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An Integrated Accident and Consequence Analysis Approach For Accidental Releases Through Multiple Leak Paths

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Abstract

This paper presents a consequence analysis for a postulated fire accident on a building containing plutonium when the resulting outside release is partly through the ventilation/filtration system and partly through other pathways such as building access doorways. When analyzing an accident scenario involving the release of radioactive powders inside a building, various pathways for the release to the outside environment can exist.

This study is presented to guide the analyst on how the multiple building leak path factors (combination of filtered and unfiltered releases) can be evaluated in an integrated manner starting with the source term calculation and proceeding through the receptor consequence determination.

The analysis is performed in a two-step process. The first step of the analysis is to calculate the leak path factor, which represents the fraction of respirable radioactive powder that is made airborne that leaves the building through the various pathways. The computer code of choice for this determination is MELCOR. The second step is to model the transport and dispersion of powder material released to the atmosphere and to estimate the resulting dose that is received by the downwind receptors of interest. The MACCS computer code is chosen for this part of the analysis.

This work can be used as model for performing analyses for systems similar in nature where releases can propagate to the outside environment via filtered and unfiltered pathways. The methodology provides guidance to analysts outlining the essential steps needed to perform a sound and defensible consequence analysis.

Introduction

This study addresses the evaluation of the Leak Path Factor (LPF) and consequences associated with a fire-induced release of plutonium oxide powders in a non-reactor facility. The computer code chosen for the calculation of the Leak Path Factor is MELCOR[1], and the code chosen for the evaluation of the consequences is MACCS[2]. The consequences of interest are the total effective dose equivalent (TEDE) incurred by the onsite occupationally exposed person (OEP), and the maximally exposed offsite individual (MOI). The TEDE includes the 50-year committed effective dose equivalent (CEDE) from inhalation both during plume passage and after from resuspension of deposited ground material, the cloudshine effective dose equivalent (EDE), and the groundshine EDE. For this analysis the TEDE calculation does not include the ingestion CEDE from consumption of contaminated water and foodstuffs. The inhalation CEDEs are evaluated using values based on Publication 68 and 72 of the International Commission on Radiological Protection[3,4].

The Leak Path Factors for the fire accident is first calculated and it is then used for the evaluation of the consequences. Consequence results are presented for both the 50th percentile level and 95th percentile level for various receptors up to 10 km.

Overview of MELCOR Computer Code

MELCOR 1.8.5 was developed by Sandia National Laboratories under support of the United Stated Nuclear Regulatory Commission (USNRC). MELCOR is a fully integrated, engineering-level computer code whose primary purpose is to model the progression of accidents in light water reactor nuclear power plants. A broad spectrum of severe accident phenomena in both boiling and pressurized water reactors is treated in MELCOR in a unified framework. MELCOR estimates fission product source terms and their sensitivities and uncertainties in a variety of applications. MELCOR is a mature code that is exposed to a wide spectrum of user worldwide, and it can be intelligently adapted to evaluate the Leak Path Factor for accident conditions in non-reactor facilities using its robust built-in models capabilities in aerosol dynamics.

MELCOR modeling is general and flexible, making use of a “control volume” approach in describing the plant/facility system. No specific nodalization of a system is forced on the user, which allows a choice of the degree of detail appropriate to the task at hand. The various code packages have been written using a carefully designed modular structure with well-defined interfaces between them.

The MELCOR code is composed of a large number of modules that together model the major systems of a nuclear reactor. The great majority of these models are not required for Leak Path Factor analyses, and when performing LPF studies for non-reactor facilities the modules used are then reduced, through input specification, to those which will enable the modeling of the release and transport of aerosolized materials.

Overview of MACCS Computer Code

MACCS Version 1.5.11.1 was developed by Sandia National Laboratories under support of the United Stated Nuclear Regulatory Commission (USNRC). MACCS Version 1.5.11.1 is a maintenance release version of the MACCS 1.5.11 code, the primary probabilistic consequence assessment code used by the USNRC.

MACCS models the transport and dispersion of radioactive particles in the atmosphere. Depending upon release scenario, phenomena that are modeled may include building wake effects, buoyant plume rise, and deposition. Doses and associated health effects are computed for inhalation from the plume, immersion or cloudshine, groundshine, deposition on the skin, and inhalation of resuspended ground contamination. Long-term effects such as ground contamination and economic impacts, and ingestion of contaminated water and foodstuffs may also be calculated, but are not of interest here. The result of interest for comparison against radiological evaluation guidelines is the total effective dose equivalent for the plume centerline.

Meteorological variability is treated within MACCS with a sampling algorithm in which samples of the full site-specific meteorological data are randomly selected and sorted into pre-assigned bins (normally chosen to find high-consequence conditions). An example of this approach is Latin Hypercube Sampling. A complementary cumulative distribution function is calculated for the consequence of interest (e.g., plume centerline TEDE). The MACCS output includes the average, median, and 95th percentile consequences for specified receptor locations.

Analyses

An ideal non-reactor facility is the subject of this study. A two-floor building is analyzed where two rooms are selected to have fire-induced release of plutonium oxide powder. The two fire locations are selected to show how the analysis results can be affected by the location of the fire with respect to other rooms and proximity to outside doors. The first step to be taken in this analysis is the creation of a MELCOR mathematical model of the facility to analyze, and then the assessment of the consequences is analyzed.

A simple schematic arrangement of the facility is shown in Figures 1 and 2.

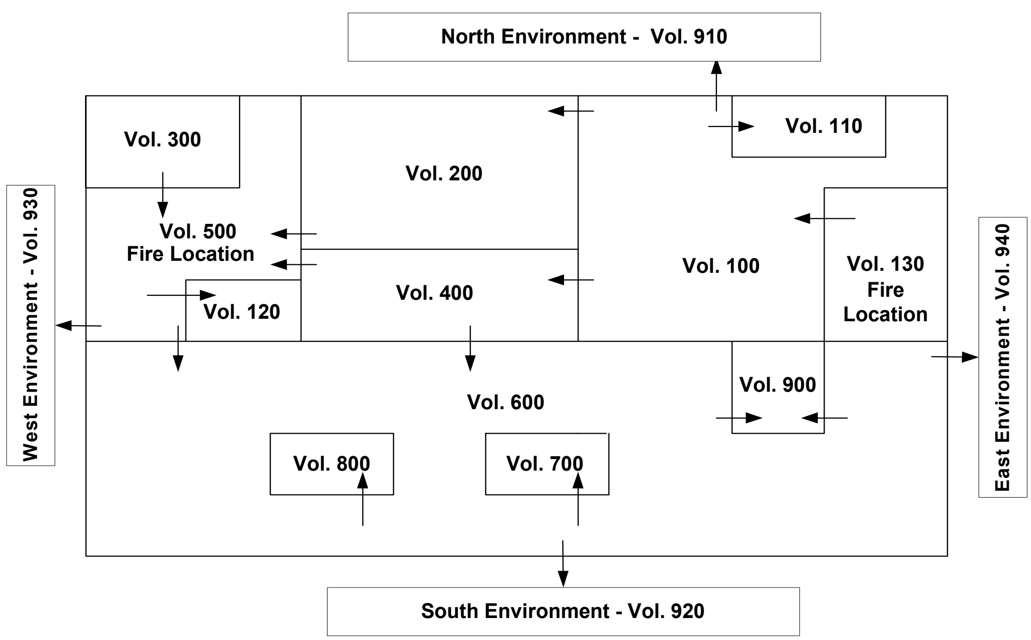

Figure 1 – Sketch of Building First Floor.

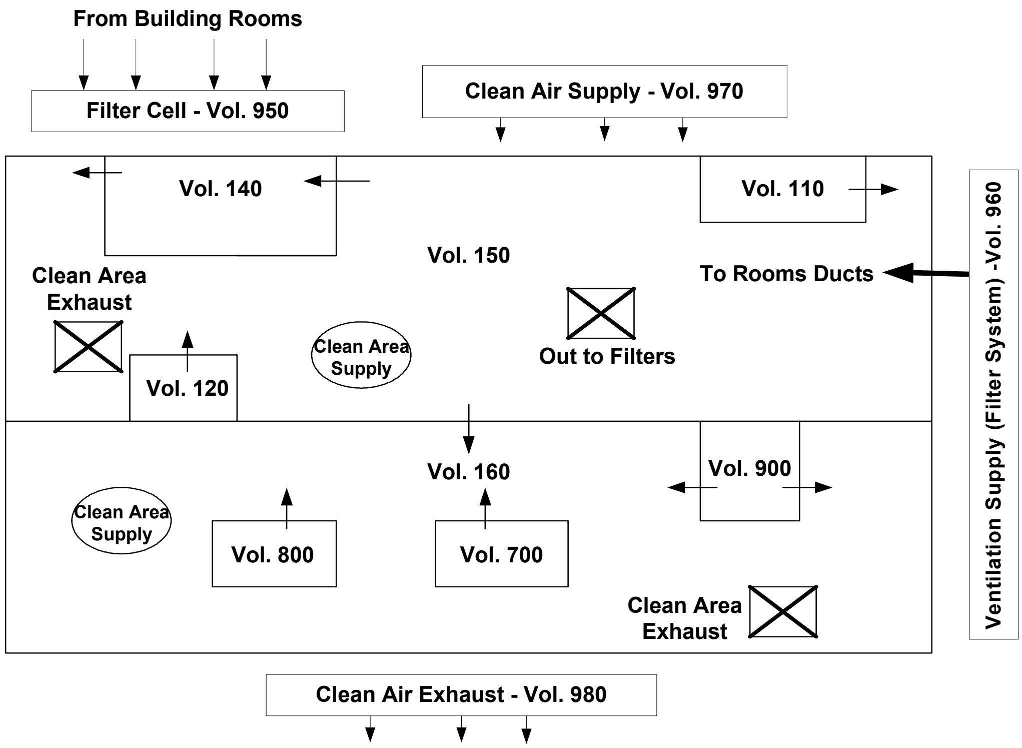

Figure 2 – **Sketch of Building Second Floor.**

The figures above show also the various building external volume will be used to simulate the building external environment and ventilation sources and sinks.

The locations selected for the two fires are volumes 500 and 130 as shown in Figure 1. These are also the location where the fire-induced release of plutonium oxide takes place. A simple block diagram shown in Figure 3 is generated to synthesize the two sketches for used in the MELCOR analysis.

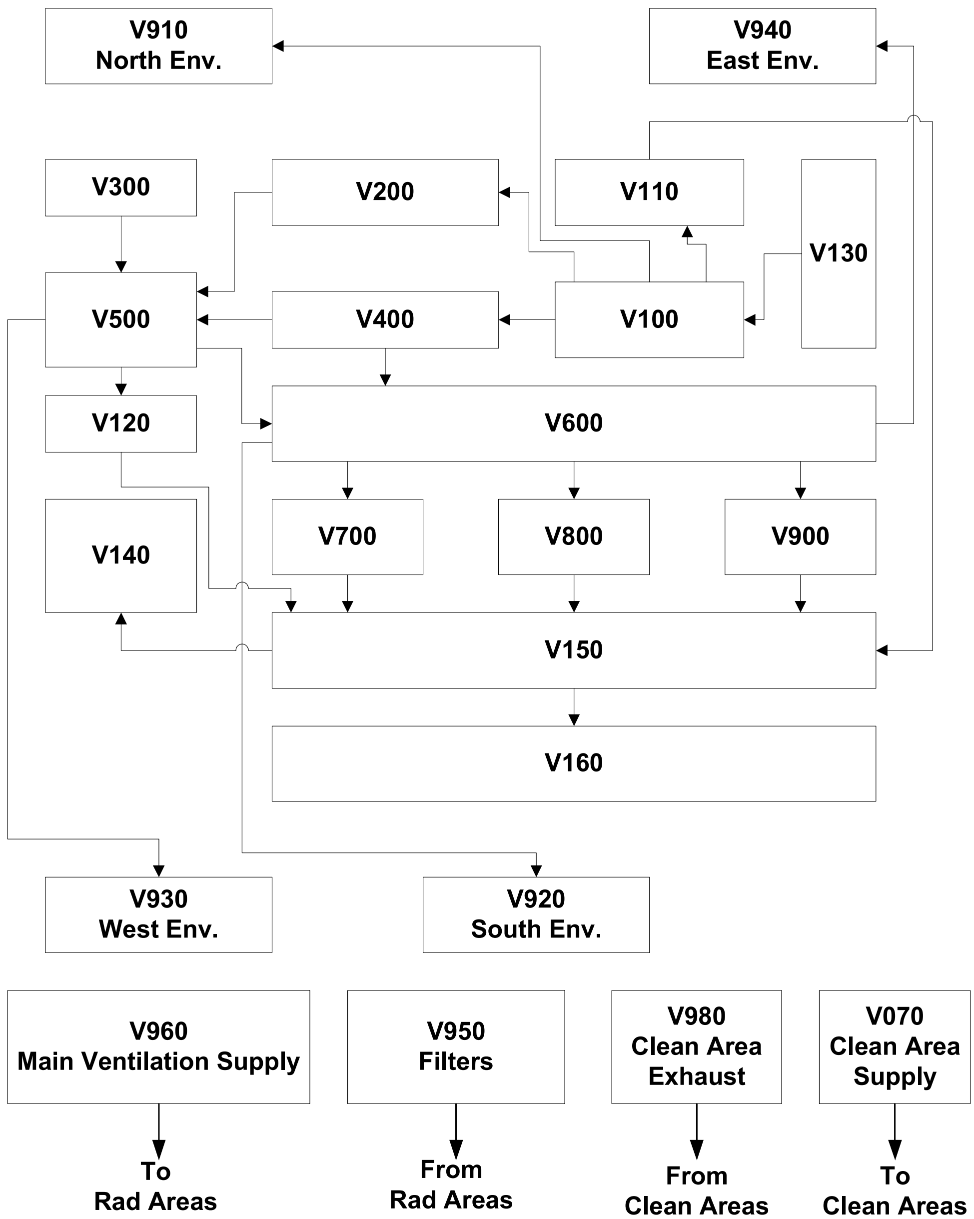

Figure 3 – Building Block Diagram.

It has to be noted that the direction of the flow shown in Figure 3 is an assumed positive direction for MELCOR to initialize the simulation. The code will assign the proper flow direction based on the computed actual flow direction.

The building internal air temperature used in the analysis is 294 K (70 °F), and the building outside environment temperature used is 283 K (50 °F). The wind speed and direction used to simulate an overall pressure differential across the building are 2.24 m/s (5 mph) and wind from the south. The effective fire power used in both volumes is given in Figure 4.

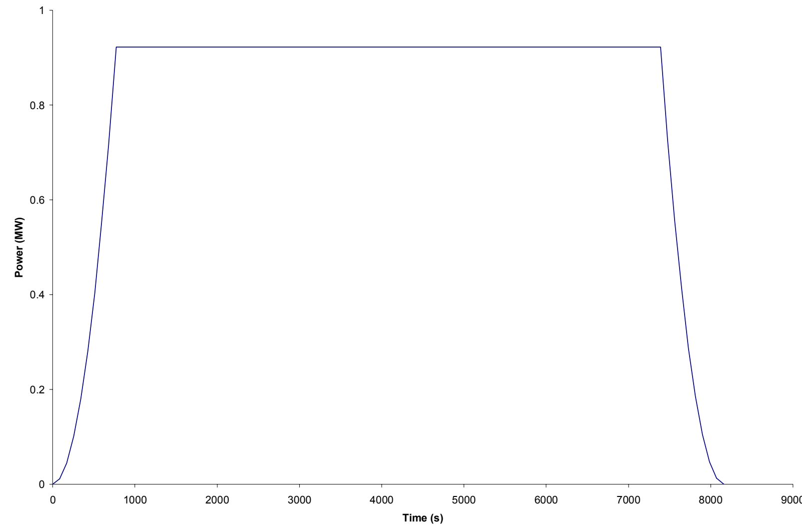

Figure 4 – Fire Power Profile.

The release of the plutonium oxide powder is modeled to take place 3000 s after the fire start to assure the fire has already released energy into the volumes where the fire is located. The amount of powder released for the MELCOR simulation is 1.0 g of Pu^{238}. Releasing a small amount of material is generally in the conservative direction[5]. The calculated value of the LPF can decrease for a larger amount of material released because of enhanced agglomeration of smaller particles. Generally for fire analyses, the effects of agglomeration are not significant. Agglomeration effects can be important for non-energetic events in which there is no ventilation flow and wind-induced pressure forces on the building are the driving mechanism for air exchange. Figure 5 shows the results of a parametric study on agglomeration effects for this type of situation. Specifically, Figure 5 shows the increased effects of agglomeration through lower LPF values that occur as the quantity of airborne mass of plutonium powder increases[5].

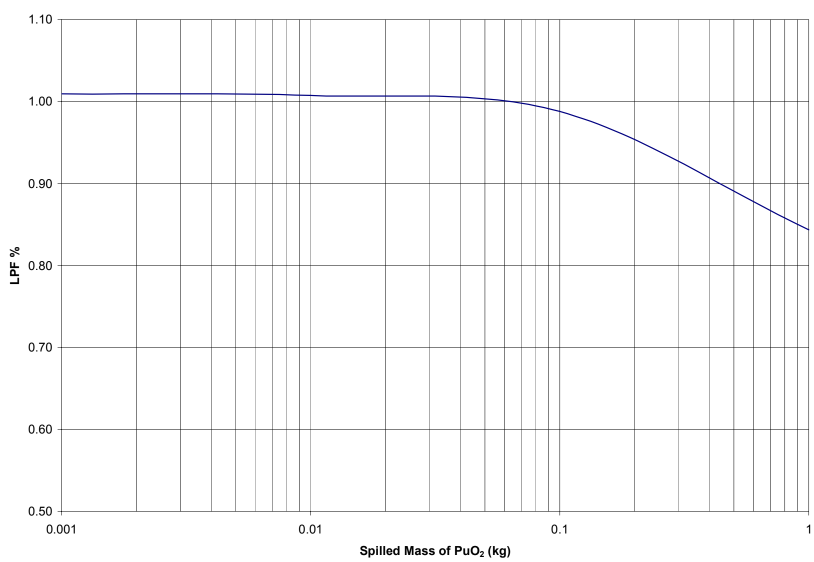

Figure 5 – Influence of released mass on LPF.

The plutonium oxide powder particle size distribution used is obtained from experimental data[6].

Maximum aerosol particle diameter = 3 μm
Minimum aerosol particle diameter = 0.003 μm
Volume-equivalent mass median particle diameter = 2.3 μm
Geometric standard deviation of the particle size distribution = 2

With the parameters described above approximately 63% of the airborne particles distribution is smaller than 3 μm (10 μm Aerodynamic Equivalent Diameter) and respirable.

The Probability Density Function (PDF) for a lognormal distribution used in MELCOR is

$$PDF = \frac{1}{\sqrt{2\pi}\, d_p \ln(\sigma)} e^{-\frac{1}{2}\frac{\ln^2(d_p/d_m)}{\ln^2(\sigma)}}$$

Where:

d_p is the distributed variable particle diameter,
d_m is the volume-equivalent mass median particle diameter, and
σ is the geometric standard deviation

Figure 6 shows the initial distribution of Pu^{238} powder particles used in the analyses.

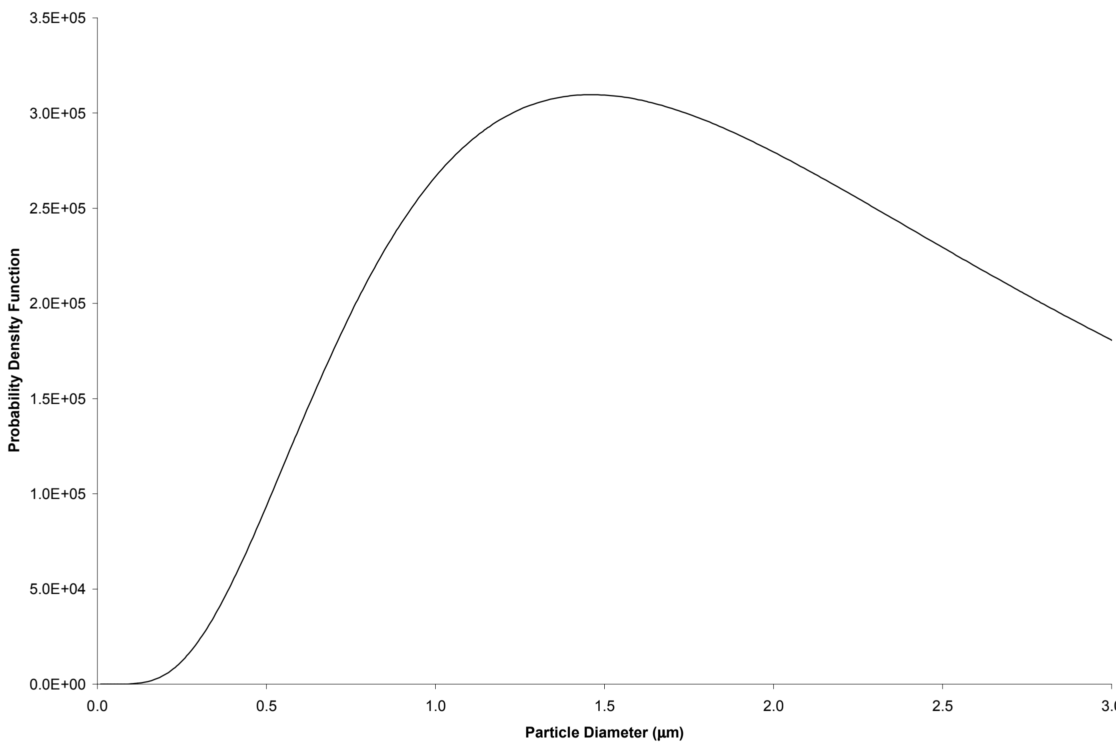

Figure 6 – Lognormal distribution of Pu^{238} Powder Particles.

A total of 1 g of Pu^{238} powder with this particle size distribution is initially made airborne in the analyses. The small quantity is used to ensure that agglomeration effects are conservatively negligible. The accident analysis that is required to estimate the amount of respirable material that is made airborne during the fire is outside the scope of this paper. The consequences results of this paper can easily be scaled to reflect whatever airborne mass is calculated by the accident analysis.

The filtration system selected for this study is set to be resistant to hot gases generated by fires (sand filter type) and the efficiency used for the system is 0.995, with ventilation remaining operational during the fire event.

With all this information at hand, the MELCOR building model can be built to evaluate the various contributors to the building overall leak path factor.

It is advisable to set external environmental volumes connected to the building via all the flow paths of interest (e.g., when it is important to assess the amount of aerosol released via a filtration system with a given efficiency).

For both fire locations (volumes 500 and 130) the ventilation flow rates used in the analysis are 0.6 m^3/s for the air supply and 0.7 m^3/s for the air exhaust, and all building doors are kept closed with small gaps.

A MELCOR analysis is performed separately for each fire location and the results provided show how the total building LPF is accounted for.

Figure 7 shows the MELCOR calculated LPF (total LPF and individual contributions) for a fire in volume 500.

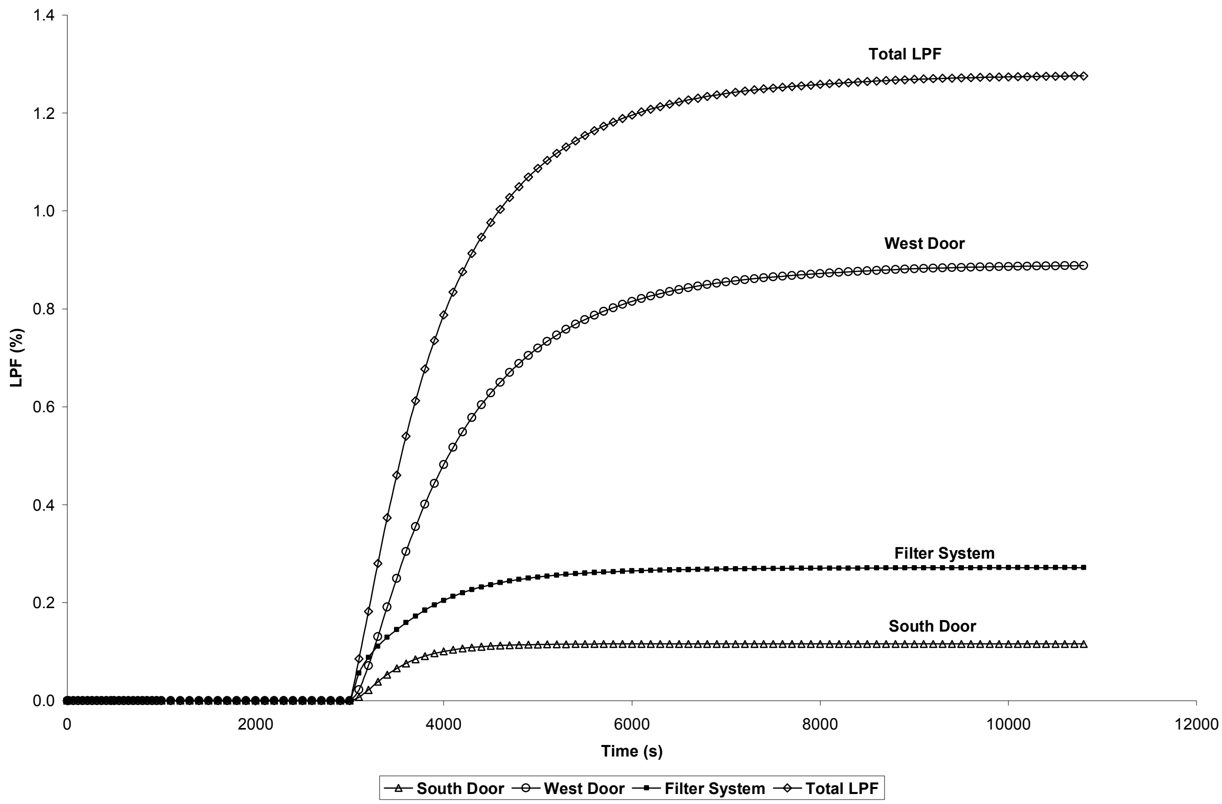

Figure 7 – Leak Path Factor Summary – Fire in Volume 500.

Figure 7 shows that the contribution to the LPF due to the doors (West + South) is larger than the contribution due to the filter system release. That is caused by the model geometry and flows established by the MELCOR simulation for the given boundary conditions. The volume 500 area has a pathway closely connected to the outside environment through the West door, consequently the fire induced pressure inside the volume 500 space causes most of the aerosolized release to occur through the West door (much less goes out the South door). The filter in the ventilation system significantly reduces the amount of aerosolized material that exits the building through this pathway. All other pathways not shown contribute negligibly to the atmospheric release. It is expected to have a larger amount of aerosolized material leaving the volume 500 area toward the outside through the West door then through the filter system and the South door because of the fire-induced pressurization inside the volume 500 area.

Figure 8 combines the unfiltered and unfiltered contributions of the leak path factor.

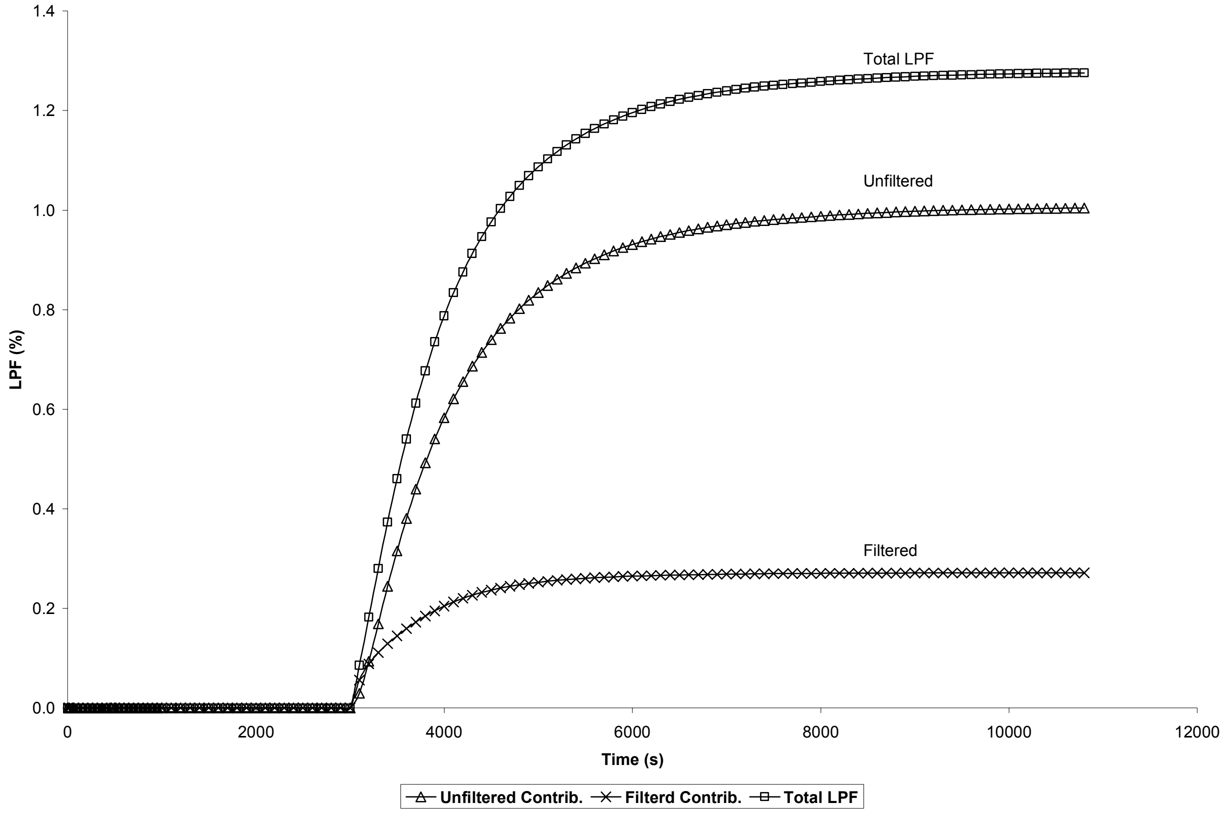

Figure 8 – Unfiltered and Filtered Contribution to the LPF - Fire in Volume 500.

A new analysis is now performed where the fire is in volume 130, the north east side of the building. In this case, volume 130 is not closely connected to and door leading to the outside of the building. All the parameters used in this new analysis are the same. This new arrangement shows how the results change with a different fire location.

Figure 9 shows the MELCOR calculated LPF (total LPF and individual contributions) for a fire in volume 130. The value of the calculated LPF is much smaller.

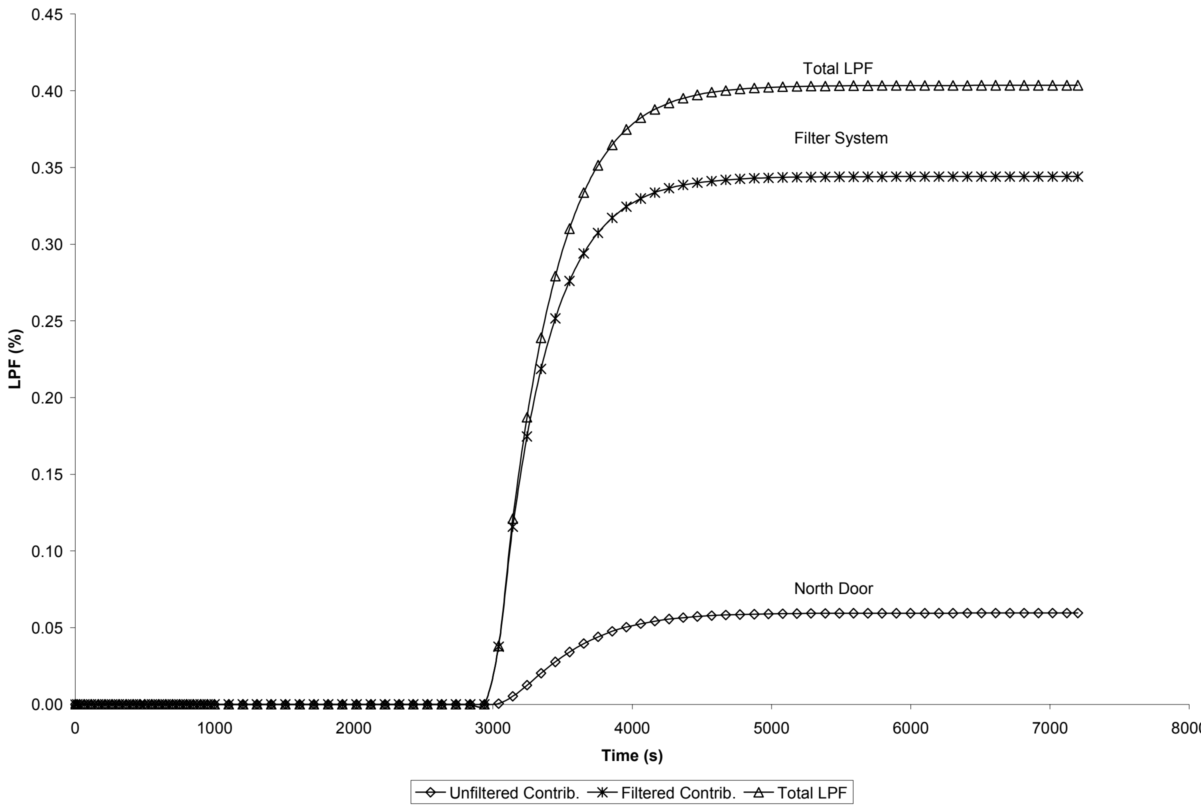

Figure 9 – Leak Path Factor Summary – Fire in Volume 130.

Figure 9 also shows that the contribution to the LPF due to the filter system release is larger than the contribution due to the release from the North door. That is caused by the model geometry and flows established by the MELCOR simulation for the given boundary conditions. Volume 130 has doors closely connected to the building inside, and the North door is not closely connected to volume 130. As a consequence the amount of aerosolized material leaving the volume 130 toward the filter system is larger than the amount exiting by the North door. All other pathways not shown contribute negligibly to the atmospheric release.

For the purpose of evaluating the consequences (subsequent MACCS analysis), the unfiltered and filtered LPF curves given in Figures 8 and 9 are transformed to make them more suitable as input into MACCS computer code.

The curves are shifted in time to have a time zero coinciding with the start of the release out of the building (the new time=0.0 is equivalent to about time=3000 s), and the curves are also simplified by using a bounding 4-piece linearization for ease of use in MACCS. Note that the release is complete at the end of the third segment.

Figure 10 shows the simplified unfiltered and filtered contribution to the leak path factor for the fire in volume 500.

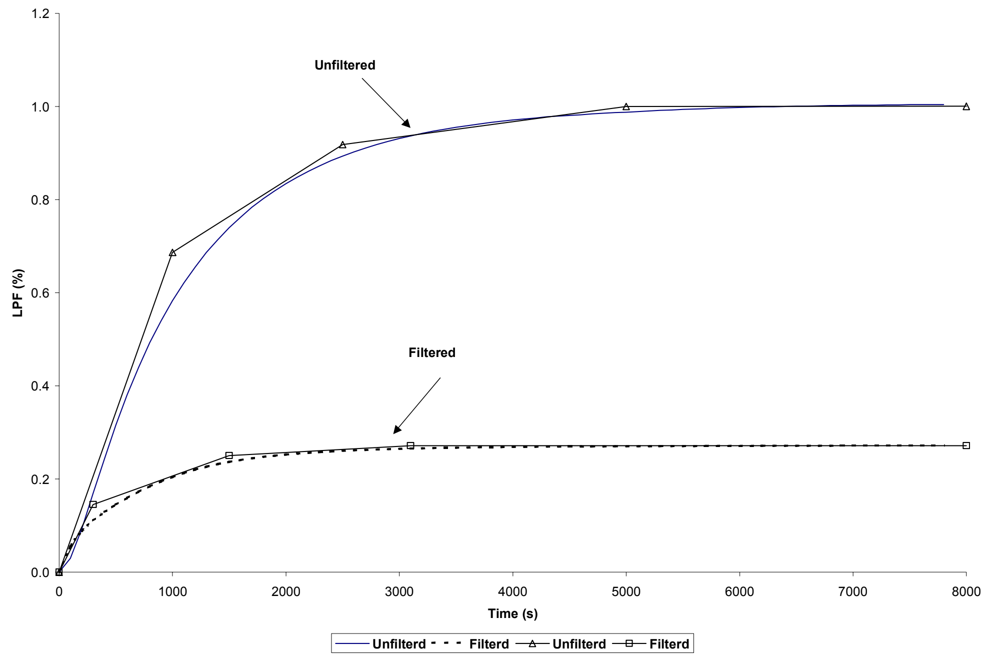

Figure 10 – Unfiltered and Filtered Contribution to the LPF - Fire in Volume 500.

Figure 11 shows the simplified unfiltered and filtered contribution to the leak path factor for the fire in volume 130.

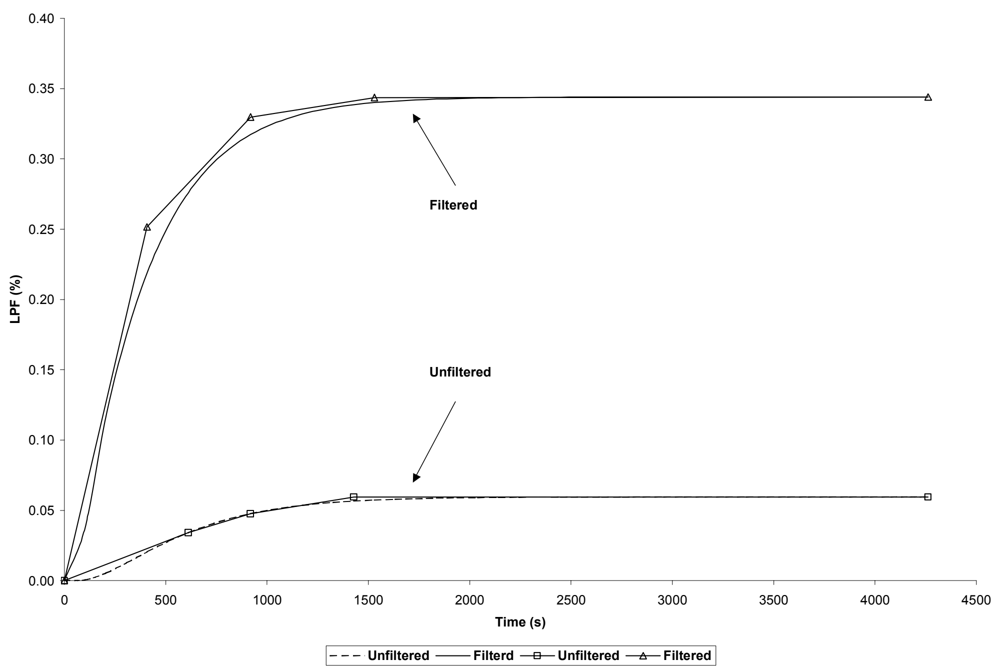

Figure 11 – Unfiltered and Filtered Contribution to the LPF - Fire in Volume 130.

The MACCS analysis is based on the release of 17.1 Ci (1 g) of Pu238 in volumes 500 and 130 as two separate events. It has to be noted that the filtered portion of the release is assumed to take place through a building stack. The EPA has established criteria for a good engineering practice stack height that defines the height of the stack that is needed for the plume to simply pass over nearby buildings without significant disruption of the plume flow by the wake region that forms behind each of these buildings[7]. The stack height of this analysis meets the criteria.

To simplify this study, the wake effects of the building are not included. The building height and width are set equal to the lowest allowable value[2] of 1.0 m.

The Pu^{238} release is considered without sensible heat. A fraction of the inventory is released from ground level (unfiltered) and a fraction of the inventory is released through the stack (filtered) as determined by the MELCOR runs. For each release scenario, two MACCS runs are executed to calculate separately the receptor doses from each release mode (i.e., ground and stack). For each release elevation, the plume is modeled with three sequential plume segments with a Leak Path Factor applied to each segment as determined from the MELCOR runs in order to model both the amount of material that leaves the building at each elevation and the time-dependent characteristics of the release. The Leak Path Factor is applied through the MACCS release fraction input.

For non-noble gas radionuclides (when included in the source term), only dry deposition is assumed (no wet deposition is assumed). The particulates that are released at ground level are assumed to have a deposition velocity of 0.01 m/s consistent with an unfiltered release. This dry deposition velocity corresponds to a particle with an Aerodynamic Equivalent Diameter of 2 to 4 microns[8]. The particulates that are released through the stack are assumed to have a deposition velocity of 0.001 m/s consistent with a filtered release. This dry deposition velocity corresponds to a particle with an Aerodynamic Equivalent Diameter of 0.2 to 0.4 microns[8].

Five years of site meteorological data are used. The meteorological data used is composed of hourly readings of atmospheric stability class, wind direction, and wind speed at a measured wind speed height of 10 meters.

Using the Leak path factor data as given in Figures 10 and 11 above, a MACCS analysis is performed to assess the consequences for the volumes 500 and 130 fires. The following figures show the results of the MACCS runs using a 17.1 Ci of Pu^{238} source term.

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Figure 12 and Figure 13 show the TEDE results for the fire-induced release in volume 500 at the 50^{th} percentile level and 95^{th} percentile level, respectively.

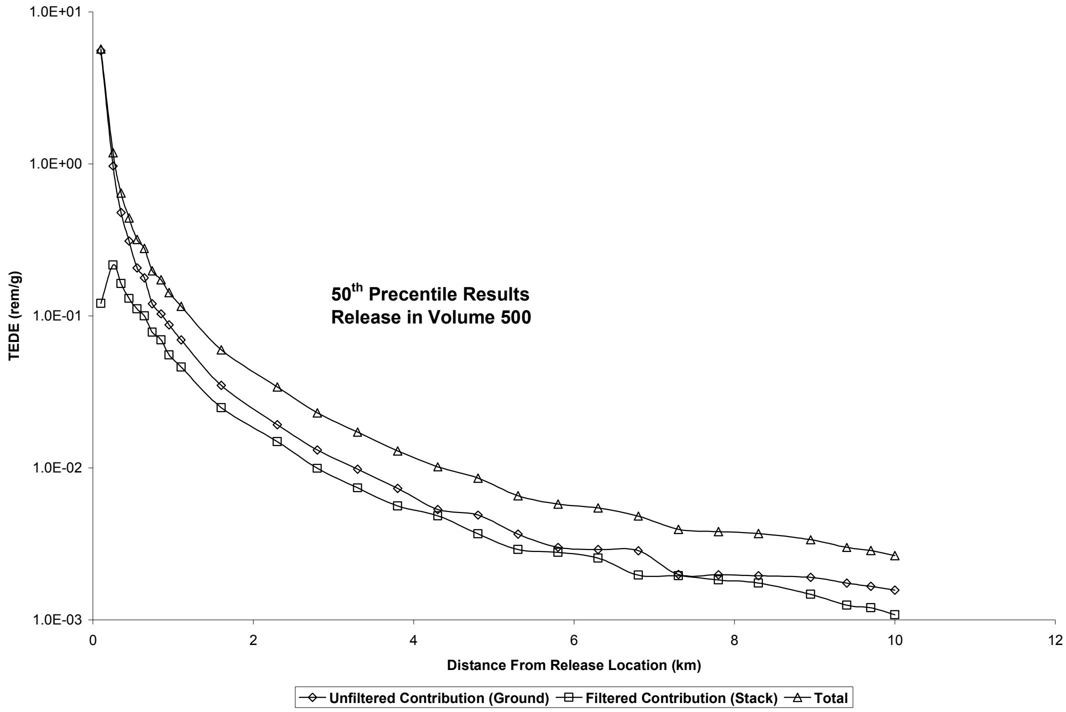

Figure 12 – 50th Percentile Resulting TEDE For Volume 500 Fire.

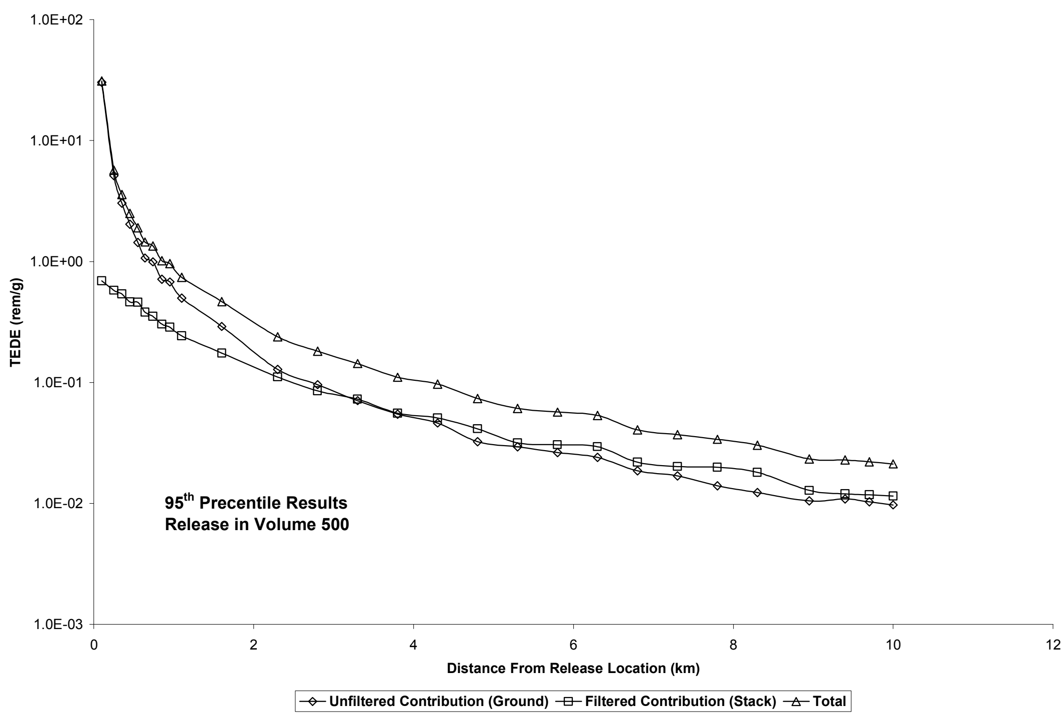

Figure 13 – 95th Percentile Resulting TEDE For Volume 500 Fire.

The results of Figure 12 and Figure 13 show that the contribution from the ground level release is much greater than that from the stack release at distances close to the release location. Recall from Figure 8 that more material is leaving the building at ground level. In addition, the plume from the elevated stack is initially separated from the ground such that the plume essentially passes over the receptor at the ground near the stack. As the plume from the stack travels downwind, mixes with ambient air, and grows in size, the initial separation from the ground (from plume rise) becomes less important. The dose contributions from the two pathways become essentially equal at far distances. Deposition effects are largely responsible for this trend. Because of the larger particles in the ground level plume with respect to those in the stack plume, deposition occurs at a faster rate that serves to deplete the ground level plume to a greater extent.

Figure 14 and Figure 15 show the TEDE results for the fire-induced release in volume 130 at the 50th percentile level and 95th percentile level, respectively.

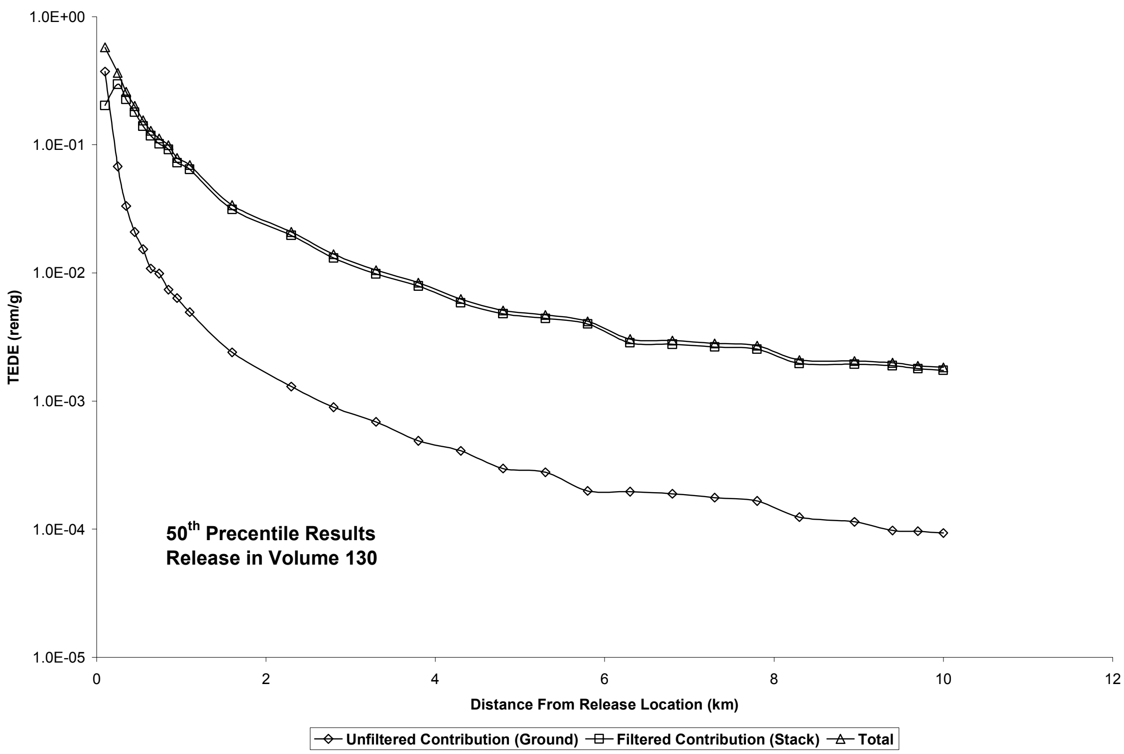

Figure 14 – 50th Percentile Resulting TEDE For Volume 130 Fire.

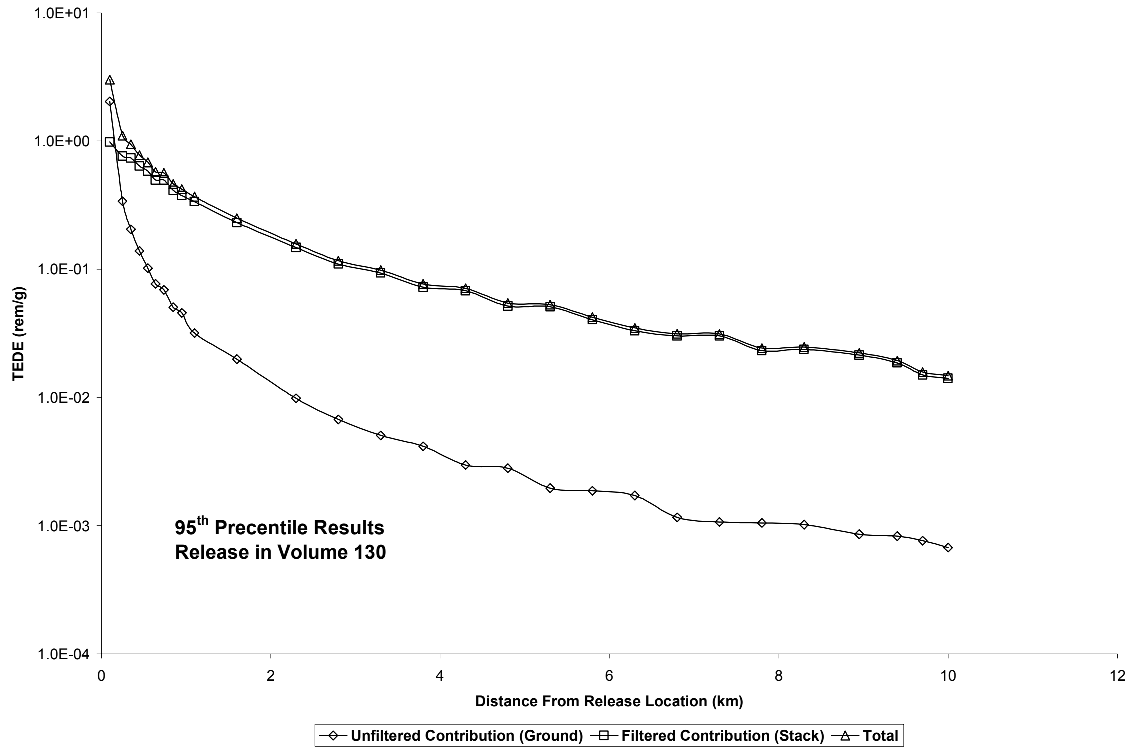

Figure 15 – 95th Percentile Resulting TEDE For Volume 130 Fire.

The results of Figure 14 and Figure 15 show that the contribution from the ground level release is consistently much less than that from the stack release in the Volume 130 fire at distances greater than 100 m, in contrast to the results for the Volume 500 fire.

It has to be noted again that the results given were calculated for 1 gram of airborne material inside the building. In a complete accident analysis calculation, the estimated amount of airborne material inside the building would consider the Material-at-Risk (MAR) together with the accident-specific Damage Ratio (DR), Airborne Release Fraction (ARF), and Release Fraction (RF). The consequences results of this paper can easily be scaled to reflect whatever airborne mass is calculated by accident-specific source term analysis.

Concluding Remarks

The results given in this paper show how the value of the time-dependent LPF and resulting dose change with the location of the fire-induced release of powder. The approach used in the analysis is simple and it is based on a careful evaluation of the leak path factor for the facility. The use of a time-dependent LPF is a viable methodology to evaluate a time-dependent source term for the subsequent consequence analysis. This results in more realistic doses. The combined use of MELCOR and MACCS offers a robust method to assess consequences for various configurations found in non-reactor facilities.

Using the methodology presented in this paper, the chief benefit that can be found is the integration of source term evaluation and its consequence analysis. This work can be used as model for performing analyses for systems similar in nature where releases can propagate to the outside environment via filtered and unfiltered pathways. The methodology provides guidance to analysts outlining the essential steps needed to perform a sound and defensible consequence analysis.

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