Leak Path Factor Study at Savannah River Site

By

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Abstract

The Leak Path Factor analysis has been traditionally performed at Savannah River Site for various facilities subject to accident analysis. This paper addresses some recent work for the FB-Line building, which needed refinements to previous work that was based on a single volume approach. To model the entire building and all its simultaneous spills of contaminants in the different floors after a seismic event, a more complex multi-compartment analysis was performed using the CONTAIN 2.0[1] computer code. This work enabled the analysts to improve the assessment of the source term for the subsequent evaluation of the onsite and offsite doses.

The model developed for the FB-Line building includes 45 control volumes connected by 72 flow paths, and the contaminants were located at each floor of the building. The seismically qualified structures were modeled to bound the various volumes, and the interconnecting flow paths were modeled as closed doors with gaps, open doors, and doors opening with specified flow area time-history. Since the ventilation system is not seismically qualified, it was kept non-operational. The model included cracks in the expansion joints of the structural walls, and additional paths to the outside environment such as doorways and roll-up doors. The only forcing condition applied to the building was the wind pressure across the structures. Because of the geometrical location of the pathways to the outdoor environment, the analyses were performed using one contaminant location at a time, with wind pressure applied at the four wind directions independently. Heat transfer was included to account for the difference in temperature between the building environment and the outside. The outside environment was modeled using five volumes (one at each side of the building, and one on top) at set ambient conditions and large enough to maintain constant pressure and temperature. This yielded a bounding LPF for each contaminant location and wind direction.

Since the LPF is strongly dependent on the contaminant location and building geometrical configuration, the five calculated LPF's were used to evaluate five source terms, which in turn were added for the consequent dose evaluation. The calculated LPF values were lower than those previously calculated, thus successfully reducing the source term.

This type of analysis using CONTAIN was very efficient. The building model, when well detailed, can subsequently be used for additional LPF analyses such as fires, accidental spills, uncontrolled blowdown of gas bottles, and others. The analyses were performed using the PC version of the computer code in a Windows NT environment. The code execution time was quite fast considering the large amount of computation for the size of the model. The code is simple to use and it has shown great improvement for the performance of this type of analyses.

Introduction

At the Savannah River Site there are various facilities which need assessment studies for accident analysis. The evaluation of the Leak Path Factor (LPF) plays an important role in the evaluation of the source term to be used in the subsequent offsite radiation dose releases. In the past, various analyses were performed and found adequate while using upper bound data. Recently, an analysis was performed for the FB-Line facility to assess the consequences of a post-seismic event involving the release of radioactive materials. The analysis was performed with a model which lumped the entire facility into a single volume, developed using the Mathematica[2] software. The results of the model were predicting values of the LPF, which unfortunately yielded excessive consequences for spills postulated in deep internal cells. In order to ameliorate the consequences of the accident without making facility design changes, it was decided to use the CONTAIN 2.0 computer code to more realistically model the facility and have better results to re-assess the consequence analysis. This new approach enabled the analysts to more accurately model the facility to account for the sub-compartmentalization of the FB-Line, and to analyze releases of radioactive materials in different locations within the facility, which was not feasible with the previous approach.

The new analysis provided a more robust solution to the problem while still maintaining conservatism and providing lower values of the LPF. The resulting values of the LPF for the actual analyses performed for the FB-Line are higher than the values reported here. The various parameters used in the analyses were purposely set to yield results on the high end of LPF values. The results reported in this paper are lower since many parameters influencing the analyses were optimized to more realistic values while still maintaining a good degree of conservatism.

Description of the CONTAIN Model

The CONTAIN model constructed for the FB-Line includes 45 cells and 72 flow paths. Included with the 45 cells are 7 dummy cells (34 through 40, these dummy cells were included for future uses and are modeled as connected to other cells via flow paths, which are maintained closed during the computation). Each cell contains structures (walls, floors, and ceilings) which are used for heat transfer and deposition of aerosols. Figures 1 through 8 represent a block diagram of the building. Figures 1 though 5 represent the connectivity of the cells at each building elevation, while figures 6 through 8 show the connectivity between elevations.

Cells 41 through 45 represent the outside environment which was subdivided into zones to account for the directional wind pressure coefficients. Cell 41 is the environment at the south of the building and cell 42 represents the north. Cells 43 and 44 represent the west and east environment respectively. Cell 45 is the environment on top of the building.

Cell numbers 1 and 2, 7 and 8, 17, 23, and 30 are the cells where the spill of radioactive materials takes place in the 6th, 5th, 4th, 3rd, and 2nd level respectively. Cells 6, 9, and 18, depicted in figure 6, represent the connectivity of the stairwell between the 6th, 5th, and 4th levels. Cells 16 and 22 in figure 7 represent the connectivity of the stairwell between the 4th and 3rd levels, and cells 2, 7, 17, and 23 represent the connectivity of the dumb waiter between the 6th, 5th, 4th, and 3rd levels.

During the seismic event the Heating Ventilating and Air Conditioning System (HVAC) is not operational, since it is not seismically designed, and in the modeling of the facility cell 31 represents the supply duct from the 6th level and cell 32 the supply duct from the 5th level, both connected to cell 33. Cell 33 represents the supply manifold outside of the building and this is assumed to be open to the atmosphere during and after the accident. The exhaust portion of the HVAC system is excluded in the analysis since it was assumed that the exhaust stack collapsed and blocked the flow out of the sand filters. The cell connectivity shown in figure 8 represents the various connections between the stairwells, elevator well and landing at each floor.

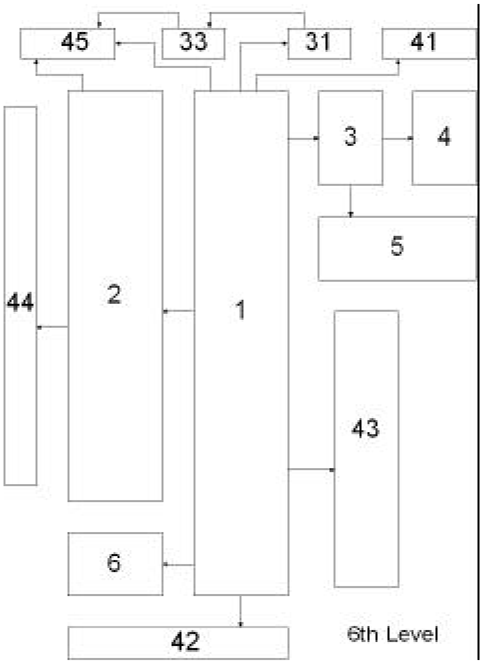

Figure 1 – 6th level nodalization

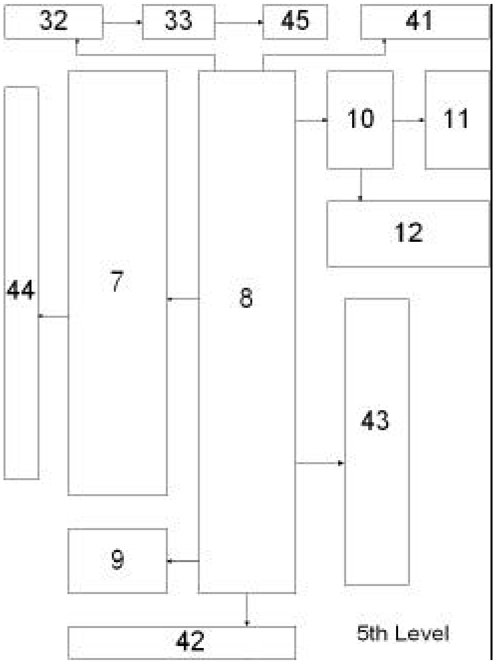

Figure 2 - 5th level nodalization

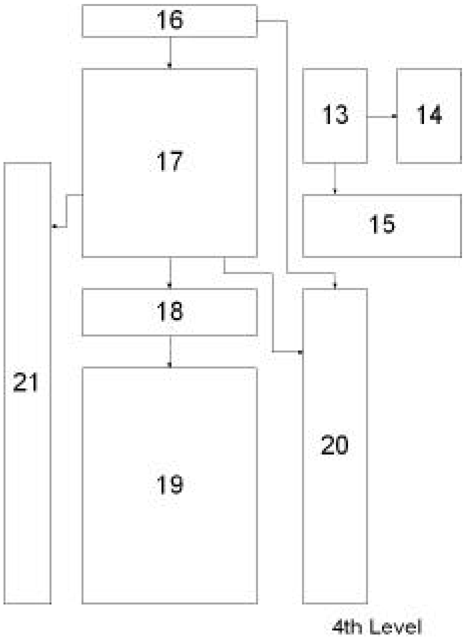

Figure 3 – 4th level nodalization

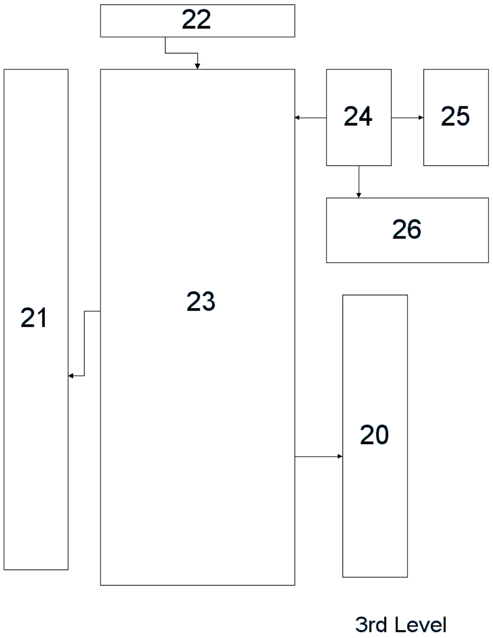

Figure 4 – 3rd level nodalization

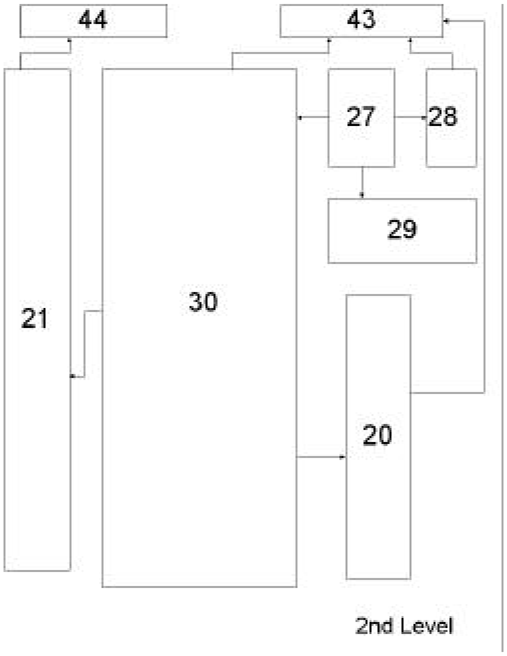

Figure 5 – 2nd level nodalization

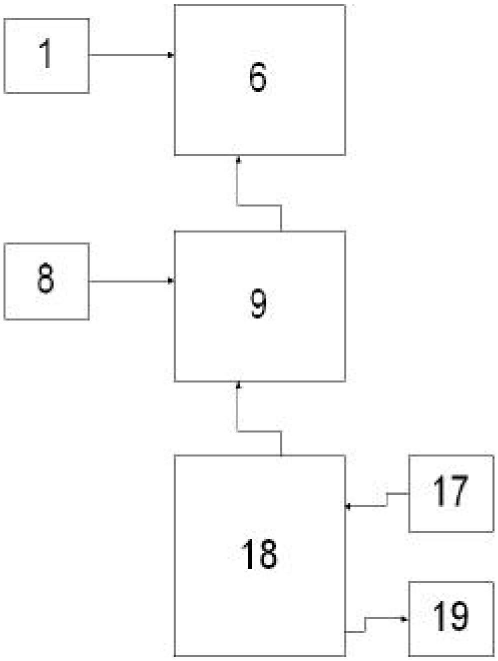

Figure 6 – Connections between levels

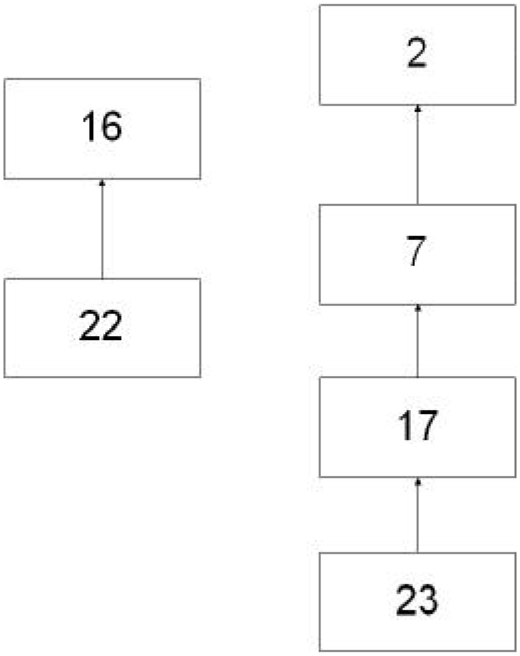

Figure 7 - Connections between levels

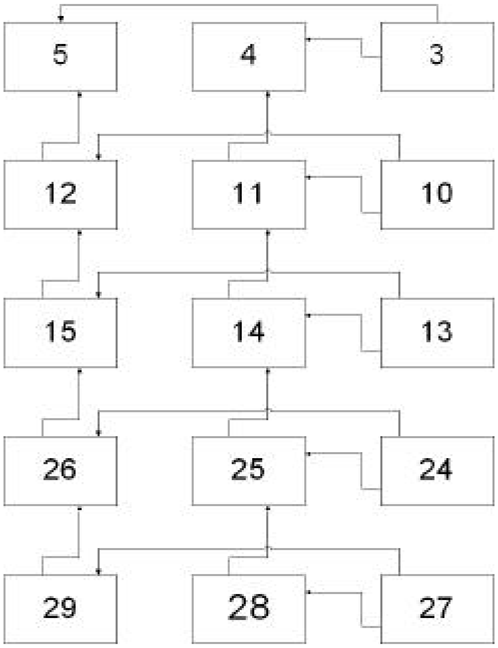

Figure 8 - Connections between levels

Cell number 34 and its connecting flow paths is not shown in the figures above.

The construction of the facility model sub-compartments is based on existing seismic analyses, thus only the structural walls surviving the seismic event are accounted as the physical boundary of the model cells. Seismic cracks in the building expansion joints are also accounted as pathways to the outdoor environment.

Wind pressure effects are evaluated using the ASHRAE[3] methodology and are applied to the model environmental cells. The building wind pressure is calculated from the dynamic head equation written in the form:

$$\Delta P_w = c_w \, r \, \frac{V_w^2}{2}$$

Where:

$\Delta P_w =$ Localized air pressure change due to wind
$c_w =$ Wind pressure coefficient
$V_w =$ Wind speed
$r =$ Air density

The wind coefficient c_w varies with wind direction relative to building surfaces. With wind impinging normally on a wall $c_w = +0.7$. Wind parallel to a wall produces a wind coefficient of –0.35 and on the down wind side of the building a coefficient of –0.4 is used. With these wind coefficients, the pressure difference across the facility was calculated and analyses were performed for each wind direction.

The selected wind speed was set to 2.24 m/s (5 mph). The consequence analysis group uses a 3.8 mph wind speed for off-site dose calculation (95% meteorology) and 5 mph is considered bounding for LPF calculations for this receptor. The 5 mph will also provide a LPF that can be used with less severe meteorology when calculating consequences to the onsite receptor.

A 0.001 kg of PuO_2 spill release was modeled as shown in the following curve:

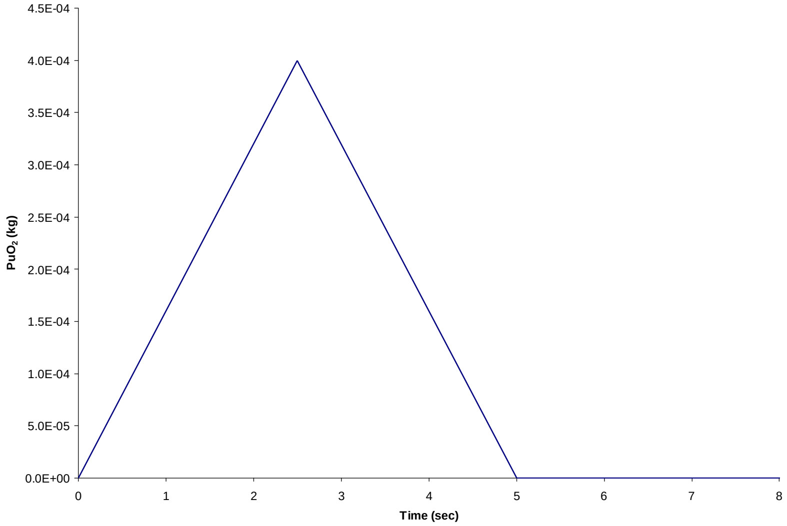

Figure 9 – PuO_2 spill time-history

With a size distribution obtained from experimental data[4]:

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 these data 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 as used in CONTAIN is:

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

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

The following figure shows the initial distribution used in the analyses.

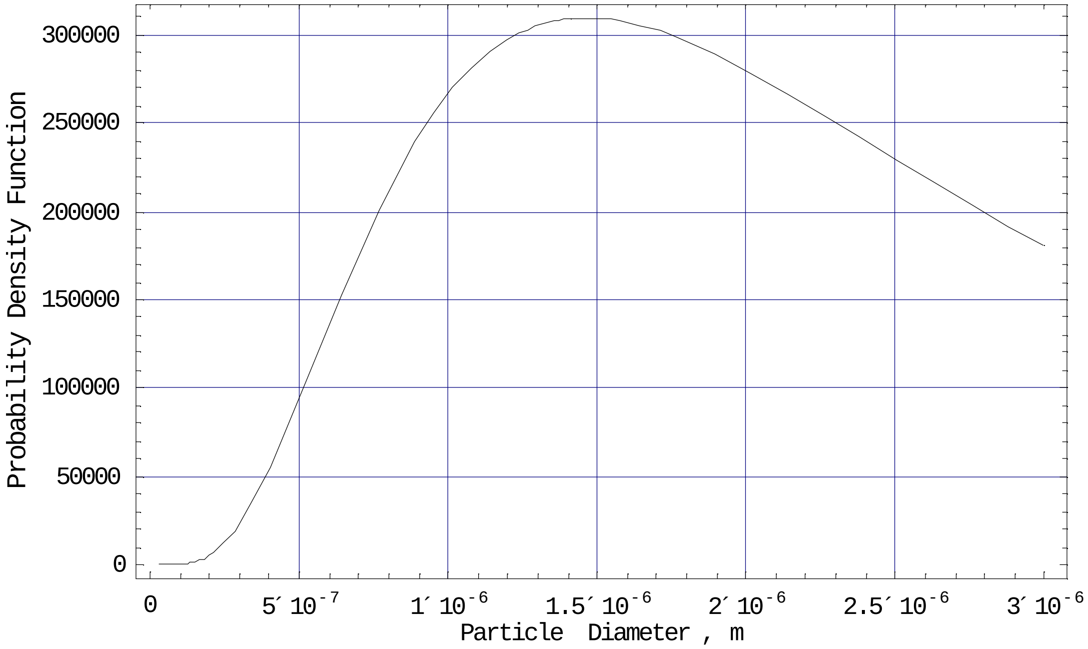

Figure 10 – Lognormal distribution of PuO_2

Two sets of analyses were performed:

a. All the doors within the facility kept closed
b. All doors opened with a prescribed time history assumed on best estimates.

When the doors were kept closed the air flow area between sub-compartments was evaluated based on estimated gaps around the closed doors, while when the doors were kept open the air flow area between sub-compartments was modeled based on the following figure. This is an assumption, based on evacuation response that will be a representative profile of the door opening.

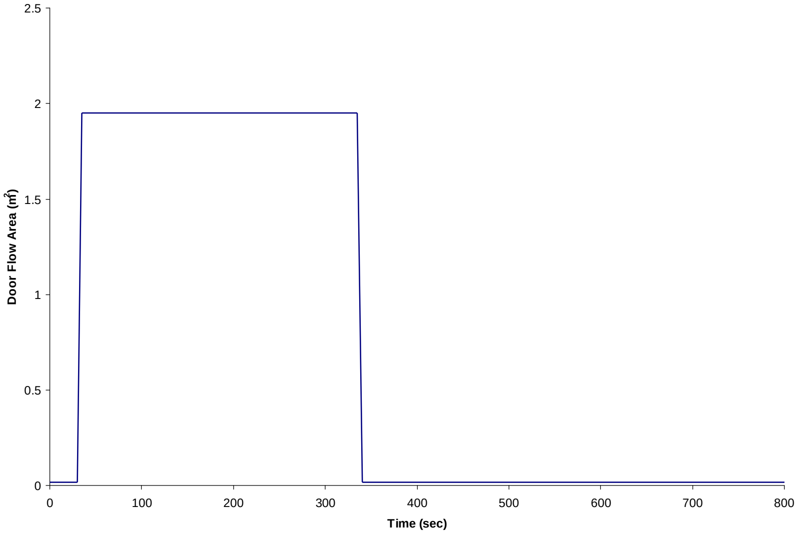

Figure 11 – Doors flow area

The temperature of the building environment was initially set at 295 K while the outside air temperature was set at 273 K. For all the cases analyzed the wind speed was kept constant for the entire duration of the analysis.

Analysis Results

The analyses were performed for a 48 hours real time simulation and the values of the resulting LPF's at steady-state are reported.

The following table shows the resulting LPF's for the analysis where all doors are opened with the prescribed flow area time-history shown in figure 11.

Table 1– LPF Summary – 2.24 m/s wind

	2nd Level LPF%	3rd Level LPF%	4th Level LPF%	5th Level LPF%	6th Level LPF%
East Wind	**1.07**	**0.268**	0.199	3.84	2.88
North Wind	0.046	0.0008	0.001	3.1	2.96
South Wind	0.268	0.008	0.002	4.14	3.29
West Wind	0.133	0.049	**1.01**	**9.47**	**11.5**

The bounding time-dependent LPF for the 4th level (Table 2), chosen as representative intermediate level, is shown in figure 12 as a sample.

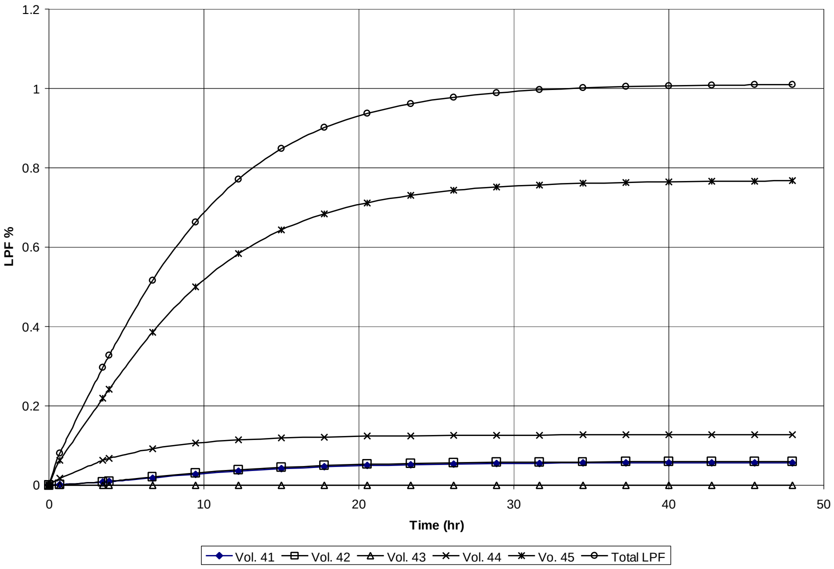

Figure 12 - LPF for the 4th level with closed doors

The following table is given to show the final distribution of the aerosol as a PuO_2 mass reconciliation for the bounding LPF for the 4th level as shown in table 1.

Table 2 – Summary of PuO_2 mass

Cell No.	Mass of PuO_2 (kg)	%	Cell No.	Mass of PuO_2 (kg)	%
1	1.02E-05	1.02	19	1.25E-07	0.013
2	1.87E-05	1.9	20	1.77E-18	Negligible
3	0.0	0.0	21	2.93E-06	0.29
4	0.0	0.0	22	4.63E-14	Negligible
5	0.0	0.0	23	3.25E-08	0.003
6	8.30E-06	0.83	24	0.0	0.0
7	1.54E-04	15.4	25	0.0	0.0
8	2.36E-05	2.36	26	0.0	0.0
9	2.25E-05	2.25	27	3.91E-30	Negligible
10	0.0	0.0	28	7.08E-38	Negligible
11	0.0	0.0	29	4.57E-37	Negligible
12	0.0	0.0	30	3.27E-25	Negligible
13	0.0	0.0	31	4.80E-11	Negligible
14	0.0	0.0	32	4.64E-11	Negligible
15	0.0	0.0	33	1.48E-10	Negligible
16	4.58E-14	Negligible	34	3.23E-07	0.032
17	6.68E-04	66.8	Dummy Cells 35, 36, 37, 38, 39, 40	N/A	N/A
18	8.09E-05	8.1	Outside Environment 41, 42, 43, 44, 45	1.01E-05	1.02
				Total 0.001	**100%**

A sensitivity study was performed to assess the influence of the quantity of spilled mass on the LPF. The results are presented in the following figure 13:

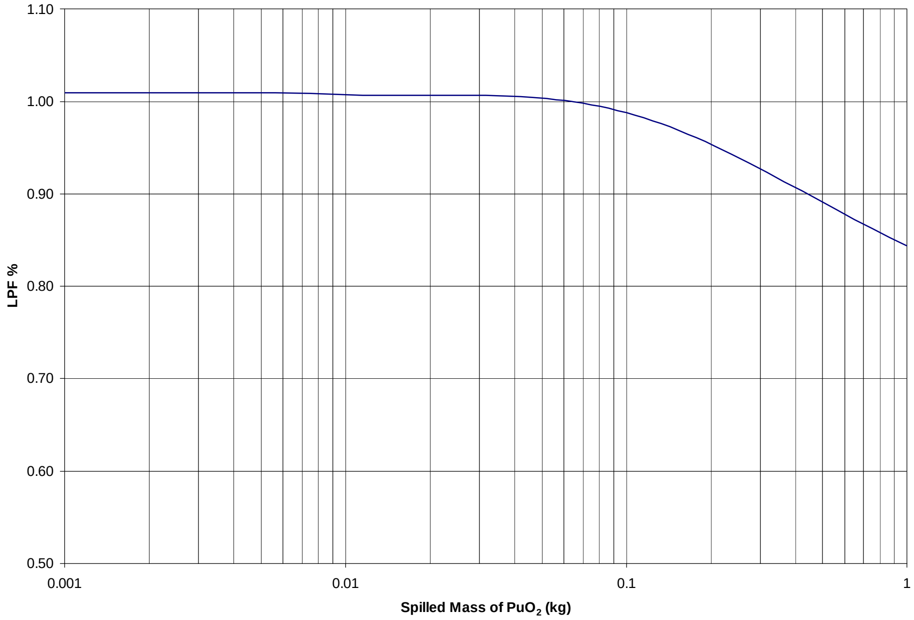

Figure 13 – Influence of spilled mass on LPF

It is evident that the agglomeration of the aerosol particles shows its effect for a spilled mass greater than about 0.08 kg.

Concluding Remarks

The results given in this paper show how the value of the LPF changes with the location of the postulated spill. The 4th level was selected as a representative case of the analysis since it is the middle level of the building. All the analyses were performed using an initial distribution of the PuO_2 particulate in the respirable range only to yield the LPF value.

The LPF for the 4th level with westerly wind and modulating doors was re-analyzed using a particulate distribution covering the respirable and non-respirable range (maximum particle diameter of 10 μm). This case resulted in a new LPF of 0.65%. This lower value of the new LPF was expected since the new particle distribution used covered also the non-respirable portion of the Airborne Released Fraction (ARF) of the particulate. The use of this new LPF and the simultaneous use of a Respirable Fraction (RF) as defined in reference [6] would not be appropriate for the source term evaluation, and it would give incorrect results. This new calculated LPF is more likely a pseudo RF x LPF calculated by CONTAIN, and its use would eliminate the need of assessing the value of RF from reference [6]. A review of the CONTAIN results using the initial spilled distribution covering the respirable and non-respirable range yields a very small fraction of non-respirable particles in the environmental cells.

Whenever possible, if experimental data on airborne particulate distribution are available, it could be a preferred methodology to use distributions covering the respirable and non-respirable range. This will yield the pseudo RF x LPF and it would be also a defendable solution, which will use the robust package of aerosol dynamics, which is included in the CONTAIN computer code.

It is important to carefully evaluate the wind pressure and the flow loss coefficients for a good solution since the results of the analysis are strongly dependent on these parameters. The determination of the mass median particle diameter for the initial distribution of the particulate is very critical. This parameter should possibly be evaluated using experimental data such as in references 4 and 5. An inappropriate selection of the mass median particle diameter can skew the distribution to the left or right and change the solution to unrealistic results.

The use of a time-dependent LPF would also be a viable methodology to evaluate a time-dependent source term for the subsequent consequence analysis. This would result in more realistic doses.

The use of CONTAIN with PC's under Windows NT environment was found quite convenient for its ease of use and the execution time was reasonable for a large model.

References

[1] Murata, K., K., et al., "Code Manual for CONTAIN 2.0: A Computer Code for Nuclear Reactor Containment Analysis," NUREG/CR-6533, SAND 97-1735, December 1997

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[4] Sutter, S., L, Johnson, J., W., Mishima, J., "Aerosols Generated by Free Fall Spill of Powders and Solutions in Static Air," NUREG/CR-2139, Battelle Pacific Northwest Laboratory, Richland, WA, December 1981

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[6] DOE Handbook "Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities," DOE-HDBK-3010-94, December 12, 1994