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MACCS2 Consequence Analysis for BWR Mark I and Mark II Filtered Containment Venting

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ABSTRACT

The consequence analyses provide the U.S. Nuclear Regulatory Commission (NRC) with technical information and insights for the NRC staff regarding the imposition of new requirements related to containment venting systems for boiling water reactors (BWR) with Mark I and Mark II containments.

When a decontamination factor is applied to an external filtered vent path, the latent cancer fatality risk, land contamination area, population dose, and economic results are nonlinear for all cases considered in this study. A decision on the use of external filters on either a BWR drywell or wetwell vent path should not be solely based on health effect risk, land contamination, population dose, or economic costs.

ACKNOWLEDGEMENT

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ACRONYMS

ATD	Atmospheric Transport and Dispersion
CFR	Code of Federal Regulations
DF	Decontamination Factor
EAB	Exclusion Area Boundary
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPZ	Emergency Planning Zone
ESP	Early Site Permit
FDA	U.S. Food and Drug Administration
FGR	Federal Guidance Report
GUI	Graphical User Interface
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
KI	Potassium Iodide
LCF	Latent Cancer Fatality
LNT	Linear No Threshold
LTSBO	Long-Term Station Blackout
MACCS2	MELCOR Accident Consequence Code System Version 2
NRC	U.S. Nuclear Regulatory Commission
PAG	Protective Action Guide
PRA	Probabilistic Risk Assessment
QHO	Quantitative Health Objective
RPV	Reactor Pressure Vessel
SOARCA	State-of-the-Art Consequence Analyses
SRV	Safety Relief Valve

1.0 GENERAL DESCRIPTION OF MACCS2

The MELCOR Accident Consequence Code System Version 2 (MACCS2), is the U.S. Nuclear Regulatory Commission's (NRC's) code that was specifically developed to evaluate off-site consequences from a hypothetical release of radioactive materials into the atmosphere [1],[2]. The code models atmospheric transport and dispersion (ATD), emergency response actions, exposure pathways, health effects, and economic costs. MACCS2 evolved from predecessor codes. MACCS was used to support NUREG-1150, CRAC2 was used to estimate consequences in the 1982 Siting Study, and CRAC was initially developed for WASH-1400, which was published in 1975. These codes have been developed mainly as tools to assess the risk and consequences associated with accidental releases of radioactive material into the atmosphere in probabilistic risk assessment (PRA) studies.

The MACCS2 code currently is used by U.S. nuclear power plant license renewal applicants to support the plant specific evaluation of Severe Accident Mitigation Alternatives (SAMAs) that is required as part of the environmental assessment for license renewal. Applicants follow NRC's regulatory analysis guidelines in NUREG/BR-0058 and NUREG/BR-0184, which specifically recommend the use of MACCS2 to estimate the averted "Offsite Property Damage" cost benefit and the offsite averted dose cost elements. The information from MACCS2 code runs supports a cost-benefit assessment for various potential plant improvements, called SAMAs. MACCS2 is also routinely used in environmental impact statements (EIS) supporting early site permits (ESP) reviews. The NRC is required under the Regulation (10 CFR 52) to prepare EIS as part of the review of an ESP application. Three types of severe accident radiological consequences are evaluated by MACCS2 code in ESP reviews: (1) human health, (2) economic cost, and (3) land area affected by contamination. Human health effects are expressed as both early fatalities and latent fatalities. In the State-of-the-Art Consequence Analyses (SOARCA) study, the MACCS2 code was used to estimate consequences in terms of early fatality risk and latent cancer fatality risk.

MACCS2 estimates consequences in four steps:

1. atmospheric transport and deposition onto land and water bodies,

2. the estimated exposures and health effects for up to seven days following the beginning of release (early phase),

3. the estimated exposures and health effects during an intermediate time period of up to one year (intermediate phase), and

4. the estimated long-term (e.g., 50 years) exposures and health effects (late-phase model).

The assessment of offsite property damage in terms of contaminated land and economic consequences use all four parts of the modeling. The assessment of offsite property damage in MACCS2 can be comprehended with the following overview of the code.

MACCS2 includes all of the relevant dose pathways: cloudshine, inhalation, skin contamination, resuspension, groundshine, and ingestion. Figure 1 provides a graphic showing the atmospheric transport processes and dose pathways modeled by MACCS2 and used in this study. Because MACCS2 is primarily a probabilistic risk assessment (PRA) tool, it accounts for the uncertainty in weather that is inherent with a hypothetical accident that could occur at some point in the future. WinMACCS is a user-friendly front end to MACCS2 that facilitates the selection of input parameters, sampling of uncertain inputs, and performs post-processing of results.

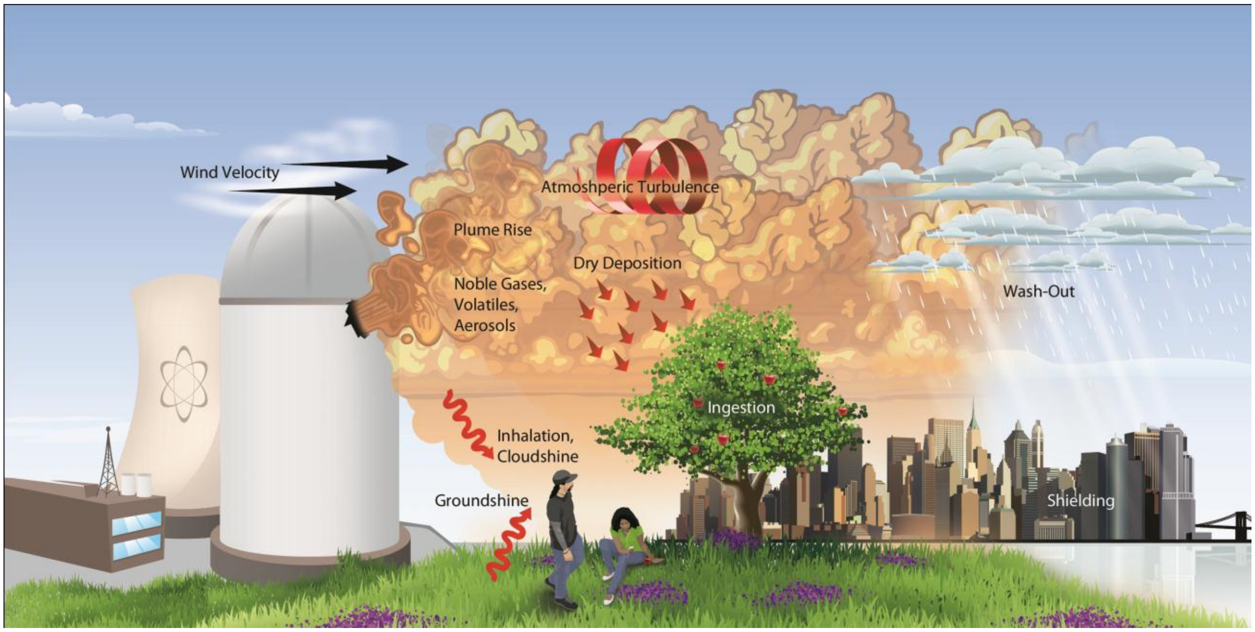

Figure 1 Relevant MACCS2 exposure pathways used in this study

1.1 Atmospheric Transport and Dispersion Model

MACCS2 models dispersion of radioactive materials released into the atmosphere using the straight-line Gaussian plume model with provisions for meander and surface roughness effects. The ATD model treats the following: plume rise due to the sensible heat content (i.e., buoyancy), initial plume size due to building wake effects, release of up to 200 plume segments, dispersion under statistically representative meteorological conditions, deposition under dry and wet (precipitation) conditions, and decay and ingrowths of up to 150 radionuclides and a maximum of 6 generations. Phenomena not treated in detail in this model are irregular terrain, spatial variations in the wind-field, and temporal variations in wind direction.

The user has the option to select meteorological sampling, such as a single weather sequence or multiple weather sequences. One of the weather sampling options is used in PRA studies to evaluate the effect of weather conditions at the time of the hypothetical accident.

The results generated by the ATD model include contaminant concentrations in air, on land, as a function of time and distance from the release source, and are subsequently used in early, intermediate, and late-phase exposure modeling. The MACCS2 ATD model has been compared against two Gaussian puff codes (e.g., Rascal and Ratchet) and a Lagrangian particle tracking code (e.g., LODI from NARAC). The study showed that the MACCS2 mean results, over weather, were within a factor of 2 for arc-averages and a factor of 3 at a specific grid location out to 100 miles from the point of release.

A new and alternative ATD model, with the capability to model three-dimensional, time-dependent wind fields, is planned as part of the MACCS2 update and maintenance program.

The initial work plan and schedule started in May 2012. A fully implemented and tested model, including documentation, is envisioned by the end of 2013.

1.2 Early Phase Model and Exposure Pathways

The early-phase model in MACCS2 assesses the time period immediately following a radioactive release. This period is commonly referred to as the emergency phase and it can extend up to seven days after the arrival of the first plume at any downwind spatial interval. Early exposures in this phase account for emergency planning, i.e. sheltering, evacuation, and relocation of the population. The early-phase modeling in MACCS2 is limited to seven days from the beginning of release. In MACCS2, sheltering and evacuation actions are modeled within the Emergency Planning Zone (EPZ). Different shielding factors for exposure to cloudshine, groundshine, inhalation, and deposition on the skin, are associated with three types of activities: normal activity, sheltering, and evacuation.

Outside the sheltering/evacuation zone, dose dependent relocation actions may take place during the emergency phase. That is, if individuals at a specific location are projected to exceed either of two dose thresholds over the duration of the emergency phase, they are relocated at a specified time after plume arrival.

For a radioactive release containing radioiodine, some of the iodine is highly likely to be absorbed by the thyroid. As a consequence the chance of thyroid cancer to the individual may be increased. Potassium iodide (KI) can saturate the thyroid with iodine and thereby reduce the amount of radioiodine that can be absorbed. KI is distributed near some nuclear power plants. A KI model has been implemented in MACCS2 to account for the beneficial effect of taking KI. It accounts for the fraction of the population taking KI and the efficacy, or dose reduction, provided by the KI.

1.3 Intermediate Phase and Exposure Pathways

An intermediate phase with duration of up to one year following the early phase can be modeled in MACCS2. The only mitigative action modeled in this phase is relocation. That is, if the projected dose leads to doses in excess of a threshold, the population is assumed to be relocated to an uncontaminated area for the entire duration of this phase, with a corresponding per-capita economic cost defined by the user. The intermediate phase duration can be modeled as being zero (i.e., no intermediate phase).

If the projected dose does not reach the user specified threshold, exposure pathways for groundshine and inhalation of resuspended material are treated.

1.4 Long-Term Phase Model and Exposure Pathways

In the long-term phase, (e.g., 50 years of potential exposure), protective actions are defined to minimize the dose to an individual by external (i.e., groundshine) and internal (i.e., food consumption and resuspension inhalation) pathways. Decisions on mitigative actions are based on two sets of independent actions; (1) decisions relating to whether land, at a specific location and time, is suitable for human habitation (i.e., habitability) or (2) agriculture production (i.e., farmability). Habitability is defined by a maximum dose and an exposure period to receive that dose. Habitability decision making can result in four possible outcomes:

1. land is immediately habitable,

2. land is habitable after decontamination,
3. land is habitable after decontamination and interdiction[1], or
4. land not deemed habitable after 30 years of interdiction (i.e., it is condemned).

Land is also condemned if the cost of decontamination exceeds the value of the land. The dose criterion for the MACCS2 modeling of individuals returning back to the affected (i.e., contaminated) area is a user input, and is typically from the U.S. Environmental Protection Agency (EPA) Protective Action Guides (PAGs).[2]

Decisions on decontamination are made using a decision tree. The first decision is whether land is habitable. If it is, then no further actions are needed. The population returns to their homes and receive a dose from any deposited radionuclides for the entire long-term phase. If land is not habitable, the first option considered is to decontaminate at the lowest level of dose reduction, which is also the cheapest to implement. If this level is sufficient to restore the land to habitability, then it is performed. Following the decontamination, the population returns to their homes and receives a dose based on the residual contamination for the duration of the long-term phase. If the first level of decontamination is insufficient to restore habitability, then successively higher levels are considered. Up to three decontamination levels are considered in MACCS2. If the highest level of decontamination is insufficient, then interdiction for up to 30 years is considered following the decontamination. During the interdiction period, radioactive decay and weathering work to reduce the dose rates that would be received by the returning population. If the highest level of decontamination followed by interdiction is sufficient to restore habitability, then it is employed and the population is allowed to return. Doses are accrued for the duration of the long-term phase. If habitability cannot be restored by any of these actions, then the land is condemned. Also, if the cost of the required action to restore habitability is greater than the value of property, then that land is condemned.

The decision on whether land is suitable for farming is first based on prior evaluation of its suitability for human habitation. That is, land cannot be used for agriculture unless it is habitable. Furthermore, farmland must be able to grow crops or produce dairy products that meet the U.S. Food and Drug Administration (FDA) requirements (i.e., it must be farmable). If farmland is habitable and farmable, a food chain model is used to determine doses that would result from consuming the food grown or produced on this land. The COMIDA2 food chain model is the latest model developed for use in MACCS2. COMIDA2 represents a significant improvement over the older food-chain model embodied in the original MACCS code and used in NUREG-1150. The capability of bypassing (i.e., not modeling) the food-chain/ingestion model has been recently implemented in MACCS2 because it is generally thought that food availability in the U.S. would preclude the need for individuals to consume contaminated food or water.

MACCS2 values of total long-term population dose and health effects account for exposures received by workers performing decontamination. While engaged in cleanup efforts, workers

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1 In this context, interdiction generally refers to the period of time in which residents are not permitted to return to live on their property because the radiation doses they would receive from external sources and inhalation exceed the habitability criterion. Interdiction allows for radioactive decay, decontamination, and weathering to potentially bring these doses to a point where they would no longer exceed the habitability criterion.

2 EPA developed the PAG Manual to provide guidance to state and local authorities on actions to help protect the public during emergencies: http://www.epa.gov/rpdweb00/rert/pags.html.

are assumed to wear respiratory protection devices; therefore, they only accumulate doses from groundshine.

1.5 MACCS2 Economic Consequence Model

The economic model in MACCS2 includes costs associated with various actions or modeling within six categories as follows [3]:

1. Evacuation and relocation costs (e.g., a per diem cost associated with displaced individuals). The per-diem costs are associated with the population that is temporarily relocated. These costs are calculated by adding up the number of displaced people times the number of days they are displaced from their homes.

2. Moving expenses for people displaced (i.e., a onetime expense for moving people out of a contaminated region). There is a one-time moving expense for the population displaced from their homes because of decontamination, interdiction, or condemnation. The modeling can include loss of wages.

3. Decontamination costs (e.g., labor, materials, equipment, and disposal of contaminants). These are the costs associated with decontaminating property. These costs include labor and materials for performing the decontamination. They depend on the population and size of the area that needs to be decontaminated as well as the level of decontamination that needs to be performed. They can include the cost to dispose of contaminated material. The model estimates the costs only if decontamination is cost effective.

4. Cost due to loss of land use of property (e.g., costs associated with lost return on investment and for depreciation of property that is not being maintained). These costs are associated with loss of use of property. These costs include an expected rate of return on property and depreciation caused by lack of routine maintenance during the period of interdiction, the time when the property cannot be used.

5. Disposal of contaminated food grown locally (e.g., crops, vegetables, milk, dairy products, and meat).

6. Cost of condemned lands (i.e., land that cannot be restored to usefulness or is not cost effect to do so). These are costs of condemning property that cannot be restored to meet the habitability criterion. The habitability criterion used for Peach Bottom is consistent with the State of Pennsylvania Bureau of Radiation Protection guidance, which is that an area is habitable in the long-term if an occupant would receive less than 0.5 rem.

All of the costs for the six cost categories are summed over the entire offsite area affected by the assumed atmospheric release to get the total offsite economic costs. Nearly all of the values affecting the economic cost model are user inputs and thus can account for a variety of costs and can be adjusted for inflation, new technology, or changes in policy. Also, the isotopic composition of the source term significantly impacts the costs that would be needed to decontaminate. Some isotopes require no decontamination at all while others might require extensive decontamination. Thus applying a DF to the particulate source term release fraction will not result in a linear extrapolation of the results.

1.5.1 Decontamination Model

Decisions on decontamination are made using a decision tree. The first decision is whether land is habitable. If it is, then no further actions are needed. The population returns to their homes and receive a dose from any deposited radionuclides for the entire long-term phase. If land is not habitable, the first option considered is to decontaminate at the lowest level of dose reduction, which is also the cheapest to implement. If this level is sufficient to restore the land to habitability, then it is performed. Following the decontamination, the population returns to their homes and receives a dose based on the residual contamination for the duration of the long-term phase. If the first level of decontamination is insufficient to restore habitability, then successively higher levels are considered. MACCS2 considers up to three decontamination levels. If the highest level of decontamination is insufficient, then interdiction for up to 30 years is considered following the decontamination. During the interdiction period, radioactive decay and weathering work to reduce the dose rates that would be received by the returning population. If the highest level of decontamination followed by interdiction is sufficient to restore habitability, then it is employed and the population is allowed to return. Doses are accrued for the duration of the long-term phase. If habitability cannot be restored by any of these actions, then the land is condemned. The land is also condemned if the cost of the required action to restore habitability is greater than the value of property.

MACCS2 values of total long-term population dose and health effects account for exposures received by workers performing decontamination. While engaged in cleanup efforts, workers are assumed to wear respiratory protection devices; therefore, they only accumulate doses from groundshine.

1.5.2 Land Contamination Areas

Land areas contaminated above a threshold level can be calculated in several ways. The simplest is to report land areas that exceed activity levels per unit area for one or more isotopes. This is the approach used to report contaminated areas following the Chernobyl accident (i.e., land areas exceeding threshold levels of Cs-137 activity were reported). Currently, MACCS2 estimates such areas based on the Gaussian plume model for atmospheric transport and deposition.

1.6 Recent Improvements to the MACCS2 Code

The MACCS2 code has gone through additional improvements since its original release in 1997. Version 2.5 of the code has been released recently together with the graphical user interface (GUI), WinMACCS Version 3.6 [4]. The three most important modeling features implemented in WinMACCS are:

1. the ability to easily evaluate the impact of parameter uncertainty,
2. the ability to manipulate input parameters for network evacuation modeling, and
3. the ability to model alternative dose-response relationships for latent cancer fatality evaluation (e.g., linear with threshold model).

2.0 CONSEQUENCE ANALYSES OVERVIEW

The MACCS2 consequence model (Version 2.5.0.9) was used to calculate offsite doses and land contamination, and their effect on members of the public with respect to fatality risk, land contamination, population dose, and economic costs for the cases considered in this study. Updates to the SOARCA version of the MACCS2 code (Version 2.5.0.0) used for offsite consequence predictions are discussed in NUREG-1935, Section 5. The MACCS2 updates from SOARCA to this study deal with the following:

- Provide file locations on MACCS2 cyclical files (e.g., MELMACCS source term files) to provide enhanced traceability between inputs and results. This update did not affect the results;

- A lower plume density limit (PLMDEN) consistent with the MACCS2 User Manual [1]. This update did not affect the results. It only allowed calculations to be performed over a wider range of input parameters;

- Change to a FORTRAN compiler compatible with the Windows 7 operating system. This change did create minor differences (i.e., less than 10%). The new compiler uses a different representation for real numbers. Slight changes in the real values affect the rounding of these values to create integer values, which in turn affect the random values that are calculated; particularly the set of weather trials that are selected. This difference is considered acceptable and not an error because there is no reason to think that one set of random choices is better than the other; and

- Correction of the NRC Regulatory Guide 1.1.45 plume meander model [5]. This correction did not have any impact on the SOARCA results or this study's results because neither of these analyses used this model.

The principal phenomena considered in MACCS2 are atmospheric transport using a straight-line Gaussian plume segment model of short-term and long-term dose accumulation through several pathways including cloudshine, groundshine, inhalation, deposition onto the skin, and food and water ingestion. The ingestion pathway model was used in these analyses. The following dose pathways are included in the reported latent cancer fatality (LCF) risk metrics:

- Cloudshine during plume passage.

- Groundshine during the emergency and long-term phases from deposited aerosols.

- Inhalation during plume passage and following plume passage from resuspension of deposited aerosols. Resuspension is treated during both the emergency and long-term phases.

MACCS2 does not include ingestion of contaminated food or water in the LCF risk calculation. However, the ingestion pathway is included in the population dose calculation.

Another risk metric considered in this study is prompt fatality risk. The NRC quantitative health objective (QHO) for prompt fatalities ($5x10^{-7}$ pry) is generally interpreted as the absolute risk within 1 mile of the exclusion area boundary (EAB). For Peach Bottom, the EAB is 0.5 mile from the reactor building from which release occurs, so the outer boundary of this 1-mile zone is at 1.5 miles. The closest MACCS2 grid boundary to 1.5 miles used in this set of calculations is at 1.3 miles. Evaluating the risk within 1.3 miles should reasonably approximate the risk within 1 mile of the EAB.

Prompt fatality risk is based on doses large enough to exceed the dose thresholds for early fatalities for the 0.5 percent of the population that are modeled as refusing to evacuate. The red bone marrow is usually the most sensitive organ for prompt fatalities. The minimum acute exposure that can cause a prompt fatality is about 2.3 gray (Gy) (i.e., 1 Gy = 100 RAD) to the red bone marrow. Additional acute exposure threshold are also considered for the lungs (13.6 Gy) and the stomach (6.5 Gy). None of the cases considered for this study exceeded the lung and stomach acute exposure thresholds.

This work uses the Peach Bottom unmitigated long-term station blackout (LTSBO) MACCS2 input deck from the SOARCA project as a starting point. As mentioned above, one basic change is that the ingestion pathway was modeled in this study, but was excluded in the SOARCA analyses. The only other changes were to modify source terms to account for variation in the LTSBO scenario and the effect of adding an external filter to the wetwell vent path. None of the source terms considered in this study are the same as the LTSBO source term used in SOARCA.

As part of SOARCA, a number of code enhancements were made to MACCS2 [6]. In general, these enhancements implemented some of the recommendations obtained during the SOARCA external review and needs identified by the broader consequence analysis community. The code enhancements implemented for SOARCA were primarily to improve realism and code performance and to enhance existing functionality.

Many of the user-specified modeling practices used for consequence analysis in SOARCA are different than previous studies. SOARCA applied the most current weather sampling and updated modeling techniques, and differing dose-response options to create a more detailed, integrated, and realistic analysis than past consequence analyses. Some of the MACCS2 enhancements used in SOARCA included increased angular resolution, updated dose conversion factors, and a larger number of cohorts.

Studies prior to the SOARCA analyses used 16 compass directions. For SOARCA, 64 compass directions were used [7], and are maintained for this study.

MACCS2 analyses prior to SOARCA used dose conversion factors based on the International Commission on Radiological Protection (ICRP) publications ICRP 26 [8] and ICRP 30 [9]. The SOARCA project used dose conversion factors from Federal Guidance Report 13 (FGR-13) [10], which are also used in this study.

MACCS2 previously allowed up to three emergency-phase cohorts. A cohort is a population group that mobilizes or moves differently from other population groups. Each emergency-phase cohort represents a fraction of the population who behave in a similar manner, although MACCS2 allows response times to be a function of radius, so there can be some limited variation within a single cohort. As an example, a cohort might represent a fraction of the population who rapidly evacuate after officials instruct them to do so. To treat public response more realistically, the number of emergency phase cohorts allowed in MACCS2 was increased to 20. This allows significantly more variations in emergency response (e.g., variations in preparation time before evacuation) to more accurately reflect the movement of the public during an emergency. In a similar way, modeling evacuation routes using the network-evacuation model in MACCS2 adds more realism than had been employed in previous studies.

The population near the Peach Bottom plant was modeled in SOARCA using six cohorts [7], and this approach was maintained in this study. Cohorts were established to represent members of the public who may evacuate early, evacuate late, those who refuse to evacuate, and those who evacuate from areas not under an evacuation order (e.g., the shadow evacuation). The following cohorts were used for these analyses:

<u>Cohort 1: 0 to 10 Public.</u> This cohort includes the public residing within the emergency planning zone (EPZ) which is the radial area within 10 miles of the plant.

<u>Cohort 2: 10 to 20 Shadow.</u> This cohort includes the shadow evacuation from the 10-mile to 20-mile area beyond the EPZ.

<u>Cohort 3: 0 to 10 Schools and 0 to 10 Shadow.</u> This cohort includes elementary, middle, and high school student populations within the EPZ. A shadow evacuation from within the EPZ is included that is assumed to mobilize at the same time as the schools. Both the evacuation of the schools and the shadow evacuation are triggered by the sounding of sirens indicating a site area emergency (SAE).

<u>Cohort 4: 0 to 10 Special Facilities.</u> The special facilities population includes residents of hospitals, nursing homes, assisted-living communities, and prisons. Special facility residents are assumed to reside in robust facilities such as hospitals, nursing homes, or similar structures that provide additional shielding. Shielding factors for this population group consider this fact.

<u>Cohort 5: 0 to 10 Tail.</u> The 0 to 10 tail is defined as the last 10 percent of the public to evacuate from the 10-mile EPZ.

<u>Cohort 6: Non-Evacuating Public.</u> This cohort represents a portion of the public from 0 to 10 miles who are assumed to refuse to evacuate. This cohort is 0.5 percent of the population and they are modeled as though they continuing to perform normal activities

2.1 Consequence Analyses Overview

The results of the consequence analyses are presented in terms of risks to the public, land contamination, population dose, and economic costs for each of the cases. 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).

The risk metrics are LCF risk and prompt fatality risks to residents in circular regions surrounding the plant. 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.

Table 1 provides a brief description for each MELCOR scenario used in the regulatory analysis (i.e., Case 2, Case 3, Case 6, Case 7, Case 12, Case 13, Case 14, and Case 15).

Table 1 Matrix of MELCOR scenarios used in the consequence analyses

Case	DC Battery time (16 hours)	Core spray after RPV failure	Drywell spray at 24 hours	Wetwell venting at 60 psig	Main steam line failure	Drywell venting at 24 hours
2	X					
3	X			X		
6	X	X				
7	X	X		X		
12	X				X	X
13	X		X		X	X
14	X		X			
15	X		X	X		

For ease of discussion, four groups were constructed to compare the effect of venting and additional mitigative actions (e.g., core spray and drywell spray). The MELCOR cases were grouped as follows:

- Base Case – Case 2 and Case 3
- Core Spray – Case 6 and Case 7
- Drywell Venting – Case 12 and Case 13
- Drywell Spray – Case 14 and Case 15

A discussion of health effect risks (Section 3 through Section 6), land contamination (Section 3 through Section 6), population dose (Section 7), and economic costs (Section 8) is provided for each group of cases.

For this work, neither MELCOR nor MACCS2 were used to mechanistically model the decontamination effect of an external filter for the wetwell or drywell 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 all of the aerosol sizes and is assumed to be time independent. A more realistic approach would account for the DF for each aerosol bin and possibly account for the effect of temperature and radionuclide concentration in the pool of water in the external filtration system

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 study are inherently nonlinear. Land contamination area is a good example because this includes thresholds for which values 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 study, 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 study (e.g., Case 15), part of the source term is from water flowing 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 would be expected. The wetwell DF is typically considered to be an order of magnitude higher when the T-quenchers are not bypassed. The reduced DF in the wetwell will cause more 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 study with DF values of 10 and 100. The results show a reduction of consequences for the filtered cases.

For the calculations presented in this study, a minimum DF value of 1,000 was considered for the drywell external filter. Since there are no scrubbing effects from the wetwell for drywell venting, the external filter is considered to be 99.9% efficient. As a sensitivity study, a DF of 5,000 was applied to Case 12 (i.e., external filter is 99.98% efficient) to determine the effect of an increased efficiency.

3.0 BASE CASES

Table 2 provides a brief description of source terms for the Peach Bottom accident scenarios analyzed for Case 2 and Case 3. Each of the filtered cases 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 (i.e., Case 3 – wetwell vent left open), the relationship is nonlinear between the inverse of DF and the source term. For the filtered cases, the wetwell vent path is not the only release pathway to the environment. 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 line failure is a permanent leak path out of the containment to the environment without any benefit of wetwell pool scrubbing associated with the wetwell vent.

Table 2 Brief source term description for MELCOR scenarios discussed in the Base Cases consequence analyses

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
Case 2	0.77	0.013	0.0014	0.019	0.016	0	0.003	0	0	25.7	48
Case 3	1.00	0.0046	0.0081	0.028	0.033	0	0.0004	0.0002	0	23.9	48
Case 3 DF=2	1.00	0.0029	0.0047	0.017	0.022	0	0.0003	0.0001	0	23.9	48
Case 3 DF=10	1.00	0.0015	0.0020	0.0077	0.013	0	0.0002	0.00002	0	23.9	48
Case 3 DF=100	1.00	0.0011	0.0014	0.0057	0.011	0	0.0002	0.000002	0	23.9	48

3.1 Base Cases - LCF and Prompt Fatality Risk

Exposure of the public to a radioactive release and the risk associated with that exposure can be analyzed with MACCS2. One of the risk metrics used in these analyses is LCF risk for residents in circular regions surrounding the plant. The risks are averaged over the entire residential population within the circular region, and represent the calculated number of fatalities for all dose pathways, except ingestion, divided by the population. The LCF risk metric accounts for the distribution of the population within the circular region and for the relationship between the population distribution and the wind rose probabilities, as well as other meteorological characteristics. LCF risk results are presented for the LNT dose-response model.

Table 3 shows the individual, mean LCF risks per event for residents within a circular area at specified radial distances for Case 2 and Case 3. As seen in Table 3, when a DF is applied to the pathway that flows through the filtered vent (i.e., Case 3 – wetwell vent left open), the relationship is nonlinear between the inverse of DF and LCF risk.

As discussed above for the filtered case, the wetwell vent path is not the only release pathway to the environment. As a result of this additional environmental release pathway (i.e., the drywell liner failure), the relationship between the assumed DF and the LCF risk is sublinear.

The sublinear behavior is more pronounced at shorter distances. This trend is primarily due to short-term and long-term mitigative actions. For smaller releases, less offsite protective actions are needed and employed. Thus, doses and LCF risks diminish less than linearly. 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.

Table 3 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Base Cases

	Case 2	**Case 3**	**Case 3 DF 2**	**Case 3 DF 10**	**Case 3 DF 100**
0-10 miles	$1.6x10^{-4}$	$9.6x10^{-5}$	$8.0x10^{-5}$	$5.6x10^{-5}$	$4.5x10^{-5}$
0-20 miles	$1.2x10^{-4}$	$8.7x10^{-5}$	$6.5x10^{-5}$	$3.9x10^{-5}$	$3.1x10^{-5}$
0-30 miles	$8.4x10^{-5}$	$6.1x10^{-5}$	$4.4x10^{-5}$	$2.6x10^{-5}$	$2.1x10^{-5}$
0-40 miles	$5.7x10^{-5}$	$4.0x10^{-5}$	$2.8x10^{-5}$	$1.6x10^{-5}$	$1.3x10^{-5}$
0-50 miles	$4.8x10^{-5}$	$3.3x10^{-5}$	$2.3x10^{-5}$	$1.3x10^{-5}$	$1.0x10^{-5}$

In terms of the type of long-term radiation that would be emitted, the most important isotope is Cs-137. Cs-137, decays to Ba-137m, which rapidly decays and emits gamma radiation. Most of the resulting doses are from groundshine; resuspension inhalation and ingestion of cesium are relatively unimportant because cesium is rapidly excreted from the body, and so these pathways do not lead to large doses. Groundshine from deposited cesium continues until the land has been decontaminated or the cesium has decayed.

The noble gases, primarily xenon and krypton, are responsible for a significant amount of the released radioactivity that results from a severe accident. However, these gases do not deposit and do not contribute significantly to doses to humans because they are very inert (i.e., they are nonreactive and do not absorb onto surfaces). Since the noble gases do not absorb onto the surfaces of the lungs and are thus quickly exhaled, they insignificantly contribute to the inhalation dose. As a result of these attributes, the noble gases contribute little to the LCF risk.

Figure 2 shows the individual, mean LCF risk per event using the LNT model for residents within a circular area at specified radial distances for Case 2 and Case 3. Each column is the combined (total) LCF risk from the emergency and long-term phases (i.e., the results shown in Table 3). Table 3 and Figure 2 show that the filtered cases have a lower total LCF risk than the unfiltered case (i.e., Case 2). For Case 3, assuming a DF of 100 for the external filter, the total LCF risk is reduced by 53% for the 10-mile radial distance to 69% for the 40-mile and 50-mile radial distances.

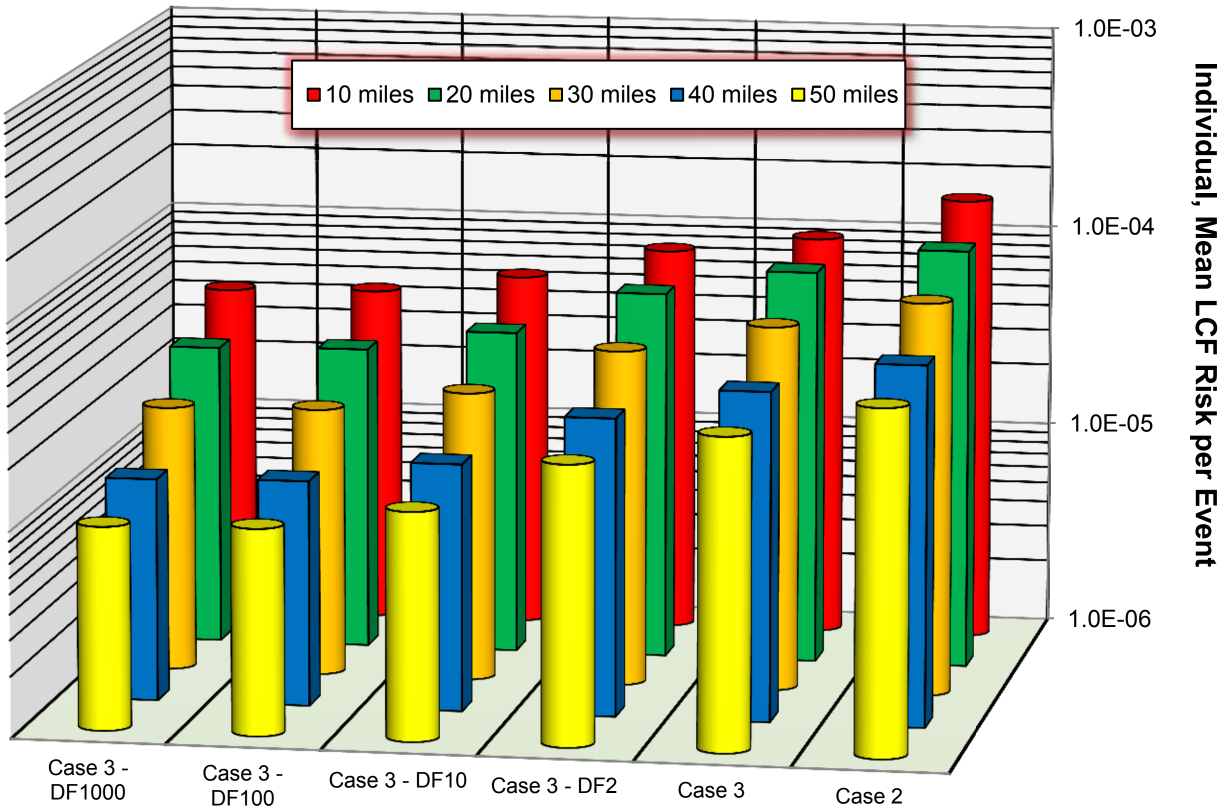

Figure 2 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Base Cases

Figure 3 shows the individual, mean LCF risk per event using the LNT dose-response model for residents within a circular area at the specified radial distances for Case 2. The figure shows the emergency and long-term phases. The entire height of each column shows the combined (total) LCF risk for the two phases (i.e., the results shown in Table 3). 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 risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 15% of the total LCF risk beyond 20 miles.

The long-term phase risk dominates the total risks for this case with the LNT dose-response model. 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.

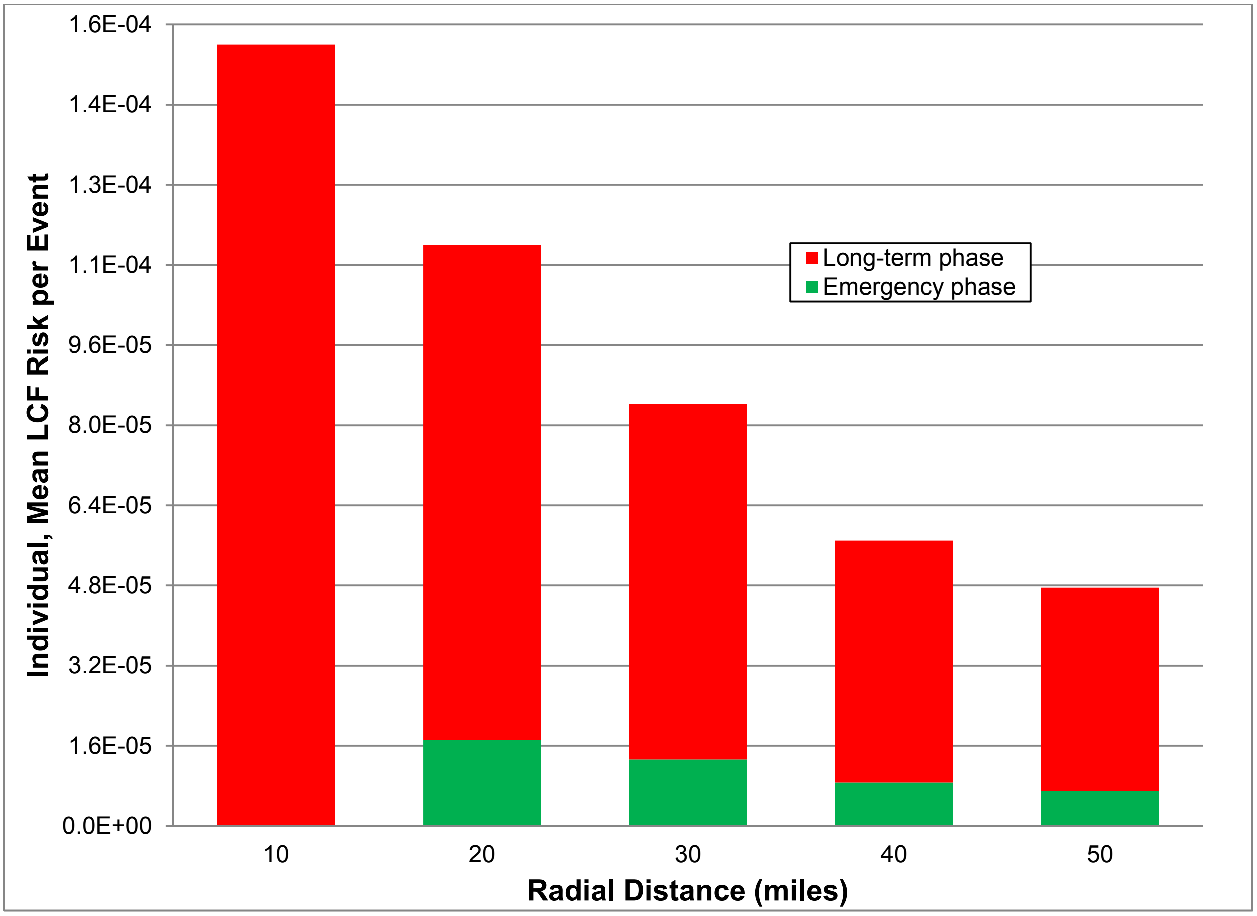

Figure 3 Case 2 individual, mean LCF risk per event for residents within a circular area at specified radial distances

Figure 4 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances using the LNT dose-response model for Case 3 with each of the DFs applied. Again, the emergency response is very effective within the evacuation zone (10 miles) during the early phase, so those risks are very small and entirely represent the 0.5 percent of the population who are modeled as refusing to evacuate. The explanations provided for Figure 3 also apply to Figure 4. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 35-45% of the total LCF risk beyond 20 miles for all DF values.

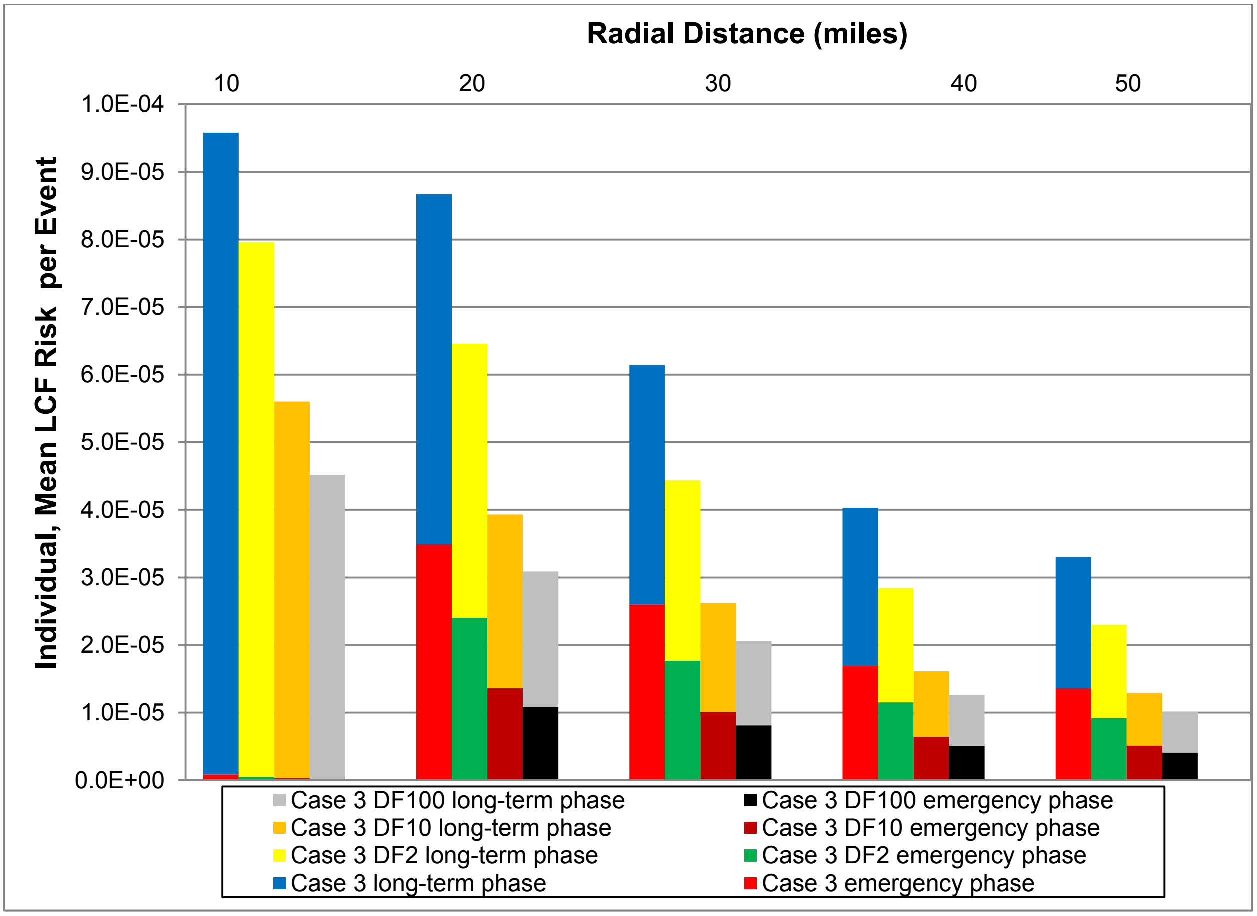

Figure 4 Case 3 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

The prompt fatality risks are zero for these cases. This is because the release fractions (i.e., see in Table 2) 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) for these cases is about 0.06 Gy to the red bone marrow. As discussed previously, 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 to the red bone marrow. Clearly, the calculated exposures are all well below this threshold.

3.2 Base Cases - 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 using the same threshold levels of Cs-137 as were used following the Chernobyl accident [11].

Other than the noble gases, each of the isotopes can deposit onto surfaces and cause contamination, but most of them have short half-lives and only remain in the environment for days or weeks. For example, iodine-131 has an eight-day half-life. Thus, in 80 days (i.e., 10 half-lives) its concentration is diminished to $2^{-10} \approx 0.001$ of its initial activity. As a result, it contributes to short-term doses but does not require decontamination because it disappears on its own. 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.

Cs-137 land contamination discussed by the International Atomic Energy Agency (IAEA) for the Chernobyl accident were reported at levels of 1, 5, 15, and 40 Ci/km^2, which are the same as 1, 5, 15, and 40 μCi/m^2, respectively. Based on these land contamination levels, the IAEA report was able to estimate annual effective external doses. Table 4 provides the annual effective external dose estimates based on Cs-137 soil-surface contamination [11].

Table 4 Chernobyl annual effective external dose estimates for 1986 to 1995

Soil Deposition (μCi/m^2 of ^{137}Cs)	**Annual Effective External Dose (rem)**									
	1986	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
15	0.79	0.20	0.19	0.18	0.18	0.18	0.17	0.15	0.14	0.13
5	0.25	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.04	0.04
1	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 5 provides the mean, contaminated area prior to decontamination for specified Cs-137 contamination levels for Case 2 and Case 3. 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.

Figure 5 shows the mean, land contamination area per event for Case 2 and Case 3. When the unfiltered case (i.e., Case 2) is compared with the filtered case, a DF of 10 or 100 results in a one or two order-of-magnitude reduction in land contamination area.

Table 5 Mean, contaminated area per event above the specified contamination level for the Base Cases

Contamination Level (μCi/m^2 of ^{137}Cs)	**Contaminated Area (km^2)**				
	Case 2	**Case 3**	**Case 3 DF 2**	**Case 3 DF 10**	**Case 3 DF 100**
1	8,920	1,990	1,050	427	338
5	1,040	254	125	49	39
15	280	54	24	8	6
40	74	11	4	1	1

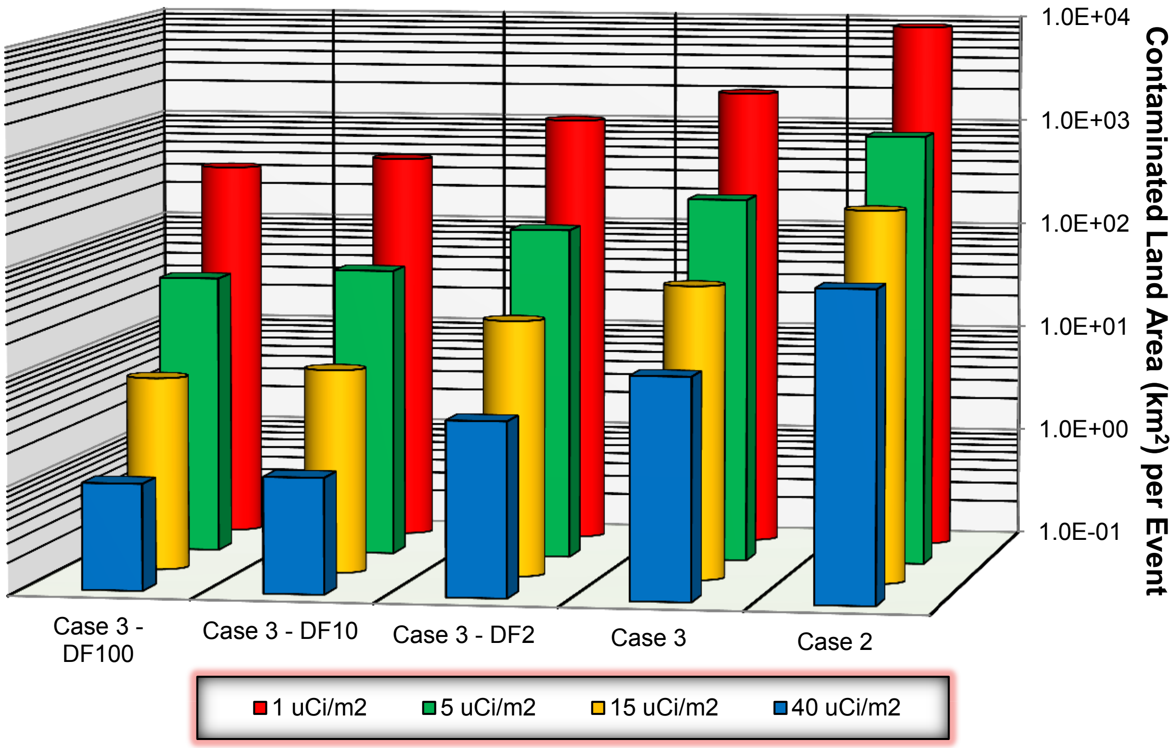

Figure 5 Mean, land contamination area per event for the Base Cases

4.0 CORE SPRAY CASES

Table 6 provides a brief description of source terms for the Peach Bottom accident scenarios analyzed for Case 6 and Case 7. Each of the filtered cases 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 (i.e., Case 7 – wetwell vent left open), the relationship is linear between the inverse of DF and the source term. For the filtered cases, the wetwell vent path is the only release pathway to the environment.

Table 6 Brief source term description for MELCOR scenarios discussed in the Core Spray Cases consequence analyses

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
Case 6	0.73	0.004	0.001	0.016	0.035	0	0	0	0	25.7	48
Case 7	1.00	0.003	0.001	0.024	0.009	0	0	0	0	23.9	48
Case 7 DF=2	1.00	0.002	0.0005	0.012	0.005	0	0	0	0	23.9	48
Case 7 DF=10	1.00	0.0003	0.0001	0.002	0.001	0	0	0	0	23.9	48
Case 7 DF=100	1.00	0.00003	0.00001	0.0002	0.0001	0	0	0	0	23.9	48

4.1 Core Spray Cases - LCF and Prompt Fatality Risk

LCF risk results are presented for the LNT dose-response model. Table 7 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances for Case 6 and Case 7. As seen in Table 7, when a DF is applied to the pathway that flows through the filtered vent (i.e., Case 3 – wetwell vent left open), the relationship is nonlinear between the inverse of DF and LCF risk.

For the filtered cases, even though the only release pathway to the environment is through the wetwell vent, the relationship between the assumed DF and the LCF risk is sublinear. The 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 limited. Thus, doses and LCF risks diminish less than linearly. 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.

Table 7 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Core Spray Cases

	Case 6	Case 7	Case 7 DF 2	Case 7 DF 10	Case 7 DF 100
0-10 miles	8.5×10^{-5}	6.4×10^{-5}	4.4×10^{-5}	1.3×10^{-5}	1.5×10^{-6}
0-20 miles	6.6×10^{-5}	4.6×10^{-5}	2.7×10^{-5}	7.2×10^{-6}	1.4×10^{-6}
0-30 miles	4.6×10^{-5}	3.1×10^{-5}	1.8×10^{-5}	4.6×10^{-6}	1.0×10^{-6}
0-40 miles	3.0×10^{-5}	2.0×10^{-5}	1.1×10^{-5}	2.8×10^{-6}	6.4×10^{-7}
0-50 miles	2.5×10^{-5}	1.6×10^{-5}	9.1×10^{-6}	2.2×10^{-6}	5.2×10^{-7}

Figure 6 shows the individual, mean LCF risk per event using the LNT model for residents within a circular area at specified radial distances for Case 6 and Case 7. Each column is the combined (total) LCF risk from the emergency and long-term phases (i.e., the results shown in Table 7). Table 7 and Figure 6 show that the filtered cases have a lower total LCF risk than the unfiltered case (i.e., Case 6). Assuming a DF of 100 for the external filter for Case 7, the total LCF risk is reduced by ~98% at the five specified radial distances.

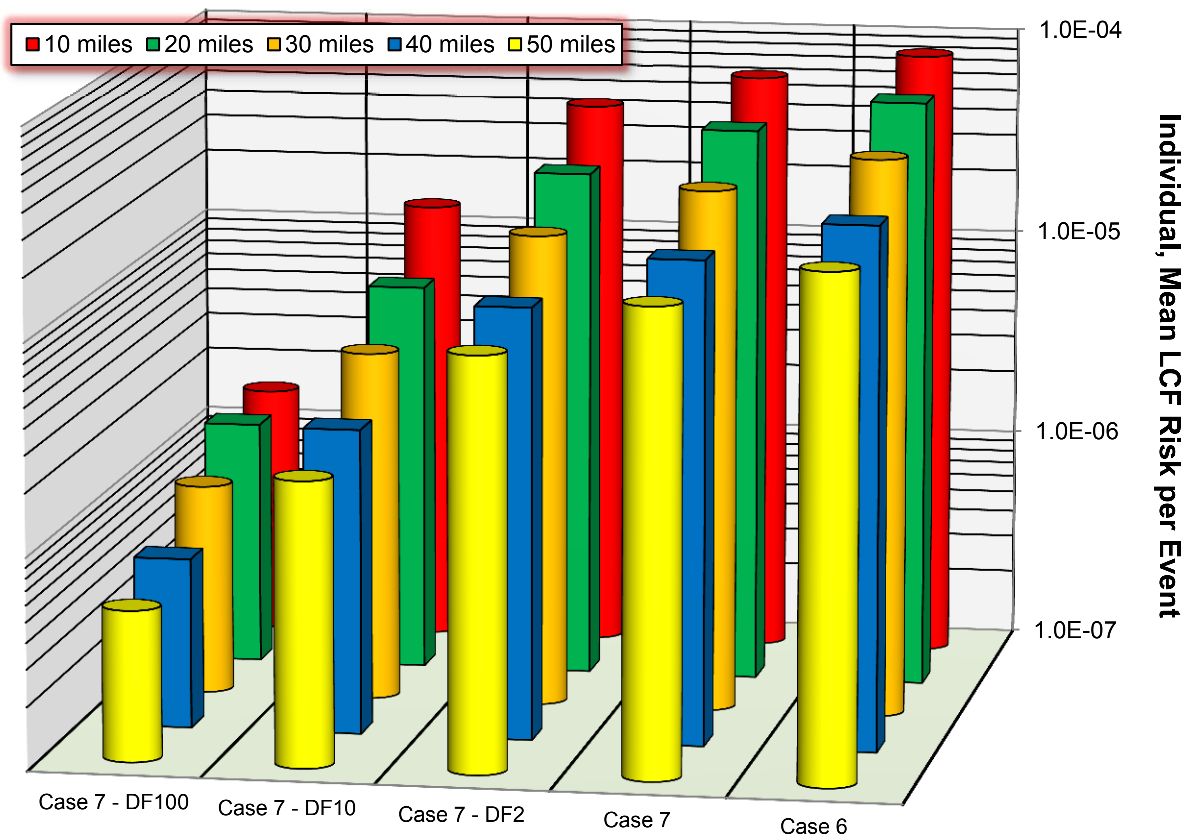

Figure 6 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Core Spray Cases

Figure 7 shows the individual, mean LCF risk per event using the LNT dose-response model for residents within a circular area at the specified radial distances for Case 6. The figure shows the emergency and long-term phases. The entire height of each column shows the combined (total) LCF risk for the two phases (i.e., the results shown in Table 7). 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 who are modeled as refusing to evacuate. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 35% of the total LCF risk beyond 20 miles.

The long-term phase risk dominates the total risks for this case when the LNT dose-response model is used. 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.

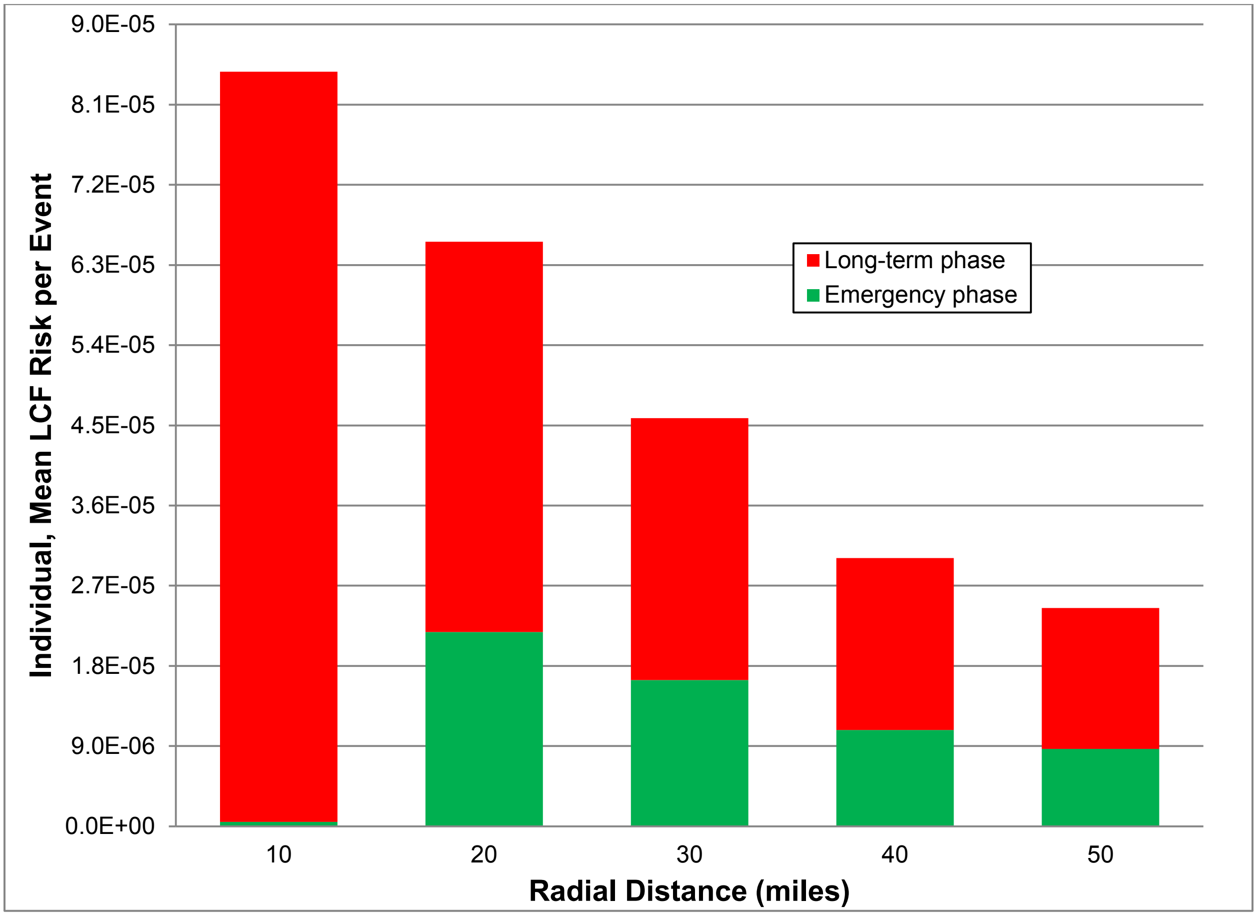

Figure 7 Case 6 individual, mean LCF risk per event for residents within a circular area at specified radial distances

Figure 8 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances using the LNT dose-response model for Case 7 with three values of DF applied. Again, the emergency response is very effective within the evacuation zone (10 miles) during the early phase, so those risks are very small and entirely represent the 0.5 percent of the population who are modeled as refusing to evacuate. The explanations provided for Figure 7 also apply to Figure 8. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 25-70% of the total LCF risk beyond 20 miles for all DF values.

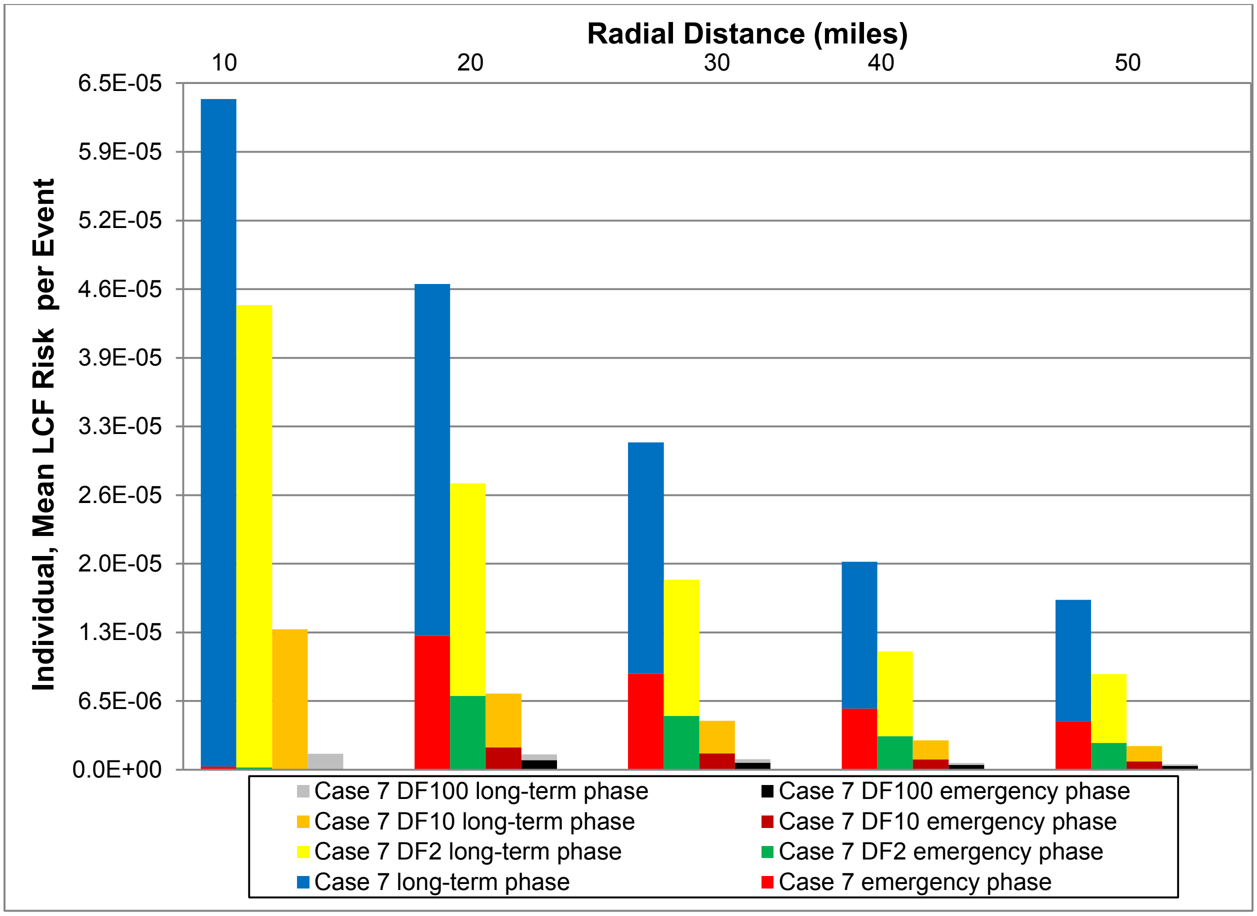

Figure 8 Case 7 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

The prompt fatality risks are zero for these cases. This is because the release fractions (i.e., see in Table 6) 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) for these cases is about 0.06 Gy to the red bone marrow. As discussed previously discussed, 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 to the red bone marrow. The calculated mean, acute exposures are all well below this threshold.

4.2 Core Spray Cases - Land Contamination

Table 8 provides the mean, contaminated area prior to decontamination for specified Cs-137 contamination levels for Case 6 and Case 7. 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.

Figure 9 shows the mean, land contamination area per event for Case 6 and Case 7. When the unfiltered case (i.e., Case 6) is compared with the filtered case, a DF of 10 or 100 results in a several order-of-magnitude reduction in land contamination area.

Table 8 Mean, contaminated area per event above the specified contamination level for the Core Spray Cases

Contamination Level (µCi/m^2 of ^{137}Cs)	Contaminated Area (km^2)				
	Case 6	Case 7	Case 7 DF 2	Case 7 DF 10	Case 7 DF 100
1	1,760	1,440	585	62	1
5	267	175	62	4	0.02
15	72	34	11	0.4	0.002
40	19	7	2	0.04	0.0001

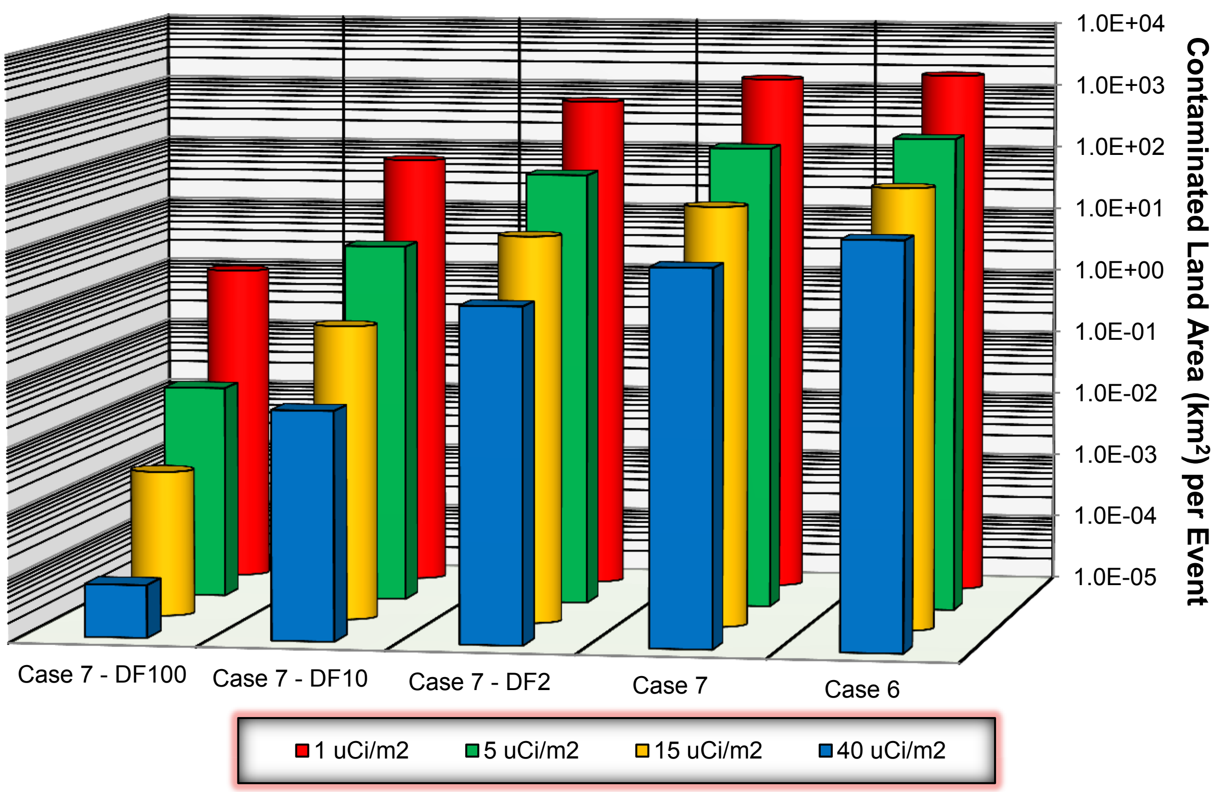

Figure 9 Mean, land contamination area per event for the Core Spray Cases

5.0 DRYWELL VENTING CASES

Case 12 and Case 13 are unique when compared to the other accident scenarios analyzed for this study in that containment is vented via the drywell vent path, and both cases experience a main steam line failure. These two cases were considered as an alternative to wetwell venting. If the cavity is deeply flooded, as in some European plants, the wetwell vent path will be ineffective in which case venting will occur through the drywell vent.

Additionally, the safety relief valve (SRV) stochastic failure probability was disabled (i.e., the SRV stochastic failure probability was set to zero – no failure) in MELCOR which resulted in failure of the main steam line. With a longer valve cycling period, the main steam line experiences high temperature gases exiting the reactor pressure vessel (RPV) to the wetwell via the SRV. These increased temperatures ultimately result in a failure of the main steam line at 27.7 hours. The main steam line failure allows radionuclide released from the fuel to bypass the wetwell and directly enter the drywell. This results in a larger environmental release when either drywell venting occurs or when containment fails.

For Case 12 and Case 13, drywell venting occurs before the main steam line failure. Since the main steam line failure is such a large pressure transient (i.e., >50 psid in 2 seconds in the drywell), that even when the use of containment sprays (i.e., Case 13) is considered, the unfiltered drywell vent path results in a large environmental release.

Table 9 provides a brief description of source terms for the Peach Bottom accident scenarios analyzed for Case 12 and Case 13. Since there are no scrubbing effects from the wetwell for drywell venting, the external filter is considered to be 99.9% efficient (i.e., DF = 1,000). As a sensitivity study to determine the effect of increased filter efficiency, Case 12 assumes the external filter is 99.98% efficient (i.e., DF = 5,000).

When a DF is applied to the pathway for flow through the filtered vent (i.e., Case 12 – drywell vent left open), the relationship is nonlinear between the inverse of DF and the source term. For the filtered cases, the wetwell vent path is not the only release pathway to the environment. At ~35 hours, the containment fails due to core melt through of the drywell liner for both cases. The drywell liner failure provides a lower resistance pathway to the environment than through the drywell vent.

Table 9 Brief source term description for MELCOR scenarios discussed in the Drywell Venting Cases consequence analyses

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
Case 12	1.00	0.194	0.037	0.490	0.364	0.001	0.043	0.003	0	25.5	48
Case 12 DF=1000	1.00	0.0012	0.002	0.015	0.010	0	0	0.0001	0	25.5	48
Case 12 DF=5000	1.00	0.0010	0.002	0.014	0.010	0	0	0.0001	0	25.5	48
Case 13	1.00	0.186	0.048	0.484	0.380	0.001	0.041	0.005	0	25.5	48
Case 13 DF=1000	1.00	0.0002	0.0005	0.001	0.0005	0	0	0	0	25.5	48

5.1 Drywell Venting Cases - LCF and Prompt Fatality Risk

LCF risk results are presented for the LNT dose-response model. Table 10 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances for Case 12 and Case 13. As seen in Table 10, when a DF is applied to the pathway that flow through the drywell filtered vent (i.e., either case), the relationship is nonlinear between the inverse of DF and LCF risk.

As discussed above for both cases, the drywell vent path is not the only release pathway to the environment. As a result of this additional environmental release pathway (i.e., the drywell liner failure), the relationship between the assumed DF and the LCF risk is sublinear. The 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 limited. Thus, doses and LCF risks diminish less than linearly. 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.

Table 10 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Drywell Venting Cases

	Case 12	**Case 12 DF 1000**	**Case 12 DF 5000**	**Case 13**	**Case 13 DF 1000**
0-10 miles	4.0×10^{-4}	1.1×10^{-4}	9.3×10^{-5}	4.0×10^{-4}	3.6×10^{-5}
0-20 miles	8.5×10^{-4}	5.7×10^{-5}	5.0×10^{-5}	9.3×10^{-4}	1.5×10^{-5}
0-30 miles	5.8×10^{-4}	3.4×10^{-5}	3.1×10^{-5}	6.3×10^{-4}	8.5×10^{-6}
0-40 miles	3.8×10^{-4}	2.1×10^{-5}	1.8×10^{-5}	4.0×10^{-4}	4.8×10^{-6}
0-50 miles	3.2×10^{-4}	1.6×10^{-5}	1.4×10^{-5}	3.3×10^{-4}	3.7×10^{-6}

Figure 10 shows the individual, mean LCF risk per event using the LNT model for residents within a circular area at specified radial distances for Case 12 and Case 13. Each column is the combined (total) LCF risk from the emergency and long-term phases (i.e., the results shown in Table 10). Table 10 and Figure 10 show that the filtered cases have a lower total LCF risk than the unfiltered cases. Assuming a DF of 1,000 for the external filter, the total LCF risk for Case 12 is reduced by ~70% for the 10-mile radial distances and ~95% for radial distances beyond 10 miles. Assuming a DF of 1,000 for the external filter, the total LCF risk for Case 13 is reduced by ~90% for the 10-mile radial distances and ~99% for radial distances beyond 10 miles.

An interesting observation is seen when the LCF risk for Case 12 is compared with Case 13. Even though containment spray is on for Case 13, the LCF risks are higher. The majority of the source term for these unfiltered cases occurs when the main steam line fails. When the source terms are compared, Case 13 has a slightly higher barium (Ba), tellurium (Te), and cerium (Ce) release fraction and a slightly lower iodine (I) and cesium (Cs) release fraction (i.e., see Table 9).

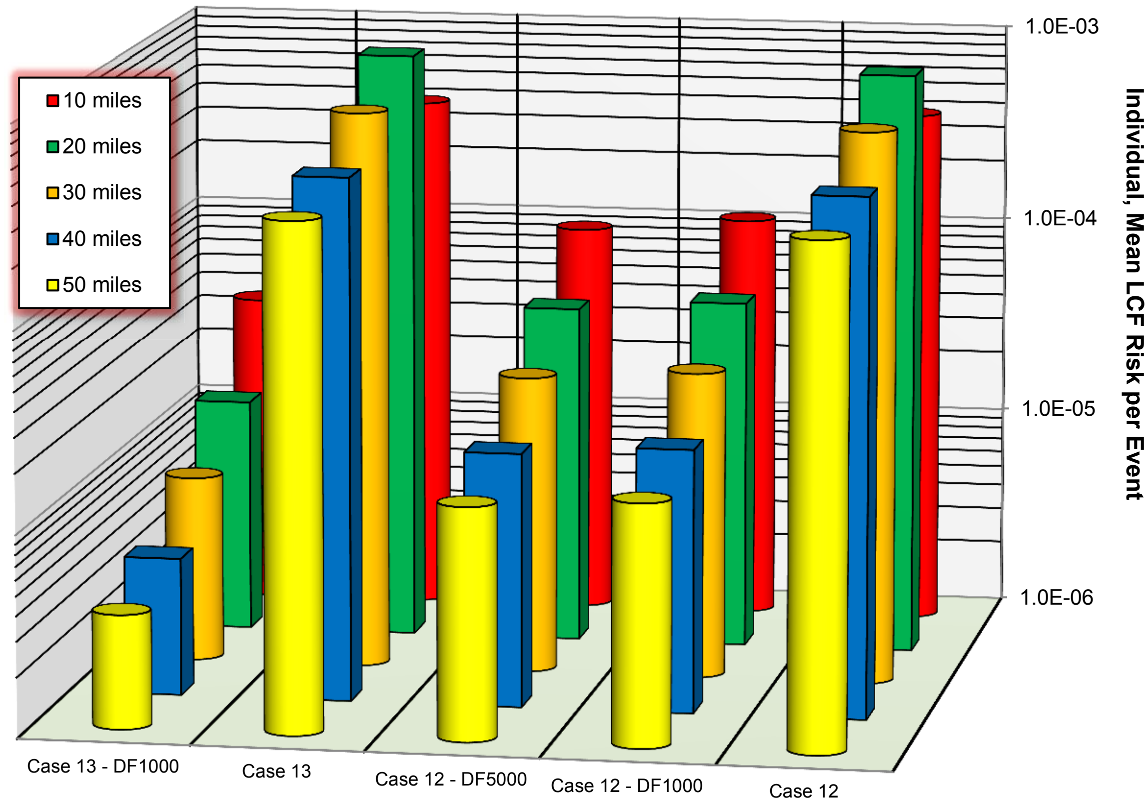

Figure 10 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Drywell Venting Cases

Figure 11 shows the individual, mean LCF risk per event using the LNT dose-response model for residents within a circular area at the specified radial distances for the unfiltered cases. The figure shows the emergency and long-term phases. The entire height of each column shows the combined (total) LCF risk for the two phases (i.e., the results shown in Table 7). As shown in Figure 11, the two unfiltered cases show similar long-term LCF risk. However, the short-term LCF risk for Case 13 is higher. This is attributed to slightly higher short-term LCF risk contributors from the Ce (e.g., Pu-238 and Pu-239) and Ba classes for acute inhalation dose. Additionally, the emergency phase accounts for 50-70% of the total LCF risk beyond 20 miles for both unfiltered cases.

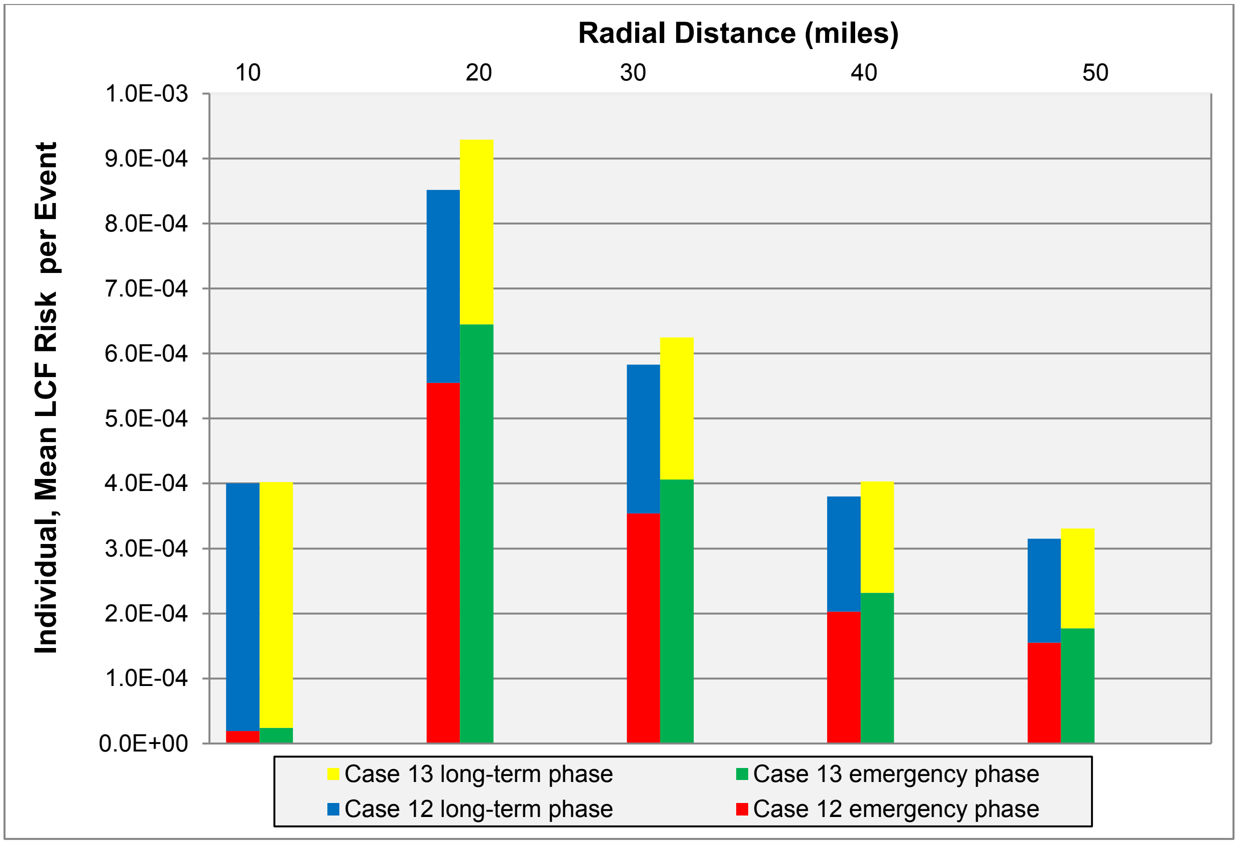

Figure 11 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for unfiltered Case 12 and unfiltered Case 13

Figure 12 shows the individual, mean LCF risk per event using the LNT dose-response model for residents within a circular area at the specified radial distances for Case 12 with respective DFs applied. The figure shows the emergency and long-term phases. The entire height of each column shows the combined (total) LCF risk for the two phases (i.e., the results shown in Table 3). 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 risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 20-30% of the total LCF risk beyond 20 miles when a DF is applied, and 50-65% of the total LCF risk beyond 20 miles for the unfiltered case.

When a DF is applied, the long-term phase risk dominates the total risks for this case. 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 the unfiltered case, the emergency phase risk dominates the total risk due to the main steam line failure. The emergency phase risk is controlled by inhalation doses during the emergency phase as a result of the large iodine release fraction.

For the sensitivity study where a DF of 5,000 is applied for Case 12, there is a sublinear relationship with the filtered Case 12 where a DF of 1,000 is applied. This sublinear relationship is attributed to the additional release pathway. As discussed above, the drywell vent path is not the only release pathway to the environment. As a result of this additional environmental release pathway (i.e., the drywell liner failure), when a DF ≥1,000 is applied the fraction of the source term that is released through the drywell liner failure dominates the overall source term (i.e., see Table 9).

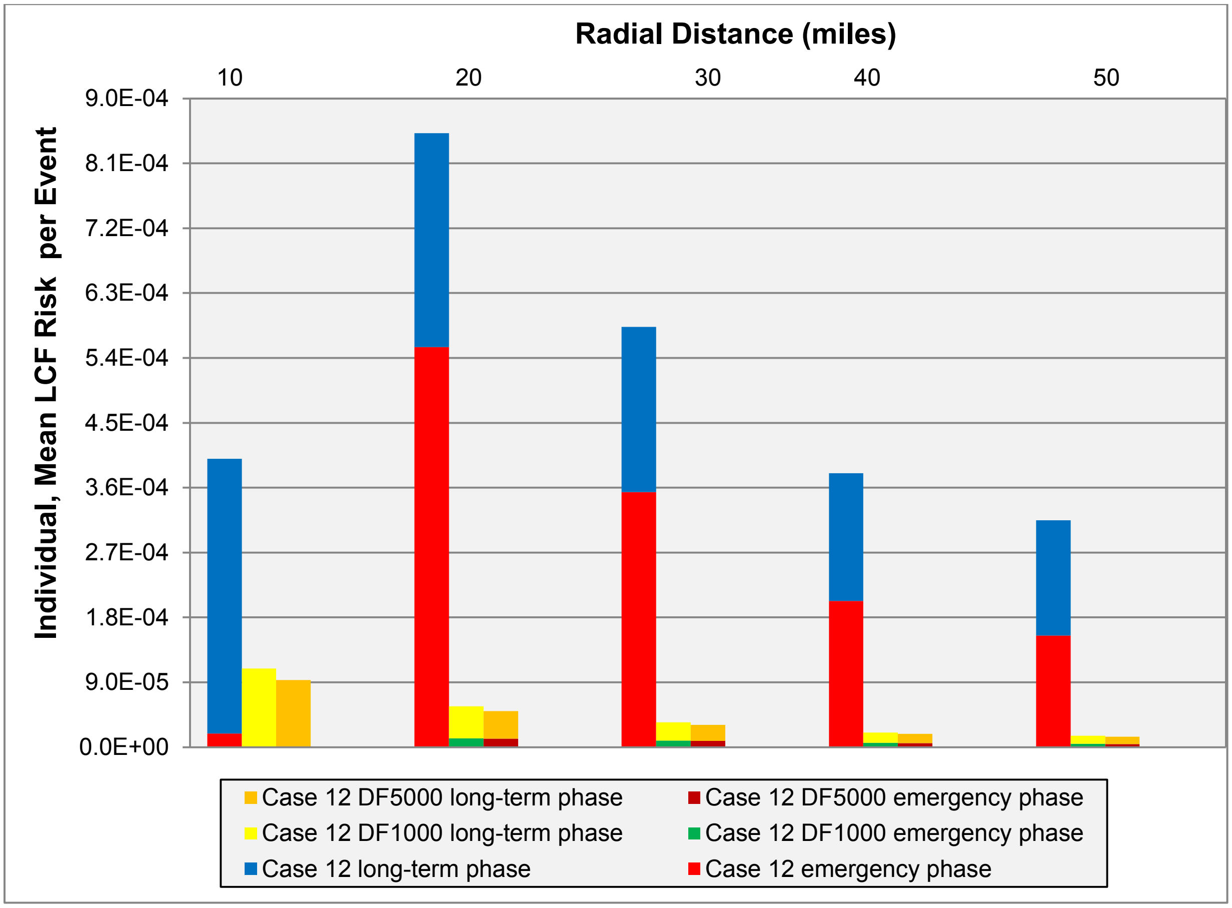

Figure 12 Case 12 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

Figure 13 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances using the LNT dose-response model for Case 13 with the respective DF applied. Again, the emergency response is very effective within the evacuation zone (10 miles) during the early phase, so those risks are very small and entirely represent the 0.5 percent of the population who are modeled as refusing to evacuate. The explanations provided for Figure 12 also apply to Figure 13. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 20-30% of the total LCF risk beyond 20 miles when a DF is applied, and 50-70% of the total LCF risk beyond 20 miles for the unfiltered case.

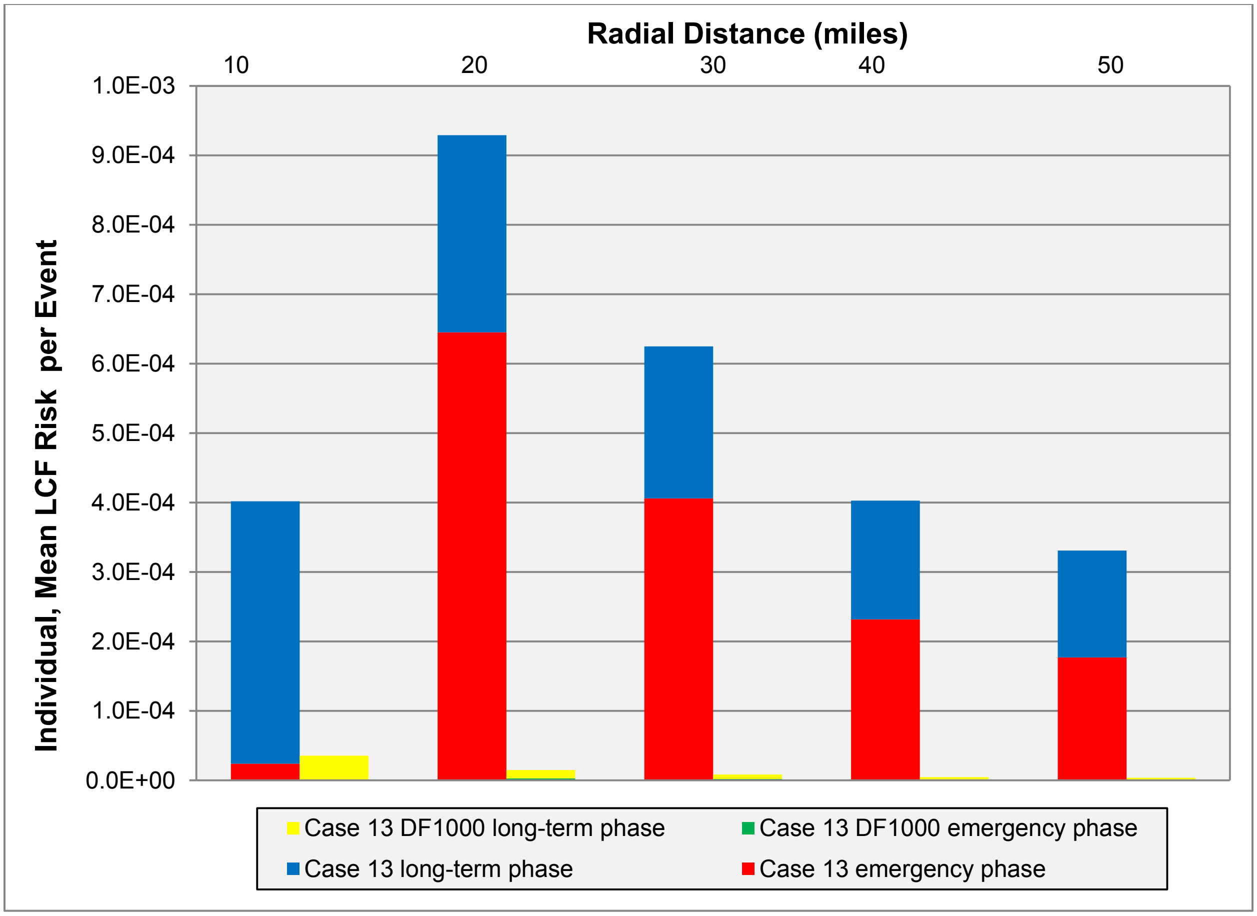

Figure 13 Case 13 individual, mean LCF risk per event for residents within a circular area at specified radial distances with a specified decontamination factor

The prompt fatality risks are zero for all cases, except unfiltered Case 13. For the cases that resulted in a zero prompt fatality risk, this is because the release fractions (i.e., see in Table 9) 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) for these cases is about 0.8 Gy to the red bone marrow (i.e., unfiltered Case 12). As discussed previously, 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 to the red bone marrow. The calculated mean, acute exposures are all well below this threshold.

For unfiltered Case 13, Table 11 provides the mean, individual prompt fatality risk per event within the 3-mile radial distance. Beyond 3 miles, prompt fatality risk is zero. For unfiltered Case 13, the mean, acute exposure for the closest resident (i.e., 0.5 to 1.2 kilometers from the plant) is about 1.0 Gy to the red bone marrow. While this is below the red bone marrow threshold for an early fatality, 0.5% of the MACCS2 weather trials produced an acute exposure greater than the threshold. As a result of these few weather trials, a nonzero mean prompt fatality risk was observed. Based on this observation and since the mean, prompt fatality risk for the 2-mile and 2.5-mile radial distances are so low, the mean, individual prompt fatality risk per event at these distances are considered essentially zero.

Table 11 Mean, individual prompt fatality risk per event for unfiltered Case 13

Radius of Circular Area (mi)	Unfiltered Case 13
1.3	0.0
2	1.9×10^{-9}
2.5	1.1×10^{-9}

5.2 Drywell Venting Cases - Land Contamination

Table 12 provides the mean, contaminated area prior to decontamination for specified Cs-137 contamination levels for Case 12 and Case 13. 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.

Figure 14 shows the mean, land contamination area per event for Case 12 and Case 13. When the unfiltered cases are compared with the filtered case, a DF of 1000 results in a several order-of-magnitude reduction in land contamination area.

For the sensitivity study where a DF of 5,000 is applied for Case 12, there is a sublinear relationship with the filtered Case 12 where a DF of 1,000 is applied. This sublinear relationship is attributed to the additional release pathway. As discussed above, the drywell vent path is not the only release pathway to the environment. As a result of this additional environmental release pathway (i.e., the drywell liner failure), when a DF ≥1,000 is applied the fraction of the source term that is released through the drywell liner failure dominates the overall source term (i.e., see Table 9). Thus, a higher DF has little effect on the overall contaminated land area.

Table 12 Mean, contaminated area per event above the specified contamination level for the Drywell Venting Cases

Contamination Level ($\mu Ci/m^2$ of ^{137}Cs)	Contaminated Area (km^2)				
	Case 12	Case 12 DF 1000	Case 12 DF 5000	Case 13	Case 13 DF 1000
1	83,200	593	505	86,000	105
5	28,900	107	93	29,100	13
15	9,150	28	25	8,830	2
40	3,260	7	6	3,020	0.02

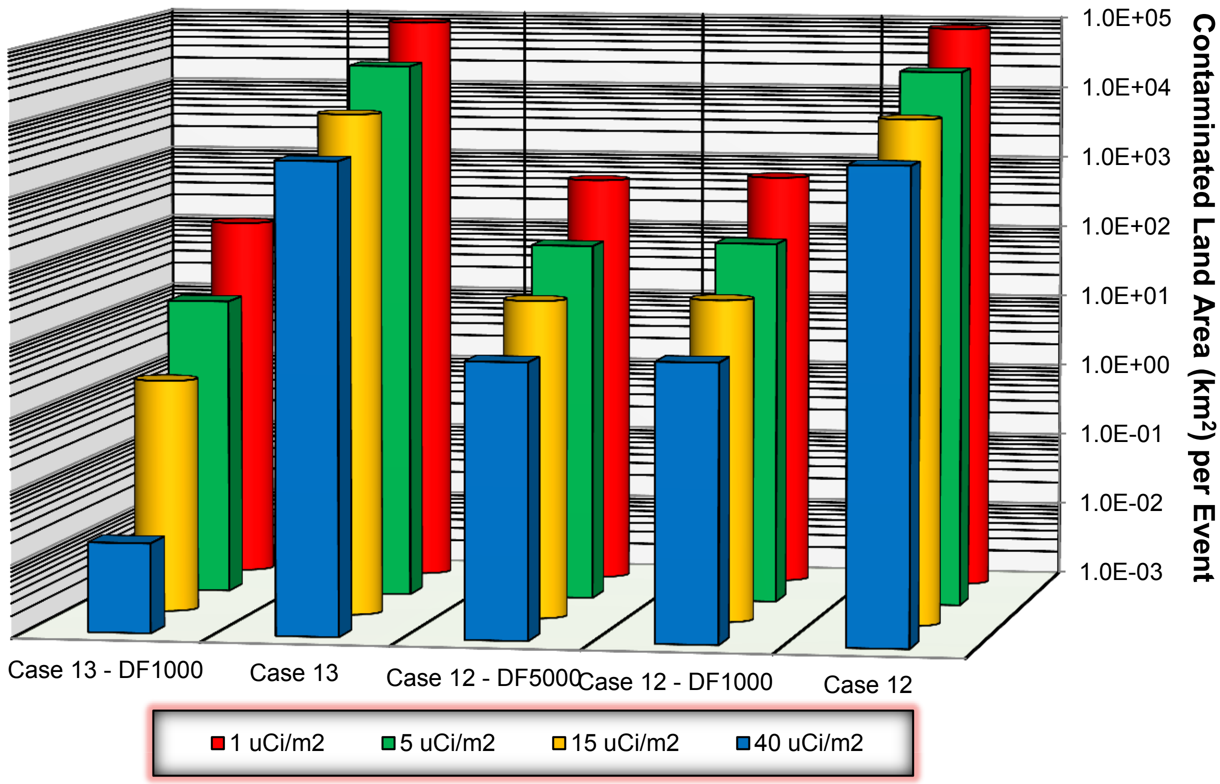

Figure 14 Mean, land contamination area per event for the Drywell Venting Cases

6.0 DRYWELL SPRAY CASES

Table 13 provides a brief description of source terms for the Peach Bottom accident scenarios analyzed for Case 14 and Case 15. Each of the filtered cases 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 (i.e., Case 15 – wetwell vent left open), the relationship is linear between the inverse of DF and the source term, with the exception of the noble gases. For Case 15, the wetwell vent path is the only release pathway to the environment.

Table 13 Brief source term description for MELCOR scenarios discussed in the Drywell Spray Cases consequence analyses

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
Case 14	0.68	0.001	0	0.004	0.005	0	0	0	0	28.2	48
Case 15	1.00	0.003	0.002	0.019	0.021	0	0	0	0	23.9	48
Case 15 DF=2	1.00	0.002	0.001	0.010	0.011	0	0	0	0	23.9	48
Case 15 DF=10	1.00	0.0003	0.0002	0.002	0.002	0	0	0	0	23.9	48
Case 15 DF=100	1.00	0.00003	0.00002	0.0002	0.0002	0	0	0	0	23.9	48

The reason the unmitigated source term (i.e., Case 14) is lower than the mitigated source term (i.e., Case 15) is in part due to the effectiveness of drywell sprays in minimizing the source term for the unfiltered case. 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 14. The head flange leakage in the MELCOR model behaves 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 RPV lower vessel head failure at 36.6 hours, and after about 4.5 hours the head flange reseats and intermittently reopens for the rest of the MELCOR simulation.

Also, the lower containment pressure in Case 15 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 15, 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 15.

The increased revaporization of cesium and iodine from RPV internals combined with the larger vent flows and imperfect wetwell scrubbing for Case 15, 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 15 relative to Case 14.

6.1 Drywell Spray Cases - LCF and Prompt Fatality Risk

LCF risk results are presented for the LNT dose-response model. Table 14 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances for Case 14 and Case 15. As seen in Table 14, when a DF is applied to the pathway that flow through the filtered vent (i.e., Case 15 – wetwell vent left open), the relationship is sublinear between the inverse of DF and LCF risk.

The 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. Thus, doses and LCF risks diminish less than linearly. 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.

Table 14 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Drywell Spray Cases

	Case 14	Case 15	Case 15 DF 2	Case 15 DF 10	Case 15 DF 100
0-10 miles	$3.3x10^{-5}$	$9.3x10^{-5}$	$6.1x10^{-5}$	$1.8x10^{-5}$	$2.1x10^{-6}$
0-20 miles	$2.1x10^{-5}$	$6.2x10^{-5}$	$3.6x10^{-5}$	$9.2x10^{-6}$	$1.7x10^{-6}$
0-30 miles	$1.3x10^{-5}$	$4.1x10^{-5}$	$2.3x10^{-5}$	$5.8x10^{-6}$	$1.1x10^{-6}$
0-40 miles	$8.0x10^{-6}$	$2.6x10^{-5}$	$1.4x10^{-5}$	$3.5x10^{-6}$	$7.1x10^{-7}$
0-50 miles	$6.4x10^{-6}$	$2.1x10^{-5}$	$1.1x10^{-5}$	$2.7x10^{-6}$	$5.7x10^{-7}$

Figure 15 shows the individual, mean LCF risk per event using the LNT model for residents within a circular area at specified radial distances for Case 14 and Case 15. Each column is the combined (total) LCF risk from the emergency and long-term phases (i.e., the results shown in Table 14). Table 14 and Figure 15 show that unlike previous filtered cases, the filtered case has a higher total LCF risk than the unfiltered case (i.e., Case 14) for a DF somewhat less than 10. This is due to increased revaporization of cesium and iodine from RPV internals combined with the larger vent flows and imperfect wetwell scrubbing in Case 15, the elastic drywell head flange MELCOR model, and the effectiveness of the drywell containment sprays leading to a larger environmental release for Case 15 relative to Case 14. Assuming a DF of 100 for the external filter, the total LCF risk is reduced by ~97% for the five specified radial distances.

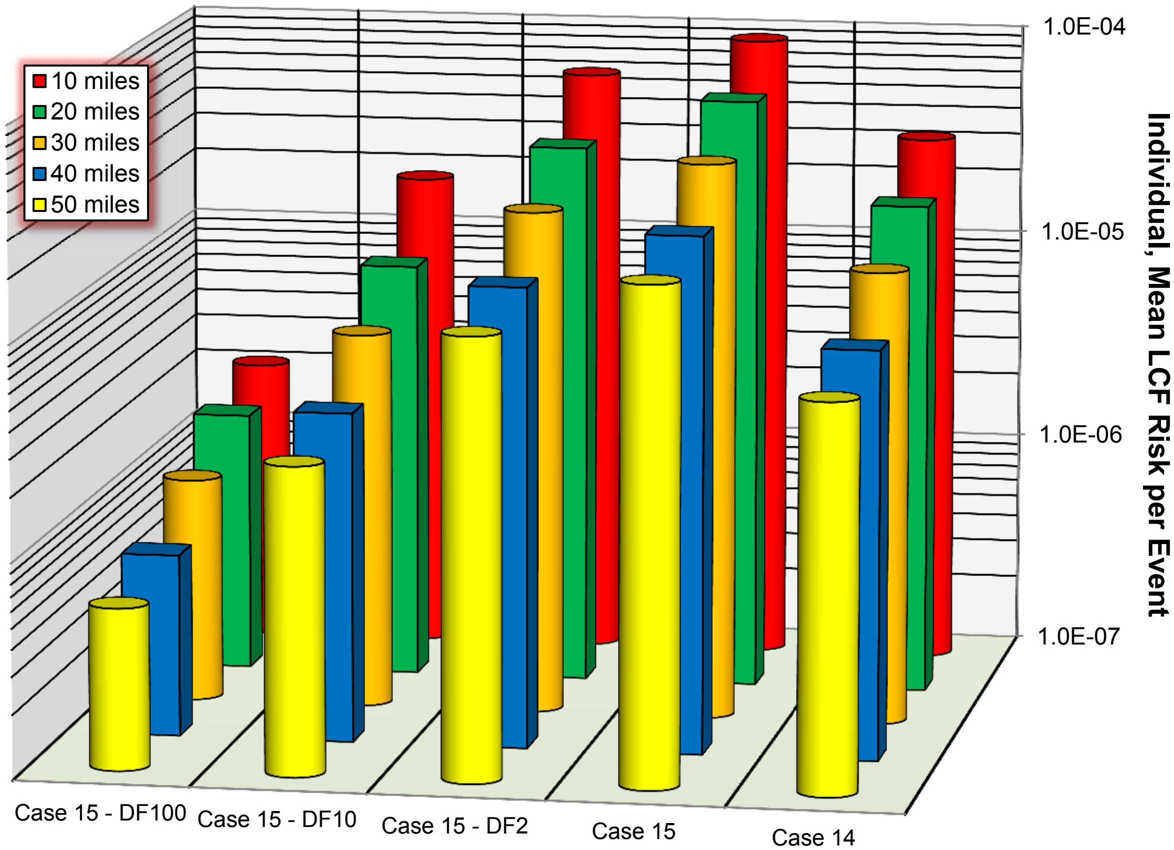

Figure 15 Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the Drywell Spray Cases

Figure 16 shows the individual, mean LCF risk per event using the LNT dose-response model for residents within a circular area at the specified radial distances for Case 14. The figure shows the emergency and long-term phases. The entire height of each column shows the combined (total) LCF risk for the two phases (i.e., the results shown in Table 14). 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 risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 30% of the total LCF risk for radii greater than 20 miles.

The long-term phase risk dominates the total risks for this case using the LNT dose-response model. 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.

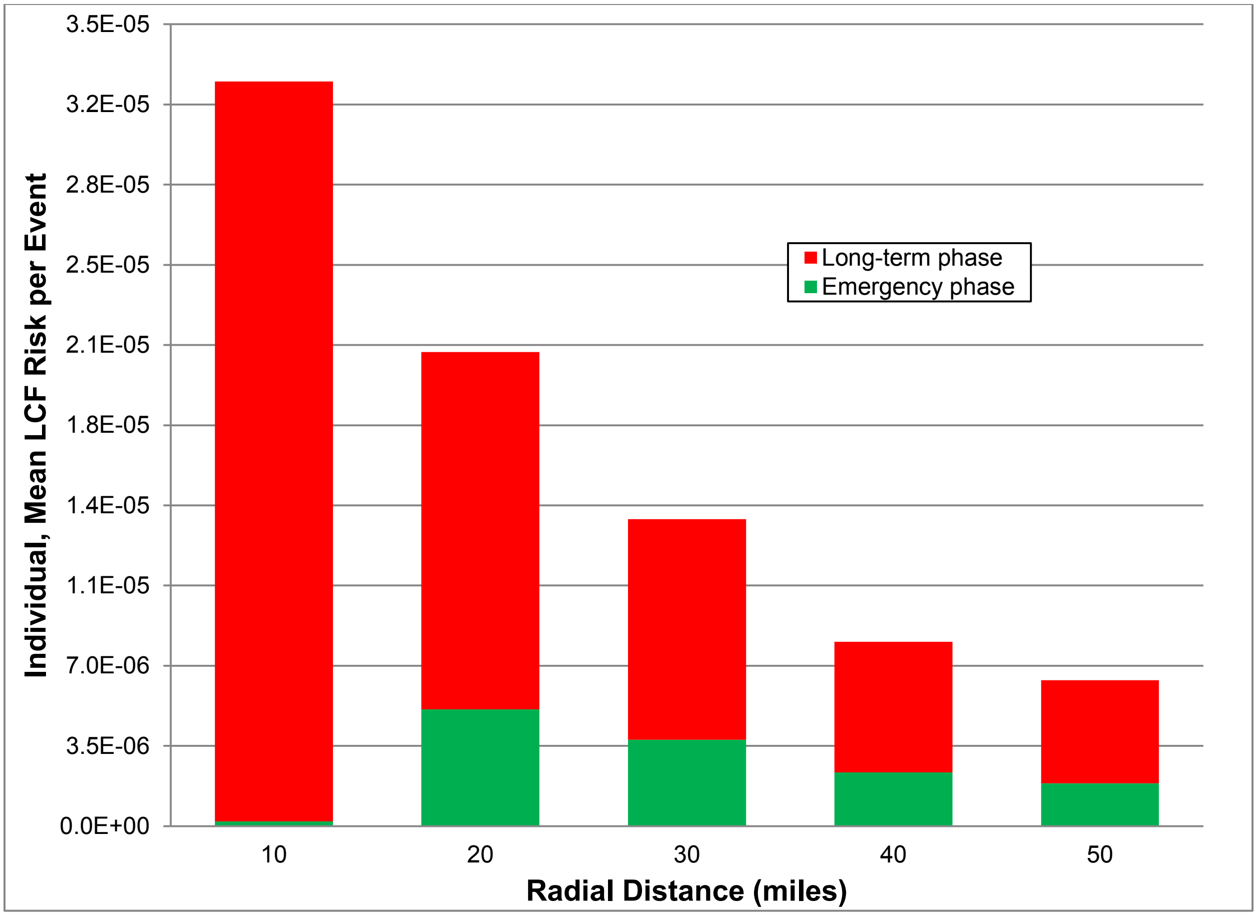

Figure 16 Case 14 individual, mean LCF risk per event for residents within a circular area at specified radial distances

Figure 17 shows the individual, mean LCF risk per event for residents within a circular area at specified radial distances using the LNT dose-response model for Case 15 with respective DFs applied. Again, the emergency response is very effective within the evacuation zone (10 miles) during the early phase, so those risks are very small and entirely represent the 0.5 percent of the population who are modeled as refusing to evacuate. The explanations provided for Figure 16 also apply to Figure 17. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. The emergency phase accounts for 30-70% of the total LCF risk beyond 20 miles for all DF values.

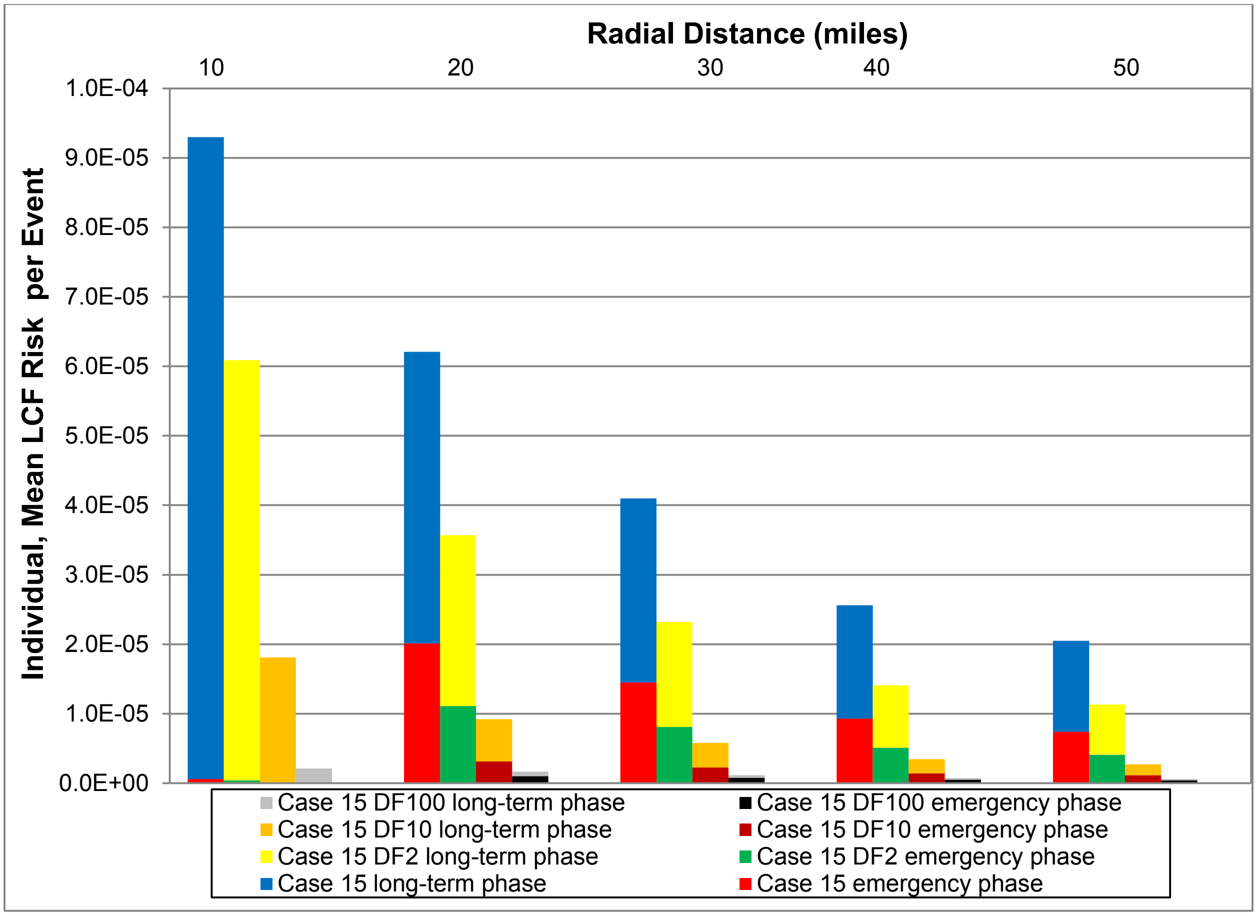

Figure 17 Case 15 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

The prompt fatality risks are zero for these cases. This is because the release fractions (i.e., see in Table 13) 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) for these cases is about 0.06 Gy to the red bone marrow. As discussed previously, 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 to the red bone marrow. The calculated mean, acute exposures are all well below this threshold.

6.2 Drywell Spray Cases - Land Contamination

Table 15 provides the mean, contaminated area prior to decontamination for specified Cs-137 contamination levels for Case 14 and Case 15. 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.

Figure 18 shows the mean, land contamination area per event for Case 14 and Case 15. When the unfiltered case (i.e., Case 15) is compared with the filtered case, a DF of 10 or 100 results in a several order-of-magnitude reduction in land contamination area.

As with the LCF risk, Table 15 and Figure 18 show that unlike previous filtered cases, the filtered case has a higher mean land contamination area than the unfiltered case (i.e., Case 14) for a DF somewhat less than 10. The increased revaporization of cesium and iodine from RPV internals combined with the larger vent flows and imperfect wetwell scrubbing in Case 15, the elastic drywell head flange MELCOR model, and the effectiveness of the drywell containment sprays lead to a larger environmental release for Case 15 relative to Case 14.

Table 15 Mean, contaminated area per event above the specified contamination level for the Drywell Spray Cases

Contamination Level (μCi/m^2 of ^{137}Cs)	Contaminated Area (km^2)				
	Case 14	Case 15	Case 15 DF 2	Case 15 DF 10	Case 15 DF 100
1	385	1,150	482	53	1
5	51	144	53	3	0.01
15	10	28	8	0.3	0.001
40	2	5	1	0.02	0

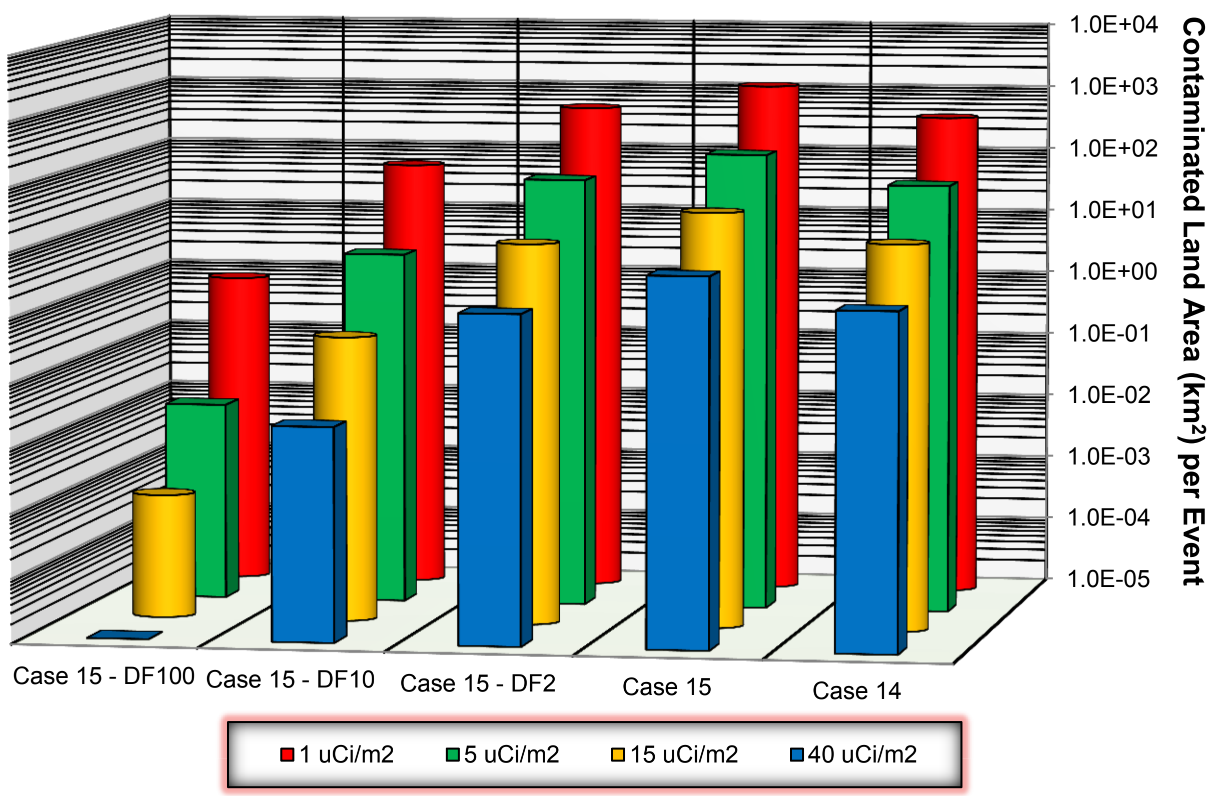

Figure 18 Mean, land contamination area per event for the Drywell Spray Cases

7.0 POPULATION DOSE

A sum of all the effective doses to all the individuals within a given radial distance roughly proportional to the number of radiation-induced health effects. The proportionality is not perfect because latent health effects are calculated using a dose and dose-rate effectiveness factor that treats doses above 20 rem as being more effective for cancer induction than those below 20 rem. Furthermore, MACCS2 models cancers for individual organs, which is more complicated than basing them on an effective dose representing an average for the whole body.

The total, effective population dose from the plume and deposited contamination, subject to remedial actions to reduce dose levels, within a 50-mile radius of the plant is shown in Table 16 for each of the cases. The population dose is for a lifetime (i.e., 50-year dose commitment period), effective dose calculated for the population residing within a 50-mile radius. The relationship between population dose and inverse DF is sublinear because less remedial action is taken at lower contamination levels.

Table 16 Mean population dose (person-rem) per event for residents within a circular area of 50-mile radius for specified decontamination factors and for all the cases considered

Case 2	Case 3	Case 3 DF 2	Case 3 DF 10	Case 3 DF 100
580,000	456,000	322,000	183,000	141,000

Case 6	Case 7	Case 7 DF 2	Case 7 DF 10	Case 7 DF 100
305,000	235,000	136,000	37,300	8,200

Case 12	Case 12 DF 1,000	Case 12 DF 5,000	Case 13	Case 13 DF 1,000
3,810,000	232,000	211,000	3,860,000	59,900

Case 14	Case 15	Case 15 DF 2	Case 15 DF 10	Case 15 DF 100
86,100	280,000	160,000	43,300	8,750

The composition and properties of the source terms affect the population dose through deposition rates, half-lives, and the types of radiation emitted. As described in the LCF risk sections, various phenomena affect dose depending on the phase of the event. During the emergency phase, evacuation within the EPZ significantly reduces 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. Emergency phase doses generally contribute less than half of the overall population dose for the cases considered. Case 7 with a DF=100 and Case 15 with a DF=100 are the only cases for which over half (i.e., 55% for both cases) of the population dose is from the emergency phase. Most of the long-term 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. For Peach Bottom, the State of Pennsylvania's habitability criterion is a dose rate of 500 mrem/yr.

Unlike the doses included in LCF risks, population doses also include the ingestion pathway. The population doses include both societal doses from the ingestion pathway and doses to decontamination workers working in the contaminated area; LCF risk does 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 dose for the wetwell venting filtered cases considered. The ingestion pathway accounts for 5% of the population dose for the drywell venting unfiltered cases considered. The ingestion pathway accounts for 20-30% of the population dose for the drywell venting filtered cases considered.

Figure 19 shows the mean population dose per event within a 50-mile radius for all cases considered. Table 16 and Figure 19 show that a DF of 10 or more for all wetwell venting filtered cases and a DF of 1,000 for all drywell venting filtered cases result in lower population doses than their respective unfiltered cases.

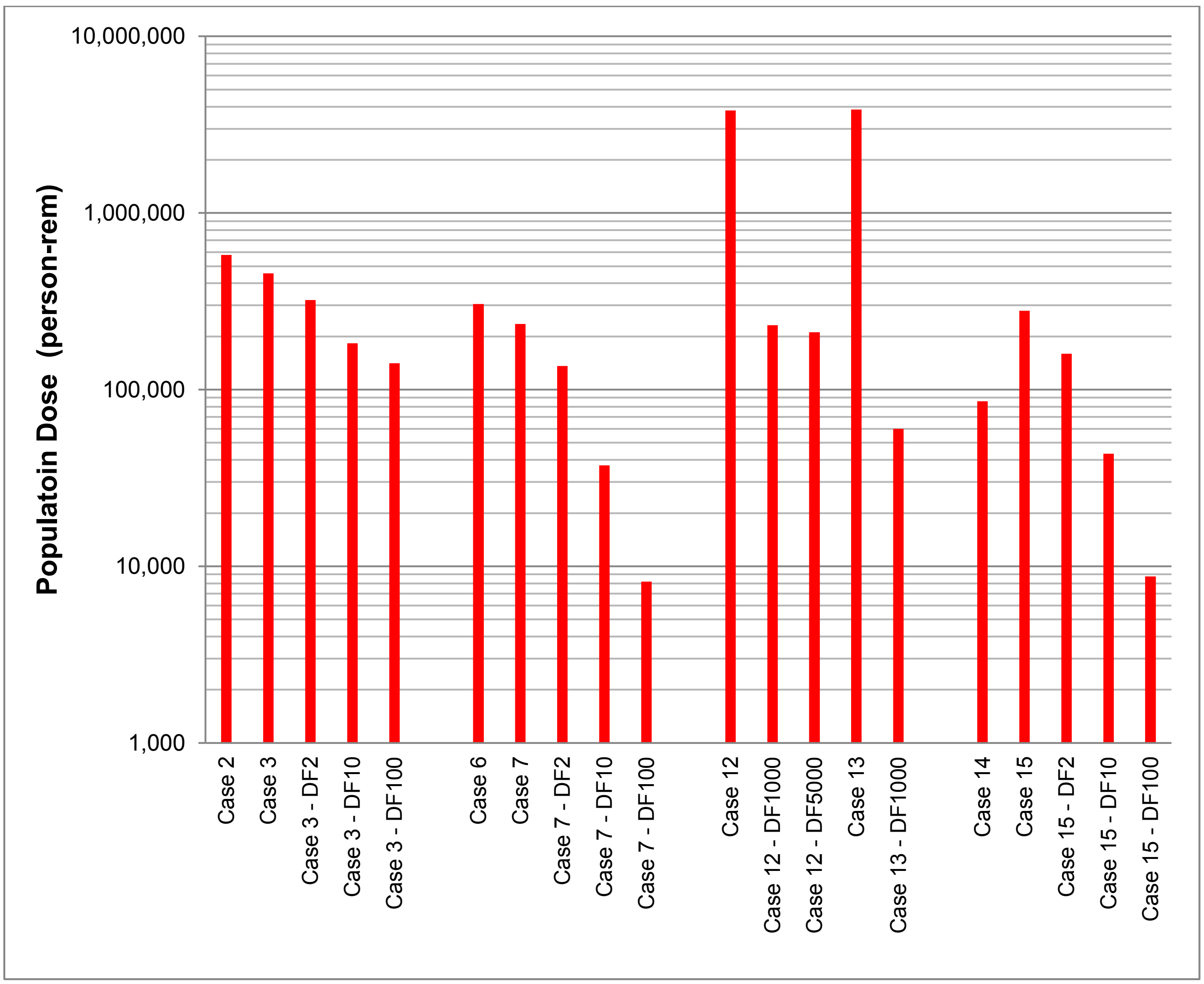

Figure 19 Mean population dose per event for residents within a circular area at the 50-mile radial distance with specified decontamination factors for all the cases considered

8.0 OFFSITE ECONOMIC COSTS

The economic model in MACCS2 includes costs that fall within six categories as follows:

- Evacuation and relocation costs
- Moving expenses for people displaced
- Decontamination
- Cost due to loss of property use
- Loss of contaminated food grown locally
- Cost of condemned lands

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 more be difficult to decontaminate.

Other than the noble gases, each of the isotopes can deposit onto surfaces and cause contamination, but most of them have short half-lives and only remain in the environment for days or weeks. For example, iodine-131 has an eight-day half-life. Thus, in 80 days (i.e., 10 half-lives) its concentration is diminished to $2^{-10} \approx 0.001$ of its initial activity. As a result, it contributes to short-term doses but does not require decontamination because it disappears on its own. 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 costs.

In terms of the type of long-term radiation that would be emitted, the most important radionuclide, Cs-137, decays to Ba-137m, which rapidly decays and emits gamma radiation. Most of the resulting doses are from groundshine; inhalation and ingestion are relatively unimportant because cesium is rapidly excreted from the body and so these pathways do not lead to large doses. On the other hand, groundshine from deposited cesium can continue for tens or hundreds of years. Buildings and other structures can provide significant shielding from these gamma doses. 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., below the habitability limit).

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.

Table 17 provides the mean, total offsite economic costs shown in millions of 2005 dollars for the 10-mile and 50-mile radial distances for the cases considered in this study. A DF of 10 for the wetwell venting cases results in about an order-of-magnitude reduction.

Table 17 Mean, total offsite economic costs ($M - 2005) per event within a circular area at specified radial distances with specified decontamination factors for the cases considered

	Case 2	Case 3	Case 3 DF 2	Case 3 DF 10	Case 3 DF 100
0-10 miles	217	195	150	88.9	66.5
0-50 miles	1,910	1,730	885	274	185

	Case 6	Case 7	Case 7 DF 2	Case 7 DF 10	Case 7 DF 100
0-10 miles	126	71.2	38.4	8.00	0.580
0-50 miles	847	484	176	17.6	0.814

	Case 12	Case 12 DF 1,000	Case 12 DF 5,000	Case 13	Case 13 DF 1,000
0-10 miles	1,370	146	137	1,300	29.5
0-50 miles	33,300	391	370	33,000	37.7

	Case 14	Case 15	Case 15 DF 2	Case 15 DF 10	Case 15 DF 100
0-10 miles	33.5	103	57.6	11.3	0.559
0-50 miles	116	588	240	20.2	0.703

All of the costs for the six cost categories are summed over the entire offsite area affected by the assumed atmospheric release considered to obtain the total offsite economic costs. As an example of the detailed costs estimates, Table 18 provides the mean cost data for the 50-mile radial distance for Case 12. All costs listed in Table 18 are shown in millions of 2005 dollars.

Table 18 Case 12 detailed mean, economic model output

Mean, Total Offsite Economic Cost Measures per Event for the 0-50 mile radial distance	($M - 2005)
Population Dependent Nonfarm Decontamination Cost	8,840
Population Dependent Nonfarm Interdiction Cost	21,400
Population Dependent Nonfarm Condemnation Cost	1,190
Farm Dependent Decontamination Cost	224
Farm Dependent Interdiction Cost	277
Farm Dependent Condemnation Cost	84.8
Emergency Phase Cost	1,010
Milk Disposal Cost	20.5
Crop Disposal Cost	309
Total Offsite Economic Costs	**33,300**

Figure 20 shows the mean, total offsite economic costs in millions of 2005 dollars per event for the 10-mile and 50-mile radial distances for all the cases considered. Table 17 and Figure 20 show that a DF of 10 or more for all wetwell venting filtered cases and a DF of 1,000 for all drywell venting filtered cases results in a lower economic costs than their respective unfiltered case.

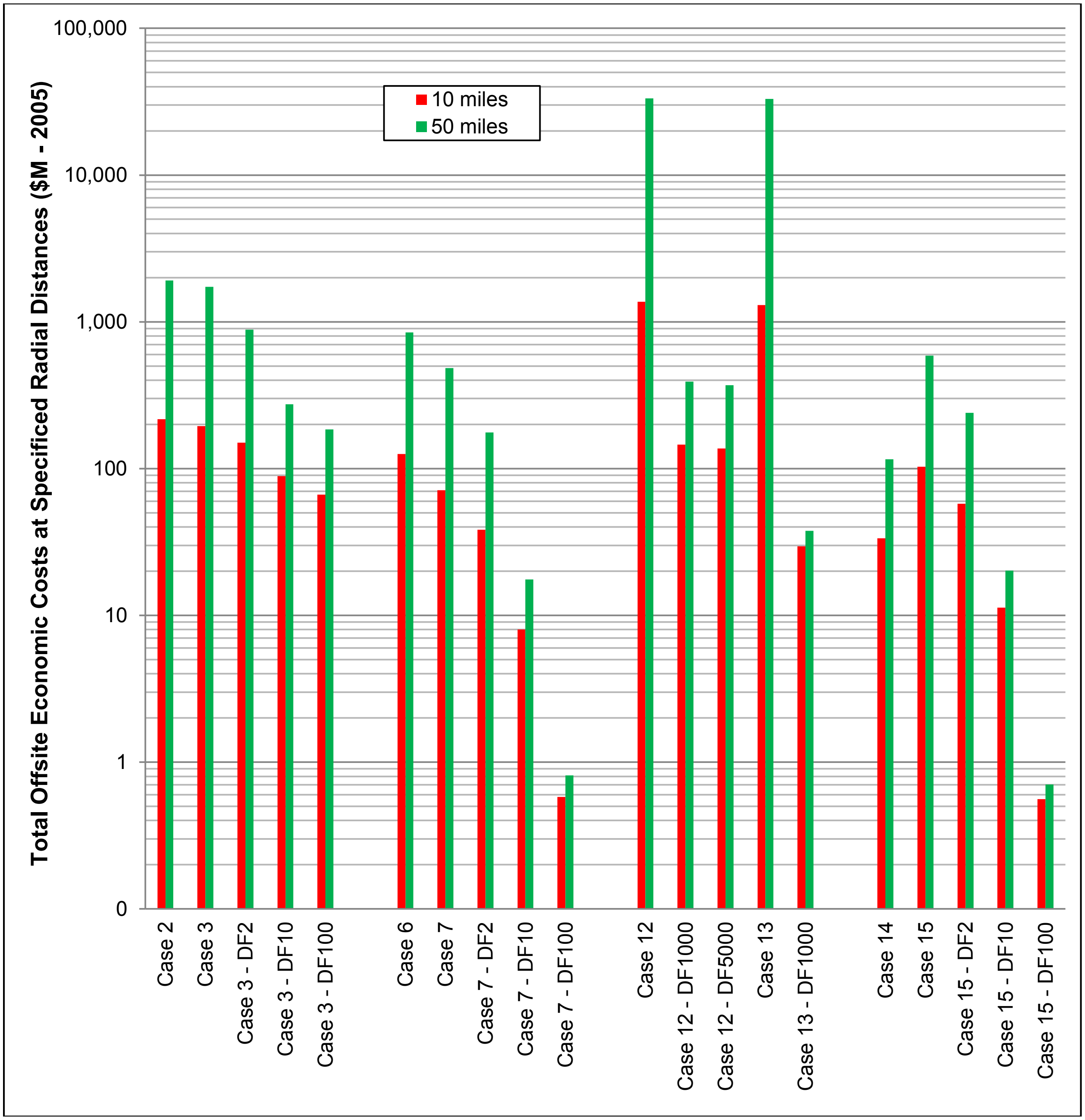

Figure 20 Mean, total offsite economic costs per event within a circular area at specified radial distances with specified decontamination factors for all the cases considered

To better identify which filtered cases have costs that are directly correlated to land contamination, Figure 21 shows the ratio of the mean, total offsite economic costs in millions of 2005 dollars per event for the 50-mile radial distance to the 15 μCi/m^2 of Cs-137 land contamination for all the cases considered. Figure 21 shows that Case 3 and Case 12 have costs that are relatively independent of DF.

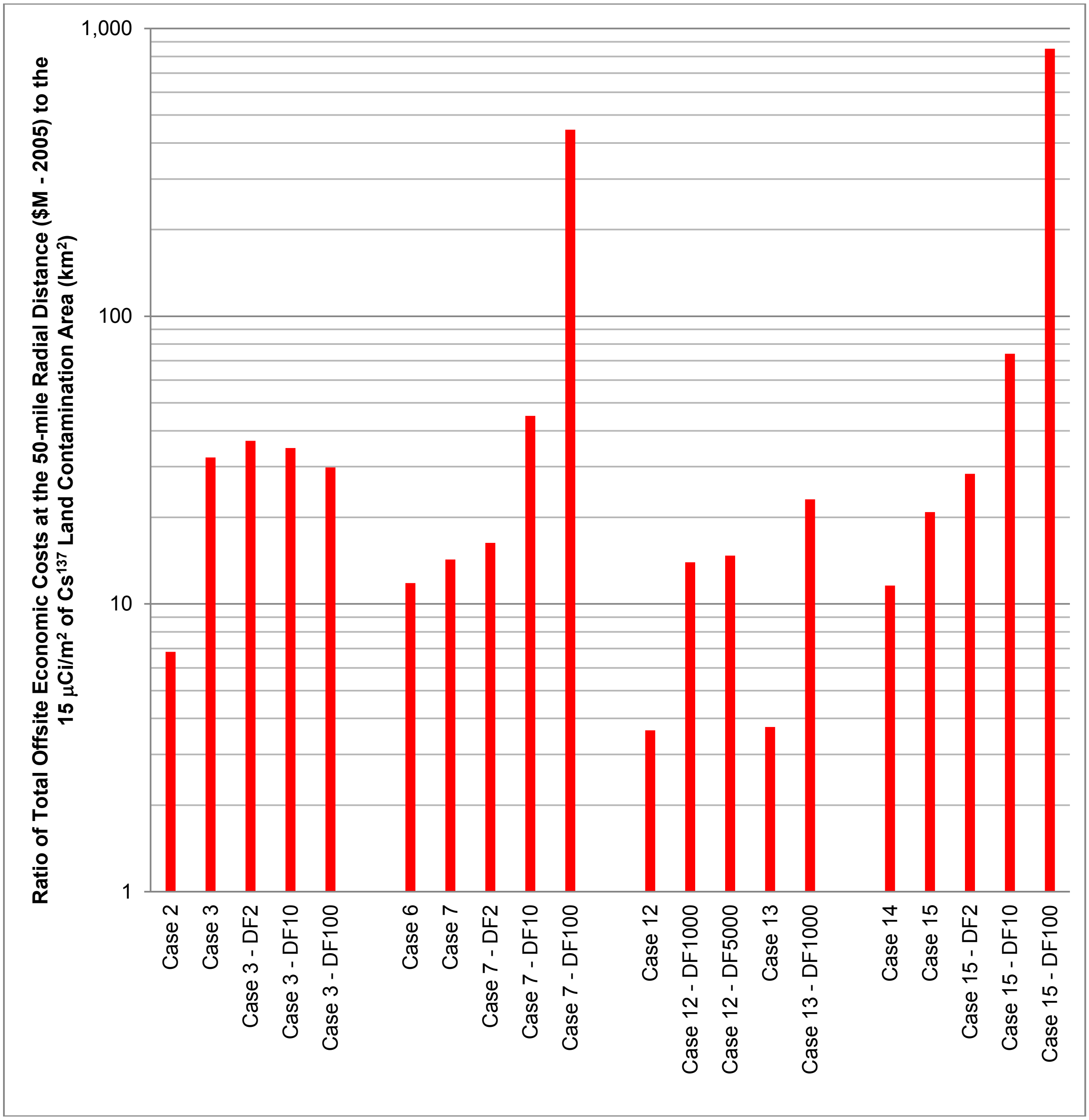

Figure 21 Ratio of mean, total offsite economic costs per event within a circular area of 50-mile radius to the land contamination area exceeding 15 μCi/m^2 of Cs-137 for all the cases considered

For Case 3, this is the only filtered wetwell venting case that has additional environmental release pathways that bypass the wetwell vent (i.e., see discussion in Section 3). As a result of these additional release pathways, the cesium release fraction is not significantly reduced when a DF is applied (i.e., see Table 2).

Case 12 is the only drywell vent filtered case that has an additional DF (i.e., DF = 5,000) applied to the drywell vent pathway. Recall that for this filtered case, there is an environmental release pathway (i.e., refueling bay blowout panels) is present, and when the DF is applied to the drywell vent path, the release through this additional pathway becomes the dominate environmental release (i.e., see discussion in Section 5). As a result of this additional release path, the cesium release fraction is not significantly reduced when a DF greater than 1,000 is applied (i.e., see Table 9).

9.0 CONSEQUENCE ANALYSES SUMMARY

The MACCS2 results for this study consider the mitigative measures listed in Table 19, and the benefit of an external filter on the wetwell or drywell vent path. For wetwell venting, Case 3, Case 7, and Case 15 consider a DF associated for the external filter of 2, 10, and 100. For drywell venting, Case 12 and Case 13 consider a DF associated for the external filter of 1,000.

Table 19 Matrix of scenarios used in the consequence analyses

Case	DC Battery time (16 hours)	Core spray after RPV failure	Drywell spray at 24 hours	Wetwell venting at 60 psig	Main steam line failure	Drywell venting at 24 hours
2	X					
3	X			X		
6	X	X				
7	X	X		X		
12	X				X	X
13	X		X		X	X
14	X		X			
15	X		X	X		

The results of the consequence analyses are presented in terms of risk to the public, land contamination, population dose, and economic costs for each of the cases. 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).

The risk metrics are LCF risk and prompt fatality risks to residents in circular regions surrounding the plant. The risk values represent the predicted number of fatalities divided by the population. LCF risks are calculated for a LNT dose-response model. The risks, land contamination, population dose, and economic costs 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. 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.

9.1 Wetwell Venting – 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 3 – wetwell vent left open), 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. Thus, doses and LCF risks diminish less than linearly. 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.

Additionally for Case 3, the wetwell vent path is not the only release pathway to the environment. As a result of the additional environmental release pathway (i.e., the drywell liner failure), the relationship between the assumed DF and the LCF risk contributes to the sub-linearity of the LCF risk results.

Case 15 does not produce lower environmental consequences than the unfiltered case (Case 14). However, when a DF of 10 or greater is applied to the wetwell vent pathway to represent the effect of the external filters, the environmental consequences are lowered.

For all wetwell venting cases, except Case 7 and Case 15 each with a DF greater than 10, the long-term phase LCF risk dominates the total LCF risks for these cases when the LNT dose-response model is used. 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 filtered wetwell venting Case 7 and Case 15 with a DF greater than 10, the emergency phase LCF risk dominates the total LCF risks. This is due the reduced source term from core spray or drywell spray, respectively. The peak emergency phase risk is at 20 miles, which is the first location in the plot outside of the evacuation zone. Table 20 shows the percent contribution of the emergency phase LCF risk to the total LCF risk for each of the wetwell venting cases considered for all the specified radial distances.

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.

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. As discussed previously discussed, 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.

Table 20 Percent contribution of the emergency phase LCF risk to the total LCF risk for all wetwell venting cases considered at the specified radial distances

	Case 2	Case 3	Case 3 DF 2	Case 3 DF 10	Case 3 DF 100
0-10 miles	0%	1%	0.5%	0.5%	0.5%
0-20 miles	15%	40%	40%	35%	35%
0-30 miles	15%	40%	40%	40%	40%
0-40 miles	15%	40%	40%	40%	40%
0-50 miles	15%	40%	40%	40%	40%

	Case 6	Case 7	Case 7 DF 2	Case 7 DF 10	Case 7 DF 100
0-10 miles	0.5%	0.5%	0.5%	0%	1.5%
0-20 miles	30%	30%	25%	30%	65%
0-30 miles	35%	30%	30%	35%	70%
0-40 miles	35%	30%	30%	35%	70%
0-50 miles	35%	30%	30%	35%	70%

	Case 14	Case 15	Case 15 DF 2	Case 15 DF 10	Case 15 DF 100
0-10 miles	0.5%	0.5%	1%	0.5%	1.5%
0-20 miles	25%	30%	30%	35%	60%
0-30 miles	30%	35%	35%	40%	70%
0-40 miles	30%	35%	35%	40%	70%
0-50 miles	30%	35%	35%	40%	70%

9.2 Drywell Venting – LCF and Prompt Fatality Risk

When a DF is applied to the pathway that flow through the drywell filtered vent (i.e., Case 12 and Case 13), the relationship is nonlinear between the inverse of DF and LCF risk.

The drywell vent path is not the only release pathway to the environment. This additional environmental release pathway (i.e., drywell liner failure) influences the relationship between the assumed DF and the LCF risk to be sublinear. The sublinear behavior is more pronounced at shorter distances. This is primarily due to short-term and long-term mitigative actions. For smaller releases, the implementation of offsite protective actions is less. Thus, doses and LCF risks diminish less than linearly. 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.

An interesting observation is that when the LCF risk for the unfiltered Case 12 is compared with that for unfiltered Case 13 (i.e., no DF is applied for an external filter on the drywell vent path), the LCF risks are higher for Case 13 even though containment spray is on. The majority of the source term for these unfiltered cases occurs when the main steam line fails. The two unfiltered cases have similar long-term LCF risk. However, the emergency phase LCF risk for Case 13 is higher. This is attributed to slightly higher short-term LCF risk contributors in the cerium class (e.g., Pu-238 and Pu-239) for acute inhalation dose. The emergency phase accounts for 50-70% of the total LCF risk beyond 20 miles for both unfiltered cases.

The emergency response is very effective within the EPZ (10 miles) during the emergency 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 risk is at 20 miles, which is the first location in the plot outside of the evacuation zone.

When an external filter is employed on the vent, the long-term phase risk dominates the total risks for these cases. 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 the unfiltered cases, the emergency phase risk dominates the total risk due to the main steam line failure. The emergency phase risk is controlled by inhalation doses during the emergency phase as a result of the large iodine release fraction. Table 21 shows the percent contribution of the emergency phase LCF risk to the total LCF risk for each of the drywell venting cases considered for all the specified radial distances.

Table 21 Percent contribution of the emergency phase LCF risk to the total LCF risk for all drywell venting cases considered at the specified radial distances

	Case 12	**Case 12 DF 1,000**	**Case 12 DF 5,000**	**Case 13**	**Case 13 DF 1,000**
0-10 miles	5%	0%	0.5%	5%	0.5%
0-20 miles	65%	20%	25%	70%	20%
0-30 miles	60%	30%	30%	65%	25%
0-40 miles	55%	30%	30%	60%	30%
0-50 miles	50%	30%	30%	55%	30%

For the sensitivity study where a DF of 5,000 is applied for Case 12, there is a sublinear relationship with the filtered Case 12 where a DF of 1,000 is applied. This sublinear relationship is attributed to the additional release pathway. As a result of this additional environmental release pathway (i.e., the drywell liner failure), when a DF ≥1,000 is applied the fraction of the source term that is released through the drywell liner failure dominates the overall source term. Thus, a higher DF has little effect on the LCF risk.

The prompt fatality risks are zero for all cases, except unfiltered Case 13. For those cases that resulted in a zero prompt fatality risk, 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) for these cases is about 0.8 Gy to the red bone marrow (i.e., unfiltered Case 12). As discussed previously, 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.

For unfiltered Case 13, there is a nonzero mean, individual prompt fatality risk per event at the 2-mile and 2.5-mile radial distances. Beyond 2.5 miles, all prompt fatality risk is zero. For unfiltered Case 13, the mean, acute exposure for the closest resident (i.e., 0.5 to 1.2 kilometers from the plant) is about 1.0 Gy to the red bone marrow. While this is below the red bone marrow threshold for an early fatality, 0.5% of the MACCS2 weather trials produced an acute exposure greater than the threshold. As a result of these few weather trials, a nonzero mean prompt fatality risk was observed. Based on this observation and since the mean, prompt fatality risk for the 2-mile and 2.5-mile radial distances are so low, the mean, individual prompt fatality risk per event at these distances are considered essentially zero.

9.3 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 [11].

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 for all filtered cases.

The mean contaminated area for specified Cs-137 contamination levels for all cases show the same trends when a DF is applied to the filtered cases. When the unfiltered case (e.g., Case 2) is compared with the filtered case (e.g., Case 3), a DF of 10 or 100 for wetwell venting and a DF 1,000 for drywell venting results in a several order-of-magnitude reduction in land contamination area.

9.4 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 and a DF of 1,000 for all drywell venting filtered cases result in lower population doses than their respective unfiltered cases.

The composition and 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 7 with a DF=100 and Case 15 with a DF=100 are the only cases 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. For Peach Bottom, the State of Pennsylvania's habitability criterion is a dose rate of 500 mrem/yr.

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. The ingestion pathway accounts for 5% of the population doses for the drywell venting unfiltered cases considered. The ingestion pathway accounts for 20-30% of the population doses for the drywell venting filtered cases considered.

9.5 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).

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. For the cases considered, a DF of 10 or more for all wetwell venting filtered cases and a DF of 1,000 for all drywell venting filtered cases results in a lower economic costs than their respective unfiltered cases.

10.0 CONCLUSIONS

When a DF is applied to the external filtered vent path, the LCF risk, land contamination area, population dose, and economic results are nonlinear. A decision on the use of external filters on either a drywell or wetwell vent path should not be solely based on health effect risk, land contamination, population dose, or economic costs.

Based on these consequence analyses, the filtered cases with an external filter on either the wetwell or drywell vent path and a DF ≥10 for wetwell venting or a DF ≥1,000 for drywell venting results in a lower conditional LCF risk when compared to the unfiltered cases. When the previously specified DFs are applied to the pathway that flows through the filtered vent, the relationship is sublinear between the inverse of DF and LCF risk. Also, the consequence analyses show that for all cases considered, the conditional prompt fatality risk is either zero or essentially zero.

Additionally, when an external filtered vent path DF is used to estimate Cs-137 land contamination, a several order-of-magnitude reduction is observed for all cases. The relationship between the inverse of DF and land contamination area is observed to be superlinear.

The relationship between population dose and inverse DF is sublinear because less remedial action is taken at lower contamination levels. In some cases, it is also sublinear because a portion of the release bypasses the filter vent path. For the cases considered, a DF ≥10 for all wetwell venting filtered cases and a DF ≥1,000 for all drywell venting filtered cases results in lower population doses than their respective unfiltered cases. The population dose results include societal doses from the ingestion pathway or doses to decontamination workers working in the contaminated area; 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 5% to 30% of the population dose for the cases considered.

Lastly, the implementation of decontamination, which along with the associated interdiction of land, is the dominant contributor to the overall economic costs, and depends on whether or not the habitability criterion is exceeded. Habitability and farmability 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. For the cases considered, a DF ≥10 for all wetwell venting filtered cases and a DF ≥1,000 for all drywell venting filtered cases results in lower economic costs than their respective unfiltered cases.

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