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SAND2013-0533
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Printed January 2013

Analysis of Dose Consequences Arising from the Release of Spent Nuclear Fuel from Dry Storage Casks

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Advanced Nuclear Fuel Cycle Technologies

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Abstract

The resulting dose consequences from releases of spent nuclear fuel (SNF) residing in a dry storage casks are examined parametrically. The dose consequences are characterized by developing dose versus distance curves using simplified bounding assumptions. The dispersion calculations are performed using the MELCOR Accident Consequence Code System (MACCS2) code. Constant weather and generic system parameters were chosen to ensure that the results in this report are comparable with each other and to determine the relative impact on dose of each variable. Actual analyses of site releases would need to accommodate local weather and geographic data. These calculations assume a range of fuel burnups, release fractions (RFs), three exposure scenarios (2 hrs and evacuate, 2 hrs and shelter, and 24 hrs exposure), two meteorological conditions (D-4 and F-2), and three release heights (ground level – 1 meter (m), 10 m, and 100 m). This information was developed to support a policy paper being developed by U.S. Nuclear Regulatory Commission (NRC) staff on an independent spent fuel storage installation (ISFSI) and monitored retrievable storage installation (MRS) security rulemaking.

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ACKNOWLEDGEMENTS

This work was conducted under NRC contract JCN# W1140. The authors gratefully acknowledge the guidance and support of Messrs. Philip Brochman and James Vaughn, of the NRC's Office of Nuclear Security and Incident Response.

The authors would also like to recognize the excellent modeling efforts of Raymond Jun, which form the technical basis of this report.

ABBREVIATIONS/DEFINITIONS

ADAMS	NRC's Agencywide Documents Access and Management System
AED	aerodynamic equivalent diameter
GWd/MTHM	gigawatt-days per metric ton of heavy metal
HLW	high level radioactive waste
ISFSI	independent spent fuel storage installation
MRS	monitored retrievable storage installation
NRC	U.S. Nuclear Regulatory Commission
NMSS	Office of Nuclear Material Safety and Safeguards
NSIR	Office of Nuclear Security and Incident Response
PWR	pressurized water reactor
SGI	Safeguards Information
SNF	spent nuclear fuel
SNL	Sandia National Laboratories

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1 INTRODUCTION

1.1 Background

On December 20, 2007, the U.S. Nuclear Regulatory Commission (Commission or NRC), in Staff Requirements Memorandum SRM-SECY-07-0148 (NRC Agencywide Documents Access and Management System (ADAMS) Accession No. ML073530119), directed the Office of Nuclear Security and Incident Response (NSIR) staff to undertake rulemaking to update the security requirements for facilities storing spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The Commission directed that the proposed security rule use a risk-informed and performance-based approach under which licensees would calculate potential releases from an independent spent fuel storage installation (ISFSI) or a monitored retrievable storage installation (MRS) in response to certain NRC-specified security scenarios. The analyses conducted for this effort builds upon the work completed by Sandia National Laboratories (SNL) in previous contract JCN# 5463 (previously JCN# 5412) with the Office of Nuclear Material Safety and Safeguards (NMSS) regarding security assessments of spent fuel storage systems.

The regulatory approach contemplated by the NRC staff under this proposed rulemaking would require licensees to calculate the dose to plant workers and/or the public from a release of radioactive material from an independent spent fuel storage installation (ISFSI) or monitored retrievable storage (MRS) due to specific sabotage events. The licensee would also be required to verify the dose from such releases is less than a specific acceptance criterion. If the results of the licensee's calculations do not meet the acceptance criteria, then the licensees would be required to modify their physical protection system, protective strategy, or the design of their facility in order to meet the dose criteria. To perform these calculations, the licensee would use a quantity of radionuclides identified by the guidance document in an acceptable dispersion model to calculate the dose consequences from their particular storage system or facility.

1.2 Objective

This report details generic dose consequence analyses for a variety of parameters including fuel contents, release fraction, release height, weather/stability class, and exposure conditions. These calculations were intentionally performed using simplistic initial and boundary conditions to remain non-site specific and unclassified. Actual dose consequence analyses performed by licensees would include details of cask type, attack methodology, local meteorological conditions, and geographic data; and thus would be controlled as Safeguards Information (SGI), in accordance with 10 CFR 73.21 and 73.22. The intent of these dispersion calculations is to provide a quick reference for an order-of-magnitude evaluation of various security scenarios.

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2 DOSE CONSEQUENCE METHODOLOGY

The general approach taken by SNL in these analyses was to make simplifying assumptions in order to reduce the complexity of the analyses while maximizing the flexibility of their application. The four simplifying assumptions for these analyses are as follows.

- The doses received in the exposure scenarios identified for this study are dominated by the material that is released from a SNF cask and is aesorolized in a plume. In particular, the doses of concern are incurred due to respirable particles that have an aerodynamic equivalent diameter (AED) between 0.1 to 10 microns (μm); and thus are susceptible to inhalation and retention in the lungs. While these analyses do include ground shine effects from deposited aerosols, the dose contribution from radioactive debris distributed locally around the cask and direct shine from the exposed SNF within the cask are ignored as localized effects.

- SNF includes numerous actinides and fission products, but fifteen of these radionuclides account for 99% of the received dose. These analyses are conducted for a one-Curie baseline value for each of these radionuclides and for each meteorological condition.

- The total dose is assumed to be a sum of the doses from the contribution of each radionuclide linearly scaled from the baseline value of one Curie to the actual quantity released.

- The release fraction for all radionuclides is applied uniformly. Previous studies indicate that certain volatiles will be preferentially released from SNF during attacks. The tools developed for these analyses are adaptable to apply independent release fractions for each radionuclide but were not used in this fashion for the sake of simplicity.

The radionuclides that dominate the inhalation dose in alphabetical order are Am-241, Ce-144, Cm-244, Co-60, Cs-134, Cs-137, Eu-154, Kr-85, Pu-238, Pu-239, Pu-240, Pu-241, Ru-106, Sr-90, and Y-90. Figure 2.1 shows the relative contribution of each these radionuclides to the total dose for 5 year old PWR 17×17 fuel with a burnup of 45 gigawatt-days per metric ton of heavy metal (GWd/MTHM). In this plot, the dose from each radionuclide has been normalized by the maximum dose (Cm-244).

All the calculations in this report assume releases as a percentage of the radionuclide inventory of a 17×17 PWR fuel assembly. However, the quantity of radionuclides in a BWR assembly with the same burnup as a PWR assembly is roughly scalable by the mass of SNF, which is approximately 2.5 times less. Therefore the release fraction from the same fuel damage would give a normalized value for BWR fuel of 2.5, i.e. an event that caused 0.1% release of a PWR assembly would result in 0.25% release from a BWR. The absolute quantity of the release is unaffected as illustrated in Figure 2.2, but the choice to normalize by the contents of a fuel assembly does alter the percentage. All the results presented through the rest of this report may be converted to BWR fuel by applying this mass correction factor.

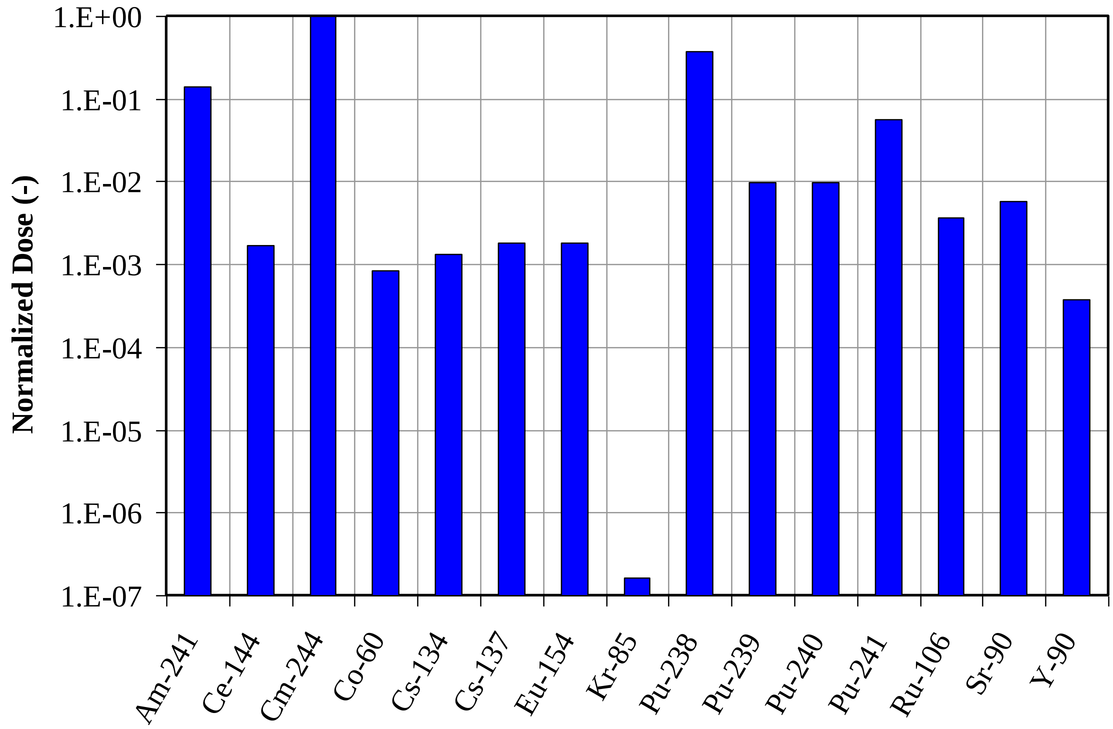

Figure 2.1 **Relative doses from dominant radionuclides in SNF normalized by maximum component dose for 5 year old 45 GWd/MTHM burnup and 4% enrichment PWR 17×17 fuel.**

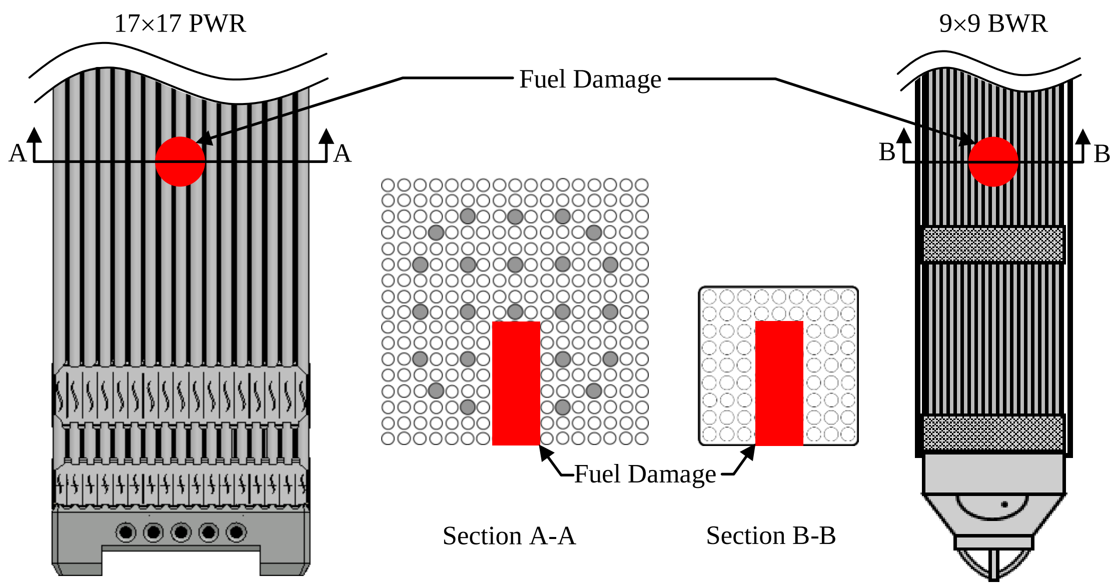

Figure 2.2 **Schematic showing the same fuel damage on PWR 17×17 and BWR 9×9 fuel assemblies.**

3 RESULTS

All calculations presented in this report were performed using the MELCOR Accident Consequence Code System Version 2 (MACCS2) straight-line Gaussian plume model.[1] MACCS2 determines the doses from potential releases of radionuclides using atmospheric transport and particulate deposition models. Further discussion of the details specific to these MACCS2 analyses are given in Appendix A.

3.1 Aerosol Size Distributions

Three aerosol size distributions were examined to determine the sensitivity of the MACCS2 results to the choice of initial particle size. Figure 3.1 shows the mass fractions of these three distributions as a function of aerodynamic equivalent diameter (AED). Two of these distributions assumed uniform particle sizes of AED of 0.6 and 3 μm. The third was a multi-bin lognormal distribution based on experimental results of conical shaped charge (CSC) interactions with spent fuel samples.[2] The last size bin of AED = 10 μm was artificially increased in order to make the total mass fraction sum to unity. Figure 3.2 shows the cumulative mass fraction as a function of AED for the Schmidt (1982) data and an aerosol distribution described by a mass median diameter (MMD) of 1.5 μm and geometric standard deviation (GSD) of 2.5. This size distribution represents the upper limit of the available data and therefore a slightly conservative choice for aerosol transport.

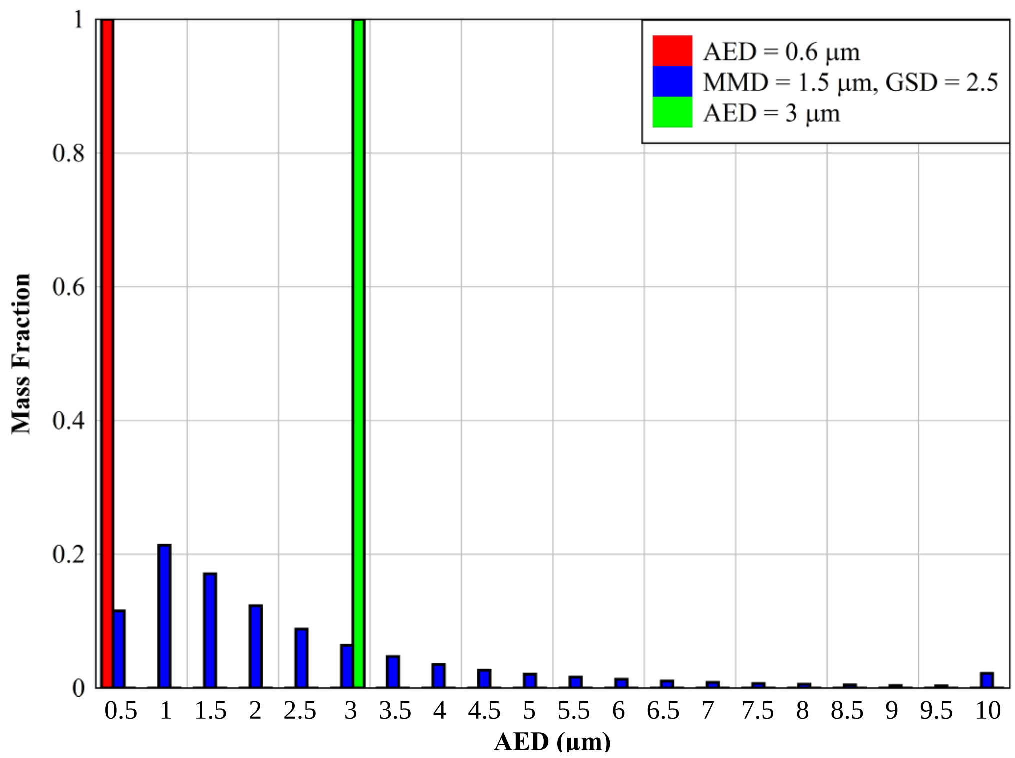

Figure 3.1 Mass fraction as a function of aerodynamic diameter for three particle size distributions.

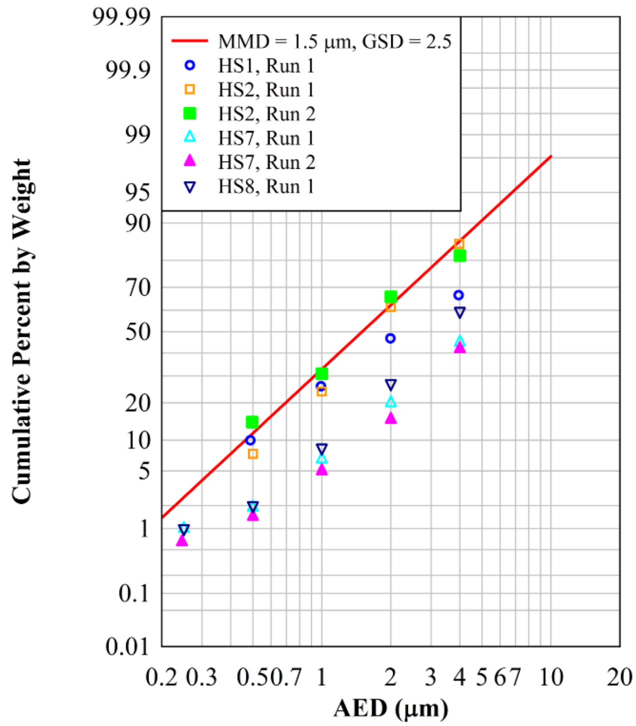

Figure 3.2 **Aerodynamic particle size distributions from spent fuel acted on by a conical shape charge.**

Data reproduced from Schmidt (1982) Figure 5-4.

Figure 3.3 shows the centerline dose as a function of distance for the three aerosol size distributions assuming 0.1% RF of a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup in a D-4 meteorological condition. The first designator in the meteorological condition is the atmospheric stability class, which dictates the rate at which the plume disperses (or mixes with the atmosphere) as the radioactive material moves away from the source of the release. The second designator in the meteorological condition is for the wind speed in meters per second. The parameters reflected in this release scenario are repeated while varying a single variable throughout this report in order to determine the relative influence of each variable. The doses at any given distance are nearly identical for all three distributions. The biggest differences are observed at the furthest distance of the computational space. At distances of 100 km, the doses resulting from the single particle size distributions are 27% higher and 13% lower for AED = 0.6 and 3 μm, respectively, as compared to the multibin distribution. For the remainder of results in this report, the multi-bin size distribution based on the Schmidt data is used.

A 0.05 Sievert (Sv) [5 rem] dose line is also included in Figure 3.3, and subsequent dose presentations, to provide a point of comparison to the 0.05 Sv dose limit at the controlled area boundary (or site area boundary) acceptance criterion contemplated by the Commission in SRM-SECY-07-0148. As can be seen in Figure 3.3, a 0.05 Sv dose threshold is exceeded at approximately one kilometer from the SNF cask due to the hypothetical release.

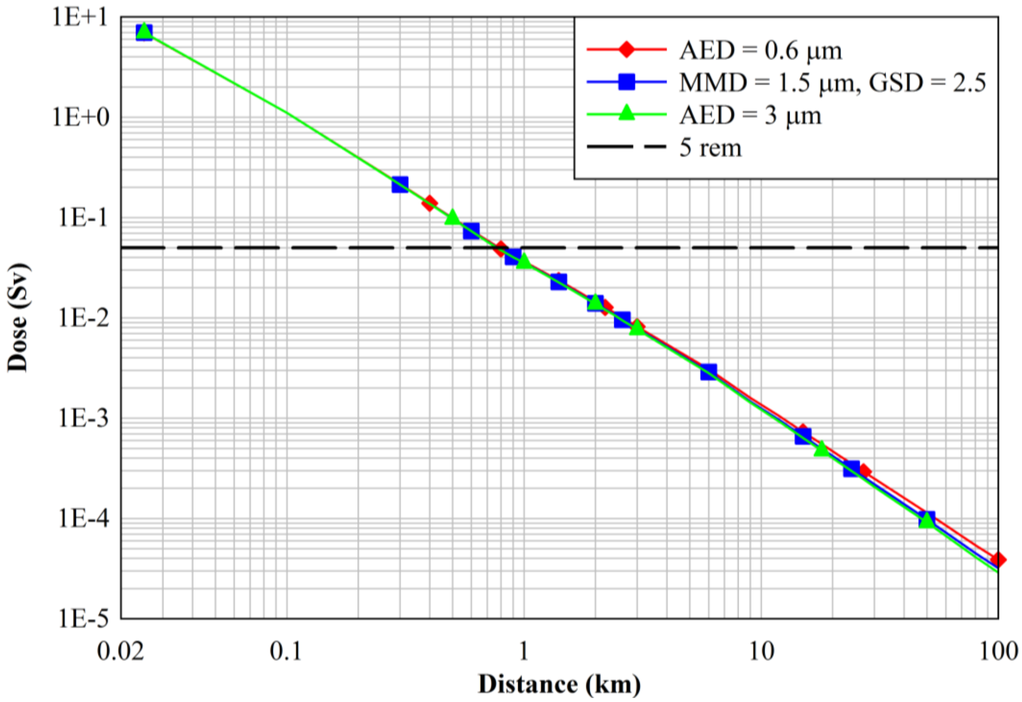

Figure 3.3 Dose as a function of distance for the three aerosol size distributions assuming ground release of 0.1% from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup in D-4 meteorological conditions.

3.2 Exposure

Figure 3.4 shows the centerline dose as a function of distance for four exposure scenarios. These scenarios include a 2 hour exposure followed by evacuation, a 2 hour exposure followed by sheltering, and a 24 hour exposure. The time of exposure is assumed to begin once the radioactive plume reaches each downstream distance. An average exposure value is also plotted. The source term was derived assuming a 0.1% release of from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup. All exposures in the graph were conducted assuming D-4 meteorological conditions.

As expected, the dose is dominated by the inhalation pathway. This dose is almost completely received during the time period in which the radioactive plume passes by the observer. This passage time is relatively short compared to the shortest exposure time of 2 hours. Therefore, all four series in the plot are within 3% of each other for all distances. The average of all three exposure scenarios is presented for the remainder of this report.

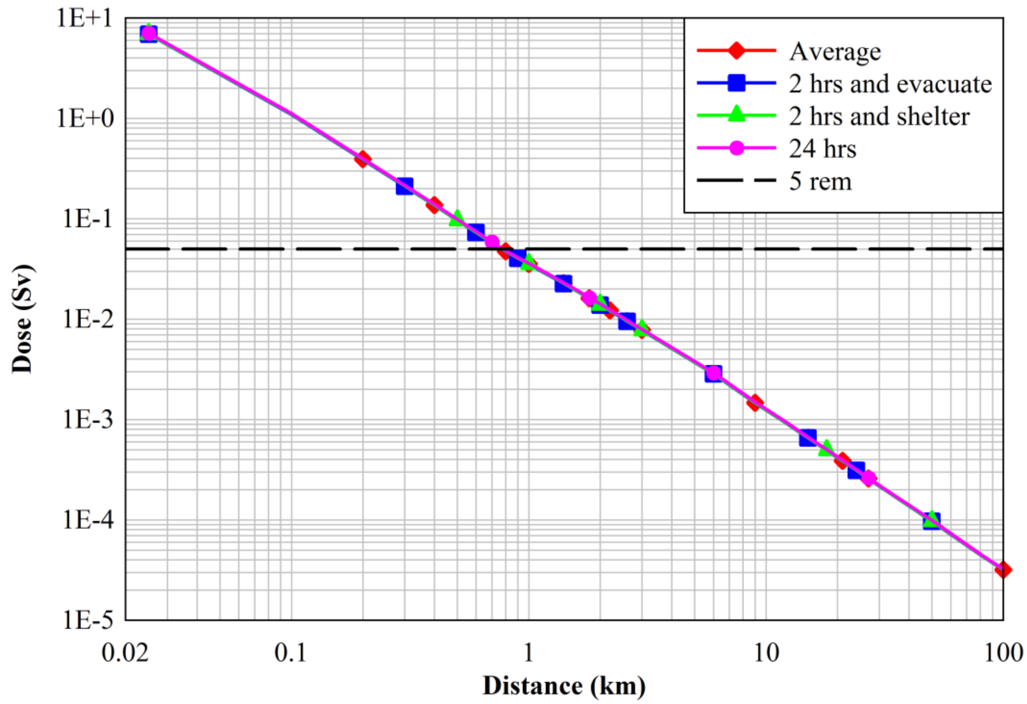

Figure 3.4 Dose as a function of distance for four exposure scenarios assuming ground release of 0.1% from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM in D-4 meteorological conditions.

3.3 Meteorological Conditions

Figure 3.5 shows the baseline release scenario of 0.1% from a single 5 year old PWR 17×17 fuel assembly with a burnup of 45 GWd/MTHM for two meteorological conditions (D-4 and F-2). The first designator in the meteorological condition is the atmospheric stability class, which dictates the rate at which the plume disperses (or mixes with the atmosphere) as the radioactive material moves away from the source of the release. The second designator in the meteorological condition is for the wind speed in meters per second, which in turn dictates the residence time of the radioactive plume at downstream locations. The F-2 meteorological class results in a dose that is a factor of 2 to 6.4 times higher than is seen with the D-4 meteorological class. This increase in centerline dose is because the "F" stability class leads to a highly coherent plume that concentrates the dose about the centerline for all downstream distances. The deviation of the data from a straight log-log regression, particularly noticeable in the F-2 curve for distances greater than 1 km, is likely due to the choice of larger grid sizes at the larger downstream distances (see Appendix A for further details).

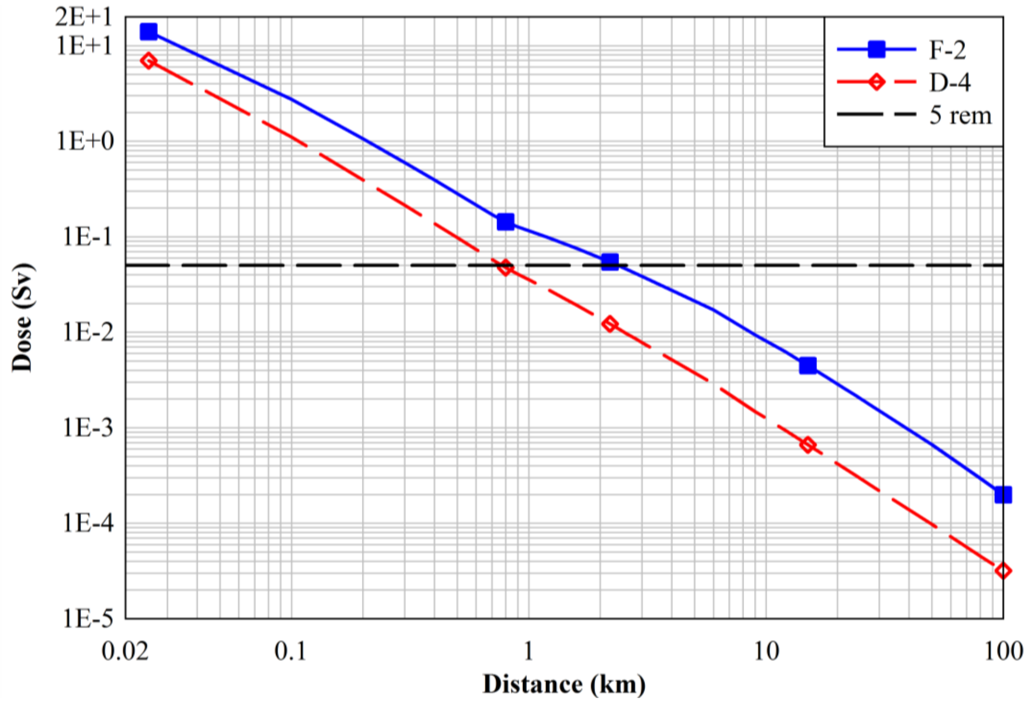

Figure 3.5 Dose as a function of distance for F-2 and D-4 meteorological conditions assuming ground release of 0.1% from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup.

3.4 Release Height

The SNF inside a storage cask has peak cladding temperatures of up to 400 °C. If the release plume contained significant thermal energy, the plume could rise buoyantly. However, the plume centerline will likely remain at or near ground level when taking into account the isentropic expansion of the internal gas to atmospheric conditions and the wake effects around the casks at the ISFSI. See the Plume Buoyancy section in Appendix A for more details. Some causal events can contribute significant amounts of thermal energy and are not considered in this report. In order to examine the effect of plume rise arbitrarily, three different release heights of the same release source were examined for the D-4 meteorological condition. Figure 3.6 illustrates the effect to the near field of different plume release heights.

Figure 3.7 shows the impact of the plume originating from three different heights for the baseline scenario. The doses are within a factor of two of the ground release inside of 0.1 and 4 km for the 10 and 100 m lofting scenarios, respectively. By downstream distances of 10 km, the doses induced by three release height scenarios are nearly identical. Caution is urged in the interpretation of the relatively low doses in the near-field of the 100 m curve. This scenario is presented solely as a parametric study. As described earlier, actual release plumes with the energy available from typical causal events would likely be captured at the release height due to the isentropic expansion of the gas from the cask and wake effects surrounding the casks.

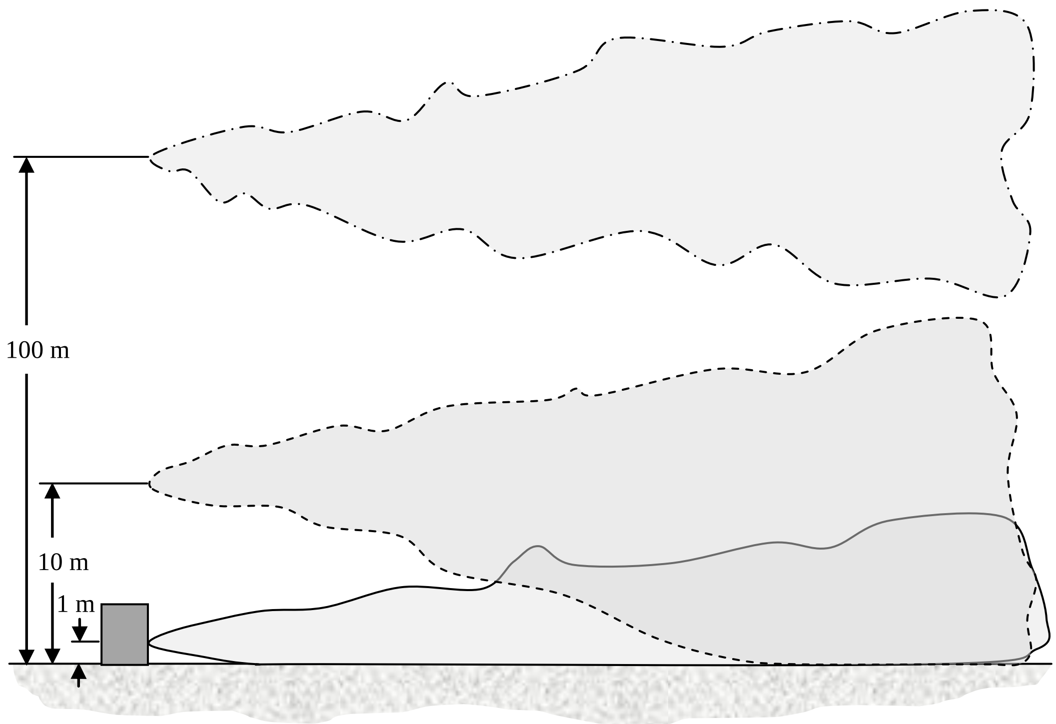

Figure 3.6 Visualization of plumes emanating from three release heights.

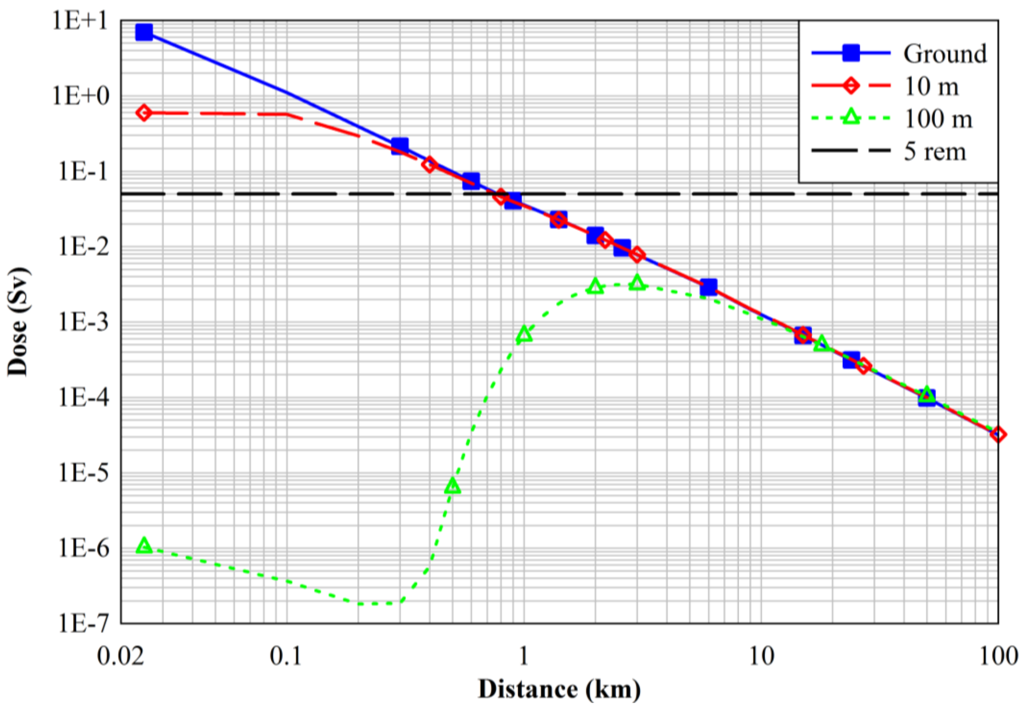

Figure 3.7 Dose as a function of distance for three release heights of 0.1% from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup in D-4 meteorological conditions.

3.5 Age of Fuel

Figure 3.8 gives the dose as a function of distance for the baseline release scenario for four different ages of fuel ranging from 5 to 50 years after offload, or discharge, from the reactor. The dose decreases with the age of the fuel slightly over the ranges investigated. The difference in dose at any given distance is within 14% between all ages of fuel. This relative insensitivity to offload age is due to the changing inventories of radionuclides within the fuel, which is because of the differing rates of radioactive decay of the 15 radionuclides of interest.

Figure 3.9 gives the individual contribution by radionuclide to the total dose for the 5, 10, 25, and 50 year old fuel for the baseline release scenario. This plot clearly shows that the inventories of most of the radionuclides are decreasing with age. The most notable exception is the increase in Americium-241 from the β^{-} decay of Plutonium-241. The increased dose from the Americium-241 is nearly sufficient to compensate for the decrease in the other radionuclides.

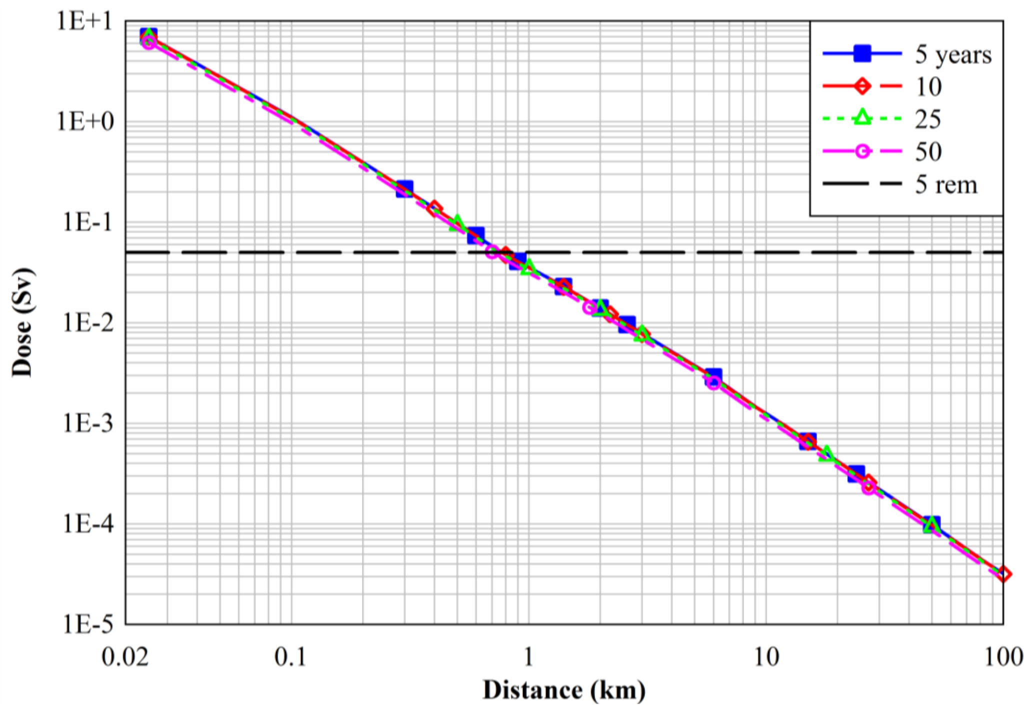

Figure 3.8 Dose as a function of distance for four fuel ages assuming ground release of 0.1% from a single PWR 17×17 fuel assembly with 45 GWd/MTHM burnup in D-4 meteorological conditions.

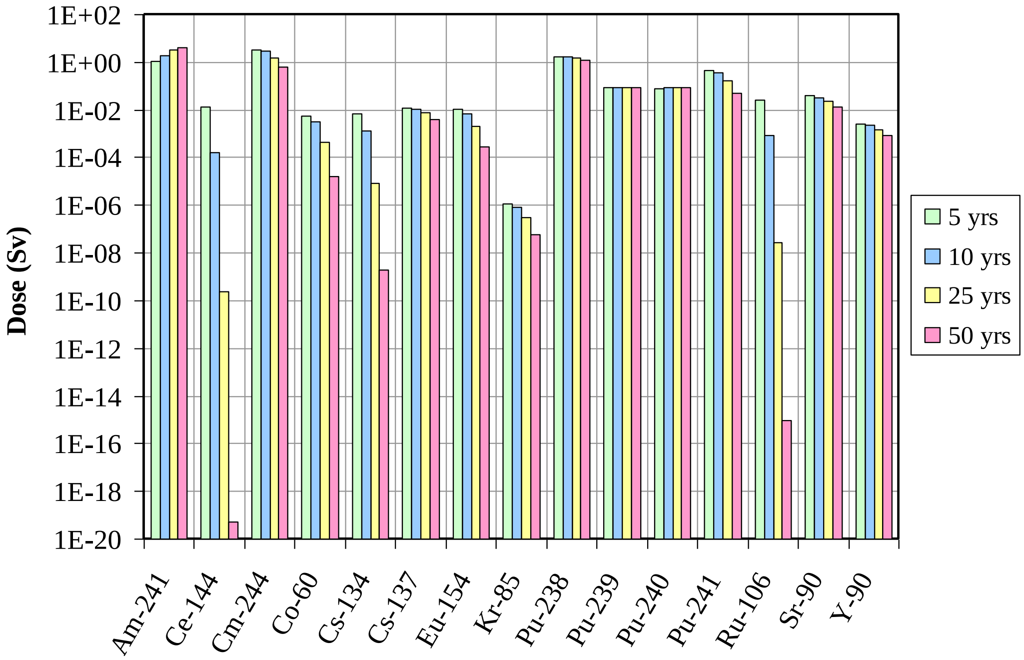

Figure 3.9 Contribution to dose by radionuclide of a ground release of 0.1% from a single PWR 17×17 fuel assembly with 45 GWd/MTHM burnup at a downstream distance of 0.025 km (25 m) for four different offload ages.

3.6 Burnup

Figure 3.10 gives the dose for burnups of 60, 45, and 33 GWd/MTHM for the baseline release scenario. The 60 GWd/MTHM dose is a factor of 1.9 times higher than the 45 GWd/MTHM dose at all downstream distances. The 45 GWd/MTHM is a factor of 1.8 times higher than the 33 GWd/MTHM dose at all downstream distances. Consequently, the 60 GWd/MTHM dose is also a factor of 3.7 himes higher than the 33 GWd/MTHM dose at all downstream distances. Figure 3.11 shows the dose by radionuclide for the three burnups examined for this study. The influence of burnup is primarily due to the increased quantities of Curium-244 and Plutonium-238 in the fuel assembly caused by production of higher-z elements during the fission process.

Similar to Figure 3.10, Figure 3.12 plots the dose for burnups of 60, 45, and 33 GWd/MTHM for 50 year old fuel with a 0.1% release of a single PWR 17×17 fuel assembly. The dose from 60 GWd/MTHM fuel is a factor of 1.3 times higher than the 45 GWd/MTHM fuel at all downstream distances. The 45 GWd/MTHM fuel results in a dose that is 1.3 times higher than the 33 GWd/MTHM fuel at all downstream distances. Consequently, the 60 GWd/MTHM dose is a factor of 2.6 times higher than the 33 GWd/MTHM dose at all downstream distances. The influence of burnup after 50 years of cooling and radioactive decay, while still notable, is somewhat muted compared to 5 year old fuel. Figure 3.13 shows the individual contribution of each radionuclide for 50 year old fuel. The contributions of Cm-244 and Pu-238 are diminished, which explains the decreasing dependence on burnup with age.

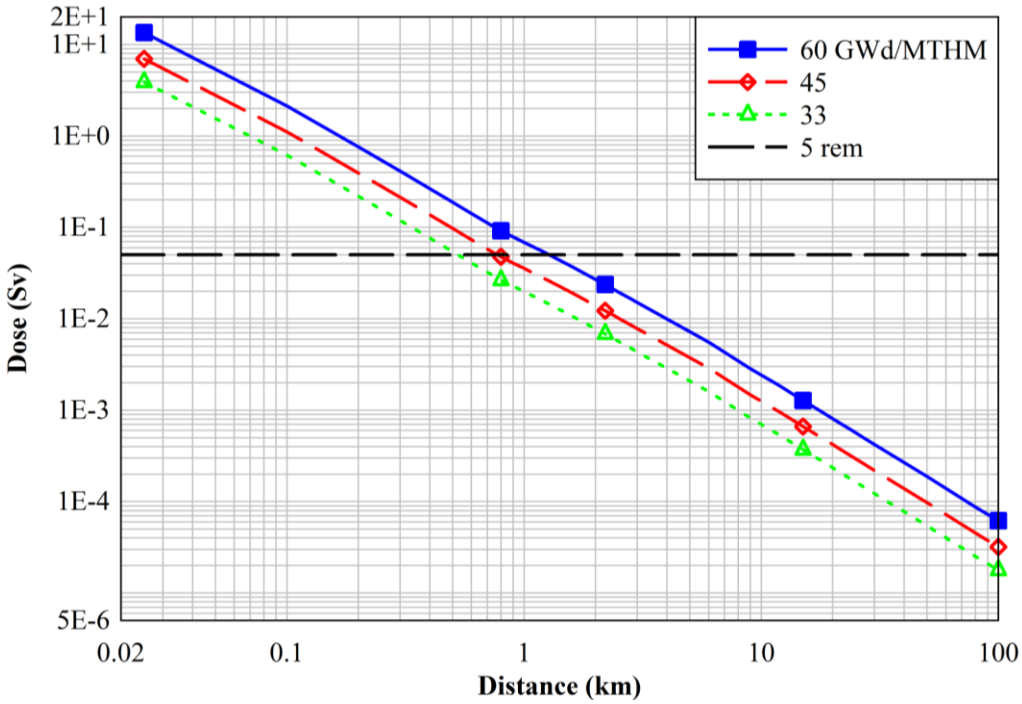

Figure 3.10 **Dose as a function of distance for three burnups assuming ground release of 0.1% from a single 5 year old PWR 17×17 fuel assembly in D-4 meteorological conditions.**

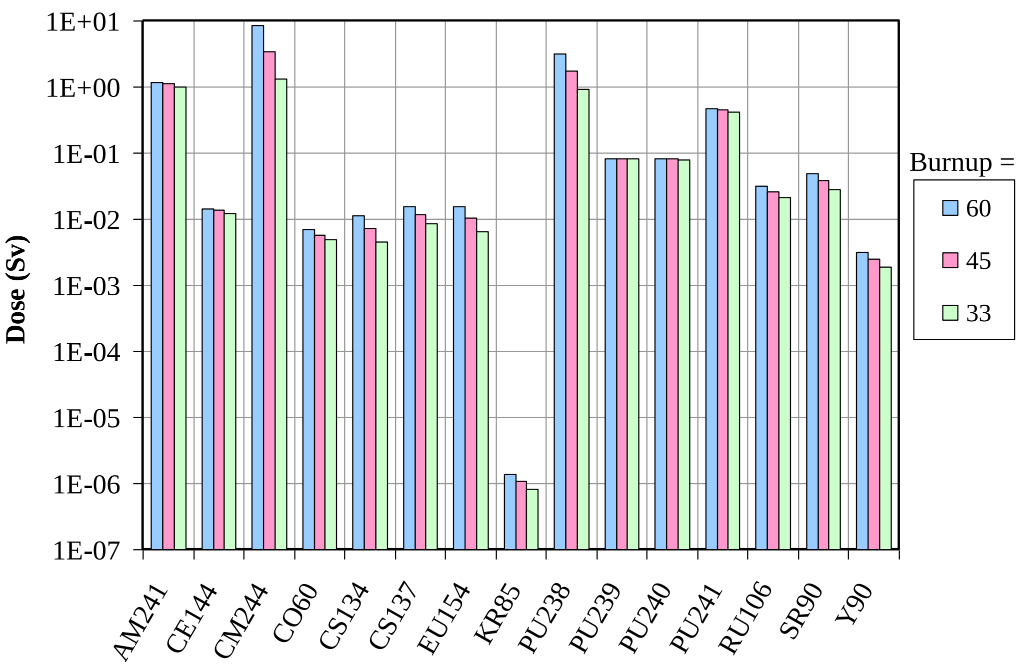

Figure 3.11 **Contribution to dose by radionuclide of a ground release of 0.1% from a single 5 year old PWR 17×17 fuel assembly at a downstream distance of 0.025 km (25 m) for three burnups.**

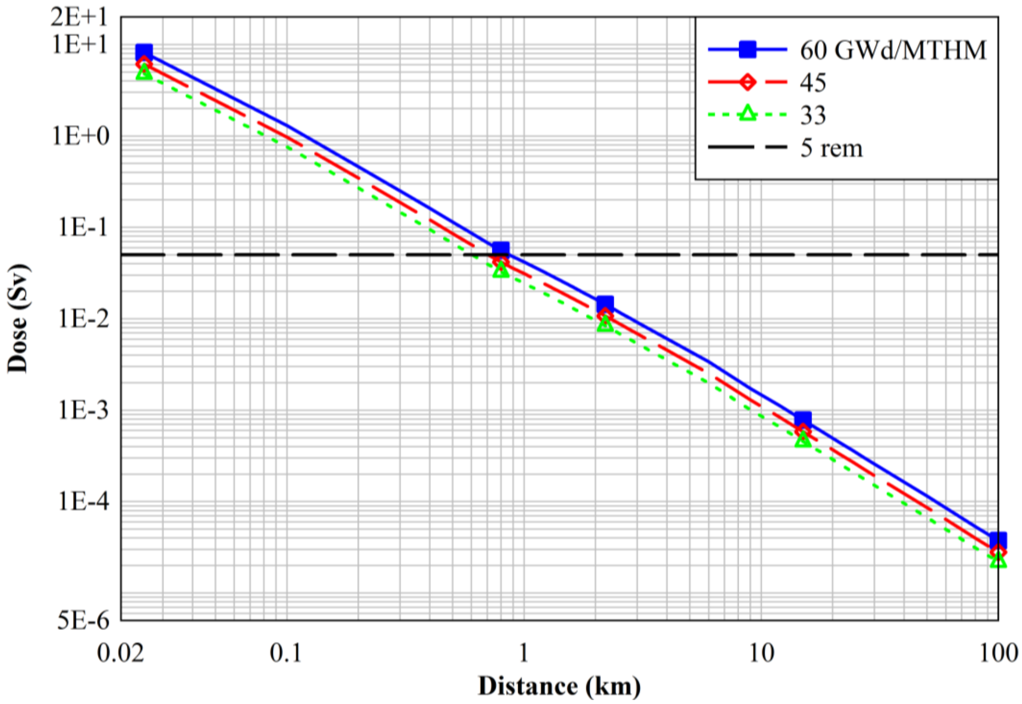

Figure 3.12 **Dose as a function of distance for three burnups assuming ground release of 0.1% from a single 50 year old PWR 17×17 fuel assembly in D-4 meteorological conditions.**

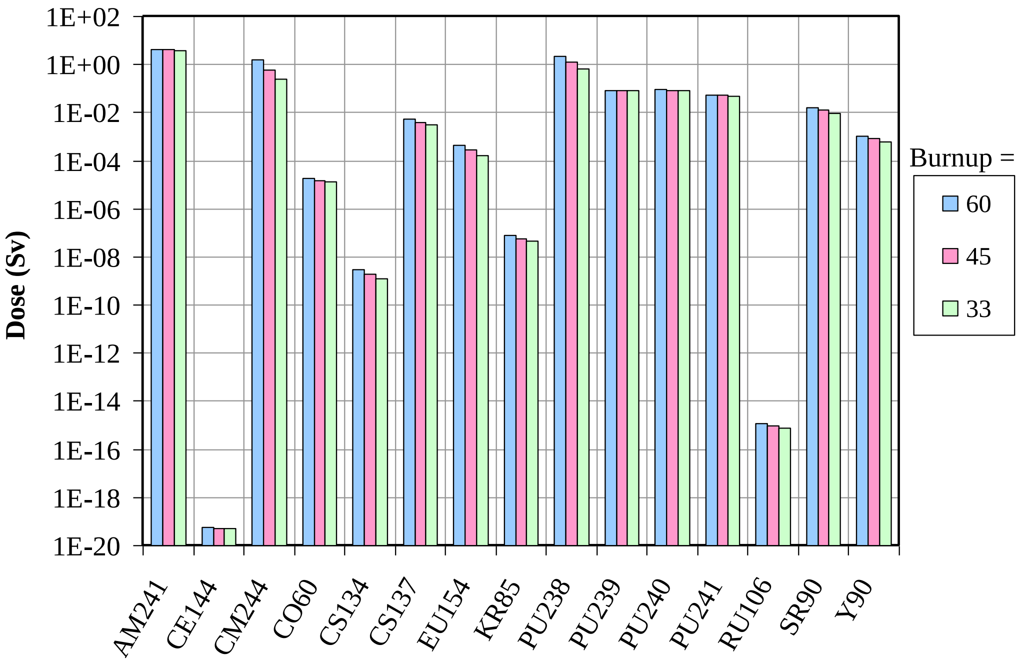

Figure 3.13 **Contribution to dose by radionuclide of a ground release of 0.1% from a single 50 year old PWR 17×17 fuel assembly at a downstream distance of 0.025 km (25 m) for three burnups.**

3.7 Release Fraction

The doses from five release fractions for the baseline release scenario are shown in Figure 3.14. The doses are linearly scalable to the release fraction at all downstream distances as expected. The dose from any release fraction may be interpolated or extrapolated from this data contained in this graph.

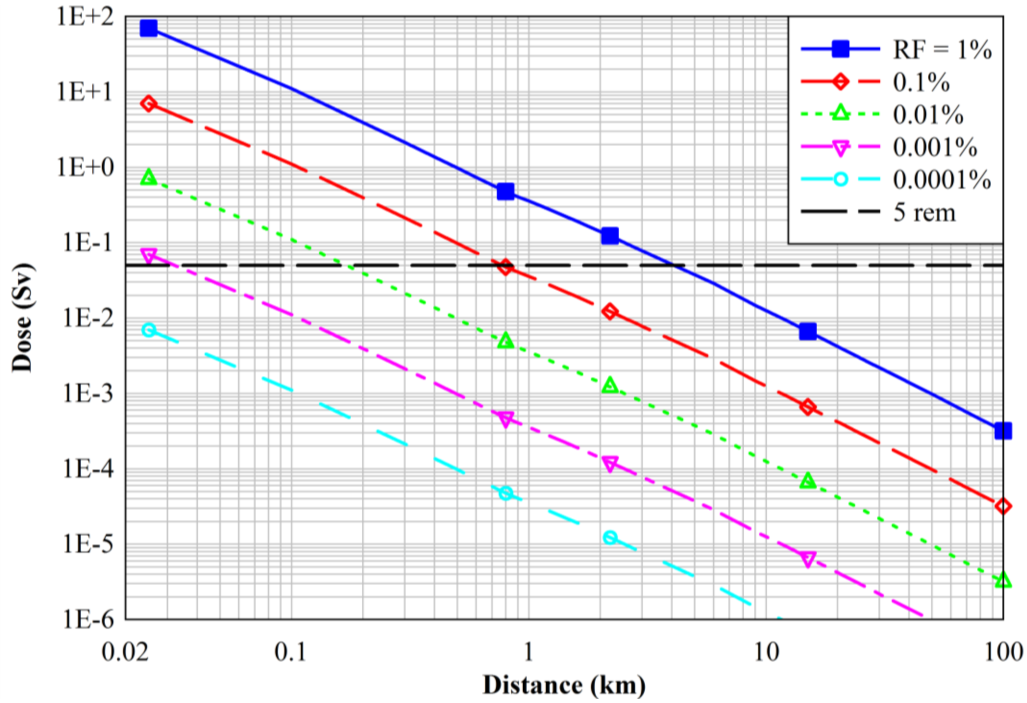

Figure 3.14 Dose as a function of distance for five release fractions assuming a ground release from a single 5 year old PWR 17×17 fuel assembly with 45 GWd/MTHM burnup in D-4 meteorological conditions.

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4 SUMMARY

Table 4.1 shows the relative impact of the various parameters of interest on the dose as compared to the baseline release scenario. This scenario examines the downstream doses from a 0.1% release from a 5 year old 17×17 PWR fuel assembly with 45 GWd/MTHM burnup in D-4 meteorological conditions. The release fraction, meteorological condition, and release height all have a significant impact on the derived dose. The effect of release height, which may be considered a simple treatment of plume buoyancy, is most significant in the near field, or distances < 0.4 km. The burnup of the fuel is most significant for fuel that is 5 years from discharge. The effect of burnup decreases with the age of the fuel from discharge. The age of the fuel, exposure scenario, and aerosol size distribution are less influential on the dose.

Table 4.1 Influence on dose for parameters of interest in this scoping study.

Parameter	Importance	Influence on Dose
Aerosol size distribution	Negligible	< 1.3× higher for smallest AED at 100 km
Exposure	Negligible	~1.03× higher for 24 hour exposure
Weather	Significant	≤ 6.4× higher for F-2 class
Release height	Significant in near field	< 12× lower for 10 m release in near field ≤ 1.1× lower for distances > 0.4 km
Age of fuel	Negligible	< 1.2× for fuel between 5 and 50 years
Burnup	Marginal	1.9× higher from 45 to 60 GWd/MTHM at 5 years 1.3× higher from 45 to 60 GWd/MTHM at 50 years
Release fraction	Significant	Linearly scalable

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5 REFERENCES

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APPENDIX A DISCUSSION OF SIGNIFICANT PARAMETERS USED IN THE MACCS2 CODE

This study used approximately 90 MACCS2 code runs to estimate atmospheric dispersion, dose and effective impact to a human body. The MACCS2 code input resembles other recent consequence studies performed for the NRC by Sandia.[1] Differences are discussed below.

A.1 Dispersion Grid

All MACCS2 simulations used the same grid geometry described in Table A.1. The grid consisted of 34 circles.

Table A.1 List of grid ring dimensions and areas.

Ring Num.	Ring Dimension (km)	Distance to Midpoint (km)	Ring Area (km^2)	Ring Num	Ring Dimension (km)	Distance to Midpoint (km)	Ring Area (km^2)
origin	0.000			18	2.550	2.550	4.52
1	0.050	0.025	0.008	19	2.650	2.600	1.63
2	0.150	0.100	0.063	20	2.950	2.800	5.27
3	0.250	0.200	0.126	21	3.050	3.000	1.89
4	0.350	0.300	0.188	22	8.950	6.000	222
5	0.450	0.400	0.251	23	9.050	9.000	5.66
6	0.550	0.500	0.314	24	14.950	12.000	445
7	0.650	0.600	0.377	25	15.050	15.000	9.43
8	0.750	0.700	0.440	26	20.950	18.000	667
9	0.850	0.800	0.503	27	21.050	21.000	13.2
10	0.950	0.900	0.565	28	26.950	24.000	890
11	1.050	1.000	0.628	29	27.050	27.000	17.0
12	1.350	1.200	2.262	30	32.950	30.000	1110
13	1.450	1.400	0.880	31	67.050	50.000	10800
14	1.750	1.600	3.016	32	93.890	80.470	13600
15	1.850	1.800	1.131	33	106.110	100.000	7680
16	2.150	2.000	3.770	34	293.890	200.000	236000
17	2.250	2.200	1.382				

Circles were defined in a non-uniform manner to create annular rings with small areas. This was done to ensure that the dose attributed to a ring was generally uniform, or at least could be accurately approximated as linearly varying. Figure A.1 illustrates the concept. In the figure, one annular ring with a radial midpoint of 1.80 km is created by two circles, one at 1.75 km radius and the other at 1.85 km radius. The annular ring has an area of 1.13 km^2 and a radial width of 0.1 km. This small area minimizes dose variation within the ring.

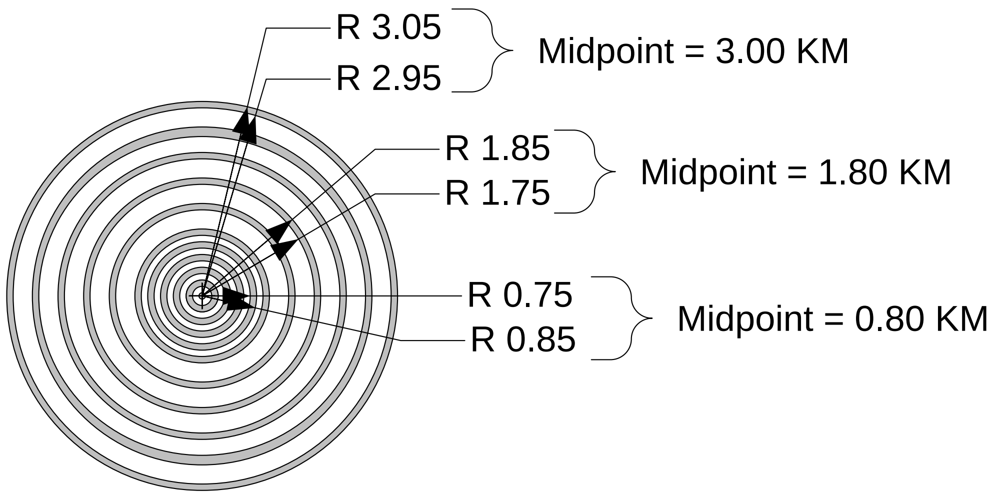

Figure A.1 Grid layout from 0 to 3.05 km demonstrating non-uniform ring selections.

A.2 Dispersion Model Parameters (σ_y and σ_z)

The code input file for MACCS2 included in tabular form dispersion model parameters based on the Tadmor and Gur parameters.[2] This tabular data is plotted in Figure A.2.

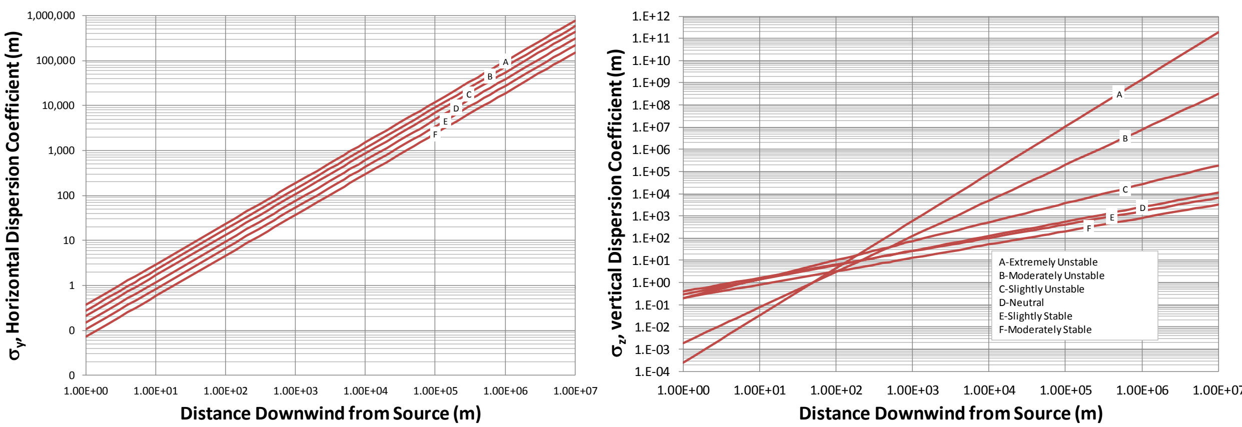

Figure A.2 Dispersion parameters used for this study.

This parameter set is intended for use over uniform terrain and are most accurate for downstream distances greater than 100 m.

A.3 Meteorological Conditions

MACCS2 is designed for use at a known site with meteorology extracted stochastically from a weather data file specific to that site. This study, however, investigates releases at undefined locations. To accommodate the lack of definition, meteorological conditions were specified as either stability class D with wind speed 4 m/s, designated D-4 weather, or stability class F with wind speed 2 m/s, designated F-2 weather. These two meteorological conditions are typically used in dose assessments where the exact site is unknown. The D stability category represents a neutral stability condition and is the most predominant class with approximately 50% of all hours exhibiting this weather category. The F stability category represents extremely stable conditions with little turbulence. This category occurs 18% of the time.

Table A.2 contains more precise statistics of the stability categories distributions:

Table A.2 Statistical analysis of weather data files for 28 US sites.

Stability Class	Number of Hours	Percent
A	2111	0.9%
B	13596	5.5%
C	29170	11.9%
D	123203	50.2%
E	33378	13.6%
F	43793	17.9%
Total	245251	100%

This table came from an analysis of the contents 28 MACCS2 weather files compiled for the siting study NUREG/CR-2239.[3] The sites provide a representative sample of weather across the continental United States. Figure A.3 contains a map showing the location of the 28 sites.

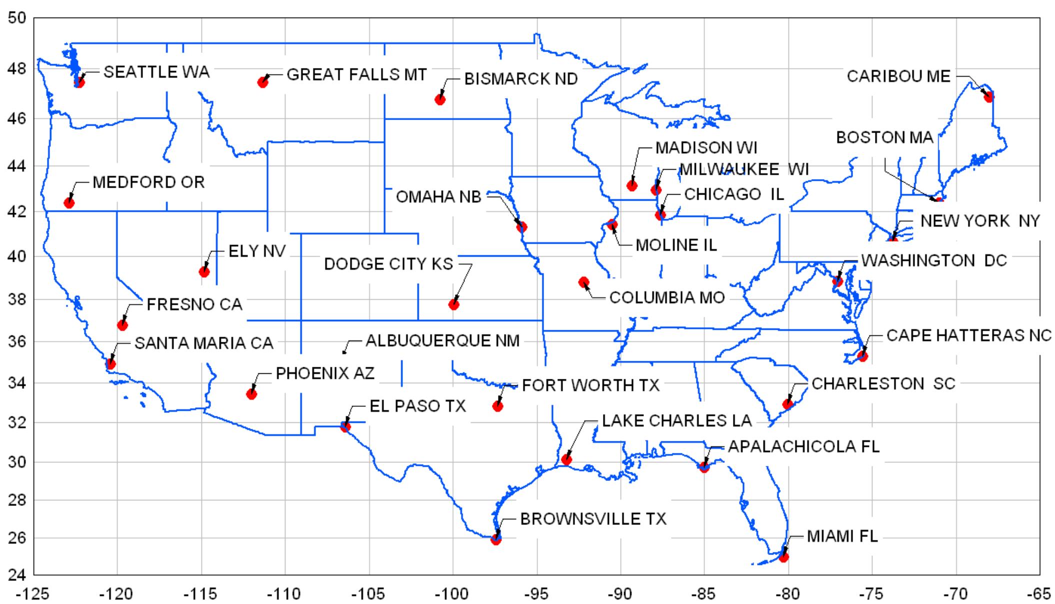

Figure A.3 Spatial distribution of weather files analyzed.

This same statistical analysis provides a measure of the distribution of wind speed within turbulence classes. Figure A.4 contains a plot summarizing these statistics for the D turbulence class. A 4 m/s rate meets or exceeds wind speeds within this category approximately 28% of the time. Based on these statistics, a D-4 weather category provides a reasonably normal, if slightly conservative dose distribution.

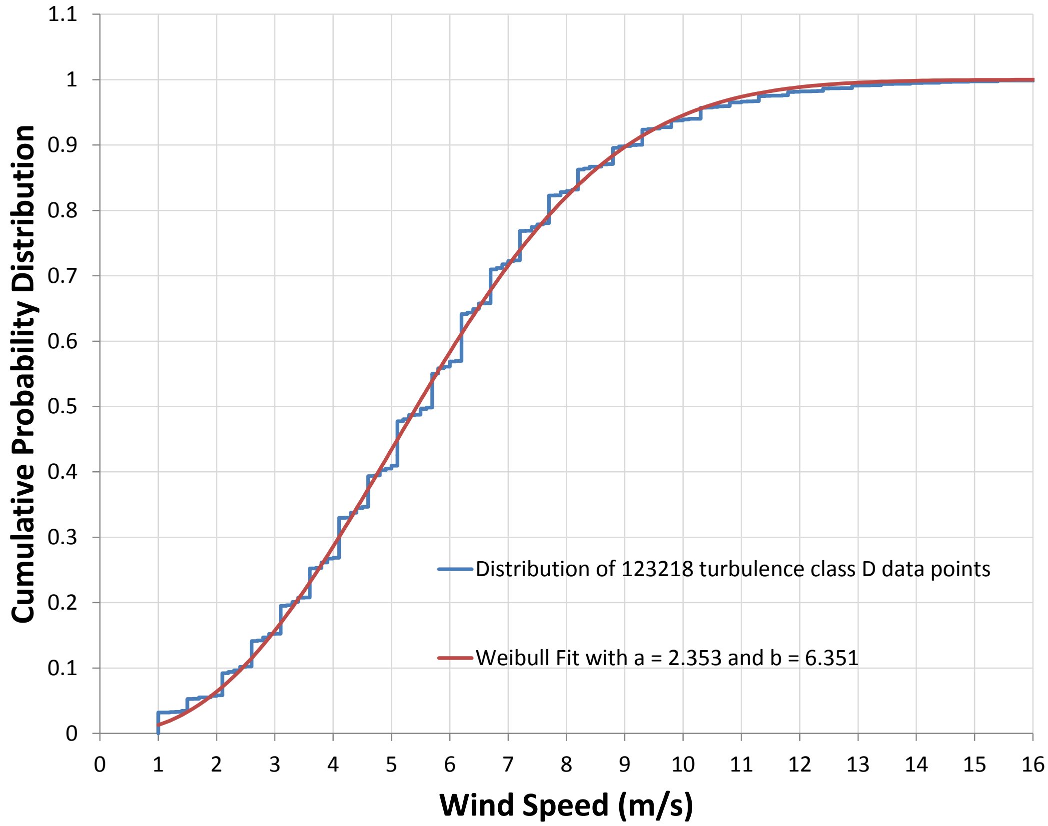

Figure A.4 Cumulative probability distribution for wind speed under Category D conditions.

Figure A.5 contains a cumulative distribution plot for category F wind speeds. Based on the curve, approximately 95% of all category F speeds exceed the 2 m/s wind speed used in this study. Thus, an F-2 weather condition provides a bracketing condition for very stable, low mixing atmosphere with low speeds. A lower wind speed results in higher contaminant concentrations at ground level and is therefore more conservative than higher wind speeds.

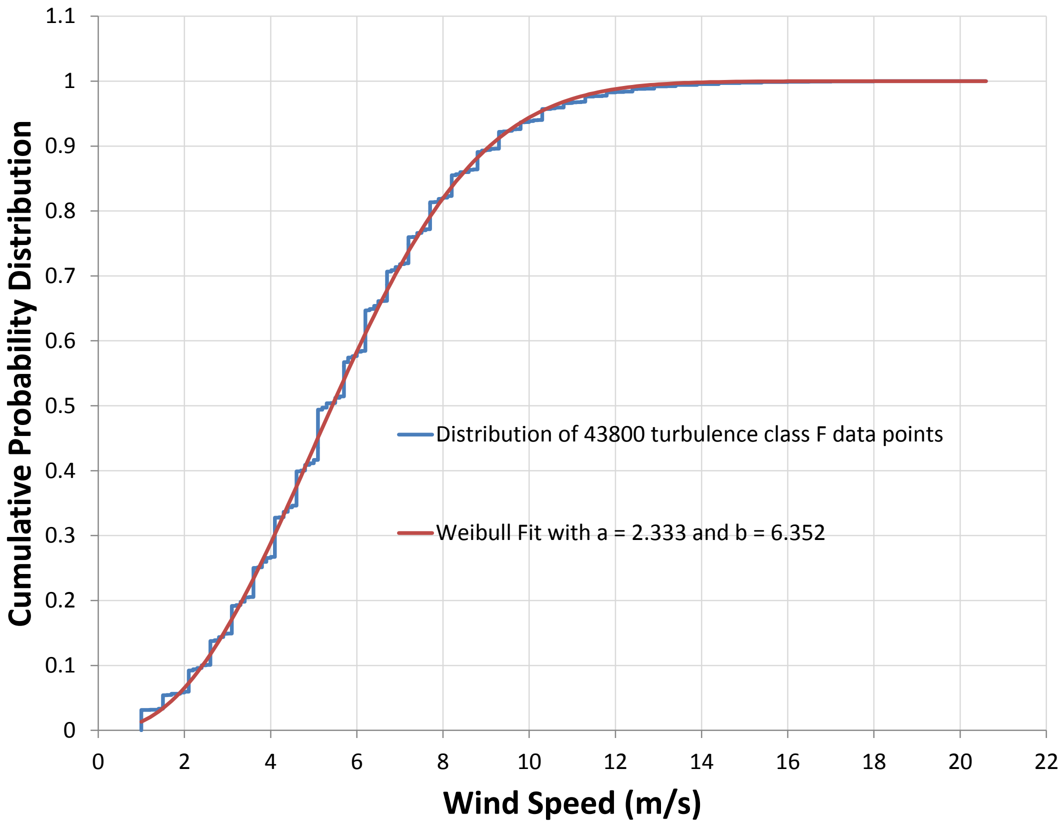

Figure A.5 Cumulative probability distribution for wind speed under Category F conditions.

A.4 Deposition Velocity

This study assumes a buoyant plume model based on Briggs.[4] The plume energy rate was set to 0.0 Watts, indicating a release at ambient temperature. Plume energy is a measure of the temperature difference between the plume and the air surrounding it. The baseline plume release height is assumed to be 1 m. Given the isothermal nature of the release relative to the environment, the plume will continue at this height without rising.

Wet deposition was disabled, eliminating the probability of early washout.

The model runs used a distribution of 20 settling velocities based on a distribution of 20 particle aerodynamic diameters. The relationship is based on Bixler et al.[5]

$$\ln(v_d) = a + b\ln(d_p) + c\left[\ln(d_p)\right]^2 + d\left[\ln(d_p)\right]^3 + e \cdot z_0 + f \cdot {z_0}^2 + gv \qquad \text{A.1}$$

Where the following definitions and units apply.

v_d	*deposition velocity*	cm/s
d_p	*aerodynamic particle diameter*	μm
z_0	*aerodynamic roughness length*	m
v	*wind speed*	m/s
$a \ldots g$	*correlation coefficients*	

The coefficients *a* through *g* depend on the stochastic quantile desired. This study used the median quantile. With this assumption, the coefficients were as follows.

a	*b*	*c*	*D*	*e*	*f*	*g*
-2.996	0.992	0.19	-0.072	5.922	-6.314	0.169

Figure A.6 contains plots of the baseline particle diameter vs. probability distributions used in the MACCS2 runs performed for this study.

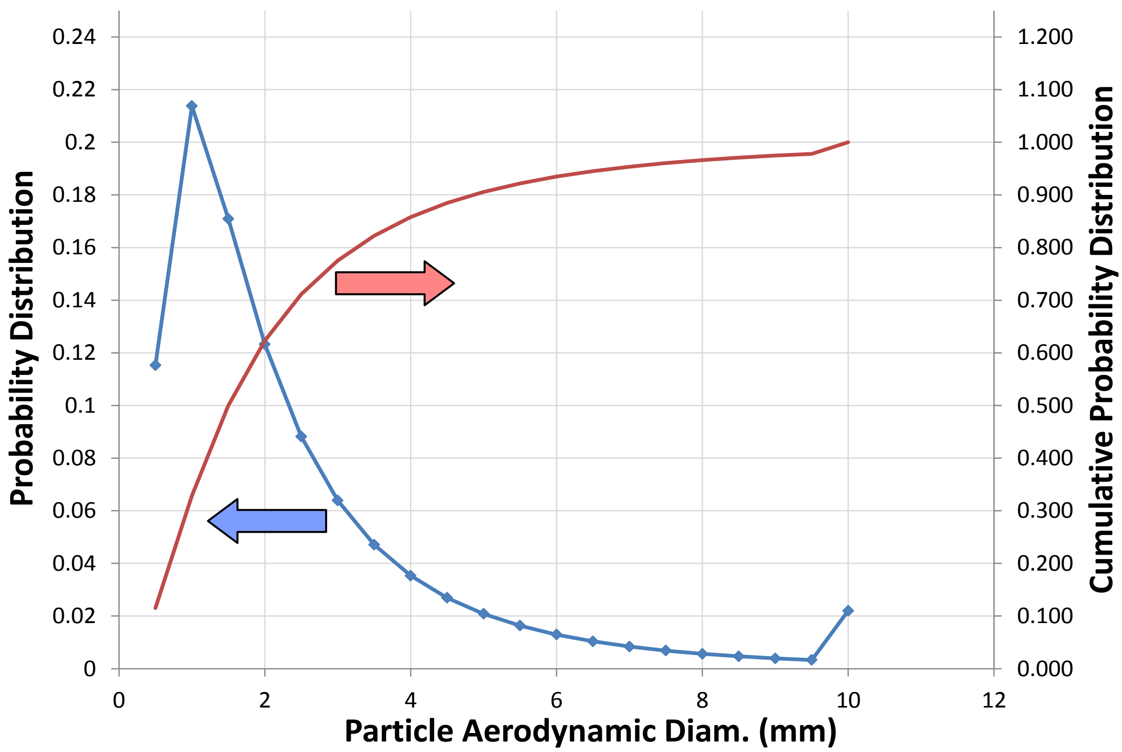

Figure A.6 Distribution of particle diameter.

The aerodynamic roughness length, z_o, used for these calculations was a uniform 0.1 m. Based on the classifications described in Table A.3 such a z_o describes low crops or scrub with only occasional larger obstacles. This roughness length was chosen on the assumption that larger values require manmade structures associated with larger populations than would be expected around storage sites. An exception to this generalization would be the presence of natural forests.

Table A.3 Davenport-Wieringa roughness-length classifications.[6]

Aerodynamic roughness (m)	Classification	Landscape
0.0002	sea	sea, paved areas, snow-covered flat plain, tide flat, smooth desert
0.005	smooth	beaches, pack ice, morass, snow-covered fields
0.03	open	grass prairie or farm fields, tundra, airports, heather
0.1	roughly open	cultivated area with low crops and occasional obstacles (single bushes)
0.25	rough	high crops, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards
0.5	very rough	mixed farm fields and forest clumps, orchards, scattered buildings
1.0	closed	regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, natural forests
Greater than or equal to 2	chaotic	centers of large towns and cities, irregular forests with scattered clearings

Figure A.7 contains plots of resulting deposition velocities based on the above discussion as a function of particle diameter. The lowest (solid) two curves correspond to the weather conditions and terrain used in this study. The top (dashed) two curves are provided to illustrate the impact on settling velocity of a more settled terrain with organized farms, orchards, isolated forest, the occasional building and other taller natural and man-made structures.

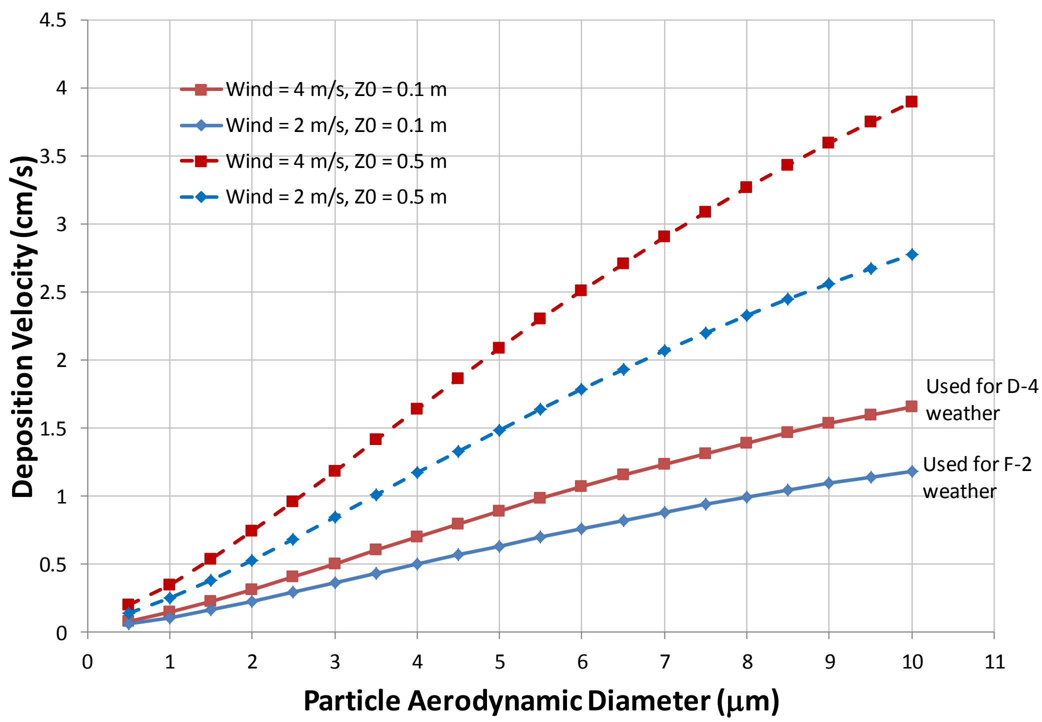

Figure A.7 Settling velocity as a function of particle diameter.

A.5 Cohort Types and Sheltering Coefficients

The MACCS2 consequence code allows for separate scenarios to describe the various impacts of radiation on population. The population group experiencing a given radiation scenario is called a "cohort". This study used three cohorts:

1. Two hours of exposure outdoors after plume arrival followed by evacuation,

2. Two hours of exposure outdoors after plume arrival followed by taking shelter, and

3. Twenty-four hours of outdoor exposure after plume arrival.

The intent within MACCS2 is to combine cohorts linearly to provide sheltering scenarios for the whole population. This report addresses this intent by providing a "Combined" option in which each of the three cohorts is assigned to 33.3% of the population, i.e. an arithmetic average value.

Within a cohort, MACCS2 uses various parameters to describe factors important to human exposure. These include such parameters as breathing rate and inhalation or skin exposure shielding factors within shelters.

Most factors are equivalent to those used in Sample Problem A of the MACCS2 manual and are identical to the factors used in the SOARCA study. The inhalation and skin protection factors for sheltering come from NUREG/CR-4551, Vol.2 Rev.1 Part 7 and are consistent with SOARCA.[7] The study assumed that evacuees disappear as soon as the evacuation begins. Normal activities were assumed to occur outside with no shielding. The exception is ground shine where the shielding factor was halved. This reduced ground shine shielding factor reflects an assumption of irregular ground surfaces combined with some additional shielding. Additional shielding would occur, for example if the evacuee were in an automobile. Cloud shine and ground shine shielding factors for the sheltering cohort derive from the NUREG 1150 values used for location around the Zion plant. This power station is in Illinois where housing and other shelters would be more robust (brick or stucco) than would be expected in warmer climates.[8]

A.6 Plume Buoyancy

With the exception of the release height parametric study, all results in this report assume that releases occur at 1 m above ground level without additional plume rise. Storage casks may be pressurized with up to 8 bar (800 kPa) of helium at peak temperatures of 673 K. Although this helium carrier gas may imply the possibility of a significant plume rise, examination of the volumetric expansion of the gas outside the casks and the plume capture in the wake of the cask indicates that the plume will not rise due to buoyancy effects.

Figure A.8 illustrates the issue of cooling with expansion. Helium in the cask at 673 K and 8 bar will expand nearly ideally (adiabatically and isentropically) as cask material exits the cask to ambient pressure. Inside the cask the helium entropy will be 27,900 J/kg·K. Helium at 1 bar and an entropy of 27,900 J/kg·K will have a temperature of 293 K. Allowing for non-ideal expansion and entrainment with other gases, helium will exit the cask approximately at or near ambient temperature (~300 K). At this temperature the plume will have no significant thermal energy relative to the ambient.

Helium escaping from a cask at 2 bar cools less as it expands. At this pressure, helium within the cask exists with entropy of 30,800 J/kg·K. When the helium in this situation expands ideally, the final temperature of exit temperature of the plume is 510 K. However, even this amount of thermal energy is only marginally sufficient to overcome the building wake effects generated by the cask as detailed next.

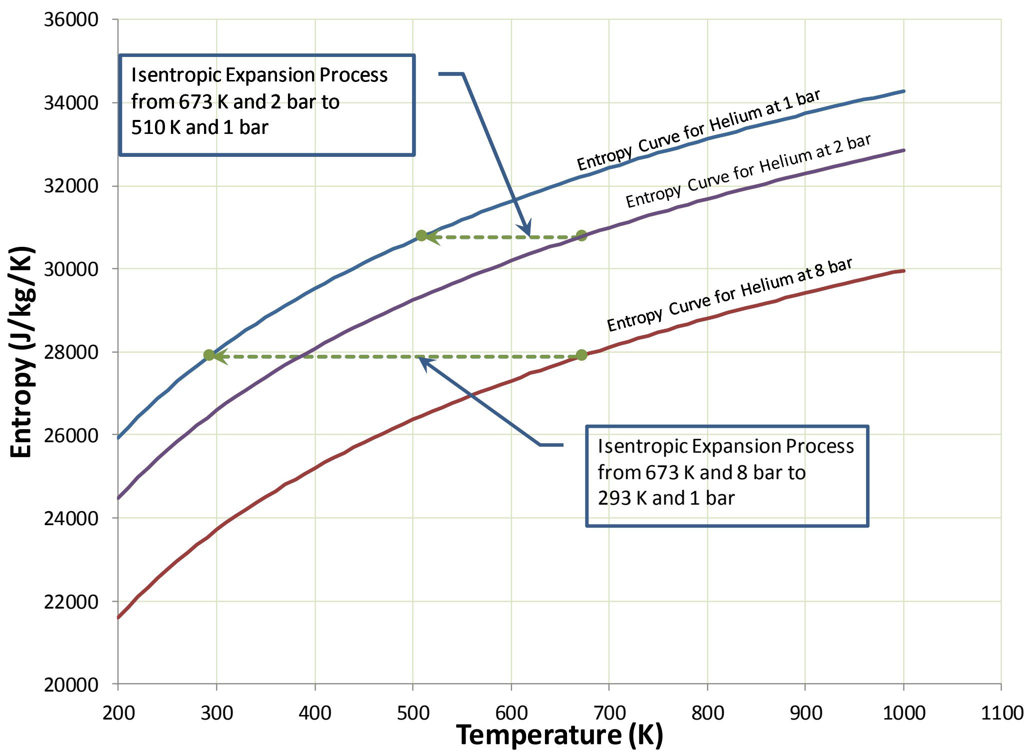

Figure A.8 Helium isentropic expansion process.

Figure A.9 illustrates the macroscopic flow around a structure with wake. Such flows generate a trapped cavity of air in the wake of the structure as well as large eddies which serve to mix the flow downstream of the structure.

In the case of this analysis, the structure is the cask itself. Flow over or around the cask will likely trap any material emitted from the cask in the structure's wake. The MACCS2 software assumes that if a plume is trapped in a wake, the entrapment lasts long enough that the plume loses coherence and never lifts off the ground. Notice from the figure that wake entrapment occurs even if a leak occurs on the top of the cask.

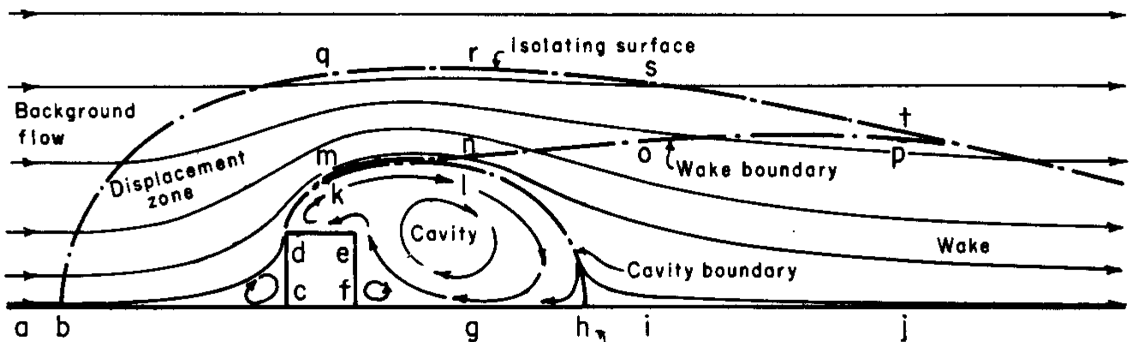

Figure A.9 Illustration of the wake downstream of a structure.[9]

A plume with sufficient buoyancy, i.e. thermal energy, is capable of breaking free of the wake. For this to happen, the structure/weather environment must satisfy the following criteria.

$$u < \left(\frac{9.09F}{H_b} \right)^{\frac{1}{3}} \qquad \text{A.2}$$

Where

u is the horizontal wind speed (*m/s*)

H_b is the cask height (*m*)

F is the buoyancy flux (m^4/s^3)

The buoyancy flux can be equated to the energy content of the plume by the following approximation.

$$F = 0.00000879 \dot{m} C_p \left(T_{plume} - T_{ambient} \right) \qquad \text{A.3}$$

Where

$\dot{m}$ is the mass flow rate from the cask (*kg/s*)

C_p is the specific heat of the cask effluent ($J/kg{\cdot}K$)

T is the temperature of either the effluent, T_{plume}, or the ambient air, $T_{ambient}$ (*K*)

This analysis assumes conservatively that the effluent is 100% helium. Specific heats for air or other potential gases will be less, resulting in lower estimates for critical trapping velocity. Values for the parameters used in the above equations are contained in Table A.4.

Table A.4 Summary of Calculation Parameters

Parameter	Value	Units
Plume Temperature, T_{plume}	310 and 510 (for 8 and 2 bar, respectively)	*K*
Ambient Temperature, $T_{ambient}$	300	*K*
Mass flow from Cask, $\dot{m}$	0.6 and 0.9 (for 8 and 2 bar, respectively)	*kg/s*
Specific heat, C_p	5194	*J/kg·K*
Cask Height, H_b	Variable	*m*

Storage casks are approximately 4 meters high. The analysis depicted in Figure A.10 varies the structure height from 0 to 8 m high. The two curves show the depressurization of casks at initial pressures of 2 and 8 bar and isentropic plume temperatures of 510 and 310 K, respectively. Recall that the 8 bar case was calculated to emit at a temperature less than the assumed ambient temperature of 300 K. For this analysis, the temperature of the 8 bar plume was assumed to be 310 K in order to obtain a nontrivial result. Both curves show the minimum wind speed needed to keep the plume captured in the downstream wake as a function of the structure, or cask, height. The calculated minimum wind speeds at a cask height of 4 m are 2.7 and 0.9 m/s for casks at initial pressures of 2 and 8 bar, respectively. Therefore, plumes emitted from casks loaded initially between 2 and 8 bar are incapable of escaping the building wake effects for the D-4 meteorological condition and only marginally capable of escaping for the F-2 condition.

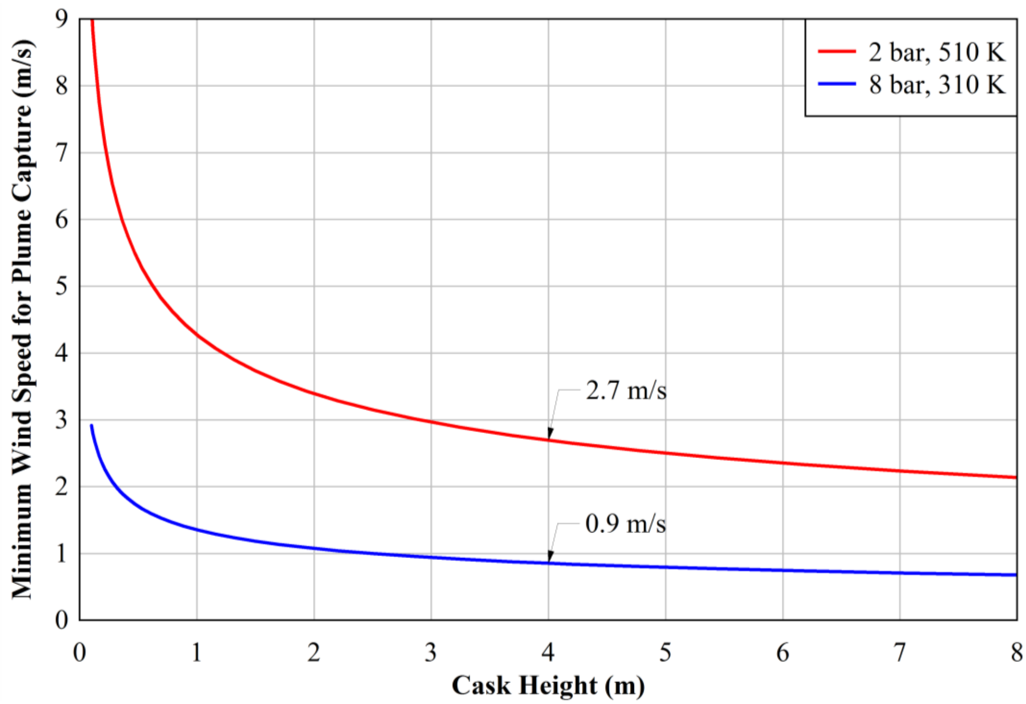

Figure A.10 Minimum wind speed for plume capture as a function of cask height.

A.7 Medical Impact

The figure of merit used in this study is the peak centerline L-ICRP60ED dose. Units are in Sieverts (Sv). This effective dose equivalent was developed in 1990 to account for doses from both external and internal exposure sources.[9] This effective dose equivalent performs the same function as the older Total Effective Dose Equivalent (TEDE) originally used by the NRC. The NRC began allowing the ICRP dose equivalent in 2002.[11]

A.8 Linear Dose Assumption and other Simplifications

This section presents and discusses the assumptions used to simplify the calculations plus other possible simplifications. The linear dose summation discussed in the report is discussed next.

The final analysis uses 15 separate MACCS2 simulations of 1 Curie releases each for the fifteen most influential radionuclides. Each of these MACCS2 simulations produces a centerline dose at a given distance, d_i. This paper assumes that the total dose, d_T, as a function of downstream distance, x, is the weighted sum of the fifteen individual doses. That is:

$$d_T\left(x\right) \approx \sum_{i=1}^{15} f_i d_i\left(x\right) \qquad \text{A.4}$$

In the above equation, f_i represents the total number of curies released via that nuclide. Figure A.8 contains plots of d_i versus distance for the fifteen nuclides used in this study assuming a 1 Ci release. This plot illustrates the potential for further simplifying assumptions.

First, the dose impacts of three plutonium nuclides Pu-238, Pu-239, and Pu-240 are effectively the same. One may total the Curies of each of these three nuclides and treat that sum as just Pu-238 with minimal impact. Second, the dose impact of Ce-144 and Eu-154 are nearly identical. As with the plutonium nuclides, one could group these two nuclides into a single sum. Finally, the impact of Kr-85 is more than two orders of magnitude lower than the next closest nuclide. It may be ignored without negatively influencing the resulting calculations.

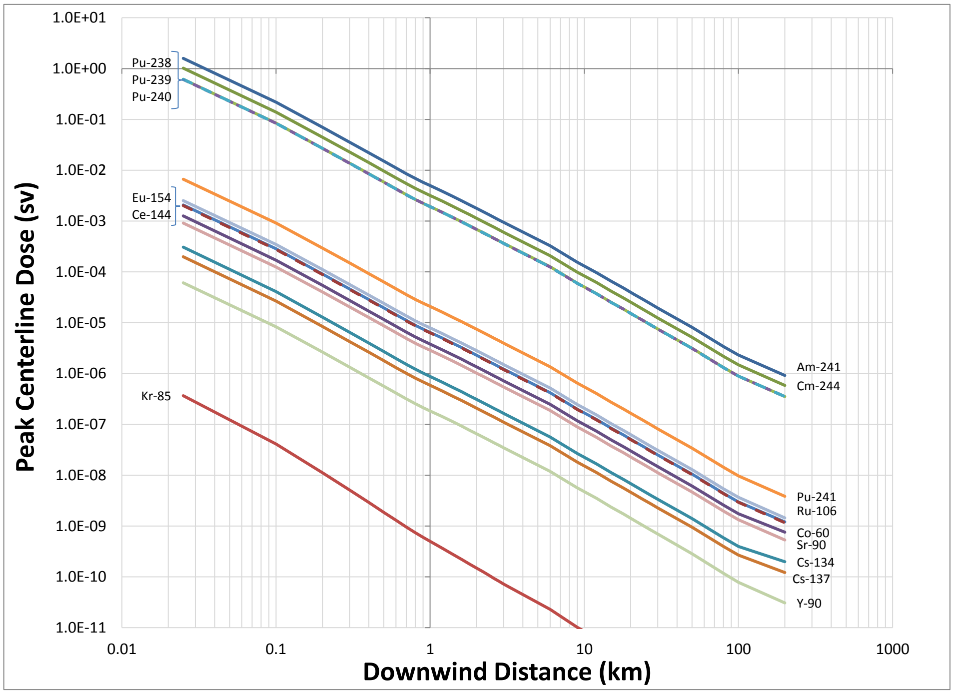

Figure A.11 Dose vs. distance for individual 1.0 Ci releases.

Figure A.9 illustrates the lack of impact of these issues on the overall results. This figure contains plots of dose versus distance calculated five separate ways:

1. One MACCS2 simulation using all 15 radionuclides each at full release strength,

2. 15 MACCS2 simulations run independently, one for each radionuclide. Each simulation assumed a 1.0 Ci release of the appropriate radionuclide. The results from these runs were multiplied by the released quantities used in item 1 above and summed,

3. Identical to item 2 above, but ignoring Kr-85,

4. Identical to item 2 except Pu-238, Pu-239 and Pu-240 were grouped as Pu-238, and

5. Identical to item 2 except Ce-144, and Eu-240 were grouped as Ce-144.

The differences in the simulations are negligible, thus demonstrating the validity of the linearity assumption. These results also indicate that the analyses may be simplified to include fewer radionuclides without loss of accuracy.

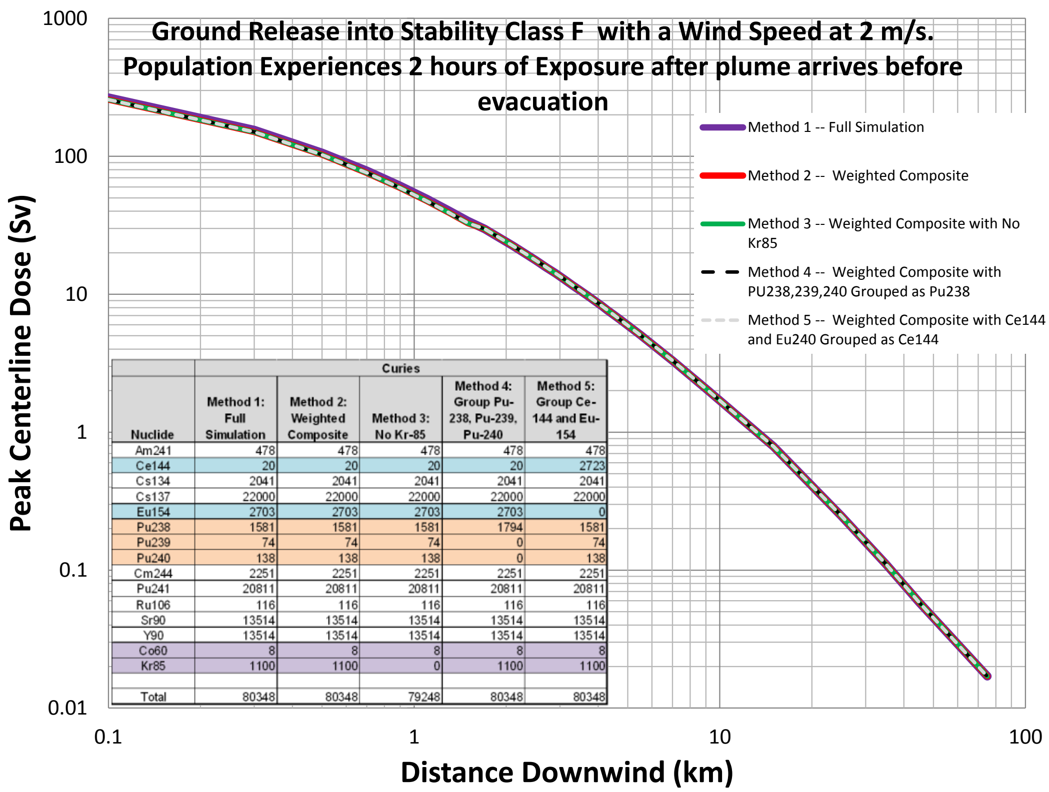

Figure A.12 Dose vs. distance for different methods of compiling the same nuclides.

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