Enclosure 5b
MACCS Consequence Analysis

CONTENTS

MACCS CONSEQUENCE ANALYSIS

This enclosure documents the MACCS2 analysis of the same selected accident scenarios (cases) discussed in the MELCOR accident analysis enclosure. 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 individual prompt and latent cancer fatality risk, land contamination areas, population dose, and economic costs. This enclosure begins with a general description of MACCS, followed by the consequence analyses for the selected cases. The results are used in the regulatory cost-benefit analyses of various accident prevention and/or mitigation strategies.

1. GENERAL DESCRIPTION OF MACCS

The MELCOR code provides input to a companion code, MELCOR Accident Consequence Code System (MACCS) Version 2, or MACCS2 for short, for the analysis of radioactive material dispersion in the environment and the consequences of this dispersion. The code was specifically developed for the U.S. Nuclear Regulatory Commission (NRC) to evaluate offsite consequences from a hypothetical release of radioactive materials into the atmosphere. The code is used as a tool to assess the risk and consequences associated with accidental releases of radioactive material into the atmosphere in probabilistic risk assessment (PRA) studies. The code models atmospheric transport and dispersion, emergency response actions, exposure pathways, health effects, and economic costs.

MACCS2 is used by U.S. nuclear power plant license renewal applicants to support the plant-specific evaluation of severe accident mitigation alternatives (SAMAs) that may be required as part of the applicant's environmental report for license renewal. MACCS2 is also routinely used in severe accident mitigation design alternative (SAMDA), or severe accident consequences analyses for environmental impact statements (EISs) supporting design certification, early site permit, and combined construction and operating license reviews for new reactors. The NRC's regulatory analysis guidelines in NUREG/BR-0058, "Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission" [1], and NUREG/BR-0184, "Regulatory Analysis Technical Evaluation Handbook" [2], recommend the use of MACCS2 to estimate the averted "offsite property damage" cost (benefit) and the averted offsite dose cost elements. The information from MACCS2 code runs supports a cost-benefit assessment for various potential plant improvements as part of SAMAs or SAMDAs.

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 7 days following the beginning of release (early phase)

(3) the estimated exposures and health effects during an intermediate time period of up to 1 year (intermediate phase)

(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 uses all four parts of the modeling. An overview of the code is provided below to explain the assessment of health effects and offsite property damage in MACCS2.

1.1 Atmospheric Transport and Dispersion (ATD) 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 resulting from the sensible heat content (i.e., buoyancy), initial plume size caused by 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 six generations. The model does not treat in detail 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. The latter of these 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, and as a function of time and distance from the release source; these results are subsequently used in early, intermediate, and late-phase exposure modeling.

1.2 Early Phase (Emergency Phase) Model

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 7 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 7 days from the beginning of release. MACCS2 models sheltering and evacuation actions 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 (i.e., the hotspot relocation (5 rem in 12 hours) and normal relocation (0.5 rem in 24 hours) MACCS2 inputs) 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 may 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. MACCS2/WinMACCS has implemented a KI model to account for the beneficial effect of taking KI. This model accounts for the fraction of the population taking KI and the efficacy, or dose reduction, provided by the KI.

1.3 Intermediate Phase Model

MACCS2 can model an intermediate phase with duration of up to 1 year following the early phase. 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

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 (e.g., groundshine) and internal (e.g., food consumption and resuspension inhalation) pathways. Decisions on mitigative actions are based on two sets of independent actions (i.e., decisions relating to whether land, at a specific location and time, is suitable for human habitation (habitability) or agriculture production (farmability)). Habitability is defined by a maximum dose and an exposure period to receive that dose. Habitability decisionmaking 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]
(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]. The decision on whether land is suitable for farming is first based on prior evaluation of its suitability for human habitation.

1.4.1 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 receives a small 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 small 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.

The decision tree for farmability is similar, but 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

[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. The manual can be found at http://www.epa.gov/rpdweb00/rert/pags.html.

embodied in the original MACCS code and used in NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants."

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.

1.4.2 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 segment model for atmospheric transport and deposition.

1.5 MACCS2 Economic Consequence Model

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

(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 one-time 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.

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 decontamination factor (DF) to the particulate source term release fraction will not result in a linear extrapolation of the results.

1.6 Recent Improvements to the MACCS2 Code

The MACCS2 code has gone through 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 [1]. 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

(3) the ability to model alternative dose-response relationships for latent cancer fatality evaluation (e.g., linear with threshold model)

Uncertainty in the source term and in most of the other MACCS2 input parameters, including parameters related to emergency response, can be treated through WinMACCS.

2. CONSEQUENCE ANALYSES

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 areas, 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, "State-of-the-Art Reactor Consequence Analyses (SOARCA) Report: Draft Report for Comment," Section 5 [4]. The following are the MACCS2 code version updates from SOARCA to this study:

- 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 [4]. 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 percent). 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 others.
- Correction of the NRC Regulatory Guide 1.145, "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," plume meander model [6]. 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 object (QHO) for prompt fatalities ($5x10^{-7}$ per reactor year (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) (1 Gy = 100 rad) to the red bone marrow. Additional acute exposure thresholds 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 (the Peach Bottom SOARCA analysis is documented in NUREG/CR-7110, Volume 1, "State-of-the-Art Reactor Consequence Analyses Project—Volume 1: Peach Bottom Integrated Analysis" [7]). 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 use the modified source terms, as calculated from the MELCOR analyses for this study to account for variation in the LTSBO scenario, and the effect of adding an external filter to the vent paths. None of the source terms considered in this study are the same as the LTSBO source term used in SOARCA. This difference in source term is in part due to the difference in DC station battery duration (i.e., 4 hours for SOARCA and 16 hours for this study). However, additional mitigative actions discussed in Section 2.1, also contribute to the differences in the source term.

As part of SOARCA, a number of code enhancements were made to MACCS2 [7]. In general, these enhancements implemented some of the recommendations obtained during the SOARCA external peer review and needs identified by the broader consequence analysis community [8]. 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 multiple alternate dose-response options to create a more detailed, integrated, and realistic analysis than past consequence analyses. In this study, only the linear-no-threshold dose-response model is used, while SOARCA reported additional results for two linear-*with*-threshold dose-response models as well. Some of the MACCS2 enhancements used in SOARCA and this study included increased angular resolution, updated dose conversion factors, and a larger number of evacuation 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 [9] and ICRP 30 [10]. The SOARCA project used dose conversion factors from Federal Guidance Report 13 [11], 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:

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

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

Cohort 3: 0 to 10 Schools and 0 to 10 Shadow. 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).

Cohort 4: 0 to 10 Special Facilities. 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.

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

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

In the SOARCA analyses, SECPOP2000 [12] was used to estimate the population within 50 miles of each plant. The population for each site was projected from 2000 to 2005 using a national population growth multiplier of 1.0533 obtained from the Census Bureau. SECPOP2000 interpolates U.S. census data at the block level onto a MACCS2 grid. SECPOP2000 also interpolates U.S. land-use and economic data at the county level onto a MACCS2 grid. The economic values used in SOARCA are from the Bureau of Economic Analysis (BEA) for the year 2002. These values were scaled to 2005 dollars by applying a multiplier of 1.0900, which is the ratio of the consumer price index for 2005 to the value for 2002. The MACCS2 model used in this study uses the same Peach Bottom site-specific files for population data and economic data based on the year 2005.

2.1 Consequence Analyses Overview

The results of the consequence analyses are presented in terms of risks to the public, population dose, land contamination, and economic costs for each of the cases. All consequence results are presented as conditional consequences (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 risk to residents in circular regions surrounding the plant. The risks, 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. The land contamination areas are total areas of land exceeding a certain threshold of Cesium areal concentration (and unlike the other consequence metrics, is not limited to the 50-mile 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, land use, and property within the circular region and for the interplay between these distributions 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 (MSL) 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 with MSL failure—Case 12 and Case 13
- Drywell spray—Case 14 and Case 15

A discussion of health effect risks (Section 2.2 through Section 2.5), land contamination (Section 2.2 through Section 2.5), population dose (Section 2.6), and economic costs (Section 2.7) is provided for each group of cases.

A 48-hour truncation time was assumed for this work. This is the same truncation time used in SOARCA [7]. The 48-hour truncation time for SOARCA was based on the many resources available at the State, regional, and national level that would be available to mitigate a severe reactor accident. For the SOARCA project, the staff reviewed available resources and emergency plans and determined that adequate mitigation measures (i.e., at minimum, the ability to flood the reactor building) could be brought on site within 24 hours and connected and functioning within 48 hours. The decision to truncate releases at 48 hours was made well before the Fukushima Daiichi accident[3]. Based on the assumptions made for SOARCA, the releases that would occur within 48 hours for the Peach Bottom unmitigated LTSBO scenario cease because of reactor building flooding. Note that past studies, including PRAs such as NUREG-1150, typically truncated releases after 24 hours.

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 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 size bin and possibly account for the effect of temperature and radionuclide concentration 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 fission products in the water flowing from the drywell through the containment downcomers and into the wetwell. This path bypasses the

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3 For Fukushima, the operators delayed releases beyond the SOARCA assumption, so substantial releases occurred beyond 48 hours. In addition, the operators at Fukushima were not able to flood the reactor buildings, as assumed for SOARCA. For mitigated cases, the SOARCA analysis assumed the effectiveness of mitigation measures well within 48 hours. This assumption is considered reasonable, given the vast network of resources available in the United States. These resources include an offsite emergency operations facility, which would provide access to fleetwide emergency response personnel and equipment, including the 10 CFR 50.54(hh) mitigation measures and equipment from sister plants. These assets, as well as those from neighboring utilities and State preparedness programs, could be brought to bear on the accident if needed. In addition, SOARCA did not assume a tsunami, and such an event is considered highly unlikely at Peach Bottom. If sites were subject to tsunamis, these events could affect the availability and effectiveness of mitigation measures. In response to the recommendation of the NRC's Near-Term Task Force report, SECY-11-0093, dated July 12, 2011, the NRC is currently evaluating changes to mitigation strategies.

T-quenchers during wetwell venting. When the T-quenchers are bypassed, a lower DF occurs for the wetwell. 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 of the radionuclides to be scrubbed in the external filters and thus increase the DF for the external filters. With this in mind, the environmental consequences reported for a DF value of 2 for the external filters should be viewed 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 percent efficient. As a sensitivity study, a DF of 5,000 was applied to Case 12 (i.e., external filter is 99.98 percent efficient) to determine the effect of an increased efficiency.

In terms of the type of long-term radiation that would be emitted, the most important isotope is cesium-137 (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 health risk.

2.2 Base Cases

Table 2 provides a brief description of source terms for the Peach Bottom accident scenarios analyzed for Case 2 and Case 3. The filtered cases include 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. The reason is that 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 Base case	0.77	0.013	0.0014	0.019	0.016	0	0.003	0	0	25.7	48
Case 3 Base case with wetwell venting	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

2.2.1 Base Cases—Latent Cancer Fatality 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 linear no-threshold (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. All the vented cases (Case 3) result in smaller risks[4] than the base case, Case 2. The addition of a filter to the vented cases results in an additional reduction in risk. 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, for the reasons described below.

As discussed above for the filtered case, 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 is sublinear. In addition, the sublinear behavior is more pronounced at shorter distances, 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.

4 This is despite the fact that the release fractions for some chemical groups are higher in Case 3 compared to Case 2. The LCF risk is dominated by Cesium isotopes (as discussed in Section 2.1), whose release fractions are higher in Case 2 compared to Case 3.

Table 3. Individual, Mean LCF risk per Event for Residents within a Circular Area at Specified Radial Distances for the Base Cases

	Case 2 Base case	**Case 3** Base case with wetwell venting	**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	$4.8x10^{-5}$	$3.3x10^{-5}$	$2.3x10^{-5}$	$1.3x10^{-5}$	$1.0x10^{-5}$

Figure 1 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 1 show that the vented base case (Case 3) has a lower total LCF risk than the base case with no venting (Case 2), and all the filtered cases have a lower total LCF risk than the unfiltered cases (i.e., Case 2 or Case 3 without filter). For Case 3, assuming a DF of 100 for the external filter, the total LCF risk is reduced by 53 percent for the 10-mile radial distance to 70 percent for the 50-mile radial distances, compared to the unfiltered Case 3.

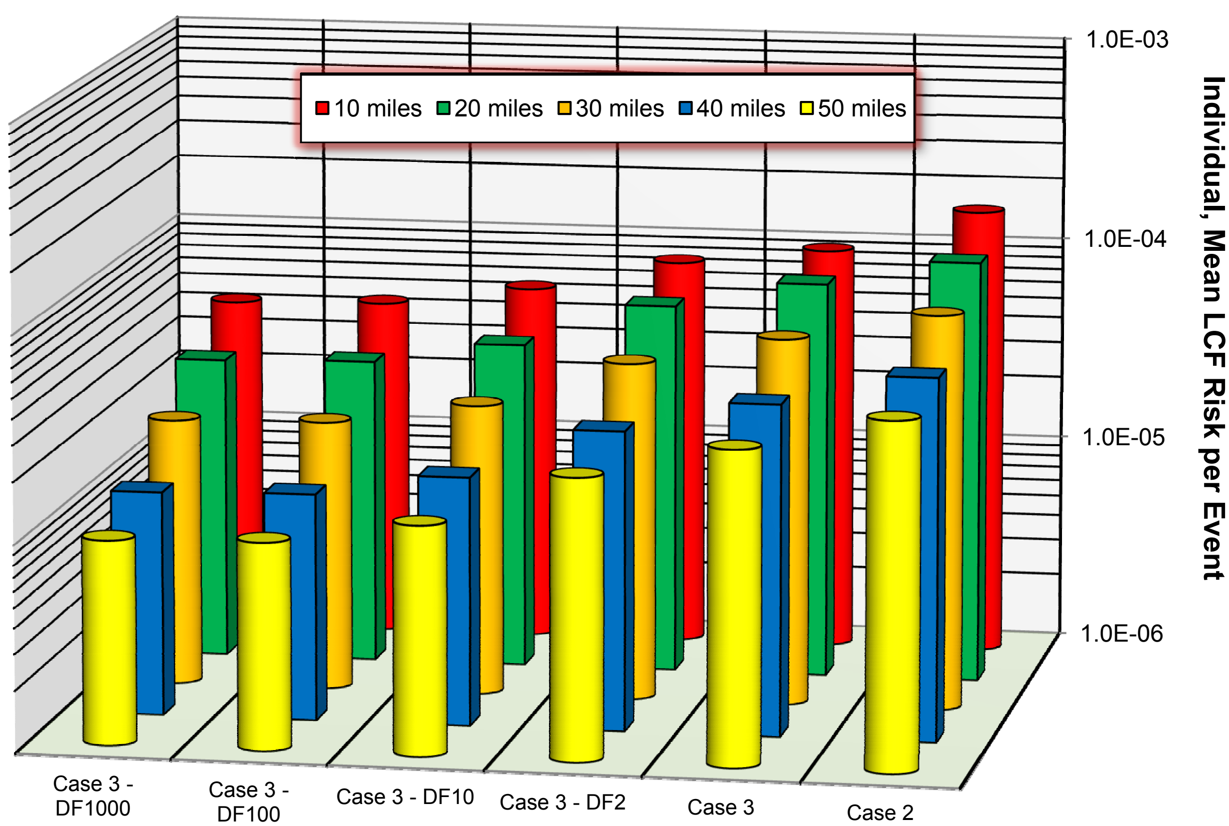

Figure 1. **Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the base cases**

Figure 2 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 emergency phase accounts for ~15 percent of the total LCF risk within the 50-mile radial distance.

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 guideline of a dose rate of 500 mrem/yr (i.e., starting in the first year) is used as the habitability criterion[5].

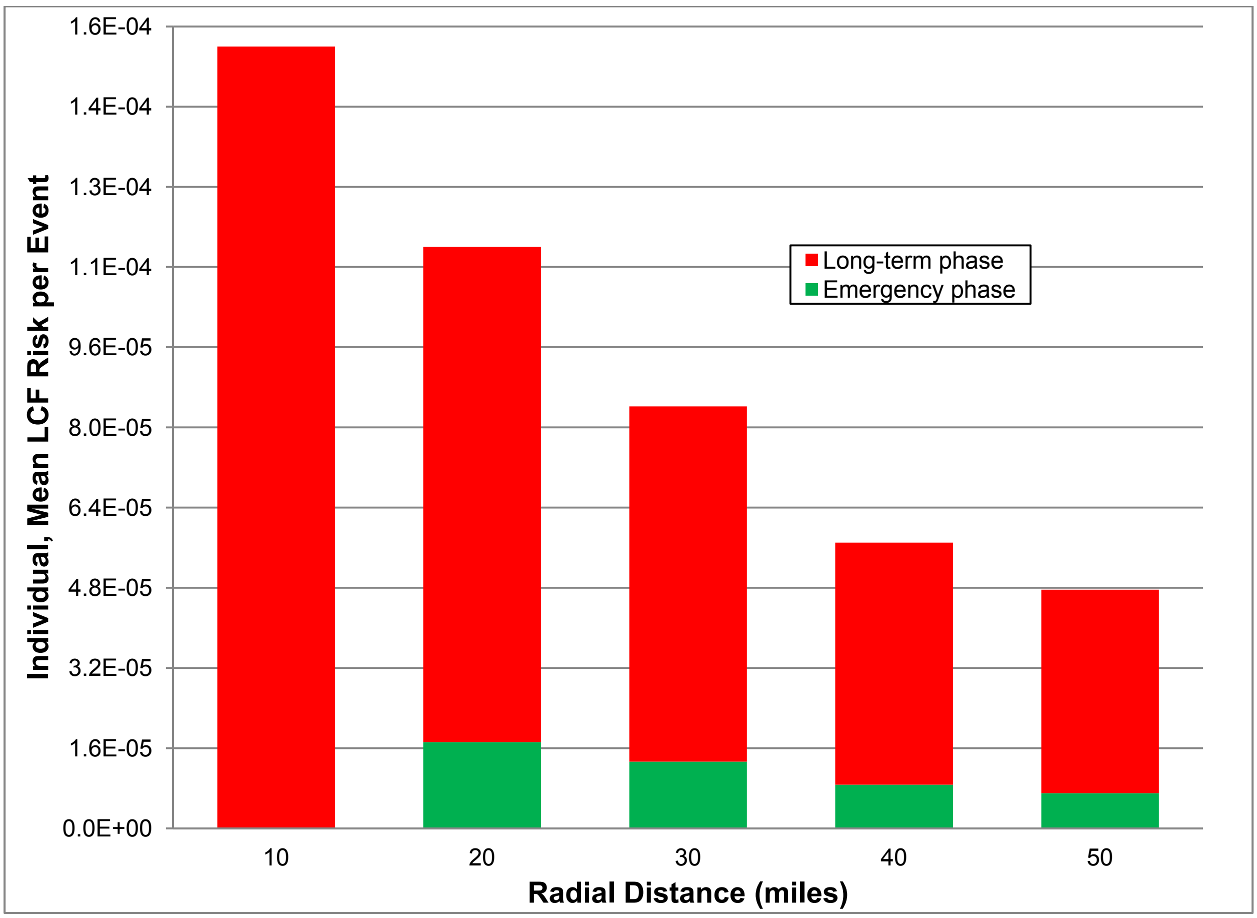

Figure 2. Case 2 individual, mean LCF risk per event for residents within a circular area at specified radial distances

5 The U.S. Environmental Protection Agency's Protective Action Guideline is 2 rem the first year, followed by 500 mrem/year starting the second year. States can choose a more restrictive guideline.

Figure 3 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 2 also apply to Figure 3. The emergency phase accounts for ~40 percent of the total LCF risk within the 50-mile radial distance for all DF values.

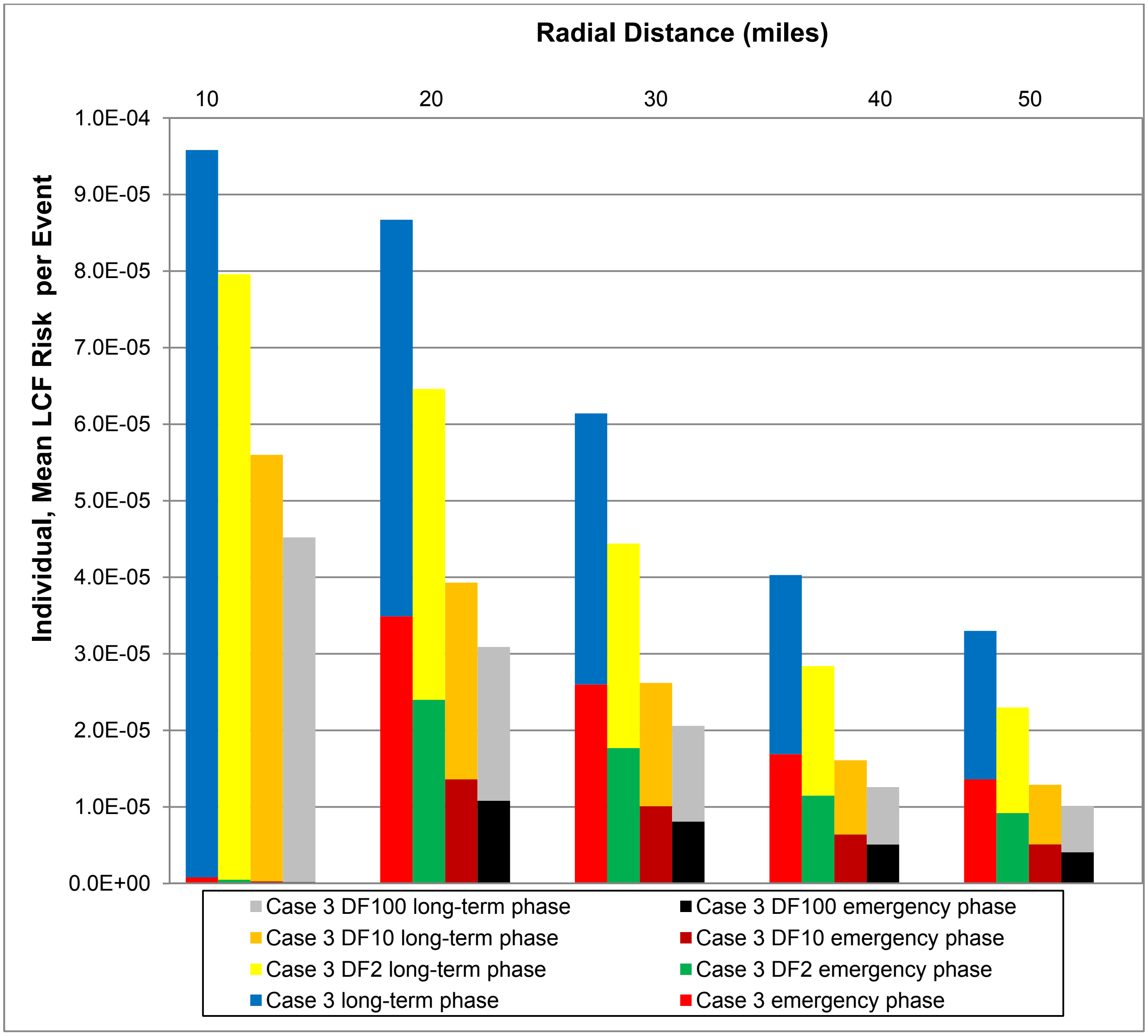

Figure 3. Case 3 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

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. As a result, the calculated exposures are all well below this threshold.

2.2.2 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 [13].

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 8-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 $\mu Ci/m^2$, 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[6] [13].

Table 4. Chernobyl Annual Effective External Dose Estimates for 1986 to 1995

Soil Deposition ($\mu Ci/m^2$ 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

* 100 rem = 1 Sievert (Sv)

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 4 shows the mean, land contamination area per event for Case 2 and Case 3. When the unvented unfiltered case (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. The filtered cases of DF of 10 or 100 result in a factor of ~5–10 reduction compared to the vented unfiltered case (Case 3).

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6 Conversion of the 40 $\mu Ci/m^2$ of Cs-137 soil deposition to Chernobyl annual effective external dose was not provided in the IAEA report.

Table 5. Mean, Contaminated Area per Event Above the Specified Contamination level for the Base Cases

Contamination Level ($\mu Ci/m^2$ of ^{137}Cs)	Contaminated Area (km^2)*				
	Case 2 Base case	**Case 3** Base case with wetwell venting	**Case 3 DF 2**	**Case 3 DF 10**	**Case 3 DF 100**
1	8,900	2,000	1,100	430	340
5	1,000	250	130	49	39
15	280	54	24	8	6
40	74	11	4	1	1

* 2.59 km^2 = 1 $mile^2$

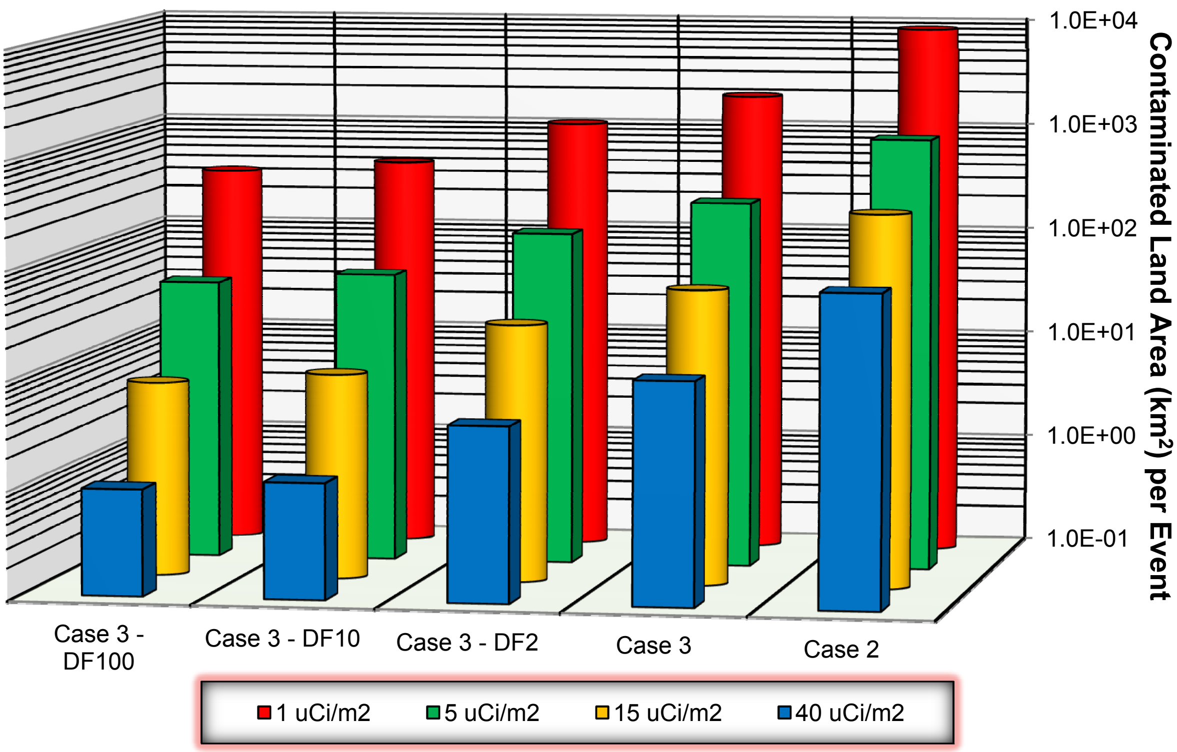

Figure 4. Mean, land contamination area per event for the base cases

2.3 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. The reason is that 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 Base case with core spray	0.73	0.004	0.001	0.016	0.035	0	0	0	0	25.7	48
Case 7 Base case with wetwell venting and core spray	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

2.3.1 Core Spray Cases—Latent Cancer Fatality 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, primarily due to short-term and long-term mitigative actions, as discussed in 2.2.1.

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 Base case with core spray	**Case 7** Base case with wetwell venting and core spray	**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 5 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 5 show that all the vented cases, unfiltered or filtered, have a lower total LCF risk than the unvented case (i.e., Case 6). If venting is used, assuming a DF of 100 for the external filter, the total LCF risk is reduced by ~98 percent at the five specified radial distances, compared to the unfiltered vented case (Case 7).

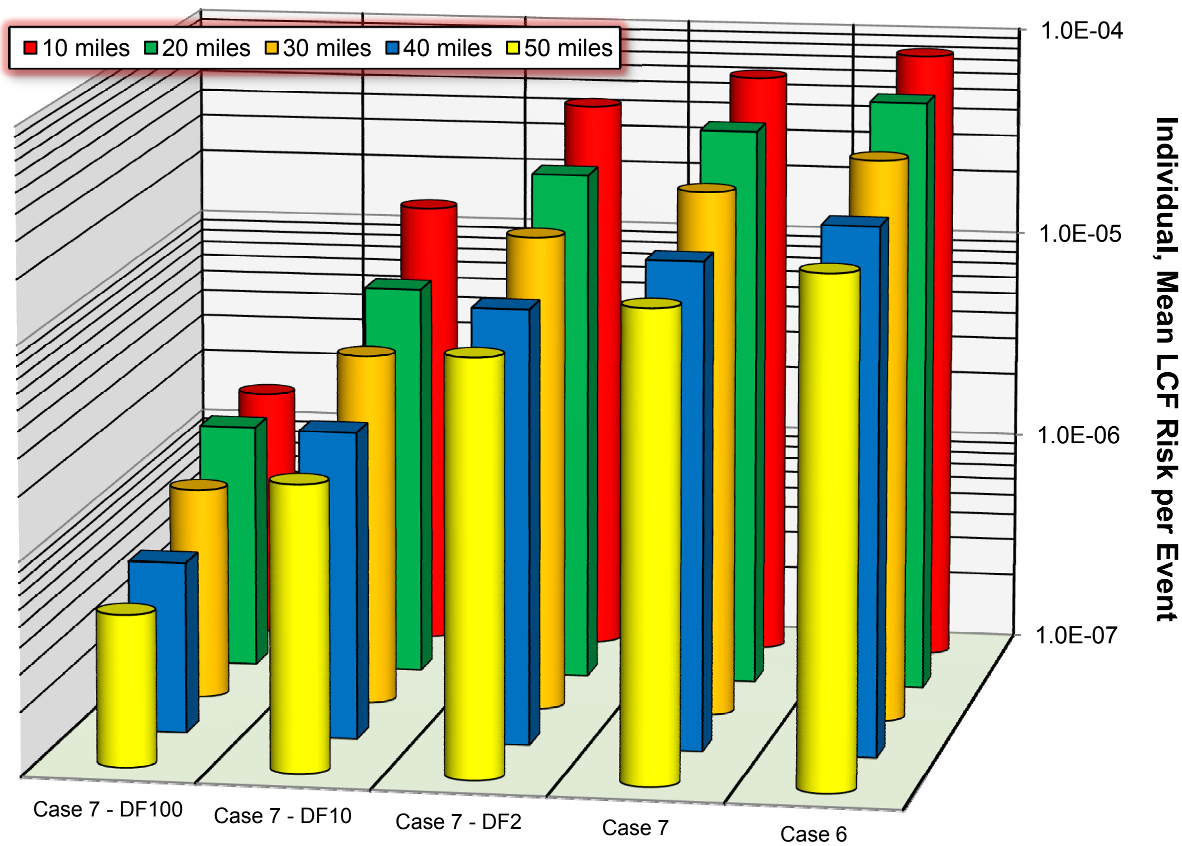

Figure 5. Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the core spray cases

Figure 6 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 emergency phase accounts for ~35 percent of the total LCF risk within the 50-mile radial distance.

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 guideline of a dose rate of 500 mrem/yr is used for the habitability criterion.

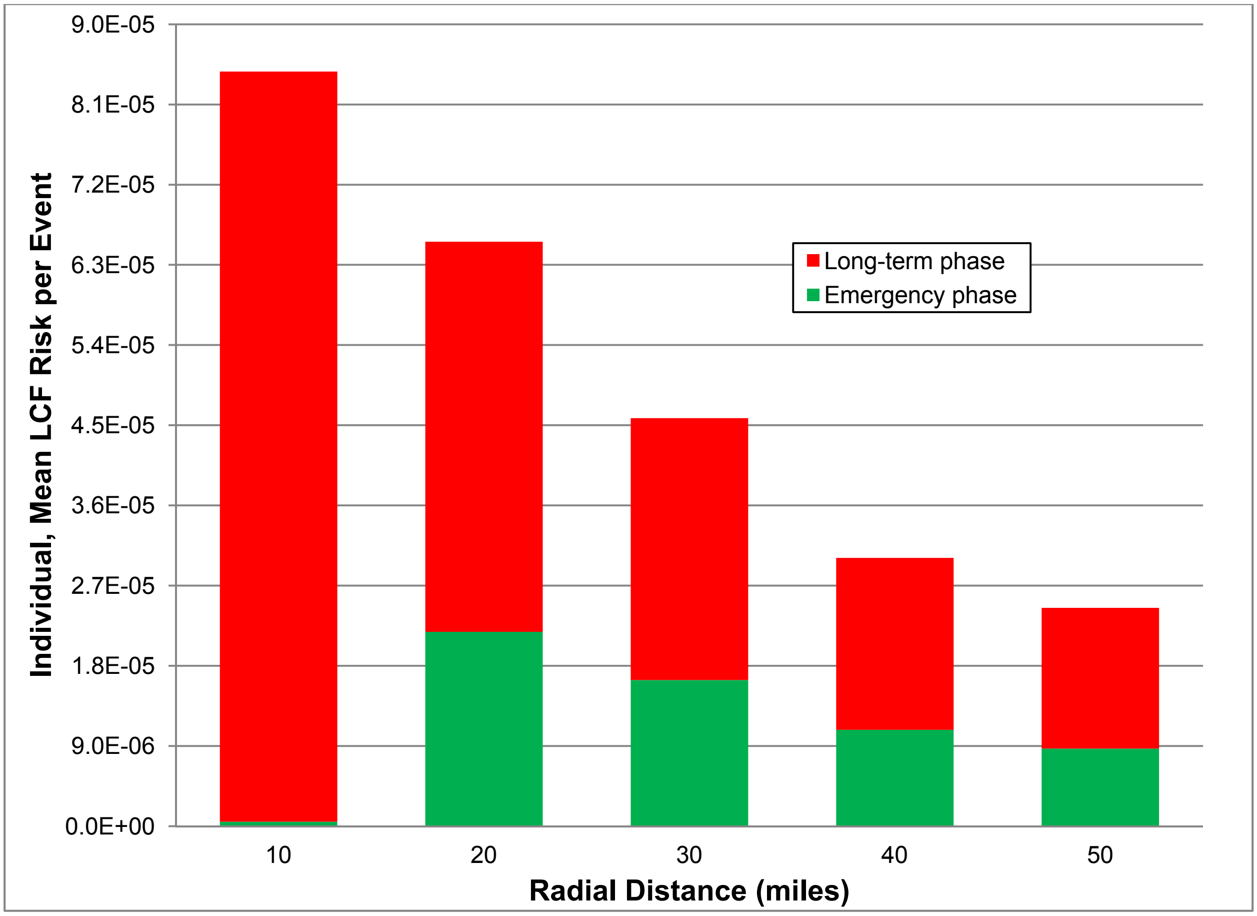

Figure 6. Case 6 individual, mean LCF risk per event for residents within a circular area at specified radial distances

Figure 7 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 6 also apply to Figure 7. The emergency phase accounts for 30–70 percent of the total LCF risk within the 50-mile radial distance for all DF values.

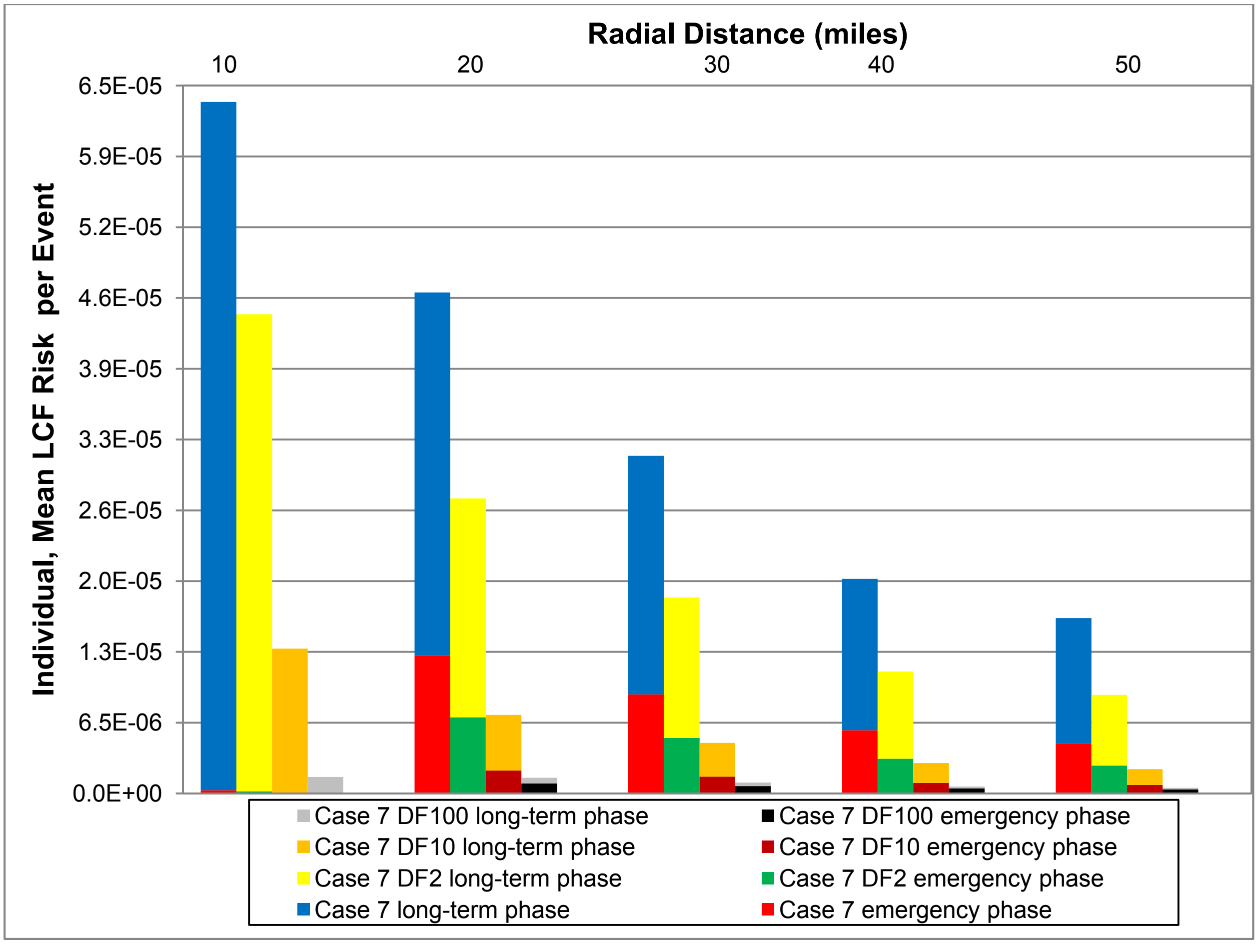

Figure 7. Case 7 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

The prompt fatality risks are zero for these cases. This is again 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 (see discussion under Section 2.2.1 above). The largest value of the mean, acute exposure for the closest resident for these cases is about 0.06 Gy to the red bone marrow.

2.3.2 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. As discussed in Section 2.2.2 above, the relationship between the inverse of DF (i.e., the quantity released) and land contamination area is superlinear.

Figure 8 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 ($\mu Ci/m^2$ of ^{137}Cs)	**Contaminated Area (km^2)***				
	Case 6 Base case with core spray	**Case 7** Base case with wetwell venting and core spray	**Case 7 DF 2**	**Case 7 DF 10**	**Case 7 DF 100**
1	1,800	1,400	590	62	1
5	270	180	62	4	0.02
15	72	34	11	0.4	0.002
40	19	7	2	0.04	0.0001

* 2.59 km^2 = 1 $mile^2$

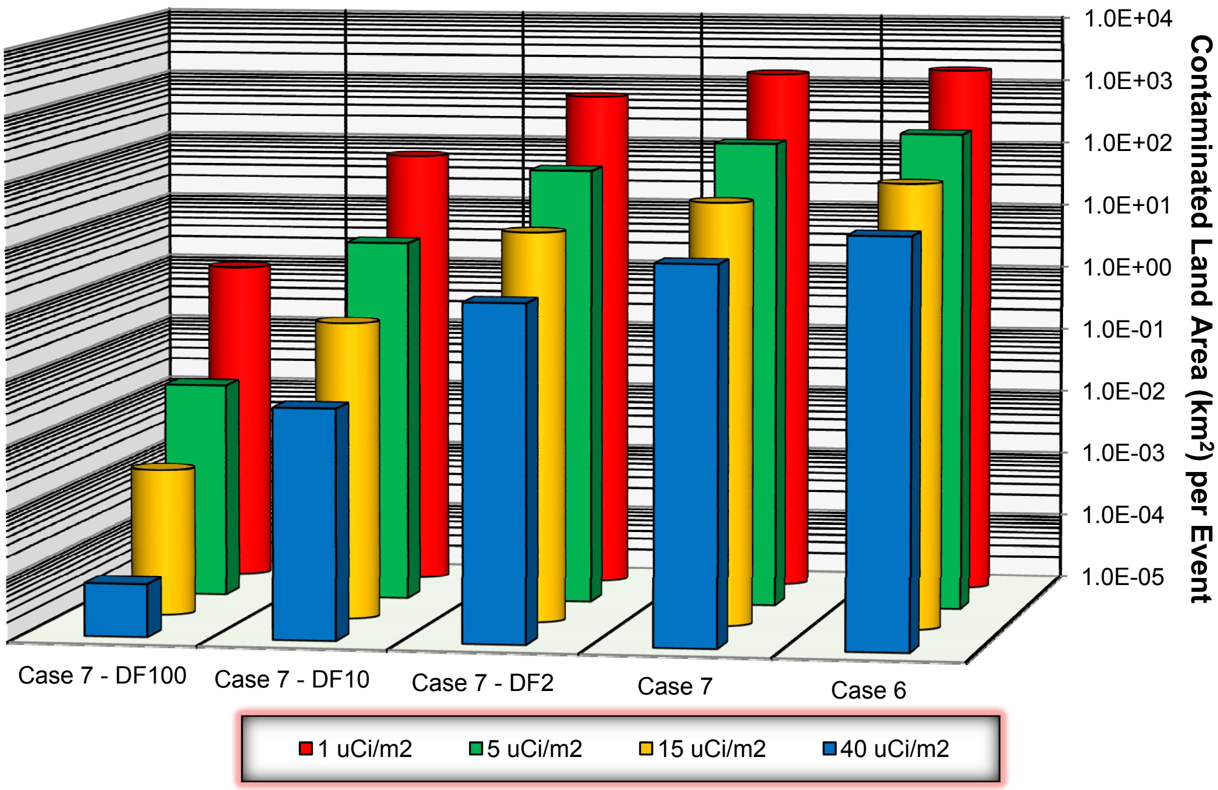

Figure 8. Mean, land contamination area per event for the core spray cases

2.4 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 radionuclides 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 percent 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 percent 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. The reason is that for the filtered cases, the drywell 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 Base case with drywell venting	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 Base case with drywell venting and drywell spray	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

2.4.1 Drywell Venting Cases—Latent Cancer Fatality 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 for 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, for reasons discussed in Section 2.2.1.

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 Base case with drywell venting	**Case 12 DF 1000**	**Case 12 DF 5000**	**Case 13** Base case with drywell venting and drywell spray	**Case 13 DF 1000**
0-10 miles	$4.0x10^{-4}$	$1.1x10^{-4}$	$9.3x10^{-5}$	$4.0x10^{-4}$	$3.6x10^{-5}$
0-20 miles	$8.5x10^{-4}$	$5.7x10^{-5}$	$5.0x10^{-5}$	$9.3x10^{-4}$	$1.5x10^{-5}$
0-30 miles	$5.8x10^{-4}$	$3.4x10^{-5}$	$3.1x10^{-5}$	$6.3x10^{-4}$	$8.5x10^{-6}$
0-40 miles	$3.8x10^{-4}$	$2.1x10^{-5}$	$1.8x10^{-5}$	$4.0x10^{-4}$	$4.8x10^{-6}$
0-50 miles	$3.2x10^{-4}$	$1.6x10^{-5}$	$1.4x10^{-5}$	$3.3x10^{-4}$	$3.7x10^{-6}$

Figure 9 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 9 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 percent for the 10-mile radial distances and ~95 percent within the 50-mile radial distance. Assuming a DF of 1,000 for the external filter, the total LCF risk for Case 13 is reduced by ~90 percent for the 10-mile radial distances and ~99 percent within the 50-mile radial distance.

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 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 10, 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 ~50-55 percent of the total LCF risk within the 50-mile radial distance for both unfiltered cases.

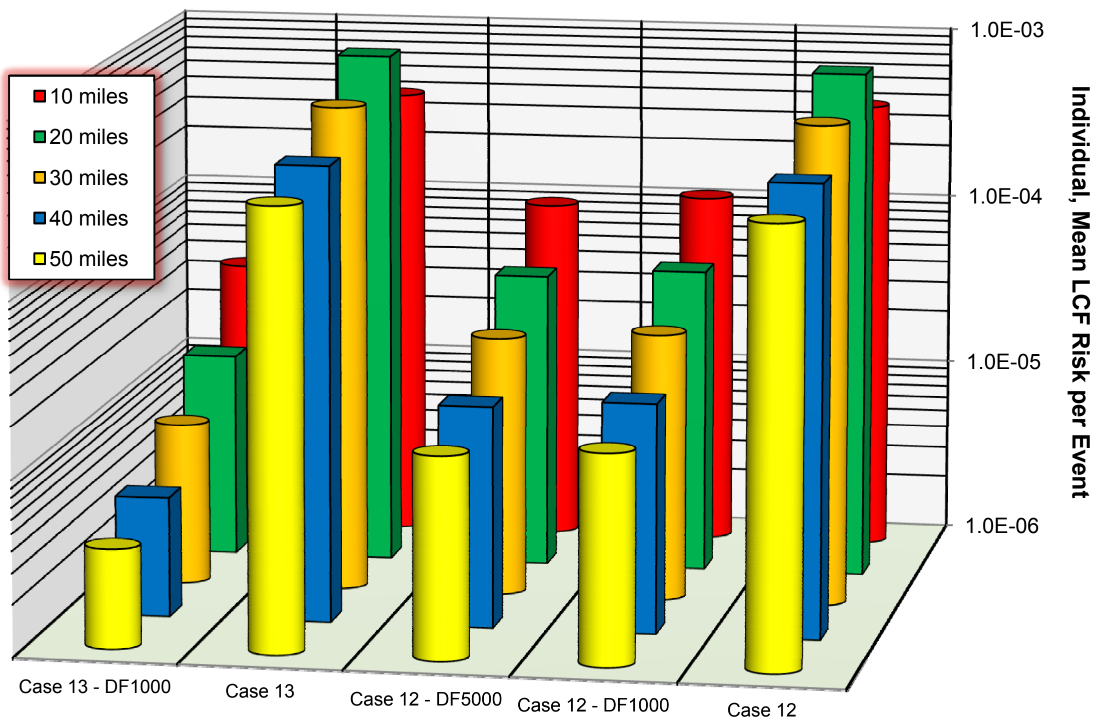

Figure 9. Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the drywell venting cases

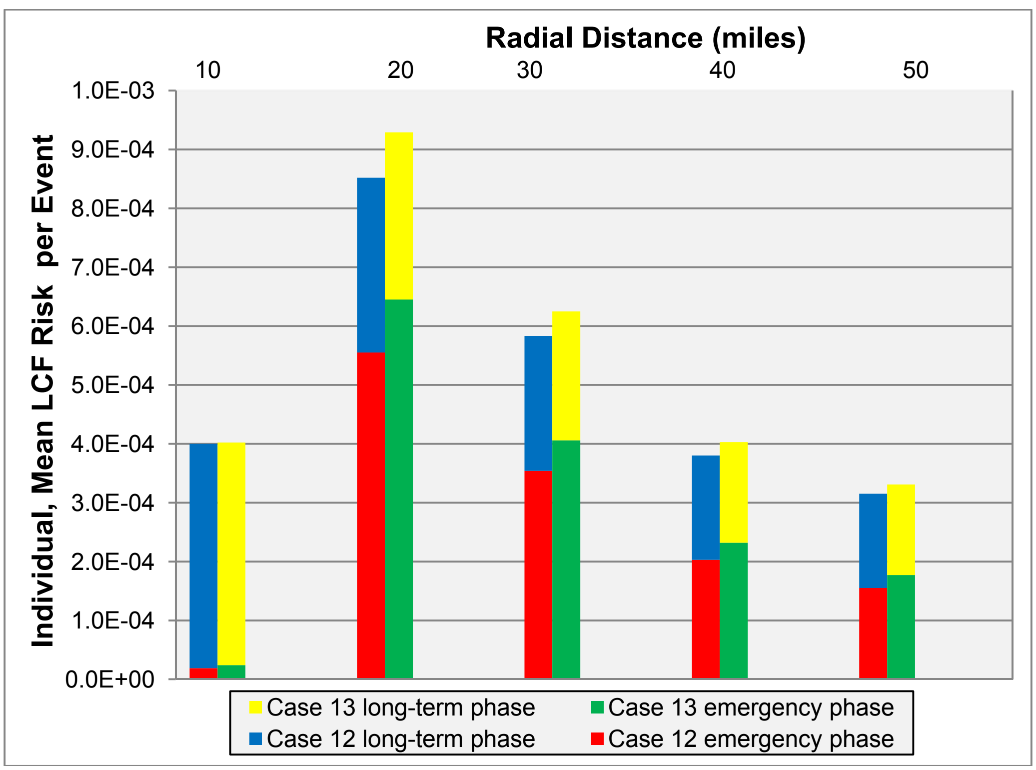

Figure 10. Individual, mean LCF risk per event for residents within a circular area at specified radial distances for unfiltered Case 12 and unfiltered Case 13

Figure 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 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 emergency phase accounts for ~30 percent of the total LCF risk when a DF is applied, and ~50 percent of the total LCF risk for the unfiltered case, within the 50-mile radial distance.

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.

For the unfiltered case, the emergency phase risk is equal to or 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 (see Table 9).

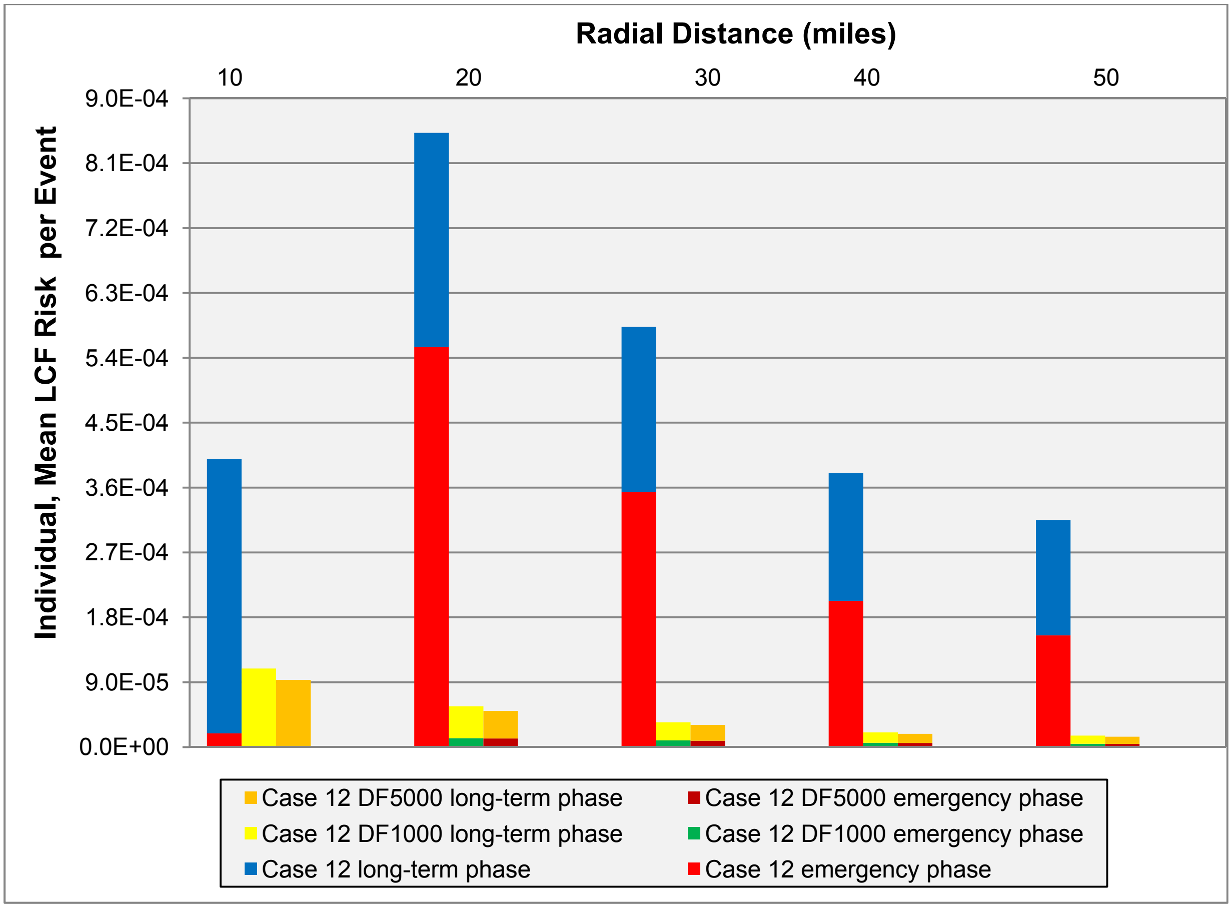

Figure 11. Case 12 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

Figure 12 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. The explanations provided for Figure 11 also apply to Figure 12. The emergency phase accounts for ~30 percent of the total LCF risk when a DF is applied, and ~55 percent of the total LCF risk for the unfiltered case, within the 50-mile radial distance.

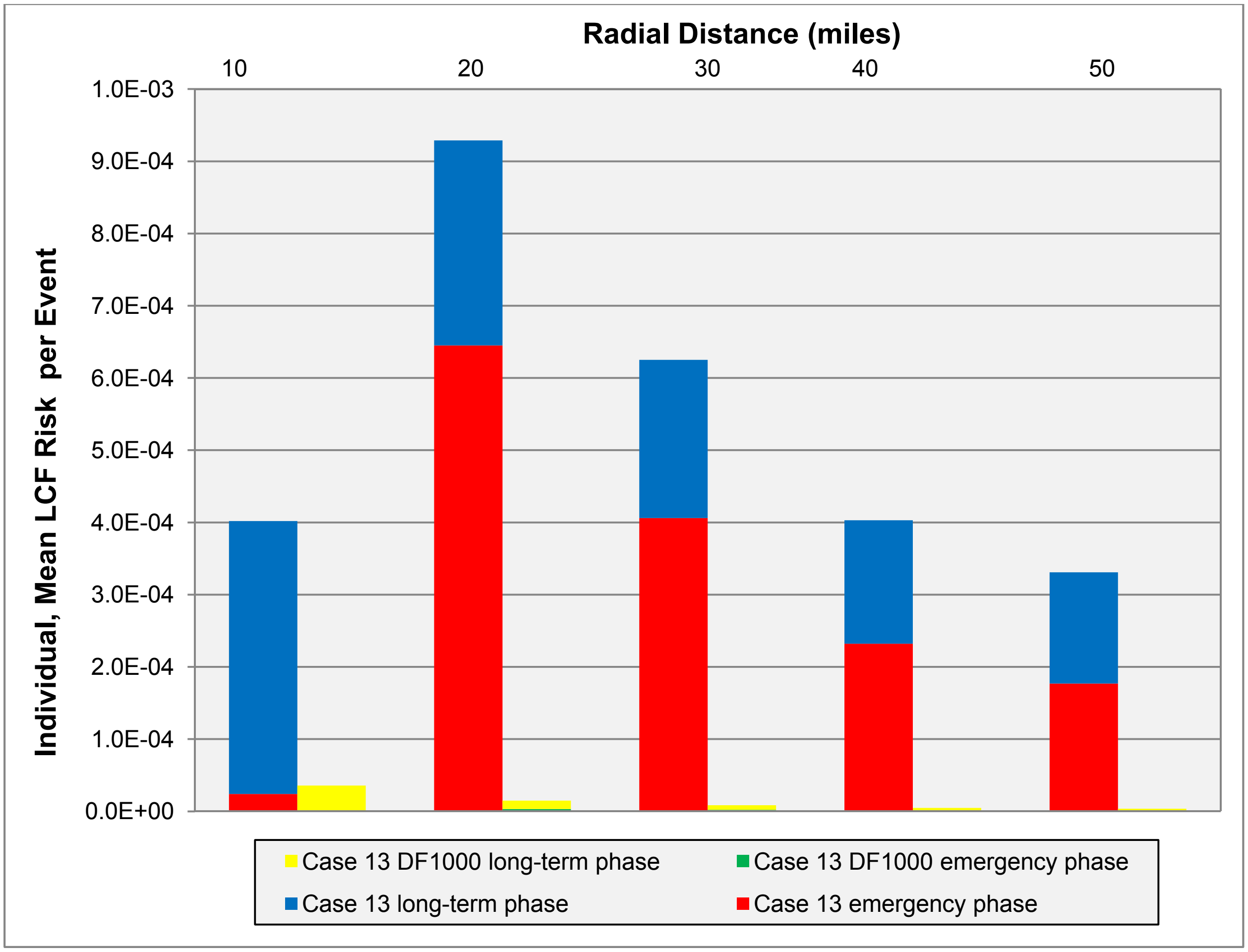

Figure 12. Case 13 individual, mean LCF risk per event for residents within a circular area at specified radial distances with a specified decontamination factor

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[7] 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[7] 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 percent 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

[7] 1.6 km = 1 mile

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 Base case with drywell venting and drywell spray
1.3	0.0
2	1.9×10^{-9}
2.5	1.1×10^{-9}

2.4.2 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. The relationship between the inverse of DF (i.e., the quantity released) and land contamination area is again superlinear for reasons discusses in Section 2.1.2.

Figure 13 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 1,000 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 Base case with drywell venting	**Case 12 DF 1000**	**Case 12 DF 5000**	**Case 13** Base case with drywell venting and drywell spray	**Case 13 DF 1000**
1	83,000	590	510	86,000	110
5	29,000	110	93	29,000	13
15	9,200	28	25	8,800	2
40	3,300	7	6	3,000	0.02

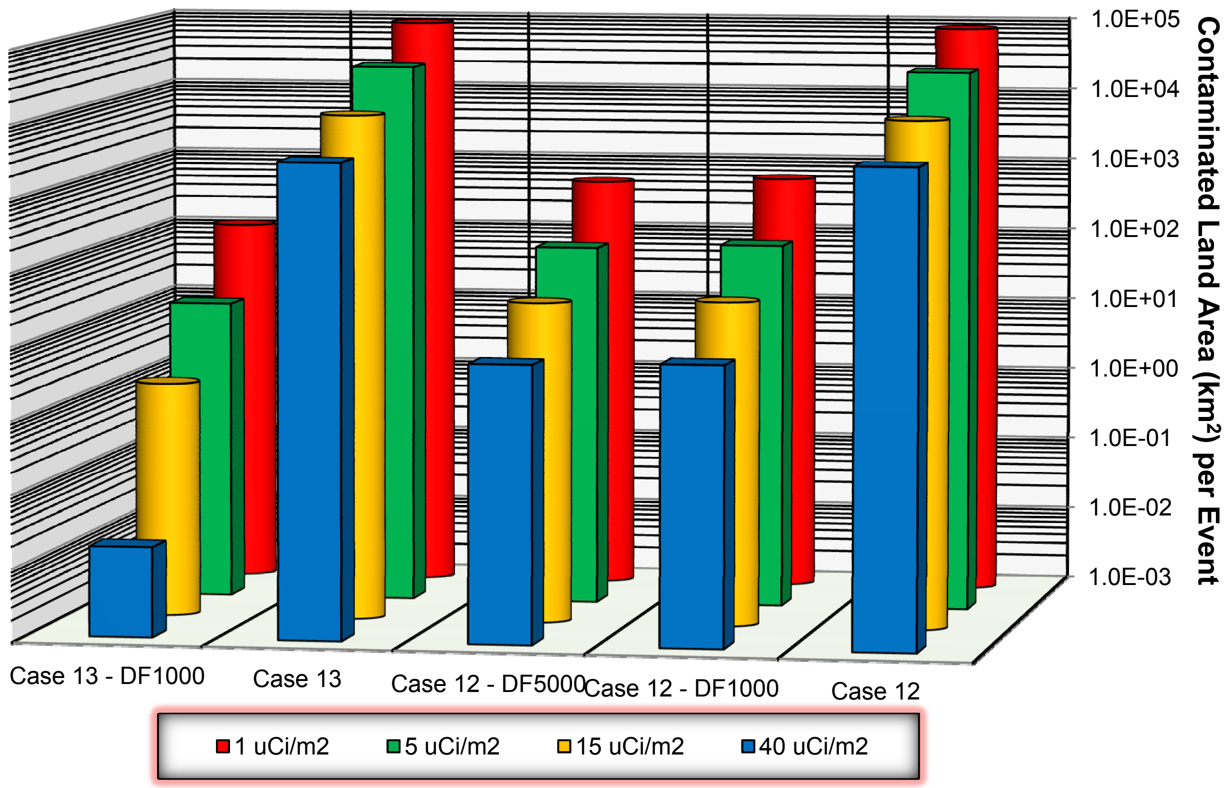

Figure 13. Mean, land contamination area per event for the drywell venting cases

2.5 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 Base case with drywell spray	0.68	0.001	0	0.004	0.005	0	0	0	0	28.2	48
Case 15 Base case with wetwell venting and drywell spray	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 source term with drywell sprays only (i.e., Case 14) is lower than the source term with drywell sprays and wetwell venting (i.e., Case 15) is mostly due to the much greater flow rate through the opened wetwell vent in Case 15 than the flow through the leaking drywell head flange in Case 14. 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 is assumed to reseat 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.

A secondary reason is that the lower containment pressure in Case 15 resulting from the wetwell venting fosters slow 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 much higher flow rates through the vent, combined with increased revaporization of cesium and iodine from RPV internals and attendant imperfect wetwell scrubbing of small aerosols produced after revaporization for Case 15, the elastic drywell head flange model in MELCOR, and the effectiveness of the drywell containment sprays lead to the nonintuitive larger environmental release for Case 15 relative to Case 14.

2.5.1 Drywell Spray Cases—Latent Cancer Fatality 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 for 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.

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 Base case with drywell spray	**Case 15** Base case with wetwell venting and drywell spray	**Case 15 DF 2**	**Case 15 DF 10**	**Case 15 DF 100**
0-10 miles	3.3×10^{-5}	9.3×10^{-5}	6.1×10^{-5}	1.8×10^{-5}	2.1×10^{-6}
0-20 miles	2.1×10^{-5}	6.2×10^{-5}	3.6×10^{-5}	9.2×10^{-6}	1.7×10^{-6}
0-30 miles	1.3×10^{-5}	4.1×10^{-5}	2.3×10^{-5}	5.8×10^{-6}	1.1×10^{-6}
0-40 miles	8.0×10^{-6}	2.6×10^{-5}	1.4×10^{-5}	3.5×10^{-6}	7.1×10^{-7}
0-50 miles	6.4×10^{-6}	2.1×10^{-5}	1.1×10^{-5}	2.7×10^{-6}	5.7×10^{-7}

Figure 14 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 14 show that unlike previous filtered cases, the vented case has a higher total LCF risk than the unfiltered case (i.e., Case 14) for a DF somewhat less than 10. The much higher flow rates through the vent, combined with increased revaporization of cesium and iodine from RPV internals and attendant imperfect wetwell scrubbing of small aerosols produced after revaporization for Case 15, the elastic drywell head flange model in MELCOR, and the effectiveness of the drywell containment sprays lead to the nonintuitive 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 percent for the five specified radial distances.

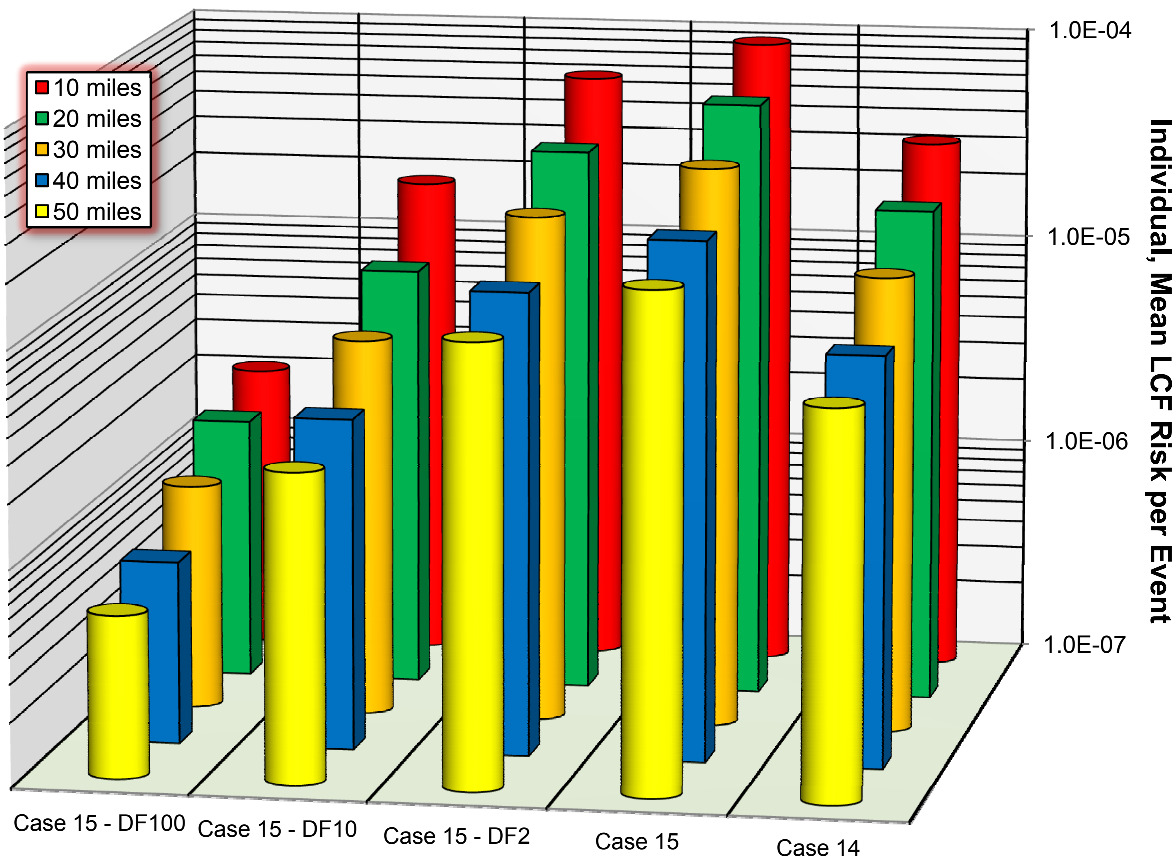

Figure 14. Individual, mean LCF risk per event for residents within a circular area at specified radial distances for the drywell spray cases

Figure 15 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 emergency phase accounts for 30 percent of the total LCF risk within the 50-mile radial distance.

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.

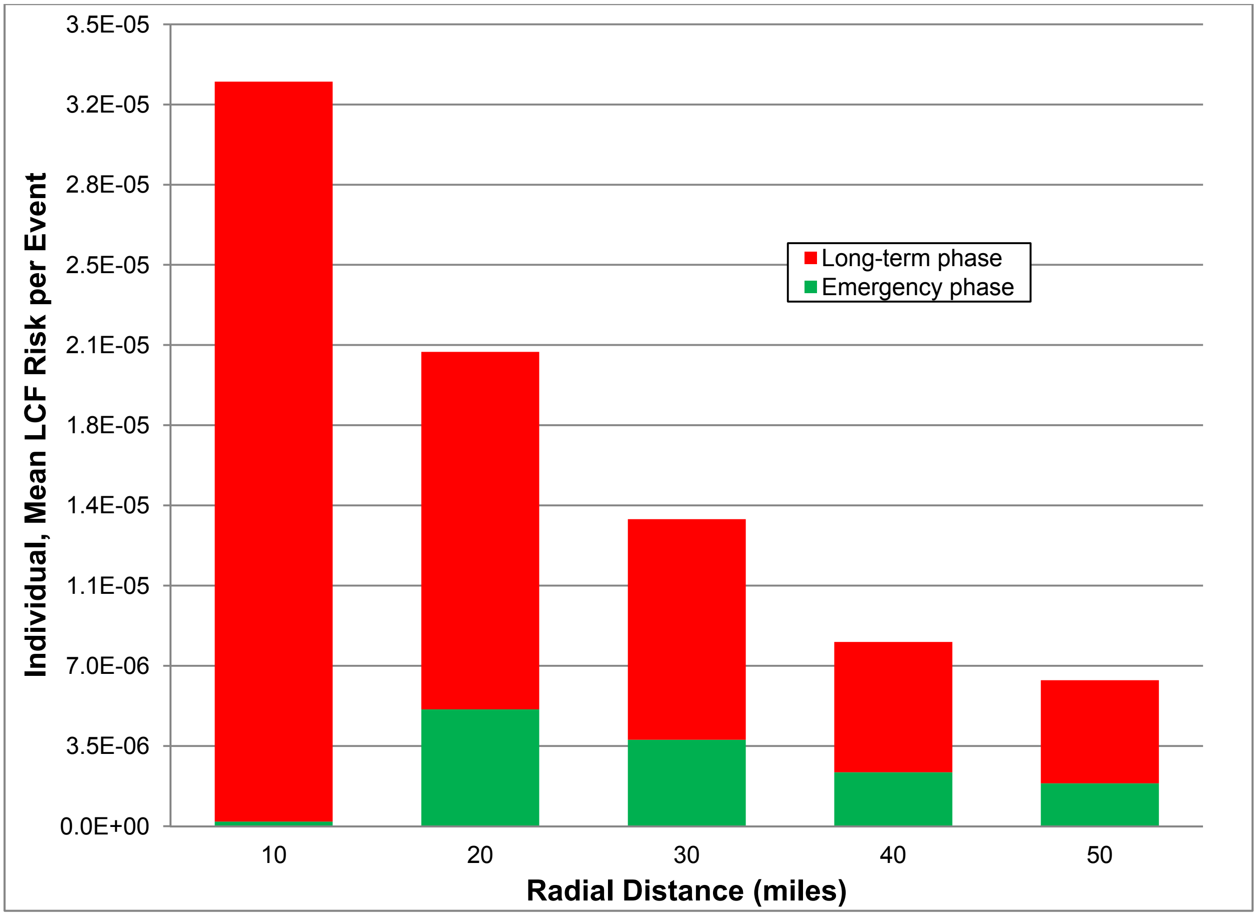

Figure 15. Case 14 individual, mean LCF risk per event for residents within a circular area at specified radial distances

Figure 16 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. The explanations provided for Figure 15 also apply to Figure 16. The emergency phase accounts for 35–70 percent of the total LCF risk within the 50-mile radial distance for all DF values.

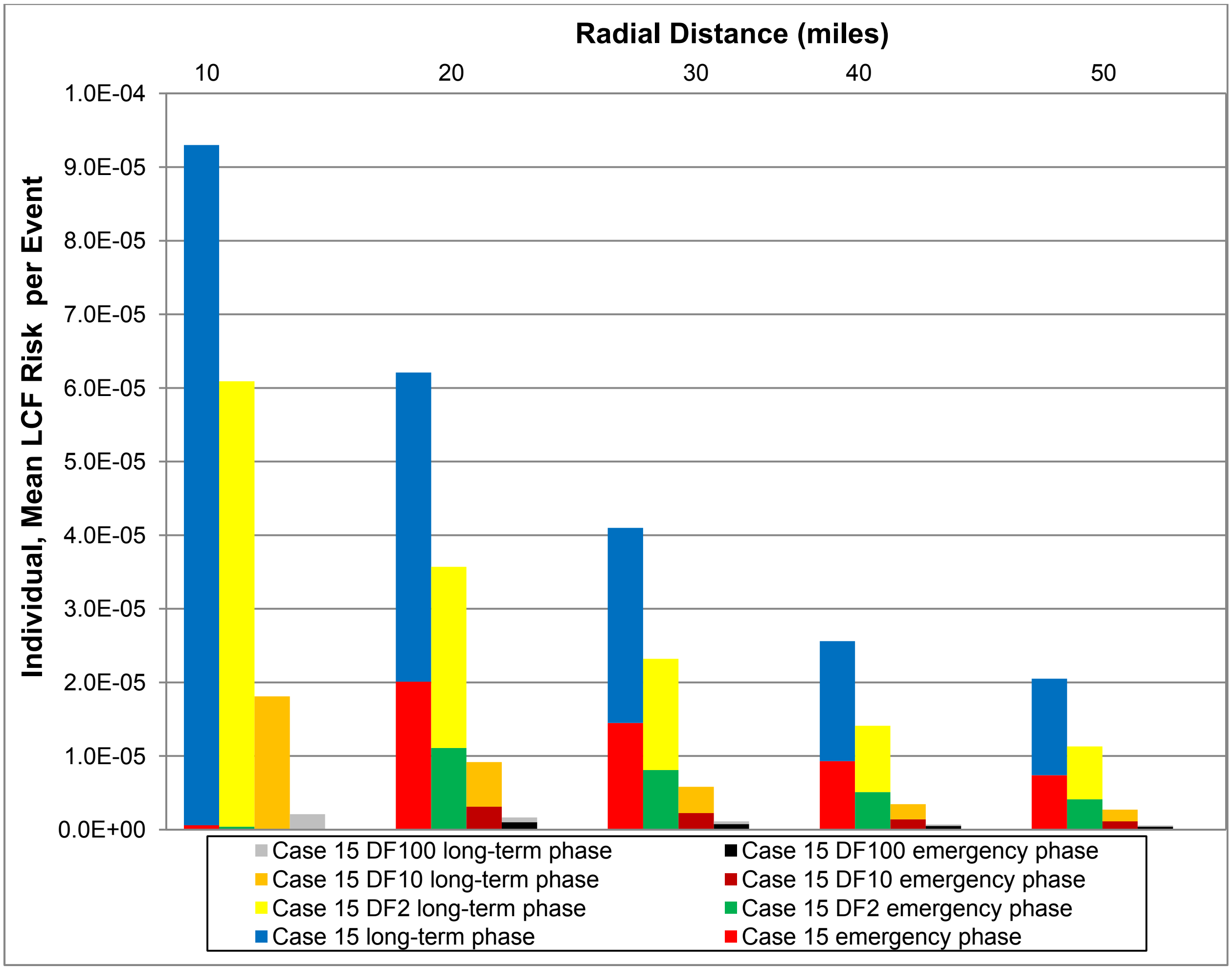

Figure 16. Case 15 individual, mean LCF risk per event for residents within a circular area at specified radial distances with specified decontamination factors

The prompt fatality risks are zero for these cases, because the release fractions (i.e., see Table 13) are too low to produce doses large enough to exceed the dose thresholds for early fatalities. 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.

2.5.2 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. As with the other cases, the relationship between the inverse of DF (i.e., the quantity released) and land contamination area is superlinear.

Figure 17 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 17 show that unlike previous filtered cases, the vented case has a higher mean land contamination area than the unvented unfiltered case (i.e., Case 14) for a DF somewhat less than 10. The much higher flow rates through the vent, combined with increased revaporization of cesium and iodine from RPV internals and attendant imperfect wetwell scrubbing of small aerosols produced after revaporization for Case 15, the elastic drywell head flange model in MELCOR, and the effectiveness of the drywell containment sprays lead to the nonintuitive 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 Base case with drywell spray	**Case 15** Base case with wetwell venting and drywell spray	**Case 15 DF 2**	**Case 15 DF 10**	**Case 15 DF 100**
1	390	1,200	480	53	1
5	51	140	53	3	0.01
15	10	28	8	0.3	0.001
40	2	5	1	0.02	0

* 2.59 km^2 = 1 mile^2

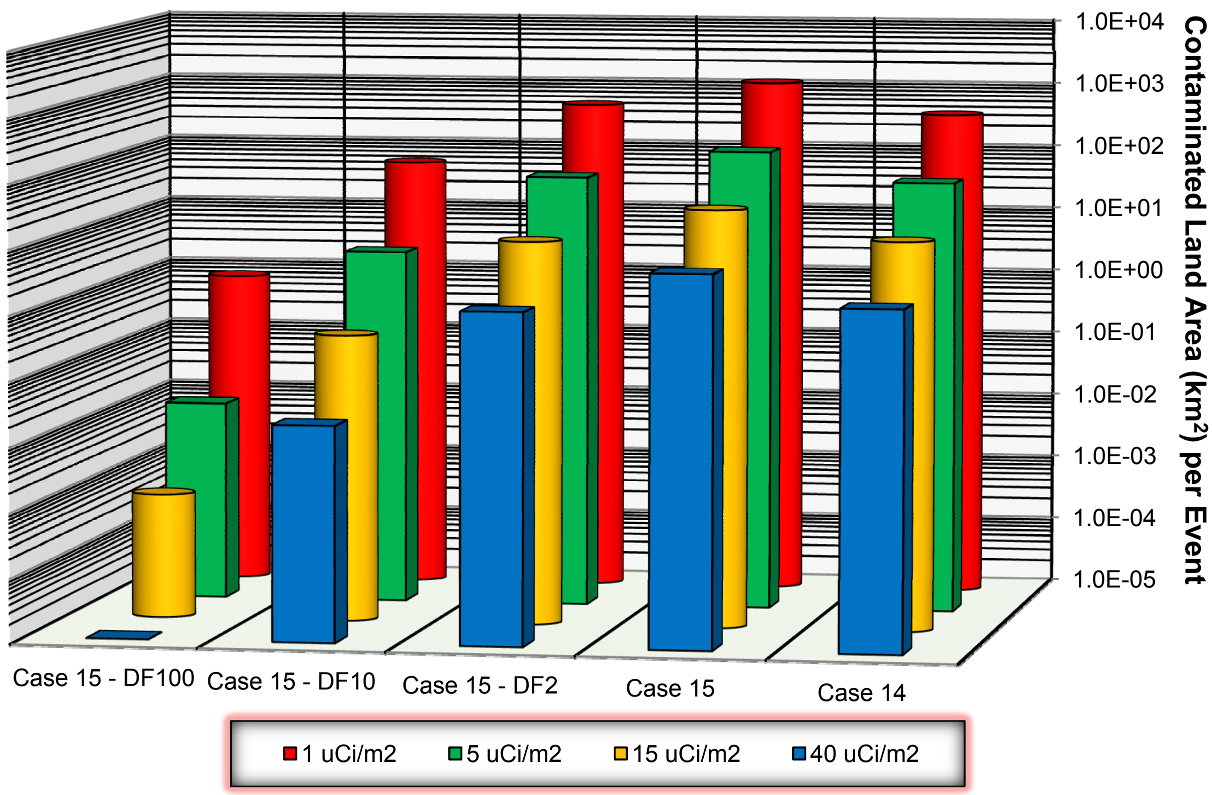

Figure 17. Mean, land contamination area per event for the drywell spray cases

2.6 Population Dose

A sum of all the effective doses to all the individuals within a given radial distance is roughly proportional to the number of radiation-induced health effects, using the LNT model. 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 Base case	**Case 3** Base case with wetwell venting	**Case 3** **DF 2**	**Case 3** **DF 10**	**Case 3** **DF 100**
580,000	460,000	320,000	180,000	140,000

Case 6 Base case with core spray	**Case 7** Base case with wetwell venting and core spray	**Case 7** **DF 2**	**Case 7** **DF 10**	**Case 7** **DF 100**
310,000	240,000	140,000	37,000	8,200

Case 12 Base case with drywell venting	**Case 12** **DF 1,000**	**Case 12** **DF 5,000**	**Case 13** Base case with drywell venting and drywell spray	**Case 13** **DF 1,000**
3,800,000	230,000	210,000	3,900,000	60,000

Case 14 Base case with drywell spray	**Case 15** Base case with wetwell venting and drywell spray	**Case 15** **DF 2**	**Case 15** **DF 10**	**Case 15** **DF 100**
86,000	280,000	160,000	43,000	8,800

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 percent 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 guideline for habitability criterion is a dose rate of 500 mrem/yr starting the first year.

Unlike the doses included in LCF risks, population doses also include the ingestion pathway. The population doses include both public doses from the ingestion pathway and doses to decontamination workers working in the offsite 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 percent of the population dose for the wetwell venting unfiltered cases considered
- 15–30 percent of the population dose for the wetwell venting filtered cases considered
- 5 percent of the population dose for the drywell venting unfiltered cases considered
- 20-30 percent of the population dose for the drywell venting filtered cases considered.

Figure 18 shows the mean population dose per event within a 50-mile radius for all cases considered. Table 16 and Figure 18 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.

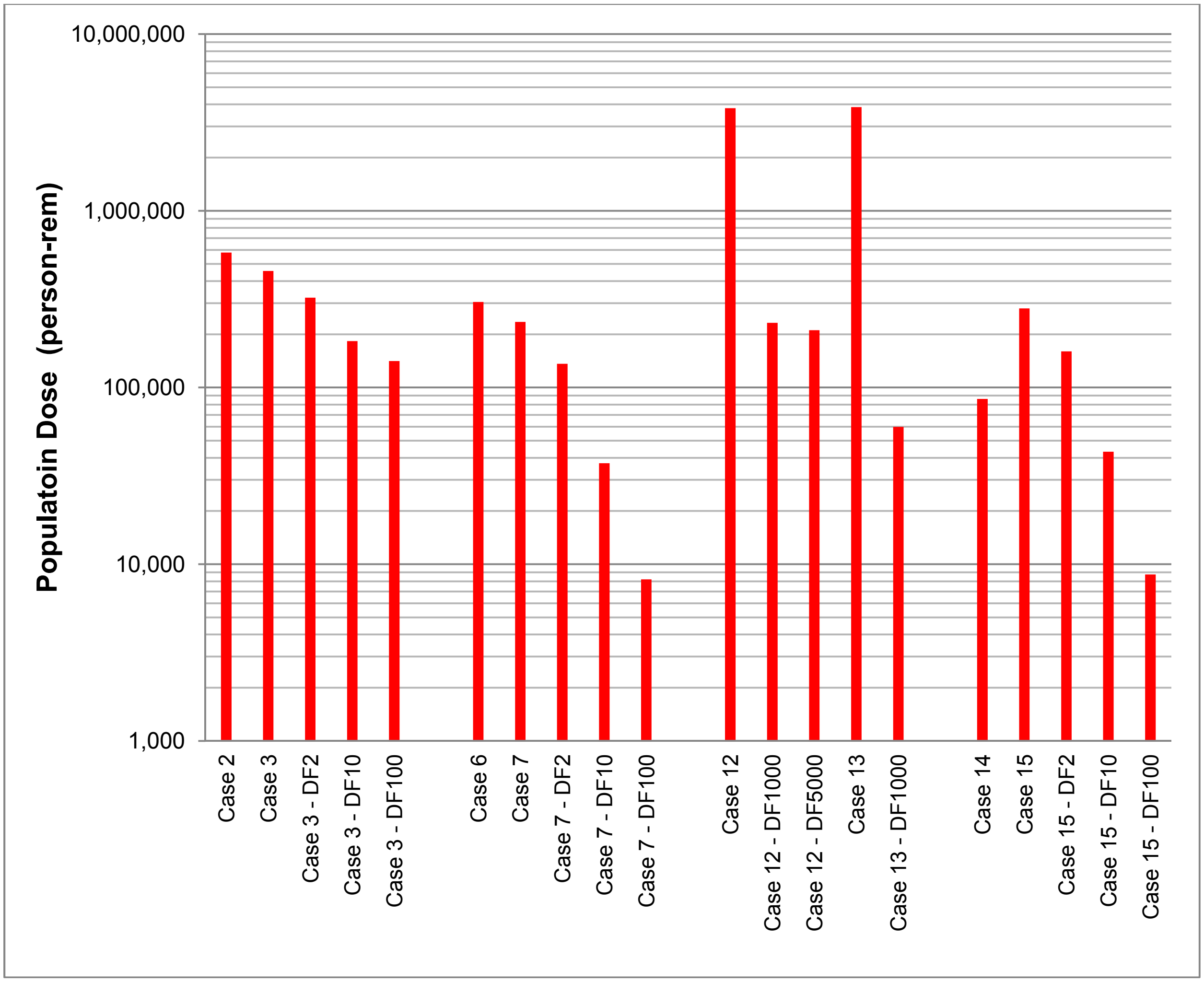

Figure 18. Mean population dose per event for residents within a circular area at the 50-mile radial distance with specified decontamination factors for all the cases considered

2.7 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 8-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. This compounds the nonlinear effect between a DF and source term magnitude due to the DF applying to only the release pathway where the filter is connected. 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 Base case	**Case 3** Base case with wetwell venting	**Case 3 DF 2**	**Case 3 DF 10**	**Case 3 DF 100**
0-10 miles	220	200	150	89	67
0-50 miles	1,900	1,700	890	270	190

	Case 6 Base case with core spray	**Case 7** Base case with wetwell venting and core spray	**Case 7 DF 2**	**Case 7 DF 10**	**Case 7 DF 100**
0-10 miles	130	71	38	8.0	0.58
0-50 miles	850	480	180	18	0.81

	Case 12 Base case with drywell venting	**Case 12 DF 1,000**	**Case 12 DF 5,000**	**Case 13** Base case with drywell venting and drywell spray	**Case 13 DF 1,000**
0-10 miles	1,400	150	140	1,300	30
0-50 miles	33,000	390	370	33,000	38

	Case 14 Base case with drywell spray	**Case 15** Base case with wetwell venting and drywell spray	**Case 15 DF 2**	**Case 15 DF 10**	**Case 15 DF 100**
0-10 miles	34	100	58	11	0.56
0-50 miles	120	590	240	20	0.70

All of the costs for the six cost categories are summed over the entire offsite area (to a maximum radius of 50 miles) 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 19 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 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 results in a lower economic costs than their respective unfiltered case.

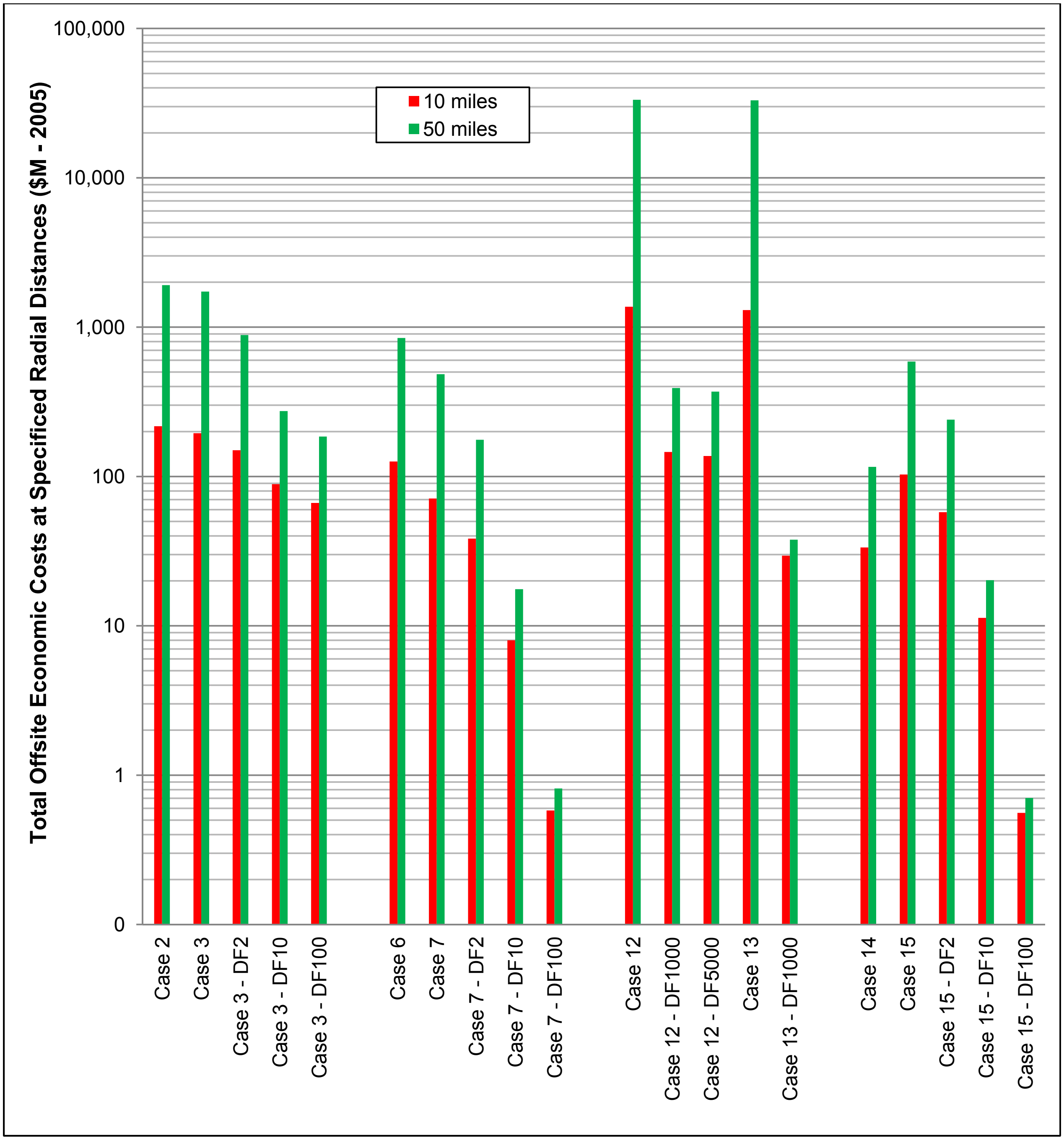

Figure 19. Mean, total offsite economic costs per event within a circular area at specified radial distances with specified decontamination factors for all the cases considered

To better identify which filtered cases have costs that are directly correlated to land contamination, Figure 20 shows the ratio of economic costs to contaminated land area; more specifically, the ratio of the mean, total offsite economic costs in millions of 2005 dollars per event for the 50-mile radial distance to the area of land exceeding the 15 μCi/m^2 of Cs-137 areal concentration, for all the cases considered. The ratio varies from ~3 to ~800. Figure 20 shows that the economic cost computation is more complicated than a constantly proportional relationship to contaminated land area.

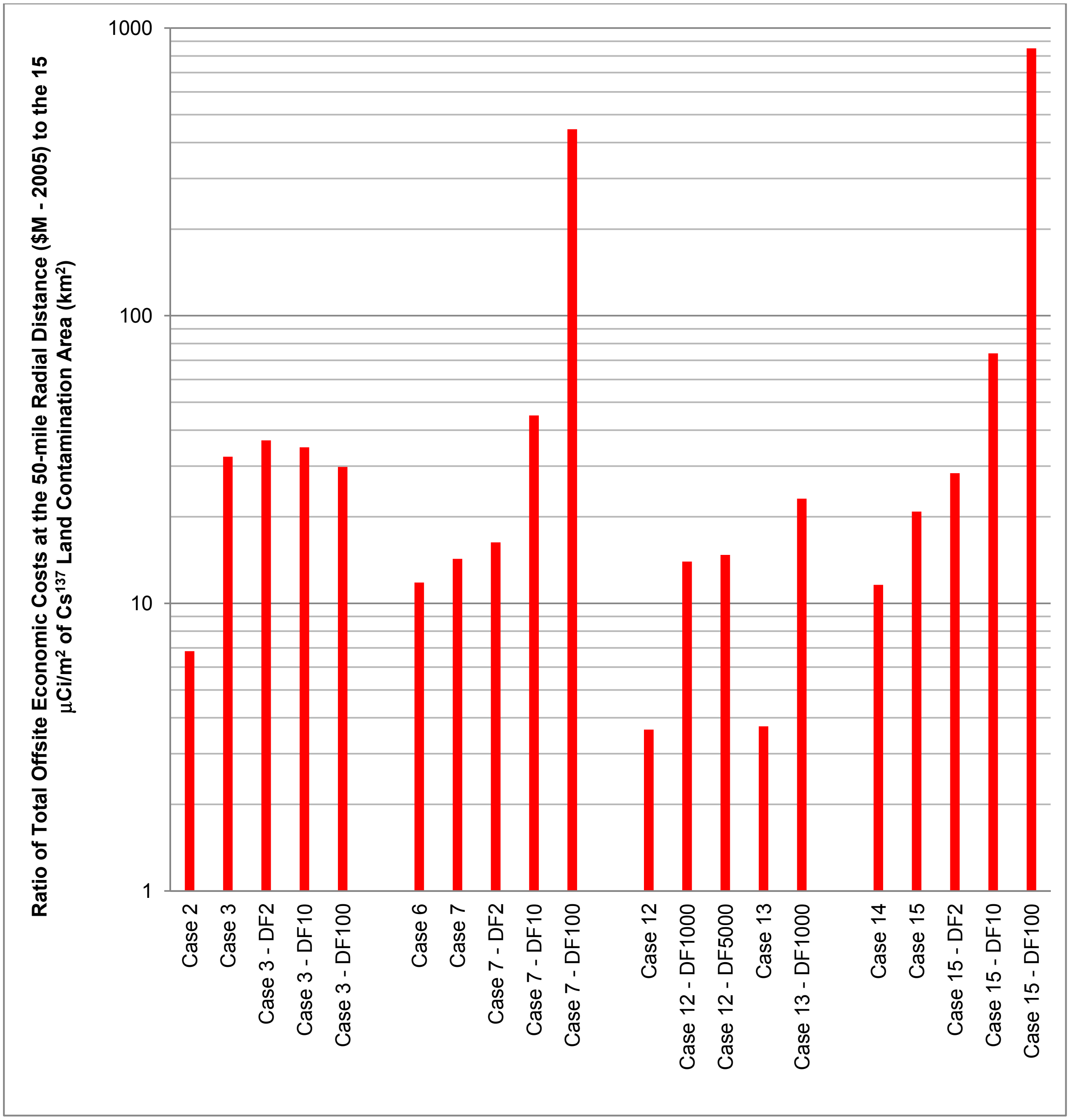

Figure 20. Ratio of mean, total offsite economic costs per event within a circular area of 50-mile radius to the land contamination area exceeding 15 μCi/m^2 of Cs-137 for all the cases considered

3. 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 public individual fatality risks, land contamination, population dose, and economic costs for each of the cases. All individual fatality 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., latent cancer fatality [LCF] risk per event or prompt-fatality risk per event). Table 20 shows the results for all four consequence metrics for the eight cases at the 50-mile radial distance and the 15 $\mu Ci/m^2$ contamination threshold with specified DFs for the wetwell and drywell venting cases considered.

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 using the 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.

Table 20. Summary of MACCS2 Results for the 50-mile Radial Distance and the 15 μCi/m² Contamination Threshold for the Cases Considered

Event	Case 2 Base case	Case 3 Base case with wetwell venting Unfiltered Filtered DF = 10	Case 6 Base case with core spray	Case 7 Base case with wetwell venting and core spray Unfiltered Filtered DF = 10
Population dose at the 50-mile radius per event (rem)	580,000	460,000 180,000	310,000	240,000 37,000
LCF risk at the 50-mile radius per event	4.8×10^{-5}	3.3×10^{-5} 1.3×10^{-5}	2.5×10^{-5}	1.6×10^{-5} 2.2×10^{-6}
Contaminated area (km²) for levels exceeding 15 μCi/m² per event	280	54 8	72	34 0.4
Total economic cost at the 50-mile radius per event ($M–2005)	1,900	1,700 270	850	480 18

Event	Case 12 Base case with drywell venting Unfiltered Filtered 1 DF = 1,000 Filtered 2 DF = 5,000	Case 13 Base case with drywell venting and drywell spray Unfiltered Filtered DF = 1,000	Case 14 Base case with drywell spray	Case 15 Base case with wetwell venting and drywell spray Unfiltered Filtered DF = 10
Population dose at the 50-mile radius per event (rem)	3,800,000 230,000 210,000	3,900,000 60,000	86,000	280,000 43,000
LCF risk at the 50-mile radius per event	3.2×10^{-4} 1.6×10^{-5} 1.4×10^{-5}	3.3×10^{-4} 3.7×10^{-6}	6.4×10^{-6}	2.1×10^{-5} 2.7×10^{-6}
Contaminated area (km²) for levels exceeding 15 μCi/m² per event	9,200 28 25	8,800 2	10	28 0.3
Total economic cost at the 50-mile radius per event ($M–2005)	33,000 390 370	33,000 38	120	590 20

3.1 Wetwell Venting—Latent Cancer Fatality 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 triggered less often. 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 sublinearity 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 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.

For all wetwell venting cases, except Case 7 and Case 15 each with a DF greater than 10 (where total LCF risks are lowest), 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 guideline of 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. Table 21 shows the percent contribution of the emergency phase LCF risk to the total LCF risk for each of the wetwell venting cases considered for the specified radial distances.

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 21. 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 **Base case**	**Case 3** **Base case with wetwell venting**	**Case 3** **DF 2**	**Case 3** **DF 10**	**Case 3** **DF 100**
0-10 miles	0%	1%	0.5%	0.5%	0.5%
0-50 miles	15%	40%	40%	40%	40%
	Case 6 **Base case with core spray**	**Case 7** **Base case with wetwell venting and core spray**	**Case 7** **DF 2**	**Case 7** **DF 10**	**Case 7** **DF 100**
0-10 miles	0.5%	0.5%	0.5%	0%	1.5%
0-50 miles	35%	30%	30%	35%	70%
	Case 14 **Base case with drywell spray**	**Case 15** **Base case with wetwell venting and drywell spray**	**Case 15** **DF 2**	**Case 15** **DF 10**	**Case 15** **DF 100**
0-10 miles	0.5%	0.5%	1%	0.5%	1.5%
0-50 miles	30%	35%	35%	40%	70%

3.2 Drywell Venting—Latent Cancer Fatality 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, primarily due to short-term and long-term mitigative actions (see discussion in Section 3.1).

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 percent 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.

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 22 shows the percent contribution of the emergency phase LCF risk to the total LCF risk for each of the drywell venting cases considered for the specified radial distances.

Table 22. 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 Base case with drywell venting	**Case 12 DF 1,000**	**Case 12 DF 5,000**	**Case 13** Base case with drywell venting and drywell spray	**Case 13 DF 1,000**
0-10 miles	5%	0%	0.5%	5%	0.5%
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 percent 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.

3.3 <u>Land Contamination</u>

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 [13].

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 unvented 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.

3.4 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 discussion for individual LCF and prompt fatality risks in 3.1 and 3.2 apply for population dose too.

One difference is that the population dose results include public doses from the ingestion pathway and doses to offsite 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 percent of the population dose for the wetwell venting unfiltered cases considered
- 15–30 percent of the population doses for the wetwell venting filtered cases considered
- 5 percent of the population doses for the drywell venting unfiltered cases considered
- 20–30 percent of the population doses for the drywell venting filtered cases considered

3.5 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 in economic cost. 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.

4. CONCLUSIONS

These MACCS consequence analyses show a clear benefit in applying an external filter to either the wetwell or drywell vent path[8]. More specifically:

- 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 latent cancer fatality [LCF] risk (i.e., 40–95 percent reduction) when compared to the unfiltered cases.

- 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 population dose (i.e., 50–95 percent reduction) when compared to the unfiltered cases. Unlike the LCF risk calculations, the population dose includes public doses from the ingestion pathway and doses to offsite decontamination workers.

- All the filtered cases with an external filtered vent path , results in a several order-of-magnitude reduction in Cs-137 land contamination.

- For all cases considered, the conditional prompt fatality risk is either zero or essentially zero.

- 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 (i.e., >60 percent to orders of magnitude reduction) than their respective unfiltered cases.

When a DF is applied to a filtered vent path, the LCF risk, population dose, contaminated land area, and economic consequence results are all nonlinearly related to the inverse of the DF (which represents the release magnitude). The relationship is sublinear between the inverse of DF and LCF risk or population dose. This relationship 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. The relationship between the inverse of DF and land contamination area is observed to be superlinear, because in this analysis land contamination is defined as exceeding particular thresholds of Cs-137 areal concentration. Lastly, economic costs are dominated by the implementation of decontamination, which depends on whether or not the habitability or farmability criterion is exceeded. Since habitability and farmability criteria are based on contamination thresholds, there is an inherently nonlinear relationship between source term magnitude and economic costs.

[8] With the exception that the external filter was not beneficial for a DF=2 for the Case 15 with drywell spray and wetwell vent path, compared to Case 14 with drywell spray and no venting.

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