

Sequoyah SOARCA Uncertainty Analysis of a STSBO Accident

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Abstract: The U.S. Nuclear Regulatory Commission initiated the state-of-the-art reactor consequence analyses (SOARCA) project to develop realistic estimates of the offsite radiological health consequences for potential severe reactor accidents. The SOARCA analysis of an ice condenser containment plant was performed because its relatively low design pressure and reliance on igniters makes it potentially susceptible to early containment failure from hydrogen combustion during a severe accident. The focus was on station blackout accident scenarios where all alternating current power is lost. Accident progression calculations used the MELCOR computer code and offsite consequence analyses were performed with MACCS. The analysis included more than 500 MELCOR and MACCS simulations to account for uncertainty in important accident progression and offsite consequence input parameters.

Consequences from severe nuclear power plant accidents modeled in this and previous SOARCA analyses are smaller than calculated in earlier studies. The delayed releases calculated provide more time for emergency response actions. The results show that early containment failure is very unlikely, even without successful use of igniters. However, these results are dependent on the distributions assigned to safety valve failure-to-close parameters, and considerable uncertainty remains on the true distributions for these parameters due to very limited test data. Even for scenarios resulting in early containment failure, the calculated individual latent fatal cancer risks are very small. Early and latent-cancer fatality risks are one focus of this paper. Regression results showing the most influential parameters are also discussed.

Keywords: SOARCA, Sequoyah, consequence analysis, STSBO, MACCS.

1. INTRODUCTION

This paper describes an integrated analysis of accident progression, fission product behavior, source term, and offsite consequences of a seismically initiated, short-term station blackout accident (STSBO) at the Sequoyah Nuclear Power Plant (Sequoyah). This is the third pilot plant to be evaluated as part of the NRC's State of the Art Reactor Consequence Analysis (SOARCA) project. The paper reports results from uncertainty and sensitivity analyses using the MELCOR (for severe accidents) and MACCS (MELCOR Accident Consequence Code System for offsite consequences) codes that are being developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (NRC). The uncertainty analysis considers epistemic (state-of-knowledge) uncertainties of key input parameters for both the MELCOR and MACCS codes.

A focus of this work is on the potential influence of hydrogen combustion on predicted consequences. Hydrogen combustion has long been considered a potential challenge to an ice condenser containment. However, the results of the analysis indicate that containment failure is much more likely from gradual pressurization than from hydrogen combustion.

The dominance of late or no (i.e., not during the 72-hr calculation) containment failure strongly influences the offsite consequence results, which are presented as individual, early fatality and latent cancer fatality risks, conditional on the occurrence of the accident. The consequence analyses account for significant seismic damage to bridges and use the linear no-threshold assumption for cancer induction; results for the hypothesis that annual doses below a threshold do not contribute to cancer

induction is considered as a sensitivity study. Even for early release cases resulting from early containment failure, there are essentially no early fatality risks. Conditional individual latent cancer fatality risk is low, but is about an order of magnitude higher in the unlikely event of early containment failure. Generally, long-term risk (as opposed to emergency phase risk) is the larger contributor to overall risk. Regression analyses indicate that time-in-cycle when the accident occurs, which influences accident progression via decay heat and consequences via isotopic inventory, has the largest influence on individual latent cancer fatality risk. Other important contributors to uncertainty in the risk within 50 miles are cancer risk factors for residual, lung, and colon cancers; containment rupture pressure; and the time of relocation of nonevacuees who exceed protective action limits.

2. APPROACH

The Sequoyah uncertainty analysis (UA) follows the approach developed for the previous Peach Bottom [1] and Surry [2] UAs. Lessons learned from the previous UAs and feedback from the NRC's Advisory Committee on Reactor Safeguards (ACRS) were considered, as well as additional knowledge gained since the Peach Bottom and Surry best estimate calculations [3,4]. Objectives for this work include: developing insights into the overall sensitivity of results to uncertainty in selected modeling inputs; evaluating the likelihood of early containment failure and resulting consequences; identifying the most influential input parameters contributing to accident progression and offsite consequences through application of a set of regression analyses; informing the NRC's Site Level 3 Probabilistic Risk Assessment (PRA) project and post-Fukushima-accident regulatory activities.

The consequence (MACCS) figures of merit are individual latent-cancer fatality (LCF) risk, using the linear, no-threshold (LNT) assumption for dose response, and early fatality (EF) risk at specified distances. These figures of merit are reported for circular and annular areas centered on the reactor site.

The accident scenario selected for this analysis was an unmitigated STSBO at the Sequoyah plant, 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 effects of offsite response parameters for the cases with early containment failure.

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

As developed, most of the parameters characterized epistemic uncertainties and a few characterized aleatory uncertainties. In practice, all uncertain parameters were treated as epistemic except for weather variability, which was treated separately as described below. In most cases, the median (50th percentile) of the distribution corresponded to the value used in the MACCS best-estimate (or "reference") analyses; in a few cases, the mode (most likely value) was used to define the best-estimate value.

MELCOR, MelMACCS, and MACCS are the three primary codes used in the integrated analysis. Uncertainties in the model inputs were propagated in a two-step Monte Carlo simulation (MCS). First, a set of source terms were generated using MELCOR by sampling uncertain MELCOR inputs. Each MELCOR result was processed with MelMACCS to produce a MACCS-formatted source-term file. Each source-term file was then coupled with one set of sampled values for uncertain MACCS inputs in a second MCS to generate a set of consequence metrics. Simple random sampling was used in both MCS steps, to enable discarding incomplete MELCOR realizations and to facilitate the use of bootstrapping methods to estimate confidence in results. The MACCS MCS further included an inner

loop of ~1,000 weather trials to represent variability due to weather, for each epistemic vector of sampled MELCOR and MACCS inputs. The results described in this paper are individual risks averaged over weather variability.

MELCOR input parameters were made uncertain across the following domains of modeling: accident sequence, in-vessel accident progression, ex-vessel accident progression, containment behavior, chemical forms of iodine and cesium, and aerosol physics. MACCS input parameters were made uncertain across the following domains of modeling: aerosol deposition, plume dispersion, radiation shielding, early health effects, latent health effects, and emergency response.

Evaluation of induced steam generator tube rupture (SGTR) had been considered as part of the Surry UA [2]. The Surry UA is currently being revised and an updated report is expected in the future. SGTR was not considered in this study for Sequoyah, but the potential for a SGTR is expected to be similar for Sequoyah to that for Surry. The only mechanism for early release in the current study is early containment failure from a sufficiently large hydrogen combustion event.

3. CONSEQUENCE RESULTS

The results of the consequence analyses are presented in terms of individual LCF risk and individual EF risk for the population residing near the plant, i.e., within 80 km. The primary results are mean values over 1,031 weather trials. To examine the variation of risk with distances from the site, the reported risk measures are evaluated for residents within specified radial distance intervals (i.e., circular or annular areas with specified radii) centered on the reactor site. They are averaged over the entire residential population within each interval and over weather variability. These individual risk values are population weighted and are computed by dividing the predicted number of excess fatalities (early or latent) by the population living within the specified interval. These risk measures account for the distribution of the population within the distance interval and for the interplay between the population distribution and the wind-rose probabilities. The results are presented as conditional risks, which are the risks predicated on the accident occurring.

3.1. LCF Risks

Table 1 shows four statistics (mean, median, 5th percentile, and 95th percentile) for the mean (over weather variability), individual, LCF risk, conditional on an accident occurring (per event) from the 567 realizations that were performed for the MACCS uncertainty analysis. Risks are reported assuming linear, no-threshold (LNT), dose response. Results in the table are provided at five spatial intervals representing annular areas centered on Sequoyah. The annular distance intervals shown are specified by the radii of the corresponding inner and outer circles defining each area. Each of the statistics in the table represents the overall epistemic (state-of-knowledge) uncertainty on the mean, over weather variability, for the groups of MELCOR and MACCS inputs that were treated as uncertain. The results show that mean conditional risks are on the order of 1.0×10^{-4} at all distances reported.

Risks within 16 km (10 miles) are slightly lower than those within larger circular areas (except for the 5th percentile results) because the modeled evacuation is effective and most of the emergency planning zone (EPZ) residents receive little or no dose during the emergency phase. The mean risk in the annular region from 16 to 32 km (10 to 20 miles) is slightly lower than the risk in the area from 32 to 48 km (20 to 30 miles), which results in part because 20% of the residents between 16 and 24 km (10 to 15 miles) are assumed to evacuate (shadow evacuation has been observed in previous studies), even though no formal evacuation order is given for this cohort. Risks diminish gradually with distance for circular and annular areas beyond 48 km.

Table 1. Mean individual LCF risk conditional on the STSBO accident occurring (per event) for five annular area intervals centered on Sequoyah

	0-16 km (0 - 10 mi)	16-32 km (10 - 20 mi)	32-48 km (20 - 30 mi)	48-64 km (30 - 40 mi)	64-80 km (40 - 50 mi)
Mean	8.0E-05	9.7E-05	1.0E-04	8.2E-05	6.6E-05
Median	6.7E-05	7.5E-05	9.1E-05	7.8E-05	6.2E-05
5th Percentile	1.2E-08	2.7E-09	1.1E-09	4.2E-10	2.6E-10
95th Percentile	2.0E-04	2.5E-04	2.4E-04	1.8E-04	1.4E-04

Figure 1 shows the complementary cumulative distribution function (CCDF) for the same radial intervals summarized in Table 2. The points on the curves represent the mean, over variable weather, individual, LCF risk for each of the 567 realizations. Each realization represents epistemic uncertainty (from both source term and consequence inputs) in this UA and the risks are conditional on the accident occurring. The curves show that the risks are bimodal and span the range of about 10^{-10} to 10^{-3} per event. The bimodal nature of the CCDF curves derives from the fact that the containment does not fail by 72 hours in 74 of the realizations (13% of the cases) and does fail before 72 hours in the remaining 495 realizations (87% of the cases). The cases with no containment failure account for the upper left (very low risk) portion of the CCDF curves; the cases with containment failure account for the right (relatively higher risk) portion of the CCDF curves. Four realizations (0.7% of the cases) represent early containment failure, and these are at the right-most portion of the CCDF curves.

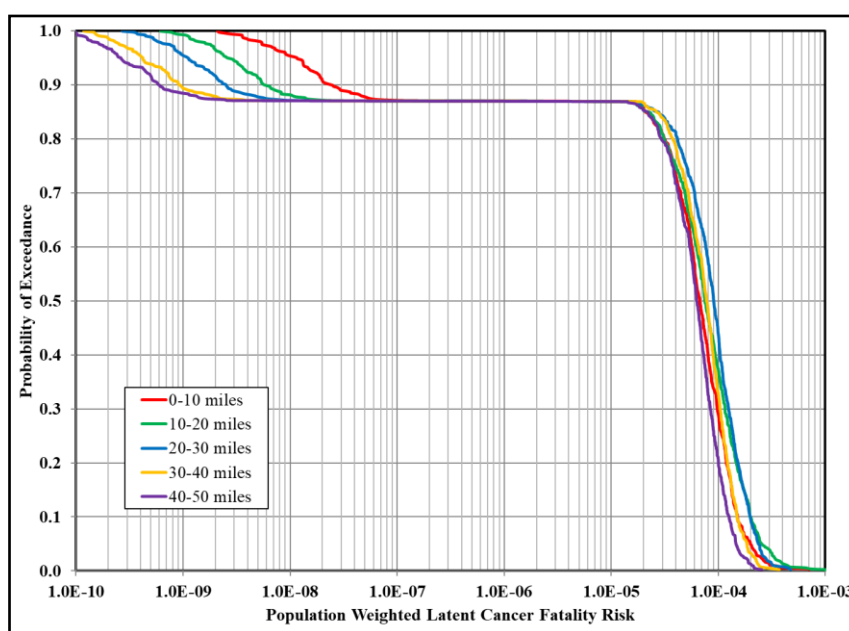


Figure 1 – CCDF of average, individual, LCF risk using LNT dose response for five annular areas. Probabilities in the plot represents epistemic uncertainties in the inputs for source term and consequence analyses.

One other notable feature of the CCDF curves is that the curves are close together for the portion representing containment failure but not for the portion representing no containment failure. This indicates that risk is nearly flat as a function of distance from the plant when containment failure occurs. On the other hand, there is more than an order of magnitude drop in risk over the set of annular intervals for the cases when containment does not fail. The difference between these two portions of the distribution is the extent to which remediation is required. More remediation (i.e., decontamination, interdiction, and condemnation of land and property) reduces consequences that would otherwise have been higher, and this occurs to a greater extent for the cases with containment failure. This is explained in more detail below.

Table 2 shows that a relatively small percentage of the overall risk is from the emergency phase. The fraction is very small within the 16-km EPZ because nearly all the population there evacuates, in most cases before environmental release begins. The peak percentage occurs beyond the distance where any evacuation is assumed to occur, in the 32- to 48-km interval. Beyond this region, the contribution of the emergency phase diminishes because long-term contributions are proportionally greater when no remediation is performed because dose levels are sufficiently small.

Table 2. Mean contribution of emergency phase to overall risk

0-16 km	16-32 km	32-48 km	48-64 km	64-80 km
0.2%	20%	36%	27%	15%

3.2. EF Risks

The median, 5th percentile, and even the 95th percentile results are 0 for mean (over weather variability) individual EF risk, conditional on an accident occurring (per event) for the MACCS uncertainty analysis. This means that EF risks are zero for every weather trial at these statistical levels. Conditional, mean, EF risks are 3.0×10^{-9} , 1.8×10^{-9} , and 8.6×10^{-10} within circular intervals centered on Sequoyah of 1.6, 2.2, and 3.2 km, respectively, with contributions from three realizations that computed nonzero EF risks, as discussed below. These statistics represent the overall epistemic (state-of-knowledge) uncertainty for the groups of MELCOR and MACCS inputs that were treated as uncertain. Early fatality risk is calculated to be zero beyond 3.2 km for all realizations. Only three of the 567 realizations have a nonzero early fatality risk, and even those risks are so small that they can be considered negligible. All three are for cases of early containment failure. Even within these three realizations, EF risks are 0 for nearly all the weather trials. Thus, the early fatality risks, even assuming the unlikely occurrence of an STSBO accident sequence at Sequoyah compounded with the unlikely occurrence of an early containment failure, are essentially zero.

3.3. Influential Parameters for LCF Risks

Tables 3 through 5 show results for the regression analysis of average, individual, LCF risk. Uncertain input parameters are listed in the first column, followed by the results from four regression techniques. The last two columns contain weighted average values of the main (individual, independent) contribution of the parameter to the result metric and the conjoint influence of the parameter on the result metric. These are calculated as averages, weighted by the fraction of variance explained by each regression model, of the contributions estimated by the four regression techniques. Values of main contribution greater than 0.02 and conjoint contributions greater than 0.1 are considered by the authors to be potentially significant and are highlighted. The parameters in the first column of the tables are ordered by the values in the column labeled Main Contribution; thus, the parameters appear in rank order according to their independent contribution to uncertainty.

The most influential parameter for LCF risk within 16 km of the Sequoyah plant shown in Table 3 is Cycle, which represents the time during the fuel burnup cycle that the accident occurs. Three values for Cycle were evaluated in this study to represent the beginning (6 days of operation after refueling, called BOC), middle (200 days, called MOC), and end (525 days, called EOC). This parameter affects both the decay heat in the MELCOR analysis and the fission product inventory in the MACCS analysis. It has the largest influence on consequences of all the uncertain inputs considered in the Sequoyah UA. Consequences are more severe as this parameter increases, but the differences are more profound between BOC and MOC and less profound between MOC and EOC.

Table 3. Mean, individual, LCF risk regression results within a 0- to 16-km (0- to 10- mi) interval based on LNT dose response

	Interval based on LINT dose Response								Main Contribution	Conjoint Contribution
	Rank Regression		Quadratic		Recursive Partitioning		MARS			
Final R ²	0.67		0.86		0.58		0.78			
Input	R ² contr.	SRRC	S _i	T _i	S _i	T _i	S _i	T _i		
Cycle	0.36	0.58	0.23	0.29	0.40	0.60	0.20	0.20	0.237	0.056
priSVcyc	---	---	0.04	0.15	0.12	0.15	0.14	0.31	0.070	0.083
CFRISK(8)	0.09	0.29	0.07	0.12	0.08	0.23	0.10	0.09	0.068	0.042
Rupture	0.06	-0.24	0.06	0.08	0.07	0.18	0.09	0.15	0.054	0.046
CFRISK(7)	0.03	0.19	0.06	0.10	0.05	0.11	0.08	0.10	0.040	0.031
GSHFAC_6(2)	0.05	0.22	0.02	0.06	0.01	0.05	0.04	0.03	0.026	0.021
CFRISK(6)	0.01	0.09	0.04	0.11	---	---	0.04	0.07	0.018	0.029
CFRISK(3)	0.02	0.11	---	---	0.00	0.01	0.03	0.10	0.011	0.018
DDREFA(8)	0.01	-0.11	0.03	0.04	---	---	---	---	0.010	0.002

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

Other influential parameters shown in Table 3 are priSVcyc, CFRISK(8), Rupture, CFRISK(7), and the GSHFAC_6(2). These are discussed in order of importance for this distance range.

One of the MELCOR parameters, priSVcycles, is more important at shorter distances where most or at least some of the population evacuates. This parameter represents the number of primary safety valve cycles that occur during the simulation. The valves continue to cycle until the system is depressurized, either because a valve sticks open with sufficient area or because another portion of the reactor coolant system fails. This behavior influences hydrogen accumulation in containment and the potential for early containment failure, leading to early releases. Early release has the potential to affect evacuees within the EPZ and shadow evacuees from 16 to 24 km because some of the evacuees are directly affected by the plume when the release is early. This parameter has a lesser influence on the nonevacuating population who are assumed to remain in place at the start of release, regardless of whether it is early or late.

CFRISK(8) is the cancer fatality risk factor for residual cancers. Residual cancers represent all the cancer types not specifically modeled. CFRISK(8) represents the largest contribution to cancer fatalities when radiation is uniformly distributed throughout the body, as it typically is for external shine exposures. Rupture is the pressure at which containment is modeled to fail and it directly influences the timing of failure as well as the likelihood of early failure. CFRISK (7) is similar to CFRISK(8) but represents colon cancers, which is the second largest contributor to fatal cancers. Finally, GSHFAC_6(2) represents groundshine shielding factors for normal activity during the emergency phase and long-term groundshine shielding factors for groundshine. Groundshine is the most important exposure pathway overall, especially for those within the 16-km EPZ where exposure during the emergency phase is zero or small because evacuation is very effective.

Table 4 shows that five of the same parameters that are important within the EPZ are also important immediately beyond the 16-km EPZ. These parameters are Cycle, Rupture, CFRISK(8), CFRISK(7), and priSVcyc. One parameter, representing the groundshine shielding factors, does not appear on the list because it is less important for members of the public who are assumed not to evacuate. While groundshine during the long-term phase is the dominant contributor to risk at this distance range, it is less dominant for those who do not evacuate and thus receive an exposure during the emergency phase.

Table 4. Mean, individual, LCF risk regression results within a 16- to 32-km (10- to 20-mi) interval based on LNT dose response

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution	Conjoint Contribution
Final R ²	0.63		0.85		0.60		0.73			
Input	R ² contr.	SRRC	S _i	T _i	S _i	T _i	S _i	T _i		
Cycle	0.32	0.61	0.23	0.27	0.32	0.51	0.22	0.21	0.215	0.050
Rupture	0.09	-0.28	0.09	0.13	0.14	0.35	0.18	0.33	0.095	0.092
TIMNRM	0.06	0.22	0.05	0.09	0.09	0.31	0.06	0.07	0.050	0.057
CFRISK(4)	0.03	0.18	0.03	0.09	0.02	0.08	0.07	0.10	0.028	0.038
CFRISK(8)	0.03	0.17	0.05	0.07	0.01	0.05	0.05	0.04	0.027	0.014
CFRISK(7)	0.02	0.16	0.04	0.04	0.01	0.06	0.05	0.06	0.024	0.013
priSVcyc	---	---	0.01	0.08	0.01	0.00	0.08	0.19	0.022	0.049
DOSNRM	0.01	0.11	---	---	0.01	0.09	0.04	0.06	0.011	0.022
DDREFA(4)	0.01	-0.10	0.01	0.05	---	---	0.02	0.07	0.009	0.023

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

Two other input parameters are important over the distance range from 16- to 32-km from the site. These are TIMNRM and CFRISK(4). TIMNRM is the time after plume arrival when nonevacuees relocate if projected doses exceed protective action limits, nominally 0.01 Sv (1 Rem) over a 4-day projection period. Thus, this parameter determines the emergency-phase exposure time for a segment of the population. CFRISK(4) is the cancer risk factor for the lungs. Inhalation is the dominant exposure pathway during the emergency phase, so it makes sense that this risk factor is important for those who are directly exposed to the plume. It is also the third largest of the cancer risk factors.

The most influential input parameters for LCF risk within 80 km (50 mi) of the Sequoyah plant are shown in Table 5. These are the parameters that most affect overall risk to the public. They are the same as the parameters shown as important in Table 4, with one exception, although the order of importance is somewhat different. Cycle is the most important parameter at all three distance ranges. CFRISK(8) is second in importance because residual cancers are the largest contributor to cancer risk overall. Rupture is the third parameter because of its contribution to the timing of containment failure and to potential exposures for the segment of the population that evacuates. CFRISK(4) and (7) are important because they are the second and third largest cancer fatality risk factors. They are especially important for exposures through the inhalation pathway because lungs and colon receive additional doses from beta and gamma radiation through this pathway. The colon receives a dose from inhalation via swallowing contaminated mucous from the sinuses. The inhalation pathway is especially important for those who do not evacuate or in the few cases with early release where evacuees are directly exposed to the plume. Finally, TIMNRM controls the exposure time during the emergency phase for a portion of the population who do not evacuate.

Table 5. Mean, individual, LCF risk regression results within a 0- to 80-km (0- to 50-mi) interval based on LNT dose response

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution	Conjoint Contribution
Final R ²	0.59		0.86		0.65		0.75			
Input	R ² contr.	SRRC	S _i	T _i	S _i	T _i	S _i	T _i		
Cycle	0.23	0.52	0.24	0.31	0.36	0.44	0.21	0.21	0.208	0.038
CFRISK(8)	0.06	0.24	0.09	0.13	0.05	0.14	0.09	0.08	0.059	0.029
Rupture	0.05	-0.21	0.06	0.10	0.05	0.22	0.10	0.25	0.052	0.086
CFRISK(4)	0.05	0.23	0.07	0.10	0.04	0.15	0.08	0.09	0.048	0.037
CFRISK(7)	0.04	0.22	0.05	0.07	0.02	0.10	0.08	0.11	0.040	0.028
TIMNRM	0.04	0.22	0.04	0.07	0.06	0.30	0.05	0.06	0.038	0.061
CYSIGA(1)	0.03	0.19	0.03	0.04	0.01	0.05	---	---	0.015	0.013
DDREFA(4)	0.02	-0.13	0.02	0.02	0.00	0.04	0.02	0.02	0.013	0.011
CFRISK(6)	0.01	0.08	0.03	0.12	---	---	0.02	0.08	0.012	0.042

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

3.4. Sensitivity Studies

Additional sensitivity studies were performed to examine the influence of key inputs on consequence results. These analyses used fixed parameters for all the inputs that were not part of the sensitivity study and were performed to evaluate shelter-in-place as an alternative to rapid evacuation; degradation of shielding factors during the emergency phase because of seismic damage to houses and other buildings; influence of the weather year chosen for the analysis; and four alternative models of dose response for cancer induction, which were a 0.1 mSv (10 mrem annual threshold, a 3.1 mSv (310 mrem) annual threshold (the value of US average natural background radiation), a 6.2 mSv (620 mrem) annual threshold (the value of US average natural plus medical radiation), and a 50 mSv (5 rem) annual threshold up to a lifetime limit of 100 mSv (10 rem) based on a Health Physics Society position statement.

The conclusions of the sensitivity studies are that rapid evacuation significantly reduces individual LCF risk as compared with shelter-in-place; shelter-in-place also increases EF risk, but it remains very small nonetheless; degraded shielding increases LCF risk, and especially so in conjunction with shelter-in-place; degraded shielding increases EF risk, but it remains very small nonetheless; generally, LCF risk for an individual weather year is within about $\pm 5\%$ of the 5-year average value; and examination of reasonable, non-LNT, doses-response models for LCF risk can result in one or more orders-of-magnitude reduction in estimated individual risk.

4. CONCLUSIONS

Average, individual, LCF risks, assuming LNT dose response, are roughly 10^{-4} per accident event (i.e., if a STSBO were to occur at Sequoyah) for spatial intervals within 80 km. Long-term exposures are generally more important than short-term (emergency-phase) exposures, indicating that LCF risks are largely controlled by the choice of habitability criterion, which in this set of analyses is based on EPA guidance. Cases where the containment is not calculated to fail within 72 hr contribute very little to the overall risk; cases where the containment does fail contribute most of the overall risk. Early containment failure is very unlikely, but risks are about an order-of-magnitude higher when containment fails early because of a large enough hydrogen combustion event. However, these results are dependent on the distributions assigned to safety valve failure-to-close parameters, and considerable uncertainty remains on the true distributions for these parameters due to very limited test data. Average, individual, early fatality risk is very small, even in the unlikely event that early containment failure occurs.

Regression analyses indicate that the time-in-cycle (Cycle) when the accident occurs has the largest influence on consequences of all the uncertain inputs considered in the Sequoyah STSBO UA. This parameter affects both isotopic inventory and the associated decay heat and so has a dual effect on consequence results. It should be noted, however, that even the BOC calculations appear to be headed toward containment failure, but it would occur after the 72-hr analysis time. If the accident could not be mitigated by 72 hr, as assumed, the impact of Cycle might be somewhat diminished.

Other important MACCS parameters for LCF risks are the cancer risk factors for residual, lung, and colon cancers and the time needed to relocate nonevacuees. The residual cancer fatality risk factor represents all cancer types not specifically treated in the current cancer induction model.

Containment rupture pressure (Rupture) is also significant for LCF risks. The pressure at which containment ruptures is correlated negatively with consequences, which means consequences decrease as containment failure pressure increases. Lower containment failure pressure generally corresponds to earlier containment failure. This could be due to reaching failure pressure earlier if failing by gradual overpressure and greater chances of early containment failure from the initial hydrogen deflagration. Correspondingly, a higher failure pressure translates to a delay in containment failure timing, which benefits both evacuation as well as aerosol fallout effectiveness within the containment.

Sensitivity studies indicate that rapid evacuation significantly reduces individual LCF risk as compared with shelter-in-place; shelter-in-place also increases EF risk, but it remains very small nonetheless; degraded shielding that may be induced by earthquake damage increases LCF risk, and especially so in conjunction with shelter-in-place; degraded shielding increases EF risk, but it remains very small nonetheless; generally, LCF risk for an individual weather year in this analysis is within about $\pm 5\%$ of the 5-year average value; and examination of reasonable, non-LNT, doses-response models for cancer induction can result in one or more orders-of-magnitude reduction in average, individual, LCF risk.

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