important input parameters.

The mean, individual prompt-fatality risks are zero for 87% of all realizations at all locations. This is because the release fractions are too low to produce doses large enough to exceed the dose thresholds for early fatalities, even for the 0.5% of the population who are assumed not to evacuate.

For mean, individual prompt-fatality risk within the circular areas less than 2-miles, the non-rank regression methods consistently rank the MACCS2 wet deposition parameter, the MELCOR SRV stochastic failure probability, the MELCOR SRV open area fraction, the MACCS2 early health effects threshold for red bone marrow, and the MACCS2 crosswind dispersion coefficient, respectively, as the most important input parameters.

For mean, individual prompt-fatality risk within the circular areas between 2.5-miles and 3.5-miles, the regression methods consistently rank the MACCS2 crosswind dispersion coefficient, the MACCS2 early health effects threshold for red bone marrow, the MELCOR SRV stochastic failure probability, and the MELCOR SRV open area fraction, respectively, as the most important input parameters.

5 REFERENCES

1. U.S. Nuclear Regulatory Commission, NUREG-1935, "State-of-the-Art Reactor Consequence Analyses (SOARCA) Report," Washington D.C. (2012).
2. Sandia National Laboratories, NUREG/CR-7110 Volume 1, "State-of-the-Art Reactor Consequence Analyses Project Volume 1: Peach Bottom Integrated Analysis," U.S. Nuclear Regulatory Commission, Washington D.C. (2012).
3. Sandia National Laboratories, NUREG/CR-7110 Volume 2, "State-of-the-Art Reactor Consequence Analyses Project Volume 2: Surry Integrated Analysis," U.S. Nuclear Regulatory Commission, Washington D.C. (2012).
4. Dotson, L.J. and J. Jones, NUREG/CR-6864, "Identification and Analysis of Factors Affecting Emergency Evacuations: Main Report (Volume 1)," Sandia National Laboratories, Albuquerque, NM (2005).
5. Jones, J., et al., NUREG/CR-6981, "Assessment of Emergency Response Planning and Implementation for Large Scale Evacuations," U.S. Nuclear Regulatory Commission, Washington D.C. (2008).
6. Bixler, N., et al., "Synthesis of Distributions Representing Important Non-Site-Specific Parameters in Off-Site Consequence Analysis," Sandia National Laboratories, Albuquerque, NM, (2010).
7. Gregory, J.J., et al., "Task 5 Letter Report: MACCS2 Uncertainty Analysis of EARLY Exposure Results," Sandia National Laboratories, Albuquerque, NM (2000).