STATE-OF-THE-ART REACTOR CONSEQUENCE ANALYSES PROJECT: UNCERTAINTY ANALYSIS OF A POTENTIAL UNMITIGATED SHORT-TERM STATION BLACKOUT AT THE SURRY NUCLEAR POWER STATION

Nathan E. Bixler[1], Kyle Ross[1], Cedric Sallaberry[1], Joe Jones[1], and S. Tina Ghosh[2]

[1] Sandia National Laboratories[a]: P.O. Box 5800, MS-0748, Albuquerque, NM 87185-074, nbixler@sandia.gov
[2] U.S. Nuclear Regulatory Commission: Washington, DC 20555-0001, tina.ghosh@nrc.gov

The State-of-the-Art Reactor Consequence Analyses (SOARCA) project evaluated the realistic outcomes of severe nuclear reactor accidents with best-estimate analyses of selected potential accident scenarios at the Peach Bottom Atomic Power Station, a BWR, and the Surry Power Station (Surry), a PWR. The SOARCA project continued with an integrated uncertainty analysis (UA) of the potential unmitigated long term station blackout (LTSBO) accident at Peach Bottom. A Surry integrated UA has just been completed to provide similar insights for a potential short-term station blackout (STSBO) accident in a PWR. Objectives of the Surry UA were to determine whether the Surry UA results corroborate the general conclusions and insights from the original SOARCA best-estimate study, to develop insights into the overall sensitivity of results to uncertainty in selected modeling inputs, to identify the most influential input parameters contributing to accident progression, source term, and offsite consequences, and to inform the NRC's Site Level 3 Probabilistic Risk Analysis and post-Fukushima regulatory activities. The focus of the Surry UA was on epistemic (state-of-knowledge) uncertainty in model input parameter values, and limited aleatory uncertainty from weather variability. In addition, the time-at-cycle (burn-up) and stochastic nature of safety relief valve failure was investigated, which represented aleatory aspects of some input parameters. Key uncertain input parameters were identified in both the MELCOR model for analysis of accident progression and radionuclide release, and the MACCS model for off-site consequence analysis. Uncertainty in these parameters was propagated in a two-step Monte Carlo simulation: a set of source terms were generated using the MELCOR model and a distribution of consequence results were generated using the MACCS model. The Monte Carlo results were analyzed with regression methods, scatter plots, and phenomenological investigations of selected individual realizations.

I. BACKGROUND

The evaluation of accident phenomena and the offsite consequences of severe reactor accidents has been the subject of considerable research by the NRC over the last several decades. As a result of this research, the capability exists to conduct detailed, integrated, and realistic analyses of severe accidents at nuclear power reactors. A desire to leverage this capability to reduce or eliminate conservative aspects of previous reactor accident analyses was a major motivating factor in the State of the Art Reactor Consequence Analyses (SOARCA) project.[1] Through the application of modern analysis tools and techniques, the SOARCA project developed a body of knowledge regarding the realistic outcomes of potential severe reactor accidents with best estimate analyses of selected accident scenarios at the Peach Bottom Atomic Power Station (Peach Bottom)[2] and the Surry Power Station (Surry).[3] The SOARCA project continued with an integrated uncertainty analysis (UA) of the unmitigated long term station blackout (LTSBO) at Peach Bottom[4] and the Surry integrated UA presented herein.

The SOARCA project[1] analyzed selected scenarios, first assuming the events proceeded without the 10 CFR 50.54(hh) mitigation measures (unmitigated), and then assuming that the 10 CFR 50.54(hh) mitigation measures were successful (mitigated). For most of the scenarios, the mitigation measures, when successfully implemented, prevented offsite releases.

In 2013, an integrated UA was completed for the unmitigated LTSBO at Peach Bottom.[4] The Peach Bottom study provided a quantitative analysis of the robustness of the deterministic calculation. In the process, it demonstrated the feasibility of performing an integrated UA, considering epistemic uncertainty in input parameters and to a lesser degree aleatory uncertainty, across accident progression, release, and consequence modeling domains. The uncertainty aspect included sampling severe accident model parameters over defined distributions and performing regression analyses to identify the importance of the input parameters with regard to the uncertainty of the results. The Peach Bottom UA results are informative, but are specific to an unmitigated LTSBO in a boiling water reactor (BWR). As with the Surry UA presented herein, the application of the results must be tempered with an understanding of the reactor type, accident scenario for which results were produced, and site specific characteristics.

II. APPROACH AND OBJECTIVES

The Surry UA followed the same approach that was developed for the Peach Bottom UA. Lessons learned from the Peach Bottom UA and feedback from the NRC's Advisory Committee on Reactor Safeguards (ACRS) on the Peach Bottom UA were considered, as well as additional knowledge gained since the SOARCA point-value calculation for Surry.[3] One of the original objectives of the Surry UA was to quantify the robustness of the Surry point-value, unmitigated, short-term station blackout (STSBO) analysis. However, since the completion of the earlier Surry SOARCA study, there have been a number of enhancements and updates to the state of the art in modeling severe accidents applied in that study. Changes to the severe accident and consequence codes and modeling practices diminish the possibility of meeting the initial objective of directly quantifying the robustness of the original analysis. Nonetheless, this UA provides a comparison of the results of the Surry best estimate analysis[3] with the current, more advanced, severe accident modeling systems applied in an uncertain framework. Additional objectives include: determining whether the Surry UA results corroborate the general conclusions and insights from the original SOARCA point-value study; developing insights into the overall sensitivity of results to uncertainty in selected modeling inputs; identifying the most influential input parameters contributing to accident progression and offsite consequences; informing the NRC's Site Level 3 PRA and post-Fukushima activities including Tier 3 items.

Figures of merit were selected to support the analysis and investigation of results. The source term (MELCOR) figures of merit were the environmental release fractions of cesium and iodine, in-vessel hydrogen production, and release timing. The consequence (MACCS) figures of merit were latent-cancer fatality (LCF) risk and early fatality (EF) risk at specified distance intervals. This paper focuses on the consequence figures of merit.

The Surry SOARCA unmitigated STSBO was selected as the accident scenario in part because of the importance of station blackout scenarios and in part because accident progression occurs relatively quickly under the postulated conditions. The relatively quick accident progression provides a basis to assess the effect of offsite response parameters while the release is potentially underway. Of the scenarios selected for Surry in the SOARCA best estimate study,[3] the unmitigated STSBO with induced SGTR was also one of the two scenarios with the highest conditional individual LCF risk.

To meet the objective of developing insights into the overall sensitivity of SOARCA results to uncertainty in selected modeling inputs, a reasonable number of modeling inputs important to the figures of merit being assessed were chosen. Many parameters are basic input, such as core inventory, material properties, sizes and lengths of piping, weather files, etc. Selecting parameters was an iterative process to identify those expected to influence the results.

As developed, most of the parameters characterize epistemic uncertainties and a few characterize aleatory uncertainties. Often the mode (most likely value) or the median (50th percentile) of the distribution corresponded to the best estimate value used in the original analysis. In an effort to represent a state of the art study, when additional or new knowledge was available, the information was considered and this resulted in the mode or median of some parameters being different than the SOARCA point value.[3]

MELCOR, MelMACCS, and the MELCOR Accident Consequence Code System (MACCS) are the three primary codes used in the integrated analysis. These codes are continually enhanced, updated, and maintained as part of the NRC research program, making it difficult to directly compare the Surry UA results with the Surry NUREG/CR-7110 Volume 2 results.[3]

III. RESULTS

A high performance computing cluster was used to execute a Monte Carlo simulation with 1200 MELCOR runs, of which 1003 successfully completed the 48 hour analysis time. In the 1003 successful calculations (i.e., realizations):

- A steam generator tube rupture (SGTR) occurred in 104 realizations (10%), and a hot leg nozzle rupture occurred in 930 (93%) realizations;
- In every realization in which an SGTR occurred, a hot leg nozzle rupture also occurred;
- A failure of one or more reactor coolant system (RCS) secondary side safety valves to close occurred in 954 realizations (95%) and an SV on the RCS primary side (on the pressurizer) failed to close in 686 realizations (68%);
- The steel containment liner yielded and tore in 742 realizations (74%); and
- Containment rebar yielded (and the concrete fractured) in 72 realizations (7%).

III.A. Source Term Results

The uncertainty analyses produced sets of time-dependent results (i.e., horsetail plots). Figure 1, shows the horsetails for Cs release over the 48-hour analysis period. A wide spread is observed between the calculated 5th percentile, median, mean, and

95th percentile curves. The 95th percentile falls in the set of SGTR realizations (those in the upper portion of Figure 1), the median in the set of non-SGTR realizations, while the mean is in between where no actual realizations exist. There is a significant time difference in the start of release between the mean and median, with the median releasing several hours later. Because the SGTR releases are about two orders of magnitude higher than those for the other realizations, they disproportionally influence the mean, which is not representative of any specific realization. The median takes the middle realization at each time, and is representative of a non-SGTR at all times, although not necessarily the same one. The calculated 5th percentile curve has an associated initial release time that is much later than the calculated median curve, and the 5th percentile remains under 0.01 percent at 48 hours. The figure shows all four calculated curves are relatively steady by 20 hours, but the median and 5th percentile start increasing at around 30 to 40 hours, primarily due to containment liner failure, and in a few cases, rebar failure, both of which are driven more by the buildup of steam pressure in containment due to decay heat rather than creation of additional non-condensable gases. The 95th percentile has no observable late increase because most of the release is via the ruptured steam generator tube (containment bypass). The mean is primarily influenced by the SGTR realizations and also does not exhibit a late increase.

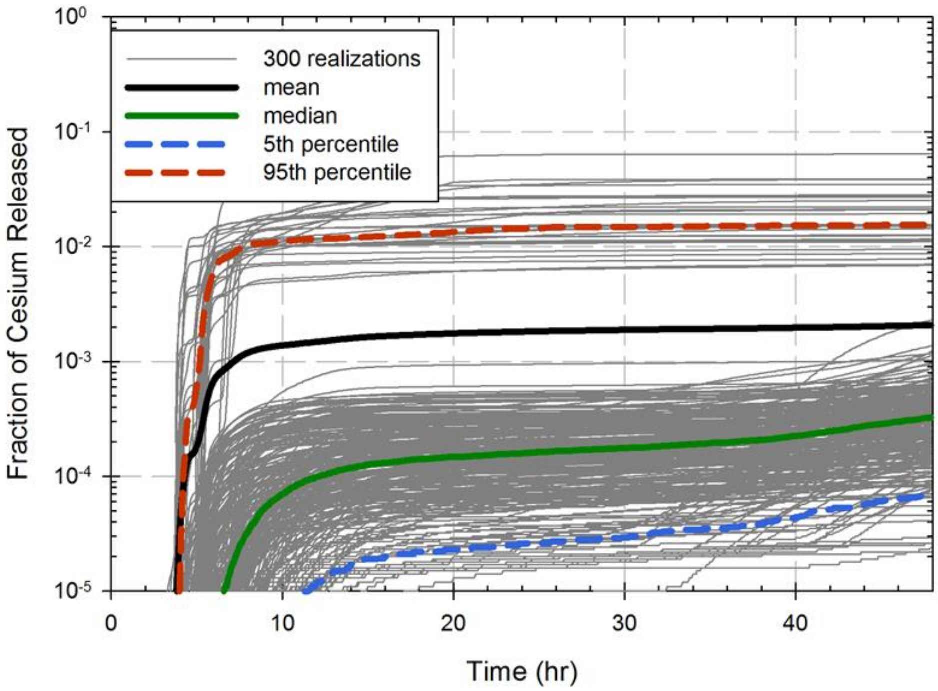


Fig. 1. Cesium release fractions over 48 hours with mean, median, 5th, and 95th percentiles.

Additional insights related to accident progression were obtained through investigation of selected single realizations to identify phenomena affecting the Cs and I releases to the environment and in-vessel hydrogen production. Key phenomena identified in the MELCOR single realization analysis include:

- Containment building rebar yielding and resulting concrete fracture;
- Importance in the timing of the pressure relief tank (PRT) dryout – little effect if the PRT fails early but a significant impact if it fails near the time of containment failure;
- The number of successful cycles experienced by the system of 3 parallel SVs serving the primary-side of the RCS, and
- Chemisorption of Cs from CsOH into the stainless steel of reactor pressure vessel (RPV) internals.

There were 104 SGTRs observed in the results, corresponding to a tube rupture in about 10 percent of the realizations. Even though only 10 percent of realizations had SGTRs, with the exception of in-vessel hydrogen production, these SGTR realizations dominated the regression results. Regression analyses are used to determine which inputs, amongst those that are uncertain, dominate the consequence uncertainty. Therefore, separate regression analyses, were performed on the full set of realizations, the set of realizations that experienced an SGTR, and the set that did not experience an SGTR, to gain an understanding of influential parameters for non-SGTR STSBO scenarios.

For the full set of realizations and the non-SGTR set, regression analyses were performed for beginning of cycle (BOC), middle of cycle (MOC), and end of cycle (EOC) to understand the extent to which time at cycle (e.g., burnup) influenced non-SGTR realizations and whether any parameters would have raised importance with time at cycle kept constant. This was accomplished by including an uncertain parameter named CYCLE, which identifies the point during the fuel cycle (BOC, MOC, and EOC) at which the accident occurs. This sampled parameter directly affects the MELCOR source term calculation through decay heat, and it directly affects the MACCS consequence analysis through fission product inventory. Of all the sampled parameters, CYCLE is the only one that has such a dual role. Because fission product inventories in the fuel increase with burnup, this parameter can have a significant influence on risk. The inventories of shorter lived isotopes increase with burnup only until secular equilibrium is established; however, the inventories of longer lived isotopes, like Cs-137, can nearly double from BOC to EOC. Because the longer lived isotopes have a significant effect on LCF risk, especially in the long-term phase, this parameter is significant to the predicted consequences. The correlation between CYCLE and predicted risk is positive, (i.e., greater burnup corresponds to increased risk).

The regression analyses were performed for results obtained at the end of the 48-hour analysis period, and it should be recognized that results could be different if results were evaluated at an earlier or later time in the calculation. Results from each regression technique for the individual contribution of a parameter and the conjoint influence of a parameter on the results are provided. Conjoint influence is the influence of two or more input parameters acting together, which may have synergistic effects that would not be uncovered by studying the influence of each parameter individually. Overall influence of a parameter is reported as an average of the influence suggested by the four regression techniques.

Almost all of the MELCOR realizations showed the iodine and cesium environmental release fractions were significantly lower than their respective Surry SOARCA calculation, except for a few non-SGTR realizations where cesium was equal or greater.[3] The lower release fractions were driven primarily by slower containment pressurization, caused by a number of factors including sampling of time at cycle, which impacts the total decay heat, and a modification to the containment failure model that incorporates a more realistic yield-before-rupture model.

As seen in Figure 1, there is a large split between SGTR and non-SGTR realizations, where SGTR realizations have one to two orders-of-magnitude higher release fractions. This is different than the original SOARCA analysis, primarily caused by a new model for secondary decontamination factors and a variation of the time between the SGTR and hot leg failure. The most influential parameters contributing to cesium and iodine environmental release fractions for non-SGTR (the majority of releases) are time at cycle (e.g., burnup), nominal containment leakage, the containment failure curve, and dynamic shape factor of aerosols. The first three influence containment pressurization rates and determine the open area from the containment to the environment, while dynamic shape factor influences agglomeration and deposition rates for aerosols before release. The time at cycle parameter is specific to Surry and is very well understood, while nominal leakage and the dynamic shape factor are based on technical specifications and well understood experimental results, respectively. There is slightly lower confidence in the containment failure curve (CFC) model, based on difficulties scaling from the 1/6th scale tests from which the model was created, but the yield-before-rupture behavior was confirmed as more realistic than the older model by structural experts. Important for iodine release fractions but not cesium was the fraction of gaseous iodine, because it does not deposit on structures but remains airborne. Thus, it is released in much higher percentages than aerosolized CsI. The two parameters that determine the amount of gaseous iodine, time at cycle and chemical form of iodine (ChemformI2), are both identified as significant main contributors by the regression analyses. For BOC analyses, design leakage becomes the most important parameter contributing to iodine and cesium release because containment liner yield is never reached and leakage is the only release path to the environment.

The two parameters that show the highest importance in determining whether an SGTR occurs are TUBTHICK, which represents the initial tube thickness of the most damaged steam generator tube in the hottest region, and SVOAFRAC, which represents the fraction of the full open area of a primary or secondary safety relief valve at the time it fails. Both of these parameters have physical bounds, providing high confidence in their uncertainty ranges. The TUBTHICK parameter directly reflects the initial damage state (and effective stress multiplier for creep) of one of the steam generator tubes. The SVOAFRAC parameter influences the depressurization of the RCS after SV failure to close, and thus controls the pressure differential across the damaged steam generator tube. Testing of SGTR realizations, through one-off calculations showed that a pressure differential of 1000 psi or more was needed during core damage to induce the SGTR. The magnitude of releases for an SGTR is primarily driven by the time between the SGTR and hot leg creep rupture, because the SGTR is the primary transport path for radionuclides released from the fuel prior to hot leg rupture. The average time difference in these realizations was 28 minutes.

III.B. Consequence Results

The MACCS results were generated for linear no-threshold (LNT) and two linear-with-threshold dose-response models (called dose truncation here), referred to as US background and Health Physics Society (HPS) truncation models. The dose truncations (thresholds) are described as: (1) annual dose truncation based on average background plus medical radiation, which is 620 mrem/yr and (2) dose truncation based on the HPS position statement, which states that "the Health Physics Society recommends against quantitative estimation of health risks below an individual dose of 5 rem in one year or a lifetime dose of 10 rem above that received from natural sources." This document focuses on latent cancer fatality (LCF) risks based on LNT dose response.

All consequence results are presented as conditional risks, which are the risks conditional on the accident occurring. The emergency phase used in this analysis is the first seven days following the beginning of release to the environment. The long-term phase immediately follows the emergency phase and lasts for 50 years. Results for the LNT dose-response show the large majority of the LCF risk is from the long-term phase at each of the distance intervals evaluated, even for the realizations with SGTR. The mean values of the fraction of risk from the emergency phase are 1 percent within 10 miles and about 15 percent at distances beyond 10 miles. Only a handful of realizations have emergency-phase contributions to risk that exceed those from the long-term phase.

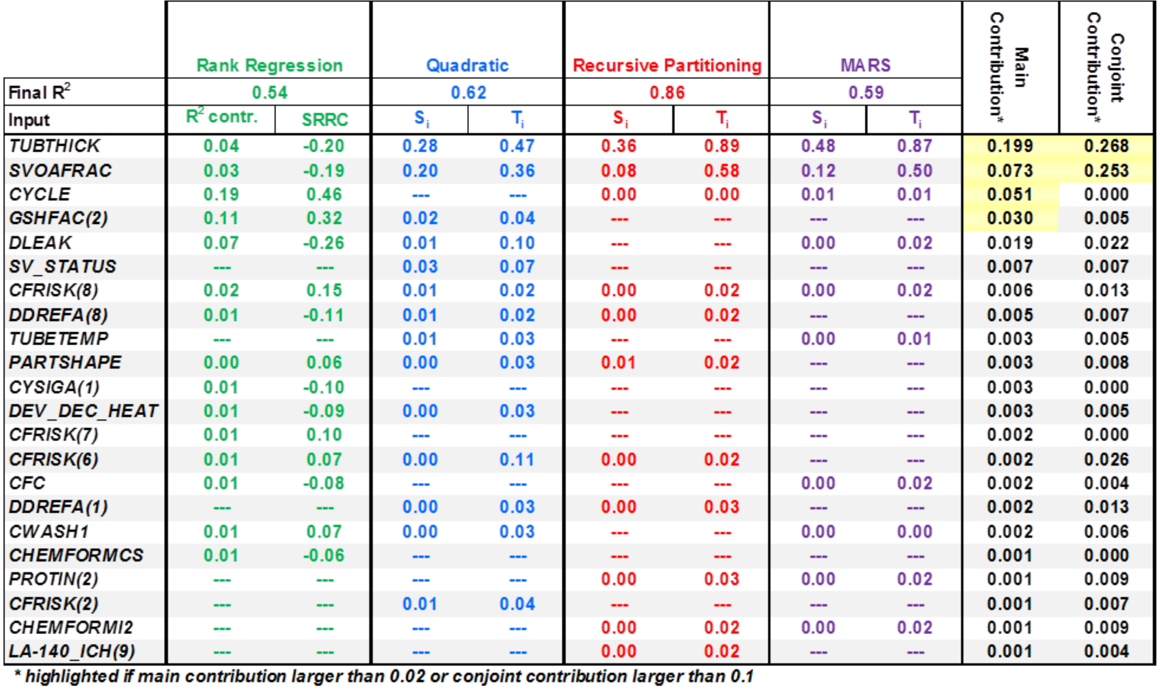
Like the original SOARCA study, the Surry UA demonstrates that early fatality risks are negligible, essentially zero. LCF risks are even lower than those evaluated in the original SOARCA study. Table I shows that the mean LCF risks from this uncertainty analysis, conditional on the occurrence of a STSBO scenario, are below 3×10^{-5}, within 10 miles of the site and the risk diminishes at longer distances. This mean value includes the 10 percent of the realizations with induced SGTRs. For comparison, these values are about a factor of three lower than the SOARCA unmitigated STSBO risks (excluding occurrence of SGTRs) at the same distance ranges (cf., Table 7-4 in Ref. 3). Furthermore, even the 95th percentile LCF risks from this UA are about a factor of two lower than the mean risks for the unmitigated SOARCA STSBO with induced SGTR (cf., Table 7-6 in Ref. 3). This is a meaningful comparison because the top 10 percentile results from this UA represent SGTR realizations; thus, the 95th percentile is approximately the median result for the subset of SGTR realizations.

TABLE I. Mean, Individual LCF Risks Using LNT Dose Response, Conditional on Surry Potential Unmitigated STSBO Occurring (per Event) at Specified Radial Intervals

	0-10 miles	10-20 miles	0-50 miles
UA Mean	2.8E-05	1.1E-05	5.3E-06
UA Median	6.3E-06	1.8E-06	8.9E-07
UA 5th percentile	6.9E-07	2.2E-07	1.0E-07
UA 95th percentile	1.7E-04	7.2E-05	3.5E-05
SOARCA estimate, STSBO	9.4E-05	N/A	1.5E-05
SOARCA estimate, STSBO with SGTR	3.2E-04	N/A	6.5E-05

Table II provides the regression results for the LNT dose-response for the regression analysis of the complete set of realizations (SGTR and non-SGTR). The top two parameters, TUBTHICK and SVOAFRAC, have an important influence on magnitude and timing of the release due to their influence on the occurrence of an SGTR, and directly influence the evaluation of LCF risk. Both parameters have large values for individual (main) and conjoint contributions. The large conjoint contributions and the lack of significant conjoint influence for the other parameters indicate that the two parameters work synergistically to affect source term. Both parameters are negatively correlated with risk, which indicates that the magnitude of the source term increases as SGT thickness and the open area fraction of a stuck-open safety valve decrease. Additional parameters that significantly increase consequences are time during cycle (fuel burnup, CYCLE) and groundshine shielding factor (GSHFAC(2)), which represents the groundshine shielding factor for normal activity during the emergency phase and all activity during the long-term phase. Numbers 1, 2, and 3 are used to represent evacuation, normal activity, and sheltering conditions for GSHFAC. CYCLE correlates positively with risk, indicating that greater burnup leads to greater risk, as expected.

TABLE II. Mean, Individual, LCF Risk (LNT Dose Response) Regression Results within a 50-Mile Circular Area for All Realizations (SGTR and Non-SGTR)



	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution*	Conjoint Contribution*
Final R^2	0.54		0.62		0.86		0.59			
Input	R^2 contr.	SRRC	S_i	T_i	S_i	T_i	S_i	T_i		
TUBTHICK	0.04	-0.20	0.28	0.47	0.36	0.89	0.48	0.87	0.199	0.268
SVOAFRAC	0.03	-0.19	0.20	0.36	0.08	0.58	0.12	0.50	0.073	0.253
CYCLE	0.19	0.46	---	---	0.00	0.00	0.01	0.01	0.051	0.000
GSHFAC(2)	0.11	0.32	0.02	0.04	---	---	---	---	0.030	0.005
DLEAK	0.07	-0.26	0.01	0.10	---	---	0.00	0.02	0.019	0.022
SV_STATUS	---	---	0.03	0.07	---	---	---	---	0.007	0.007
CFRISK(8)	0.02	0.15	0.01	0.02	0.00	0.02	0.00	0.02	0.006	0.013
DDREFA(8)	0.01	-0.11	0.01	0.02	0.00	0.02	---	---	0.005	0.007
TUBETEMP	---	---	0.01	0.03	---	---	0.00	0.01	0.003	0.005
PARTSHAPE	0.00	0.06	0.00	0.03	0.01	0.02	---	---	0.003	0.008
CYSIGA(1)	0.01	-0.10	---	---	---	---	---	---	0.003	0.000
DEV_DEC_HEAT	0.01	-0.09	0.00	0.03	---	---	---	---	0.003	0.005
CFRISK(7)	0.01	0.10	---	---	---	---	---	---	0.002	0.000
CFRISK(6)	0.01	0.07	0.00	0.11	0.00	0.02	---	---	0.002	0.026
CFC	0.01	-0.08	---	---	---	---	0.00	0.02	0.002	0.004
DDREFA(1)	---	---	0.00	0.03	0.00	0.03	---	---	0.002	0.013
CWASH1	0.01	0.07	0.00	0.03	---	---	0.00	0.00	0.002	0.006
CHEMFORMCS	0.01	-0.06	---	---	---	---	---	---	0.001	0.000
PROTIN(2)	---	---	---	---	0.00	0.03	0.00	0.02	0.001	0.009
CFRISK(2)	---	---	0.01	0.04	---	---	---	---	0.001	0.007
CHEMFORMI2	---	---	---	---	0.00	0.02	0.00	0.02	0.001	0.009
LA-140_ICH(9)	---	---	---	---	0.00	0.02	---	---	0.001	0.004

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

Table III provides the regression results for the LNT dose-response for the regression analysis of the subset of realizations with an SGTR. TUBTHICK, SVOAFRAC, and CYCLE play a diminished role for this subset. Two of the largest contributors to LCF consequences are the set of aerosol deposition velocities and delay to evacuate for special facilities residents (DLTEVA_4(8)), which is the latest of the cohorts to evacuate. Two of the significant contributors are discussed above, namely groundshine shielding factors for normal activity and sheltering. Additional parameters that affect consequences are cancer fatality risk for residual cancers (CFRISK(8)), cancer fatality risk for liver cancer (CFRISK(6)), design containment leakage rate (DLEAK), and the inhalation dose coefficients for I-134 (I-134_ICH(9)). Residual cancers account for all cancers that are not explicitly modeled. Residual cancers are based on doses to the pancreas, which is a surrogate organ to represent generic soft tissues.

TABLE III. Mean, Individual, LCF Risk (LNT Dose Response) Regression Results within a 50-Mile Circular Area SGTR Realizations

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution*	Conjoint Contribution*
Final R^2	0.68		1.00		0.73		0.56			
Input	R^2 contr.	SRRC	S_i	T_i	S_i	T_i	S_i	T_i		
VDEPOS(1)	0.10	0.26	---	---	0.19	0.22	0.24	0.24	0.093	0.008
DLTEVA_4(8)	---	---	0.00	0.03	0.33	0.37	0.00	0.01	0.080	0.023
GSHFAC(3)	---	---	0.06	0.17	0.00	0.01	0.28	0.28	0.073	0.041
CFRISK(8)	0.07	0.25	0.04	0.05	---	---	0.20	0.19	0.054	0.002
GSHFAC(2)	0.14	0.36	0.04	0.06	0.03	0.13	---	---	0.050	0.031
TUBTHICK	---	---	0.03	0.10	0.00	0.01	0.20	0.20	0.045	0.029
SVOAFRAC	---	---	0.13	0.25	---	---	---	---	0.044	0.039
CFRISK(6)	---	---	---	---	0.10	0.12	0.00	0.00	0.024	0.006
DLEAK	0.05	-0.15	0.04	0.39	---	---	---	---	0.023	0.116
I-134_ICH(9)	0.02	0.14	0.00	0.08	0.09	0.13	---	---	0.022	0.036
RCPSL	0.07	0.20	---	---	---	---	---	---	0.018	0.000
CYSIGA(1)	---	---	---	---	---	---	0.09	0.08	0.016	0.000
TIMHOT	0.02	-0.20	0.05	0.18	0.00	0.00	---	---	0.016	0.044
PROTIN(2)	0.05	0.19	0.01	0.05	0.00	0.03	---	---	0.015	0.021
CFRISK(7)	0.05	0.17	---	---	0.01	0.07	0.00	0.00	0.015	0.014
DLTEVA_5(7)	0.02	0.13	0.01	0.16	0.04	0.09	---	---	0.013	0.065
DLTEVA_2(8)	0.03	-0.15	---	---	0.00	0.03	0.00	0.00	0.008	0.008
DLTEVA_2(4)	0.02	0.14	---	---	0.00	0.00	0.00	0.00	0.006	0.001
SV_STATUS	---	---	0.02	0.04	---	---	0.00	0.01	0.005	0.008
TE-132_ICH(9)	0.02	-0.16	---	---	---	---	---	---	0.005	0.000
SR-91_ICH(9)	0.02	-0.11	---	---	0.00	0.01	---	---	0.005	0.003
DLTEVA_2(11)	---	---	---	---	0.01	0.04	0.01	0.00	0.003	0.008

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

Table IV shows the dominant parameters for the subset of realizations that do not involve SGTR. These are time at cycle, groundshine shielding factor for normal activity during the emergency phase and for all activity during the long-term phase, the design leakage rate from containment, and cancer fatality risk for residual cancers.

TABLE IV. Mean, Individual, LCF Risk (LNT Dose Response) Regression Results within a 50-Mile Circular Area for non-SGTR Realizations

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution*	Conjoint Contribution*
Final R^2	0.72		0.84		0.80		0.67			
Input	R^2 contr.	SRRC	S_i	T_i	S_i	T_i	S_i	T_i		
CYCLE	0.29	0.54	0.12	0.19	0.21	0.55	0.28	0.28	0.186	0.111
GSHFAC(2)	0.16	0.41	0.15	0.26	0.20	0.55	0.22	0.26	0.150	0.132
DLEAK	0.12	-0.34	0.05	0.18	0.03	0.14	0.10	0.10	0.062	0.066
CFRISK(8)	0.03	0.16	0.04	0.06	0.02	0.13	0.06	0.07	0.028	0.037
CFRISK(6)	0.01	0.09	0.04	0.10	0.00	0.02	0.02	0.06	0.016	0.030
CYSIGA(1)	0.02	-0.15	0.01	0.06	0.00	0.03	0.03	0.03	0.014	0.022
PARTSHAPE	0.01	0.09	0.01	0.02	---	---	0.04	0.06	0.012	0.008
CFC	0.02	-0.13	0.01	0.03	0.00	0.06	0.02	0.02	0.011	0.019
RCPSL	---	---	0.03	0.18	---	---	---	---	0.009	0.042
DEV_DEC_HEAT	0.01	-0.08	0.01	0.07	0.00	0.05	0.02	0.03	0.009	0.032
CFRISK(7)	0.01	0.12	0.01	0.02	---	---	0.02	0.03	0.008	0.006
VDEPOS(1)	0.01	0.09	0.01	0.04	0.01	0.19	0.01	0.05	0.008	0.066
CFRISK(4)	0.01	0.10	0.02	0.10	---	---	0.01	0.03	0.007	0.028
CHEMFORMCS	0.01	-0.09	---	---	0.00	0.04	0.02	0.03	0.006	0.011
GSHFAC(3)	---	---	0.02	0.05	---	---	---	---	0.005	0.008
DDREFA(8)	0.01	-0.11	---	---	---	---	---	---	0.003	0.000
CFRISK(1)	---	---	---	---	0.01	0.09	0.00	0.02	0.002	0.025
CWASH1	0.01	0.07	0.00	0.02	---	---	---	---	0.002	0.004
CFRISK(3)	---	---	---	---	0.00	0.02	0.01	0.03	0.002	0.010
CM-242_ICH(9)	---	---	---	---	0.00	0.05	---	---	0.000	0.013
ZR-95_ICH(9)	---	---	---	---	0.00	0.04	---	---	0.000	0.010
DLTEVA(1)	---	---	---	---	0.00	0.03	---	---	0.000	0.009

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

III.C. Consequence Sensitivity Analyses

Four MACCS sensitivity analyses were conducted using one of the larger source terms from MELCOR. The sensitivities evaluated emergency phase durations of 15 and 30 days, intermediate phase duration of 6 months, and a 4-day (instead of 7-day) dose projection period for the emergency phase. The results were all essentially identical with one exception, the risks for the 0- to 10-mile distance interval was noticeably larger for the case when the intermediate phase is 6 months than when there was no intermediate phase. The increase in risk for the 0- to 10-mile interval indicates that less decontamination occurs when the intermediate phase is included and that more individuals receive a larger dose when they return home than receive a smaller dose. This can occur when the 6 months of decay and weathering provided by the intermediate phase brings the dose levels below the habitability threshold without the need to decontaminate. However, these dose levels can be higher than they would have been if decontamination were performed because the MACCS decontamination modeling reduces dose levels by user-specified factors, in this case factors of 3 and 15. The larger factor is used when a reduction factor of 3 is insufficient to restore habitability.

The habitability criteria applied in these sensitivity analyses is considered to be an important uncertain parameter, but was not evaluated with this Surry UA because a detailed sensitivity analysis was performed with the Peach Bottom UA.[4] The Peach Bottom analysis showed, as would be expected, that when the dose truncation models were used, the LCF risks within the EPZ were orders of magnitude lower when the habitability criteria was below the dose truncation level. Beyond the EPZ, the habitability criteria showed a smaller effect on the overall LCF risk when a dose truncation model was applied. This is because most of the population beyond the EPZ does not evacuate and so receive larger doses during the emergency phase than those within the EPZ. Emergency-phase doses contribute to first-year doses and can cause them to exceed the dose truncation level.

IV. SUMMARY

As described above, this Surry UA used distributions for parameter values that historically were modeled with fixed values and applied multiple regression techniques to support an understanding of the results. Such an analysis produces substantial information which is described in in this document. A summary of important insights is provided below:

- SGTRs occur in about 10 percent of the Monte Carlo realizations and have release fractions one to two orders of magnitude larger than STSBOs without SGTR.
- SGTRs result from a combination of high temperatures and high pressures across the SG tubes.
- In most of the Monte Carlo realizations, iodine and cesium environmental release fractions are higher early in the transient than the Surry SOARCA calculation,[3] but all are significantly lower at 48 hours, except that cesium was essentially equal in a few realizations.
- Lower release fractions at 48 hours are primarily driven by time at cycle (particularly including BOC as an option), higher nominal containment leakage and changes to the containment failure model (gradually degrading containment versus sudden catastrophic failure). All of these lead to slower containment pressurization and the leak-before-break failure modeling prevents large amounts of revaporization.
- The LCF risk is lower than the Surry SOARCA calculation and is attributable to the lower source terms from the UA (again due to more realistic containment degradation modeling).
- The consequence analysis shows that the mean population-weighted LCF risk distribution is much narrower when only uncertain consequence parameters are considered than when both source-term and consequence parameters are considered in the analysis. It appears the results are more heavily influenced by uncertainties in source term than by uncertain consequence parameters, just as they were for the Peach Bottom uncertainty analysis.[4] This is true when a single dose-response model (LNT) is used, but uncertainties in risks created by uncertainties in dose-response model are large and most likely would have altered this conclusion if dose response had been included as part of the integrated uncertainty analysis.

The most influential input parameters were identified as follows:

- For non-SGTR realizations (90% of the realizations), the most important parameters for cesium release were time at cycle, design leakage, the containment failure curve, and the dynamic shape factor. For iodine, the amount that was assumed to be gaseous was very important, determined by time at cycle and chemical form of iodine.
- Primary SV open fraction and tube thickness were the main determinants regarding whether an SGTR occurred, and secondary SV open fraction had the highest importance in Cs and I release fractions for SGTR releases.
- For LCF risk, TUBTHICK and SVOAFRAC are the most influential parameters. These two parameters largely determine whether the accident progresses toward an SGTR. Thus, they have an important influence on magnitude and timing of the release and directly influence LCF risk.

- Five other parameters have a significant effect on LCF risk. These are time at cycle (fuel burnup), groundshine shielding factor, the set of aerosol deposition velocities, the cancer risk factor for residual cancers, and design leakage from the containment. Time at cycle affects both the amount of decay heat in MELCOR and fission product inventory in MACCS. Both of these increase LCF risk with the value of time at cycle. Decay heat quickly approaches steady state early in the fuel cycle while some influential fission products, like Cs-137, increase approximately linearly during the fuel cycle. Groundshine shielding factor directly influences dose through the groundshine pathway, which is the dominant dose pathway during the long-term phase. Deposition velocities determine the amount of deposition onto the ground and so they influence doses through the groundshine pathway. Cancer risk is proportional to cancer risk factors, and thus they play an important role in the risks that are estimated. Finally, design leakage influences the release of radioactivity through the containment, which is especially important when a SGTR does not occur.
- The most important parameter in the Peach Bottom UA, dry deposition velocity, is also important in the Surry UA but plays a lesser role. This may be because the distribution for dry deposition velocity was made narrower in the Surry UA or it may be because some other parameters are relatively more important, e.g., the parameters that influence the occurrence of SGTR. The rationale for the narrower distribution is that the one used in the Peach Bottom UA reflects variations from one weather instance to another, not variations in the best value to use for an entire year of weather data.

The project informed the Level 3 PRA by including staff in Surry parameter development meetings, presenting Level 3 PRA staff early Surry UA results, and interacting with Level 3 PRA staff on key issues of interest. In addition, like the Peach Bottom UA,[4] the results of this Surry UA corroborate the conclusions from the SOARCA project: [1]

- Latent cancer and early fatality risks from severe nuclear accident scenarios modeled are smaller than those projected in NUREG/CR-2239.
- The delay in releases calculated provides more time for emergency response actions (such as evacuating or sheltering).
- Essentially zero absolute early fatality risk is projected.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The U.S. Nuclear Regulatory Commission sponsored and participated in this work. This document is SAND2016-6266 C.

REFERENCES

1. NUREG-1935, "State-of-the-Art Reactor Consequence Analyses (SOARCA) Report," U.S. Nuclear Regulatory Commission, Washington, DC, November 2012.
2. NUREG/CR-7110 Volume 1, Rev. 1, "State-of-the-Art Reactor Consequence Analysis Project Volume 2: Peach Bottom Integrated Analysis," U.S. Nuclear Regulatory Commission, Washington, DC, August 2013.
3. NUREG/CR-7110 Volume 2, Rev. 1, "State-of-the-Art Reactor Consequence Analysis Project Volume 2: Surry Integrated Analysis," U.S. Nuclear Regulatory Commission, Washington, DC, August 2013.
4. NUREG/CR-7155, "State-of-the-Art Reactor Consequence Analyses Project, Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station," U.S. Nuclear Regulatory Commission, Washington, DC, 2016.