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MELCOR/MACCS2 Analysis for BWR Mark I Filtered Containment Venting

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INTRODUCTION

For this work, a MELCOR analysis using the State-of-the-Art Reactor Consequence Analysis (SOARCA) Project Peach Bottom Atomic Power Station model [1] was used to investigate different accident mitigation techniques during a long-term station blackout scenario. A consequence analysis was conducted using the SOARCA MELCOR Accident Consequence Code System, Version 2 (MACCS2) Peach Bottom Atomic Power Station deck [1].

The results of the consequence analyses are presented in terms of risks to the public, land contamination areas, population doses, and economic costs for each of the cases. The risk metrics are latent cancer fatality (LCF) and prompt fatality risks to residents in circular regions surrounding the plant. All risk results are presented as conditional risk (i.e., assuming that the accident occurs), and show the risks to individuals as a result of the accident (i.e., LCF risk per event or prompt-fatality risk per event).

LCF risk, prompt fatality risk, land contamination, population dose, and economic cost metrics 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 predicted number of fatalities divided by the population. LCF risks are calculated for a linear no-threshold (LNT) dose-response model. These risk, population dose, and economic cost 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.

MELCOR SCENARIOS

Table I provides a brief description of each MELCOR scenario used in the analysis (i.e., Case A through Case D) for a long-term station blackout scenario assuming a 16 hour DC station battery life. For ease of discussion, two groups were constructed to compare the effect of containment (wetwell) venting and additional mitigative actions (i.e., improvised drywell spray activation). The MELCOR cases were grouped as follows:

- No Drywell Spray – Cases A & B
- Drywell Spray – Cases C & D

Table I. MELCOR scenarios used in the consequence analyses

Case	Drywell spray at 24 hours	Wetwell venting at 60 psig
A		
B		X
C	X	
D	X	X

Decontamination Factors

For this work, a discussion of the accident sequence, health effect risks, land contamination, population dose, and economic costs is provided for each group of cases. Neither MELCOR nor MACCS2 were used to mechanistically model the decontamination effect of an external filter for the wetwell vent path. Instead, a prescribed decontamination factor (DF) value is assigned to represent the external filter. This DF is applied to the portion of the environmental source term released that would flow through the filtered vent and is not a noble gas. The DF is applied uniformly to aerosols of all sizes and is assumed to be time independent. A more realistic approach would account for variations in DF with variables such as aerosol size, venting flow rate, temperature, and depth of the pool in the external filtration system, which would implicitly add a time dependence to the DF.

The relationship between the DF value and the reduction in environmental consequence (e.g., land contamination) is nonlinear. A DF of 10 does not usually translate to a 10-fold reduction in consequence. Some of the results presented in this work are inherently nonlinear. Land contamination area is a good example because this includes thresholds for which areas are only tabulated when the threshold is exceeded. Depending on the accident sequence under consideration and the consequence metric being evaluated, the effect of a DF can be modest to significant.

For the calculations presented in this work, a minimum DF value of 2 was considered for the wetwell external filter. The external filter DF is considered in addition to any type of DF that occurs from the scrubbing effects within the wetwell. In the filtered cases analyzed for this work (e.g., Case D), part of the source term is from aerosols carried from the drywell through the containment downcomers and into the wetwell. This path bypasses the T-quenchers during wetwell venting. When the T-quenchers are bypassed, a lower DF occurs for the wetwell than might be expected. The wetwell DF is typically observed to be an order of magnitude higher when the T-quenchers are not bypassed. Figure 1 shows an example of the differences in DF as a result of aerosols bypassing the T-quenchers. The reduced DF in the wetwell causes more of the radionuclides to be scrubbed in the external filters and thus increase the DF for the external filters. With this in mind, the environmental consequences reported for a DF value of 2 for the external filters should be taken with reservation. Additional MACCS2 calculations were carried out for all wetwell venting cases included in this work with DF values of 10 and 100. The results show a reduction of consequences for the filtered cases using the larger DFs.

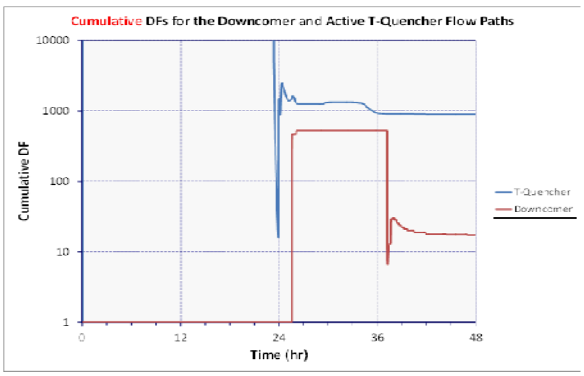

Figure 1. Example of MELCOR modeling of cumulative DF for the downcomer versus the T-quenchers

RESULTS

Each of the filtered cases (Cases B & D) has an applied DF of 2, 10, and 100 for the wetwell vent path. When a DF is applied to the pathway for flow through the filtered vent for Case B, the relationship is nonlinear between the inverse of DF and the source term. For Case D when a DF is applied to the pathway for flow through the filtered vent, the relationship is linear between the inverse of DF and the source term. By assumption, the filtered vent has no influence on the release of noble gases. For the Case B filtered cases, the wetwell vent path is not the only release pathway to the environment. For Case D, the wetwell vent path is the only release pathway to the environment.

For Case A and Case B at 36.5 hours, the containment fails due to core melt through of the drywell liner. The drywell liner failure provides a lower resistance pathway to the environment than through the wetwell vent. Unlike drywell head flange leakage, the flow path opened by melt-through of the drywell liner can never be reclosed. The drywell liner failure is a permanent leak path out of the containment to the environment that bypasses wetwell pool scrubbing and any external filter on the wetwell vent.

The source term for Case C is lower than the source term for Case D and is in part due to the effectiveness of drywell sprays in minimizing the source term. The pressure suppression by the drywell sprays minimizes leakage from the drywell head flange, which is the primary model of containment overpressure failure and is the only pathway for radionuclide release to the environment for Case C. The head flange leakage in the MELCOR model is assumed to behave elastically. Thus, after a high pressure excursion that temporarily lifts the head flange at ~26 hours for 20 minutes, the head flange reseats perfectly with no residual leakage as long as the containment sprays reduce drywell pressure below 80 psig. The head flange doesn't lift again until reactor pressure vessel (RPV) lower vessel head failure at 36.6 hours, and after about 4.5 hours the head flange re-seats and intermittently reopens for the rest of the MELCOR simulation.

Also, the lower containment pressure in Case D resulting from the wetwell venting fosters more revaporization of cesium and iodine from the RPV internals. The vapors escape the RPV and condense into aerosols that are carried towards the wetwell vent. Some of the aerosols are scrubbed in the wetwell pool but not all of them. The aerosols not scrubbed in the pool release to the environment through the wetwell vent path. In considering the scrubbing taking place in the wetwell pool during wetwell venting for Case D, the flow to the wetwell is through the downcomer vents rather than through the T-quenchers. A DF of 10 associated with the downcomer vents is markedly less than a DF of 1,000 associated with the T-quenchers as reported by MELCOR for Case D.

The increased revaporization of cesium and iodine from RPV internals combined with the larger vent flows and imperfect wetwell scrubbing for Case D, the elastic drywell head flange model in MELCOR, and the effectiveness of the drywell containment sprays lead to the non-intuitive larger environmental release for Case D relative to Case C.

LCF and Prompt Fatality Risk

For the filtered wetwell venting cases, when a DF is applied to the pathway that flows through the filtered vent (i.e., Case B), the relationship is sublinear between the inverse of DF and LCF risk. This sublinear behavior is more pronounced at shorter distances. This trend is primarily due to short-term and long-term mitigative actions. For smaller releases, the implementation of offsite protective actions is less; whereas, for larger releases, more offsite protective actions are taken. Thus, doses and LCF risks increase less than linearly with the magnitude of the source term. The offsite protective actions implemented in the MACCS2 model that are responsible for these trends are relocation during the emergency phase and enforcement of the habitability criterion during the long-term phase.

For Case B, the wetwell vent path is not the only release pathway to the environment. As a result of an additional environmental release pathway (i.e., the drywell liner melt-through), the relationship between the assumed DF and the LCF risk contributes to the sub-linearity of the LCF risk results.

Case D does not produce lower environmental consequences than Case C when the assumed DF is 2. However, when a DF of 10 or greater is applied to Case D for the wetwell vent pathway to represent the effect of the external filters, the environmental consequences are lower than Case C.

For wetwell venting Case B with a DF greater than 10, the long-term phase LCF risk dominates the total LCF risks. These 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 State of Pennsylvania's habitability criterion is a dose rate of 500 mrem/yr.

For all cases, the emergency response is very effective within the EPZ (10 miles) during the early phase, so those risks are very small and entirely represent the 0.5 percent of the population that are modeled as refusing to evacuate. The peak emergency phase LCF risk is at 20 miles, which is the first location outside of the evacuation zone. An example of this can be seen in Figure 2 for Case A, which has the highest LCF risk for all cases considered. For Case D with a DF greater than 10, the emergency phase LCF risk dominates the total LCF risks. This is due to the reduced source term from drywell spray.

The prompt fatality risks are zero for these cases. This is because the release fractions are too low to produce doses large enough to exceed the dose thresholds for early fatalities, even for the 0.5 percent of the population that are modeled as refusing to evacuate. The largest value of the mean, acute exposure for the closest resident (i.e., 0.5 to 1.2 kilometers from the plant) is about 0.06 Gy to the red bone marrow. The red bone marrow is usually the most sensitive organ for prompt fatalities, but the minimum acute dose that can cause an early fatality is about 2.3 Gy. The calculated mean, acute exposures are all well below this threshold.

Land Contamination

Land areas contaminated above a threshold level can be calculated several ways in MACCS2, the simplest of which is to report land areas that exceed activity levels per unit area for one or more of the isotopes. This is the approach used here, and areas are reported using the same threshold levels of Cs-137 as were reported following the Chernobyl accident [2] (i.e., 1, 5, 15, and 40 $\mu Ci/m^2$).

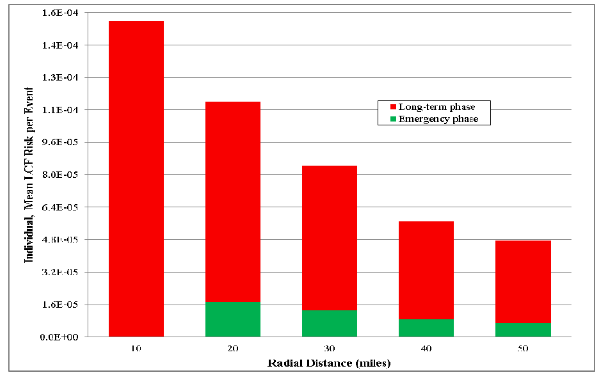

Figure 2. Case A individual, mean LCF risk per event for residents within a circular area at specified radial distances

A relatively small number of the isotopes that could potentially be released from a nuclear reactor are radiologically important and require effort to decontaminate. Among these are Cs-134 and Cs-137, which have half-lives of 2 years and 30 years, respectively, and are important isotopes for a typical nuclear reactor accident in terms of decontamination.

There is an inherently nonlinear relationship between the size of the source term and land contamination area. This is primarily because land contamination area is calculated using a threshold (i.e., land areas are only tabulated when they exceed a threshold ground concentration). It turns out that the relationship between the inverse of DF (i.e., the quantity released) and land contamination area is superlinear. An example of this can be seen in Figure 3 for Cases A & B, which have the highest land contamination for the cases considered.

The mean contaminated area for specified Cs-137 contamination levels for all cases show the same trends for filtered releases. When the unfiltered case (e.g., Case A) is compared with a filtered case (e.g., Case B), a DF of 10 or 100 for wetwell venting results in a several order-of-magnitude reduction in land contamination area.

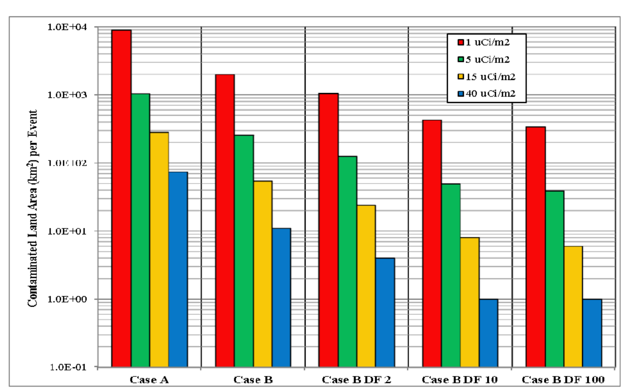

Figure 3. Cases A & B mean land contamination per event

Population Dose

The relationship between population dose and inverse DF is sublinear because less remedial action is taken at lower contamination levels. For the cases considered, a DF of 10 or more for all wetwell venting filtered cases result in lower population doses than their respective unfiltered cases. Table II shows the population dose at the 50-mile radial distance for all cases considered.

Table II. Mean population dose (person-rem) per event for residence within a circular area of 50 miles for all cases considered and specified DFs

Case A	580,000
Case B	456,000
Case B with DF=2	322,000
Case B with DF=10	183,000
Case B with DF=100	141,000
Case C	86,100
Case D	280,000
Case D with DF=2	160,000
Case D with DF=10	43,300
Case D with DF=100	8,750

The properties of the source term affect the population dose through deposition rates, half-lives, and the types of radiation emitted. As described in the LCF risk sections, various phenomena contribute to dose depending on the phase of the event. During the emergency phase, evacuation within the EPZ has a significant effect on population dose within the 10-mile radial distance. The only dose contribution within the EPZ is entirely represented by the 0.5 percent of the population that is modeled as refusing to evacuate. However, these emergency phase population doses are a small contribution and generally contribute less than half of the overall population dose for the cases considered. Case D with a DF=100 is the only case for which over half (i.e., 55% for both cases) of the population dose is from emergency phase doses. Long-term phase doses 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.

The population dose results include societal doses from the ingestion pathway and doses to decontamination workers; LCF risks do not include either of these doses. Ingestion is considered during the long-term phase from contaminated food and water. The ingestion pathway accounts for 10-20% of the population dose for the wetwell venting unfiltered cases considered. The ingestion pathway accounts for 15-30% of the population doses for the wetwell venting filtered cases considered.

Economic Costs

The isotopic composition of the source term is one element that impacts the costs of decontamination. Some isotopes require no decontamination at all while others can be more difficult to decontaminate. The purpose of decontamination is to remove enough of the cesium to reduce the level of radiation from ground and building surfaces to acceptable levels (i.e., habitability limit). Table III shows the economic costs at the 50-mile radial distance for all cases considered.

Table III. Mean, total offsite economic costs ($M-2005) per event within a circular area of 50 miles for all cases considered and specified DFs

Case A	1,910
Case B	1,730
Case B with DF=2	885
Case B with DF=10	274
Case B with DF=100	185
Case C	116
Case D	588
Case D with DF=2	240
Case D with DF=10	20.2
Case D with DF=100	0.703

Implementation of decontamination, which along with the associated interdiction of land is the dominant contributor to the overall economic costs, depends on whether or not the habitability criterion is exceeded. Remedial actions considered in the long-term phase depend on two criteria; habitability and farmability. Both of these criteria are based on contamination thresholds, which lead to inherently nonlinear relationships between source term magnitude and economic costs. Thus applying a DF to represent an external filter does not result in a linear relationship between release (i.e., reciprocal of DF) and economic costs.

A DF of 10 for the wetwell venting cases results in an order-of-magnitude reduction in economic costs. For the cases considered, a DF of 10 or more for all wetwell venting filtered cases results in a lower economic costs than their respective unfiltered cases.

REFERENCES

1. U.S. Nuclear Regulatory Commission, "State-of-the-Art Reactor Consequence Analyses Project – Volume 1: Peach Bottom Integrated Analysis," NUREG/CR-7110 Volume 1, USNRC, Washington D.C. (2012).
2. International Atomic Energy Agency, "Present and Future Environmental Impact of the Chernobyl Accident," IAEA-TECDOC-1240, IAEA, Vienna, Austria (2001).