SOARCA Peach Bottom Atomic Power Station Long-Term Station Blackout Uncertainty Analysis: Knowledge Advancement

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Abstract: This paper describes the knowledge advancements from the uncertainty analysis for the State-of-the-Art Reactor Consequence Analyses (SOARCA) unmitigated long-term station blackout accident scenario at the Peach Bottom Atomic Power Station. This work assessed key MELCOR and MELCOR Accident Consequence Code System, Version 2 (MACCS2) modeling uncertainties in an integrated fashion to quantify the relative importance of each uncertain input on potential accident progression, radiological releases, and off-site consequences. This quantitative uncertainty analysis provides measures of the effects on consequences, of each of the selected uncertain parameters both individually and in interaction with other parameters. The results measure the model response (e.g., variance in the output) to uncertainty in the selected input. Investigation into the important uncertain parameters in turn yields insights into important phenomena for accident progression and off-site consequences. This uncertainty analysis confirmed the known importance of some parameters, such as failure rate of the Safety Relief Valve in accident progression modeling and the dry deposition velocity in off-site consequence modeling. The analysis also revealed some new insights, such as dependent effect of cesium chemical form for different accident progressions.

Keywords: SOARCA, MACCS, MELCOR, Uncertainty Analysis, Severe Accident Analysis

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1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC), the nuclear power industry, and the international nuclear energy research community have devoted considerable research over the last several decades to examining severe reactor accident phenomena and offsite consequences. The NRC initiated the State-of-the-Art Reactor Consequence Analyses (SOARCA) project [1] to leverage this research and develop best estimates of the offsite radiological health consequences for potential severe reactor accidents for two pilot plants: the Peach Bottom Atomic Power Station in Pennsylvania and the Surry Power Station in Virginia. By applying modern analysis tools and techniques, the SOARCA project developed a body of knowledge regarding the realistic outcomes of select severe nuclear reactor accidents. To accomplish this objective, the SOARCA project's integrated modeling of accident progression and offsite consequences used both state-of-the-art computational analysis tools (the MELCOR code and the MELCOR Accident Consequence Code System, Version 2 [MACCS2]) and best modeling practices drawn from the collective wisdom of the severe accident analysis community. The SOARCA project is documented in NUREG-1935 (2012) [2], NUREG/CR-7110, Volume 1 [3], and NUREG/CR-7110 Volume 2.

The objectives of this SOARCA Uncertainty Analysis [1] are to evaluate the robustness of the SOARCA deterministic results and conclusions [2-3], 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.

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The SOARCA project documented in the summary report (NUREG-1935 [2]) and accompanying detailed analyses for the two pilot plants (see [3] for the Peach Bottom Integrated Analyses) included several sensitivity studies. The objective of these sensitivity studies was to examine specific issues individually and ensure the robustness of the conclusions documented in NUREG-1935 [2]. 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.

The SOARCA offsite consequence results presented in NUREG-1935 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. 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.

The U.S. Nuclear Regulatory Commission (NRC) guidance documents (i.e., Regulatory Guide 1.174 and NUREG-1855) discuss three types of epistemic uncertainty: completeness, model, and parameters. 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 only the SOARCA Peach Bottom BWR Pilot Plant Unmitigated Long-Term Station Blackout scenario rather than all seven of the SOARCA scenarios documented in NUREG-1935. The SOARCA Peach Bottom BWR Pilot Plant Unmitigated Long-Term Station Blackout scenario [3] is analyzed. While one scenario cannot provide a complete exploration of all possible effects of uncertainties in analyses for this SOARCA pilot plant, 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 are an important class of events for boiling water reactors (BWRs) in general, the phenomenological insights gained on accident progression and radionuclide releases may prove useful for BWRs in general. This work does not include uncertainty in the scenario frequency.

2. MELCOR ANALYSES

Performing the source term calculations for NUREG/CR-7155 revealed three accident progression sub-scenarios within the Peach Bottom unmitigated long-term station blackout (LTSBO) scenario: (1) early stochastic failure of the cycling safety relief valve (SRV), which was the SOARCA scenario in NUREG-1935; (2) thermal failure of the SRV without main steam line (MSL) creep rupture; and (3) thermal failure of the SRV with MSL creep rupture. Several influences were found to strongly affect the magnitude and timing of fission product releases to the environment. Most notably, with respect to the magnitude of the source term (i.e., the magnitude of cesium and/or iodine releases), the following were found to be influential:

- Whether the sticking open of the SRV (the lowest set-point SRV) occurs before or after the onset of core damage, with higher releases if after core damage,
- Whether a MSL creep rupture occurs; if MSL rupture occurs, releases will be higher due to fission products being vented straight to the drywell and bypassing wetwell scrubbing,
- The amount of cesium chemisorbed as CsOH onto the stainless steel of reactor pressure vessel (RPV) internals; more chemisorption relating to less cesium release to the environment in high-temperature scenarios such as MSL rupture,
- Whether core debris relocates from the RPV to the reactor cavity all at once or over an extended period of time with relocation all at once leading to lower releases to the environment,
- The degree of oxidation, primarily fuel-cladding oxidation, occurring in-vessel with greater oxidation resulting in larger releases, and
- Whether a surge of water from the wetwell up onto the drywell floor occurs at drywell liner melt-through with the development of surge water leading to larger releases.

The sampled parameters shown to strongly or meaningfully influence the magnitude of the fission product releases, because they contribute to the important phenomena noted above, were:

- The expected number of cycles an SRV can undergo before failing to reclose (stochastic failure rate of SRV),
- The chemical form of cesium (i.e., the amount of cesium as CsOH opposed to Cs_2MoO_4),
- The size of the breach in the drywell liner from core debris contacting and melting through the liner,
- The fractional open area of an SRV after it has failed to reseat because of overheating,
- The time-at-temperature criterion specified for loss of “intact” fuel rod geometry, and
- The temperature at which oxidized fuel cladding mechanically fails.

With respect to release timing, the strongest influences identified were:

- When the reactor core isolation cooling (RCIC) system failed,
- When the SRV failed to reseat, and
- What the open fraction of the SRV was when it failed to reseat given a thermally-induced failure.

The sampled parameters shown to strongly or meaningfully influence the timing of releases, by affecting the timing influences noted above, were:

- The time taken to exhaust the station batteries (i.e., sole determinate of when the RCIC system fails),
- The number of cycles an SRV can undergo before failing to reclose, and
- The fractional open area of an SRV after it has failed to reseat because of overheating.

The means by which fission products release to the environment in the MELCOR source term calculations are well characterized by what is observed for the release of cesium. Most of the cesium released to the environment in the calculations undergoes the following sequential processes:

1. Release from the dismantling core as CsOH, CsI, or Cs_2MoO_4 vapor.
2. Condensation into aerosols.

3. Gravitational settling onto reactor internals.
4. Re-vaporization after RPV lower head failure over approximately 24 hours.
5. Re-condensation into aerosols that are carried out a breach in the drywell liner resulting from core debris contacting and melting through the liner.

The most influential sampled parameter identified in the uncertainty analysis affecting the re-vaporization of cesium aerosols settled on reactor internals is the number of cycles an SRV can undergo before failing to reclose: a smaller number of cycles leading to less re-vaporization (and less release to the environment) and a larger number of cycles leading to more re-vaporization (and more release to the environment). While the importance of this parameter in determining whether or not MSL creep rupture occurs was not previously know, the dramatic influence of this parameter was not anticipated going into the uncertainty analysis.

An unexpected influence that arose in the analysis was that specifying the cesium inventory in the core in the form of CsOH (as opposed to Cs_2MoO_4) often led to smaller releases of cesium to the environment. This was surprising in that the lower vapor pressure dependence on temperature of CsOH than of Cs_2MoO_4 might intuitively suggest that CsOH would transport more readily. What led to a contradiction of intuition was the process of chemisorption where cesium bonds with impurities in the stainless steel of reactor internals. This process has a strong dependence on temperature, with higher temperatures yielding more chemisorption. In calculations where much of the reactor core degradation occurred with the reactor at pressure (i.e., where the lowest set-point SRV cycled as designed for a relatively long period before failing to reseat), temperatures in the RPV were higher and chemisorption potential was greater. In these calculations, if cesium were specified in the core predominantly as CsOH, more than half of the initial core inventory deposited on reactor internals through chemisorption. This deposition was permanent, making the absorbed cesium unavailable for transport and release to the environment. Previously, it was thought that cesium in the form of CsOH would lead to larger releases, but in fact for high temperature scenarios, CsOH resulted in smaller releases and thus limited the total effect of higher temperatures.

Another surprising influence in the analysis was the surging of water up from the wetwell to the drywell floor. This occurred in approximately half of the MELCOR calculations in association with large breaches[1] ($> 0.2\ m^2$) in the drywell liner caused by core debris contacting the liner and melting through it. Large breaches resulted in larger depressurizations of the containment and a greater pressure differential between the drywell and the wetwell during the depressurizations. The suddenly superheated state of the water in the wetwell contributed to the pressure differentials in the presence of which some of the water flashed to steam. The pressure differentials overwhelmed the vacuum breakers between the wetwell and the drywell and contaminated water surged out of the wetwell. Most of the water surging from the wetwell flows from the drywell to the reactor building through the breach in the drywell liner.

3. MACCS2 CONSEQUENCE ANALYSES

The results of the consequence analyses are presented in terms of risk to the public for each of the realizations analyzed using the Peach Bottom unmitigated LTSBO MELCOR and MACCS2 models. All results are presented as conditional risk (i.e., assuming that the accident occurs), and show the conditional risks to individuals as a result of the accident (i.e., latent cancer fatality (LCF) risk per event or early-fatality risk per event). The risk metrics are LCF risk and early-fatality risks to residents in different circular regions surrounding the plant. The risks are mean values (i.e., expectation values) over sampled weather conditions representing a year of meteorological data and over the entire residential population within a circular region. The risk values represent the projected number of fatalities divided by the

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[1] Breach size is a user-specified input in the MELCOR model and this was included as an uncertain parameter in this study.

population. LCF risks are calculated for a set of dose-response models, which are linear-no-threshold (LNT), a linear with threshold model where the threshold is mean U.S. natural background plus mean medical radiation as a dose-truncation level (USBGR), and a linear with threshold model where the threshold is based on the Health Physics Society (HPS) Position Statement. The HPS Position Statement suggests that health effects not be quantified below an annual rate of 5 rem/yr provided that the total excess dose over a lifetime does not exceed 10 rem. 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.

For the LCF risk results, 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 in the MACCS2 modeling). 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. 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 used is an annual dose rate of 500 mrem/yr (per Pennsylvania State guidelines). When the 10-mile and 20-mile circular area statistics are compared, there is a larger relative influence of the emergency phase for the 20-mile region compared to the 10-mile region.

The SOARCA project's point estimate for the long-term station blackout scenario was a zero early-fatality risk [3]. In considering uncertainties more fully, the uncertainty analysis calculated a non-zero early-fatality risk, within 1.3 miles in 11% of the 865 MACCS2 realizations, and out to 10 miles in 3 of the 865 (0.3%) realizations. In other words, a select few realizations result in a large enough source term that when combined with specific weather trials and sampled values of key uncertain MACCS2 parameters, that a non-zero early-fatality risk (albeit still minute in absolute terms) can be calculated out to the boundary of the EPZ. Section 3.2 below provides further explanation.

The early-fatality risks are zero for 87% of all realizations at all specified circular areas. This is because in most cases 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 zero early-fatality risk realizations is about 0.3 gray (Gy) to the red bone marrow, which is usually the most sensitive organ for early fatalities, but the minimum acute exposure that can cause an early fatality is about 2.3 Gy to the red bone marrow. The calculated exposures for these scenarios are all below this threshold.

3.1 Regression for LCF Risk

The regression techniques used to perform a sensitivity analysis (i.e., rank regression, quadratic, recursive partitioning, and multivariate adaptive regression splines (MARS)) for the consequence results were conducted with the 865 source terms evaluated with MELCOR using a set of 21 uncertain input variables and using 350 MACCS2 individual uncertain input variables in 20 parameter groups. Within the 10-mile circular area, the regression techniques indicate a confidence level >72%. Beyond the 10-mile circular area, each of the regression techniques indicate a confidence level ≥42% with the recursive partitioning analysis consistently being the highest with a confidence level of 71% to 64%.

Based on this, the statistical regression techniques used to determine the important input parameters for LCF risk are considered adequate for this work. While other regression techniques (e.g., ACOSSO or Gaussian process) not used in this study may provide additional insights, the four selected regression analyses cover a large spectrum of potential interactions and influences. Additional regression methods can be employed and may provide more insights in the analyses by confirming the influence of some parameters or perhaps capturing other kinds of interactions not considered in this work. However, since the monotonic (i.e., rank regression) and non-monotonic (i.e., quadratic, recursive partitioning, and MARS) regression techniques agree reasonably well, using more advanced methods was considered unnecessary.

All regression methods at each of the circular areas consistently rank the following, respectively, as the most important input parameters:

- MACCS2 dry deposition velocity (VDEPOS), which involves a variety of mechanisms that cause aerosols to deposit, including gravitational settling, impaction onto terrain irregularities, including buildings and other manmade structures, and Brownian diffusion,
- The MELCOR SRV stochastic failure probability (SRVLAM), an important MELCOR parameter for source term determination, and
- The MACCS2 'residual' cancer risk factor which is used for estimating residual cancers not related to the seven organ-specific cancers that were used in SOARCA (CFRISK–Residual).

Some additional parameters also consistently show some level of importance at all circular areas. These are the following:

- The MELCOR fuel failure criterion, which is the time endurance of the upright, cylindrical configuration of fuel rod bundles,
- The MELCOR drywell liner melt-through open area flow path (FL904A), and
- The MACCS2 'residual' dose and dose-rate effectiveness factor (DDREFA–Residual), which is based on BEIR-V risk factors for estimating health effects to account for observed differences between low and high dose rates.

3.2 Regression for Early-Fatality Risk

Because fewer than 7% of all the MACCS2 uncertainty analysis realizations resulted in nonzero early-fatality risk at or beyond 2 miles, these circular areas are not included. The regression did not produce any reliable results at these distances. On the other hand, the regression analyses produce non-monotonic confidence levels ≥58% at a distance at or within 2 miles. At these distances, approximately 13% of all MACCS2 realizations have a nonzero early-fatality risk, and the top one or two input parameters are correlated to a high confidence level. The rank regression analysis consistently produces a poor result, indicating that there is a non-linear relationship between the important input variables and early-fatality risk. Based on these analyses, the statistical regression techniques used to determine the important input parameters for early-fatality risk are considered adequate for the distances reported in this work. The non-rank regression methods consistently rank the following as the most important input variables, respectively:

- The MACCS2 wet deposition model, which is an important phenomenon that is very effective at rapidly depleting the plume and can produce concentrated deposits on the ground,
- the MELCOR SRV stochastic failure probability, which is an important MELCOR parameter for source term magnitude,

- the MELCOR SRV open area fraction, which is an important MELCOR parameter for source term magnitude and timing,
- the MACCS2 early health effects threshold and beta (shape) factor for red bone marrow, which is the most sensitive organ for the potential of early health effects, and
- the MACCS2 linear, crosswind dispersion coefficient, which defines how concentrated the radionuclides are within the plume (i.e., the more concentrated the radionuclides are within the plume, the higher the possible dose to an individual within the plume, and the more persistent the peak concentration is within the plume as the plume travels downwind).

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,
- The MACCS2 evacuation delay for Cohort 5; Cohort 5 is the evacuation tail (the slowest) of the general public evacuation, and
- The MELCOR DC station battery duration, which is important for release timing.

3.3 Regression for LCF Risk using Dose Truncation

Additional regression analyses were conducted as a sensitivity analysis for the dose-response models considered in this report (i.e., LNT, linear with a threshold of 0.62 rem/yr, and linear with a threshold of 5 rem/yr with 10 rem lifetime limit). The regression techniques were used with a single replicate of the Monte Carlo runs (Replicate 1) that included 284 source terms with the 21 MELCOR uncertain input variables and 350 MACCS2 uncertain input variables. The statistical regression techniques provided adequate results, as described below.

For the LNT sensitivity analysis, all circular areas for all regression methods consistently rank the MACCS2 dry deposition velocity and the MELCOR SRV stochastic failure probability, respectively, as the most important input parameters. Some additional variables also consistently show some level of importance at all circular areas, including:

- The MELCOR fuel failure criterion, and
- The MELCOR SRV open area fraction.

Since this is a smaller subset of the LCF risk regression analyses in Section 3.1 and still ranks the same top two parameters as most important, this sensitivity analysis provides additional confidence in the regression analyses for parameters considered important.

For the alternative dose-response model (i.e., thresholds of 0.62 rem/yr and 5 rem/yr with a 10 rem lifetime limit) sensitivity analyses, the five circular areas for all regression methods consistently rank the MACCS2 inhalation protection factor for normal activity, the MACCS2 lung lifetime risk factor for cancer death, and the MELCOR SRV stochastic failure probability as the most important input variables. The important MACCS2 variables for the dose threshold models are those associated with doses received in the first year and not ones associated with the long-term phase risk beyond the first year. Because the internal doses from inhalation diminish with time, most of the doses in the second and subsequent years are from the exposures during the first year. These doses are limited by the habitability criterion to be less than 500 mrem in any year. The inhalation dose used in this criterion is a committed dose (i.e., it accounts for doses received over the next 50 years). Because the annual doses allowed by the habitability criterion are less than the dose truncation levels, nearly all of the risk is from doses received during the first year. Additional variables also consistently show some level of importance at all circular areas, including:

- The MELCOR SRV open area fraction , and
- The MELCOR DC station battery duration.

For Peach Bottom, the habitability criterion used is an annual dose rate of 500 mrem/yr. This dose rate is below the threshold limit in both dose truncation models; therefore, most of the doses received during the long-term phase are below the dose truncation limit and are not counted toward health effects when using this criterion. Thus, the LCF risk calculated using the alternate dose threshold models are orders of magnitude lower than the risk calculated using the LNT model, and most of the risks associated with either truncation level are from doses received during the first year[2]. These first-year doses include most of emergency phase doses and a fraction of the long-term phase doses (the emergency and long-term phases are not easily separated in the first year). The difference in which parameters are most important for the alternate dose threshold models vs. LNT model reflects the dominance of the first-year contribution to the alternate dose models.

3.4 Habitability Sensitivity Study

A series of sensitivity analysis using five habitability criterions (i.e., 0.1 rem/yr, 0.5 rem/yr, 2 rem/yr[3], 4 rem over 5 years, and 5 rem over 7 years) were conducted for the dose truncation models considered in this report (i.e., LNT, threshold of 0.62 rem/yr, and threshold of 5 rem/yr with 10 rem lifetime limit). This sensitivity was performed to see how values of the habitability criterion might affect the results. Based on the LNT dose-response model, the majority of the LCF risk contribution within the EPZ resulted from the long-term phase for all habitability scenarios. Thus the higher the habitability criterion, the higher the LCF risk as a result of long-term dose within the EPZ. The majority of the LCF risk for the 0.1 rem/yr habitability criterion results from the emergency phase for all circular areas. While the emergency phase LCF risk for the 0.1 rem/yr habitability criterion is similar to all other emergency phase LCF risks for other habitability criteria, the low value significantly reduces long-term LCF risk, causing the emergency phase risk to exceed the long-term phase risk beyond the EPZ. Most of the risk corresponds to the long-term phase for all other choices of habitability criterion.

For the alternate dose-threshold models, most of the doses received during the long-term phase are below the dose truncation limit and are not counted toward health effects. Thus, most of the risks associated with either of the truncation levels are from doses received during the first year. When either of the dose-truncation models is used, the LCF risks within the EPZ are orders of magnitude lower when the habitability criterion is below the dose-truncation level, as compared with the cases when the habitability criterion is above the dose-truncation level. Beyond the EPZ, the habitability criterion has a smaller effect on the overall LCF risk when a dose-truncation model is applied, and yield similar results to those presented in the NUREG/CR-7110 Volume 1, Section 7, at the specified circular areas.

3.5 Single Realizations

Select individual realizations from the uncertainty analysis were further investigated in greater detail to identify the influences affecting the projected consequences. The cases investigated are broken into two

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[2] The total risk using the threshold models are substantially lower than the LNT model.

[3] The way MACCS2 implements the habitability criterion, 2 rem/yr, turned out to be more restrictive than 4 rem over 5 years.

groups, the MELCOR single realizations, and the MACCS2 Uncertainty Analysis single realizations that resulted in a nonzero early-fatality risk per event at the 10–mile circular area.

For the MELCOR single realizations, when the fraction of cesium released to the environment is compared for all the realizations investigated, there is no direct relationship to the LCF risk in the long-term phase. However, when the cesium and cerium release fractions are both considered, a better relationship to long-term risk does appear. This is a notable finding for future studies related to this scenario, as traditionally cesium release was considered to be an adequate sole indicator of long-term health risk. Additionally, the LCF risk results show emergency phase LCF risk and long-term phase LCF risk are dependent on the same input variables for all circular areas investigated (i.e., 10-, 20-, 30-, 40-, and 50-mile circular areas).

The MACCS2 Uncertainty Analysis single realization analyses focused on realizations that have a non-zero calculated conditional, mean, individual early-fatality risk (per event) out to the 10-mile circular area. Since this was not expected, a further investigation into these realizations was conducted. None of the realizations have a stochastic SRV failure; rather the accident progression for all three realizations is a SRV thermal failure followed by a main steam line creep rupture and ultimate containment failure due to wetwell rupture above the water line and drywell head flange failure.

For one of the MACCS2 Uncertainty Analysis single realizations (i.e., only one of the 865 total realizations), there is a nonzero early-fatality risk beyond the 10-mile circular area. A noticeable increase in early-fatality risk beyond the 10-mile circular area was observed and is due to the population beyond 10 miles not evacuating, except for those in the 10-20 mile shadow evacuation. As a result, the early-fatality risk beyond 10 miles while still minute in absolute terms, increases by two orders of magnitude. Also, in this outlier, 50% or greater of the MACCS2 weather trials resulted in a nonzero early-fatality risk out to the 30-mile circular area (whereas other realizations typically showed 5% or less weather trials resulting in nonzero early-fatality risk).

Further investigation into the parameters that affected these results showed that it is a combination of the MELCOR source term and the MACCS2 parameters important for early fatality risk, that enable the calculation of a nonzero early-fatality risk beyond 10 miles. Specifically the following variables are at the upper/lower end (i.e., the worst end for consequence in each input variable) of their respective distributions, and hence indicate an extremely unlikely outcome:

- The early health effects threshold for red bone marrow is near the 1st percentile of the distribution,
- The beta (shape) factor for red bone marrow is near the 10th percentile of the distribution,
- The crosswind dispersion coefficient is near the 5th percentile of the distribution,
- The vertical dispersion coefficient is near the 5th percentile of the distribution and,
- The MELCOR source term is near the 95th percentile of the distribution.

The first two relate to the most sensitive organ for the early health effects. The third and fourth parameters enable higher concentrations to reach individuals further from the plant due to a tighter plume. For all single realizations analyzed, which have the overall LCF risk dominated by the emergency phase LCF risk beyond the 10 mile circular area, those realizations further emphasize the benefit to the EPZ population of evacuation (i.e., the population at greatest risk) with significantly reduced emergency phase LCF risk within the EPZ (i.e., only the 0.5% of the population modeled as refusing to evacuate within the EPZ receive an emergency phase dose).

3.6 MACCS2 Parameter Importance

All of the MACCS2 input parameters that were identified as being important are ones that were expected. A previous internal study at Sandia National Laboratories had identified a very similar set of important parameters [5]. In this earlier study, only the LNT dose-response model was considered, so the threshold-type dose-response models considered here are new and have no analog.

One parameter was identified for early-fatality risk in the earlier study that did not show up as important in this work, which was hotspot relocation time. This parameter clearly could be important for early-fatality risk, depending on the timing of the release compared with the timing of the relocation. Even when most of the release occurs before relocation, groundshine doses would be reduced by earlier relocation. One key difference is that the source term was based on one of the NUREG-1150 source terms in the previous study and was much larger than any of the source terms evaluated in this study. As a result, the number of realizations with nonzero early-fatality risk was much greater in the previous study, allowing for better statistics in the regression analysis.

Several parameters identified for LCF risk in the earlier study were not identified as important in this work. Two of these are protection factors for inhalation and groundshine during normal activities. Another key difference between the earlier study and this uncertainty analysis is that the earlier study only considered the emergency phase contributions to risk; no calculation was done for the long-term phase. This could explain why the inhalation protection factor was identified as important in the earlier study, since inhalation is usually the most important dose pathway for the emergency phase but is relatively unimportant for the long-term phase. The groundshine protection factor, on the other hand, is the dominant dose pathway for the long-term phase and is more important for that phase than it is for the emergency phase. This implies that the groundshine protection factor should have been identified to be important in the current study. In examining why the groundshine protection factor was not identified to be important, possible answers are that this study has varied source terms, a more detailed evacuation model, and approximately 300 more MACCS2 uncertainty variables, compared to the earlier study.

The third category of parameters that was found to be important in the earlier study was the vertical dispersion coefficients for stable atmospheric conditions. These parameters can affect doses at short distances; at longer distances the plume becomes well mixed within the mixing layer and additional vertical dispersion has no effect. The connection between dispersion and LCF risk tends to be much less than linear because less dispersion results in larger doses to fewer people while more dispersion results in smaller doses to more people. For LNT dose-response, this can result in a minimal dependence of LCF risk on dispersion, especially for crosswind dispersion. In practice, the influence of the dispersion parameters is somewhat site dependent and the earlier work was for a different site, the Surry Power Station. Also, for this study the dispersion parameters for vertical and crosswind dispersion were correlated with each other and across the set of stability classes. This was not done in the earlier study, which most likely affected the evaluation of the dispersion parameters differently in the two studies.

4. USE OF MULTIPLE REGRESSION TECHNIQUES

The SOARCA project uses two complex codes to estimate the consequences of a severe nuclear accident: MELCOR and MACCS2. Both of these codes involve complex physics phenomena and interactions. Past analyses (e.g., NUREG-1150) relied mostly on linear and rank regressions which suppose that the models are mostly additive (i.e., the variance in the results is driven by single effect from individual uncertain inputs) and the influences are linear or monotonic. Such an approach was valid for some of the MELCOR parameters analyzed, however the R^2 values (i.e., coefficient of determination) estimated by the regression models ranged from 0.42 to 0.69, meaning that between 30% and 60% of the variance was not explained. The rank regression analyses performed on selected MACCS2 results were even weaker.

LCF risk analyses had an R^2 of 0.73 for a 10 miles radius and about 0.51 for larger radiuses (20, 30, 40, and 50 miles) indicating that most of the time, only half of the variance was explained. Rank analyses for early-fatality risk explained at best a quarter of the variance.

Such results are a clear indication that one cannot always rely on rank regression to provide a good indication of the effects of uncertainty in individual analysis inputs. While there are powerful techniques to fully decompose the variance of the selected results, such as Sobol decomposition or FAST, they can require such a large sample size that the cost of their implementation is prohibitive.

One of the major problems when trying to capture complex interactions is that so many different types of interactions are possible that a single parametric regression is often not effective in providing an adequate representation for model results. Some techniques, such as rank regression can be too restrictive, while others may be too broad and capture nonphysical interactions. This may happen, for instance with quadratic regression that incorporates for all 2nd-order interactions (influence of the type X_iX_j) as well as recursive partitioning. These limitations are increased when the sample size is relatively small compared to the number of input variables in consideration. As an example, 100 input variables were considered in the analyses for early-fatality risk, which leads to 10,000 possible regression terms analyzed with quadratic regression. LCF risk analyses considered 300 inputs parameters leading to 90,000 possible regression terms. In such conditions, it is likely that the regression technique will indicate some "important" relationships that are in fact due to spurious correlation, rather than actual importance.

For this reason, four regression techniques have been used for NUREG/CR-7155. Each has strengths and weaknesses. Some effects will be captured only by one or two of these techniques but the same techniques can ignore other kinds of interactions. The analysis of the resulting arrays is, consequently, not as straightforward. The confidence one has on the influence of a parameter is conditional on the number of techniques and the type of techniques capturing this influence. This analysis can only be done in conjunction with a careful physical interpretation and checking of the results. In this sense, the addition of sensitivity cases and study of selected deterministic cases (e.g., in the single realization analyses) provided information that was crucial in the interpretation of the results, as well as the subject matter experts' knowledge: any strange interaction (or non-interaction if one was expected) was double-checked in order to understand and explain it (or corrected if mistaken).

While the four selected regression analyses cover a large spectrum of potential interactions and influence, some other regression techniques (such as ACOSSO and Gaussian process for instance) have not been used in this study. They could bring more insights on the analysis by confirming the influence of some parameters (whose true importance was more uncertain) or capturing other kinds of interactions not considered by the original techniques.

The increased complexity of interpretation (compared to simple rank regression technique) derives from the complexity of the regression models and is necessary to increase the understanding with some confidence that the improvement in the R^2 is not spurious (and/or nonphysical) due to the large number of variables considered compared to the sample size. In the current analysis, the effort was fruitful as it allowed the achievement of an increase in the R^2 for all analyses such that approximately 80% or more of the variance in MELCOR results was captured, and approximately 40% to 85% for LCF risk and between 45% and 80% for early-fatality risk results from MACCS2. The increase was confirmed by several techniques and via cross-validation of physical explanation of the results.

The use of multiple regression techniques was beneficial in this study. While the R^2 associated with early-fatality risk results was lower than for other results, the vast majority of the realizations had an estimated early-fatality risk of essentially zero. This tendency was even more pronounced when the circular area was increased beyond 1.3 to 2 miles (up to having only a handful of realizations from the set of 865 with nonzero values for a 10 miles radius). Statistical analysis of sparse data remains a complex domain of study and most methods are inefficient (either not finding any relation or over-fitting with spurious relations).

5. CONCLUSIONS

This uncertainty analysis advances severe accident knowledge with the following insights for the Peach Bottom unmitigated long-term station blackout scenario:

- A major determinant of source term magnitude is whether the sticking open of the SRV (i.e., lowest set-point SRV) occurs before or after the onset of core damage. Compounding this effect is whether or not main steam line creep rupture occurs (i.e., leads to higher consequences).
- Health-effect risks vary sublinearly with source term because the study assumed effective evacuation and that people are not allowed to return home until doses are below the habitability criterion.
- Analysis confirms known importance of some phenomena (e.g., dry deposition velocity), and reveals some new phenomenological insights (e.g., late phase revaporization of cesium and other fission products within the RPV).
- The use of multiple regression techniques, most of which include non-linear interactions between input variables, to post-process Monte Carlo and LHS results provides better explanatory power of which input parameters are most important to uncertainty in results.
- When looking for a source term indicator for LCF risks, it may be more fruitful to consider cesium and cerium release in conjunction, rather than cesium release alone.

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 a BWR. This study is already informing some NRC activities. For example, the spread of LCF risk results from this uncertainty analysis was used to lend confidence to the projected spread of consequence results in the uncertainty analysis supporting SECY-12-0157, "Consideration of Additional Requirements for Containment Venting Systems for Boiling Water Reactors with Mark I and Mark II Containments" [7]. Other envisioned uses of this work are to identify key sources of uncertainty (per NUREG-1855 [8] guidance on treatment of uncertainty) for the Level 2 portion of PRA studies for BWR Mark I plants, and the Level 3 portion of PRA studies for light-water reactor severe accidents. The results also identify areas where improving our state-of-knowledge, or our state-of-modeling capabilities, could significantly reduce uncertainties in outcomes. Examples of this are improving our knowledge of BWR SRV behavior under severe accident conditions, and improving our knowledge and modeling of off-site contaminant deposition velocities. This analysis also confirms the importance of using more advanced regression techniques, such as recursive partition analysis, for identifying important inputs (and their joint influences) in complex uncertain systems.

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