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Modeling Particle Resuspension for Estimating Potential Exposure to *Bacillus* Spores

Office of Research and Development
National Homeland Security Research Center

Disclaimer

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Acronyms and Abbreviations

BG	*Bacillus globigii*
BOTE	Biological Operation Testing and Evaluation
CBR	chemical, biological and radiological
CFU	colony-forming unit
EPA	U.S. Environmental Protection Agency
FPSL	fluorescent polystyrene latex
IBAC	(trademark name, not an acronym)
INL	Idaho National Laboratory
NHSRC	National Homeland Security Research Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PBF	Power Burst Facility
PSU	Pennsylvania State University
UVAPS	Ultraviolet Aerodynamic Particle Sizer

Executive Summary

The U.S. Environmental Protection Agency (EPA) is charged with planning for and responding to intentional and unintentional releases of airborne chemical, biological and radiological (CBR) agents. The EPA conducts research to support site-specific contamination characterization and remediation decisions during such incidents. As part of these research activities, the EPA's National Homeland Security Research Center, in collaboration with several other federal agencies, conducted the Biological Operation Testing and Evaluation (BOTE) study at the Idaho National Laboratory to evaluate several *Bacillus anthracis* decontamination technologies and to better understand the potential exposure to spores before and after decontamination [1, 2]. The data collected in this study provided a unique resource to support the development of microbial exposure assessment methodologies, including the application of particulate transport modeling.

Given the great variability among built environments, potential modes of agent release, and subsequent occupant activities that may impact exposure, modeling offers an important tool to support exposure assessments. Particle transport modeling capabilities that consider specific particle characteristics, along with the impacts of building construction and building systems on particle transport, have been incorporated into multizone building airflow and contaminant transport simulation software tools. Such simulation tools provide a means to quantify the distribution and transport of contaminants within buildings as well as the potential exposure associated with the resultant spatial and temporal variations in indoor contaminant concentrations. Also, simulation parameters can be adjusted to study the impact of variations in building, agent and release parameters on potential exposure more easily than can be done in experimental studies, which require significant time and resources.

To demonstrate and assess the applicability of said simulation tools to calculate potential exposure to resuspended particles during decontamination-related sampling activities, a modeling study based upon the BOTE experiments was performed. This modeling study involved the following tasks:

- Perform a literature review of resuspension rate measurement studies to identify existing resuspension models and data
- Develop a whole-building representation of the experimental BOTE resuspension study within a multizone modelling tool
- Compare resuspension of particles determined from BOTE experimental measurements with those based on simulation results using a multizone model
- Perform a sensitivity analysis of inputs for a simplified, single-zone exposure model
- Propose a software tool to estimate exposure due to resuspension for generalized application to exposure events

The review of existing resuspension studies identified resuspension rates that could be used within the existing multizone modeling software, CONTAM, for the purpose of estimating exposure due to resuspension. A wide range of resuspension rates associated with various types and levels of activity was identified spanning almost ten orders-of-magnitude. However, the methods of measuring and reporting resuspension rates were inconsistent and varied widely due to the wide range of study types reviewed.

The whole-building, particle resuspension simulations required many assumptions related to particle transport and building conditions. Among the most significant assumptions were initial particle loadings, resuspension rates and resuspension activity levels. Considering the fairly uncertain nature of these assumptions, the order-of-magnitude agreement between measured and simulated results that was obtained is quite encouraging.

To address the wide range of uncertainty in the model inputs, a sensitivity analysis was performed. This analysis, aimed at identifying the most significant effects of several inputs to a single-zone resuspension exposure model, revealed that initial surface loading, resuspension rate and their interactions were of most significance; deposition rate, outdoor air change rate and their associated interactions were somewhat less significant but still significant; and deposition surface area and its interactions were relatively insignificant. These results were utilized in considering input parameters to a proposed software tool to estimate exposure due to resuspension.

An outline was presented of a proposed tool that could be used to provide a rapid means to broadly estimate the potential for exposure due to resuspension by those who respond to, and then decontaminate, facilities that experience a chemical, biological and radiological (CBR) event.

1 Introduction

The U.S. Environmental Protection Agency (EPA) is charged with planning for and responding to intentional and unintentional releases of airborne chemical, biological and radiological (CBR) agents [3-6]. The EPA conducts research to support site-specific contamination characterization and remediation decisions during these potential incidents. To facilitate greater risk-based remediation decision making, it is important to better understand agent transport into and within buildings, potential occupant exposure, and the effectiveness of various decontamination strategies [7, 8]. A key challenge associated with assessing the exposure due to potential releases of CBR agents is evaluating the risks of low level contamination following biothreat agent releases and subsequent decontamination efforts. This issue is of particular interest for *Bacillus anthracis*, the causative agent of anthrax [9, 10]. Given the great variability among built environments, potential modes of agent release, and subsequent occupant activities that may lead to exposure, modeling offers an important tool to support exposure assessments. Particulate transport modeling capabilities that consider specific particulate characteristics, building construction and building system (e.g., ventilation and filtration) features have been incorporated into multizone building airflow and contaminant transport simulation software tools [11, 12]. Such simulation tools provide a means to quantify the distribution and transport of contaminants within buildings as well as the potential exposure associated with resultant spatial and temporal variations of indoor contaminant concentrations. Also, simulation parameters can more easily be adjusted to study the impact of variations in building, agent and release parameters on potential exposure than experimental studies, which require significant time and resources.

The EPA's National Homeland Security Research Center (NHSRC), in collaboration with several other federal agencies, conducted the Biological Operation Testing and Evaluation (BOTE) study [1, 2] at the Idaho National Laboratory (INL) to evaluate several *Bacillus anthracis* decontamination technologies and to better understand the potential exposure to spores before and after decontamination. The data collected in this study provided a unique resource to support the development of microbial exposure assessment methodologies, including the application of particulate transport modeling.

Models have been developed to predict resuspension rates as a function of particle size, surface characteristics, human disturbances and other factors, but their applicability and accuracy for use in exposure assessment have not been fully determined. Whole-building airflow and contaminant transport simulation software was used to determine the applicability of models to estimate potential human exposures to biological contaminants. The model's applicability was tested using the field sampling data collected from the BOTE study and resuspension rates determined from existing resuspension models from the literature.

2 Literature Review

A literature review was conducted to identify models that predict resuspension rates so that they could be used in the analysis performed as part of this study. The literature review was focused on rate-based resuspension.

2.1 Background

Zhang [13] defines *particle resuspension* as "a process in which particles detach from the surface and become airborne again." For the purposes of this study, particle resuspension can be characterized into two categories: physical and rate-based. Physical resuspension characterizes particle resuspension based on the interaction between specific forces that attach a particle to and detach a particle from a surface, e.g., gravitational, mechanical and electrostatic forces. Rate-based resuspension provides resuspension rates based on source and environmental characterization including particle size and type, surface materials such as carpet or tile, and disturbance type or activity such as walking or vacuuming. Rate-based resuspension is more relevant to this effort than the fundamental physical data as the latter are more difficult to apply without taking into consideration very detailed environmental factors.

The whole-building multizone airflow and contaminant transport simulation software CONTAM [14] is a building simulation tool in which resuspension modeling has been implemented.[1] CONTAM is considered to be the most widely used software of its kind for simulating contaminant transport on a whole-building scale, and CONTAM is used in the current study. To provide context for the use of resuspension rates within CONTAM, the mass balance model employed by CONTAM is presented. This explanation is also helpful in identifying those resuspension studies presented in the literature review that are most useful to this project. Note that the results of these studies are presented in several different forms that are not always amenable to application within the mass balance model employed by CONTAM and similar simulation tools.

CONTAM employs the following mass balance equations to represent a two-compartment model of resuspension in a well-mixed zone or room. The two compartments refer to the air and surfaces for a given zone. These equations assume penetration of particles from outside the zone and that particles are removed only by deposition and airflow out of the zone.

For the air:

$$V\,\mathrm{dC}_z/\mathrm{dt} = \mathrm{P}QC_o(t) + rA_rL_s(t) + G - QC_z(t) - k_dVC_z(t) \quad (1)$$

For the surface:

$$A_s\,\mathrm{dL}_s/\mathrm{dt} = k_dVC_z(t) - rA_rL_s(t) \quad (2)$$

where:

V = zone volume [m^3]

[1] While other multizone airflow and contaminant transport simulation tools do exist, COMIS is the only tool known to the authors that is similar to CONTAM in its capabilities. However, COMIS does not directly support resuspension, and it is no longer under development within the U.S.

A_r = resuspension surface area [m^2]
A_s = deposition surface area [m^2]
C_z = zone particle concentration in air [kg/m^3]
C_o = particle concentration of air flowing into the zone [kg/m^3]
L_s = particle surface loading [kg/m^2]
Q = volumetric airflow rate [m^3/s]
r = particle resuspension rate [1/s]
k_d = particle deposition rate [1/s] ($k_d = v_d A_s / V$)
v_d = particle deposition velocity [m/s]
G = particle generation rate [kg/s]
P = particle penetration factor [-]
t = time [s]

As outlined below in discussing the literature review, measurements have been performed to estimate resuspension rates using various methods, with results being reported in various forms including *resuspension rate*, *resuspension factor*, *resuspension fraction, and emission factor*. The following presents some background information on how these various forms of resuspension rates relate to one another.

To relate these forms of resuspension measurements, steady state conditions must apply. Assuming steady state conditions in equation (1), the following equation provides the steady state concentration of particles in the air.

$$C_{ss} = \frac{G + PQC_o + rA_rL_s}{Q + k_dV} \tag{3}$$

Resuspension measurement conditions and results are sometimes reported in ways that are not conducive for them to be applied readily in the above equations. In some cases, the deposition surface area is associated with the resuspension rate, as opposed to the smaller area involved in resuspension. In other cases, a *resuspension factor*, K, is reported as the ratio of the air concentration to the surface concentration in units of inverse length, e.g., m^{-1}. However, it is not always clear whether or not the reported values were measured under steady conditions. The following equation provides the relationship between *K* and *r* at steady state.

$$K = \frac{C_{ss}}{L_s} = \frac{G + PQC_o + rA_rL_s}{L_s(Q + k_dV)} \tag{4}$$

In other case, results are reported as a dimensionless *emission factor*, E, which is the ratio of particles suspended in the air to particles available for resuspension on the surface. The emission factor can be related to the resuspension factor according to the following equation.

$$E = K\frac{V}{A_s} \tag{5}$$

These resuspension and emission factors are sometimes presented in terms of count concentrations or mass concentrations for various particle size ranges. To be useful in applying equations (1) and (2), sufficient information on measurement conditions and parameters must be provided to allow resuspension factors to be converted to a resuspension rate as presented in equation (6).

$$r = \frac{KL_s(Q + k_d V) - G - PQC_o}{A_r L_s} \tag{6}$$

For the purposes of this modeling study, resuspension rates, as addressed later in Section 2.3, were employed because they can readily be applied to predict airborne particle concentrations for conditions other than those under which the resuspension rate measurements were performed. Specifically, these values can be used directly within models using equations (1) and (2) to estimate potential exposure due to resuspension.

The *resuspension fraction*, F, is the particle resuspension intensity based on the actual area disturbed by the activity instead of the entire deposition surface area loaded with particles. For walking, it is the resuspension rate times the ratio of the floor area (A_s) to the foot contact area (A_r) divided by the contact frequency, ω [1/time] as presented in the following equation.

$$F = \frac{rA_s}{\omega A_r} \tag{7}$$

2.2 Literature Review Categories

The documents reviewed were grouped into the following categories:

- Relevant resuspension models
- Chamber measurements of resuspension rates
- Other chamber measurements
- Field measurements of resuspension rates or particle concentrations
- Other model development and application
- Reviews

This Section describes the types of studies in each category. Appendix A contains the reference of each publication examined.

2.2.1 Relevant resuspension models

Among all the literature studies, two publications described models to predict resuspension rates based on user inputs. These models were developed by the Pennsylvania State University (PSU) for the U.S. Army Center for Health Promotion and Preventive Medicine. The first, described by Bahnfleth et al. [15], is a Microsoft Excel spreadsheet that yields resuspension rates based on user input of a number of variables: particle size, particle type (from a limited set of choices), and flooring (carpet or linoleum). The second model, Freihaut et al. [16], presents an approach using “look-up” tables, which yield resuspension rates adjusted for factors such as particle type, flooring, and relative humidity. Note that the resuspension rates obtained from these two approaches do not agree with each other.

2.2.2 Chamber/Test Facility measurements of resuspension rates

The papers in this category include experimental studies in which resuspension rates were measured in laboratory test chambers or test facilities, as well as a small number of studies that do not provide resuspension rates but which are of interest nonetheless. The measurements of resuspension rates involved either actual or simulated human walking to induce resuspension for different types and sizes of particles, different flooring types and ages, and different environmental conditions, e.g., relative humidity. These studies, listed in Appendix A, include

Gomes et al. (2005, 2007) [19, 20], Hu (2008) [21], Qian and Ferro (2008) [22], Thornburg et al. (2009) [23], Rosati et al. (2008) [24], Shaughnessy and Vu [25], Manthena and Ferro (2009) [26], Tian et al. (2014) [27], and others.

2.2.3 Other measurements

Several other papers describe studies that did not measure resuspension rates but rather measured other quantities of interest. These included detailed measurements of adhesion forces holding particles to a surface. Other studies described approaches to measuring resuspension rates but did not present any measurement results. There were also a number of particle resuspension studies conducted in nuclear facilities, starting in the 1960s time frame, based on concerns about radioactive dust [16]. These studies are not covered in this report based on the unique aerosols and space types involved. Similarly, there has been and continues to be research on aerosol resuspension outdoors induced by wind and considering various environmental and soil properties [17, 18]. This work is also not considered relevant to the present study.

2.2.4 Field measurements of resuspension rates or particle concentrations

There have been a number of interesting studies in which resuspension rates were measured in actual buildings, in many cases residences. Most of these measurements involved walking, but other occupant activities were studied as well. In other field studies, only airborne particle concentrations were measured as opposed to the resuspension rates. These studies, listed in Appendix A, included Rosati et al. (2008) [24], Shaughnessy and Vu (2012) [25], Ferro et al. (2004) [28], Hambreaus (1978) [29], Karlsson et al. (1996) [30], Qian et al. (2008) [31], Thatcher and Layton (1995) [32], Buttner et al. (2002) [33], and others.

2.2.5 Other model development and application

The papers in this category include model development and application efforts of interest but not directly applicable to the current effort in that they do not provide methods for estimating resuspension rates. For example, simulation studies of resuspension impacts on particle concentrations in buildings have been conducted using building airflow and contaminant transport models. Other studies have modeled the detailed processes impacting particles on surfaces.

2.2.6 Reviews

This last category includes articles that have reviewed the literature on resuspension. Two of these were focused on outdoor resuspension rather than indoor. The reviews of indoor resuspension studies were useful in identifying relevant references and for verifying the information obtained in this literature review.

2.3 Summary of Existing Resuspension Rate Data

As noted above, a number of studies report measured resuspension data from chamber and field experiments. A wide range of resuspension rates associated with various types and levels of activity was identified spanning almost ten orders-of-magnitude. However, the methods of measuring and reporting resuspension rates were inconsistent and varied widely due to the wide range of study types reviewed. Values demonstrated strong dependencies on particle size, particle type, floor type and activity. While the values do not necessarily support predictions for a given set of field conditions, they do provide an indication of the range of resuspension rates that might be expected in the field.

2.4 Conclusions from the Literature Review

Based on the literature review, the spreadsheet model presented in Bahnfleth et al. [15], referred to herein as the PSU model, was used to estimate resuspension rates for the subsequent modeling using the BOTE INL data. In addition, given the uncertainty in resuspension rate prediction, the measured rates from the literature and other relevant parameters were also considered in conducting the sensitivity analysis presented below.

3 Description of BOTE Measurement Data Used for Modeling Study

Three rounds of biological release and decontamination experiments took place in April and May of 2011 in a building located at INL. Complete descriptions and BOTE study results can be found in the comprehensive BOTE report [1]. This Section contains a description of that building and the experimental measurements that were performed therein. Measurement results are presented against which simulation results will be compared herein for the purposes of evaluating the applicability and accuracy for determining potential particle resuspension.

3.1 Building Description

The building used in the BOTE study and for the modeling analysis described in this report is the Power Burst Facility 632 (PBF-632) located at INL and shown in **Figure 1**. This building is the same building that was used in exercises aimed at the evaluation of sample planning methods and multizone modeling validation of particle release experiments [34-36]. Floor plans for the two floors of PBF-632 are shown in **Figure 2** and **Figure 3**. Each floor is approximately 24.4 m x 15.2 m for a total of 371 m^2 per floor. Most of the floor is covered with laminate floor tile with several rooms on each floor covered with carpet including rooms 101A and 102. Each floor contains a constant volume air handler located within a mechanical room on the floor it serves with no provision for bringing in outdoor air. Supply air ducts are located above suspended ceilings on the floor that they serve. The building was modified for decontamination studies by installing dedicated return ducts and decontamination distribution ducts below the suspended ceiling, i.e., within the occupied space on each floor. A large tent (also shown in **Figure 1**) was erected around the entire building for the decontamination studies.

Figure 1. INL building PBF-632 and decontamination containment tent.

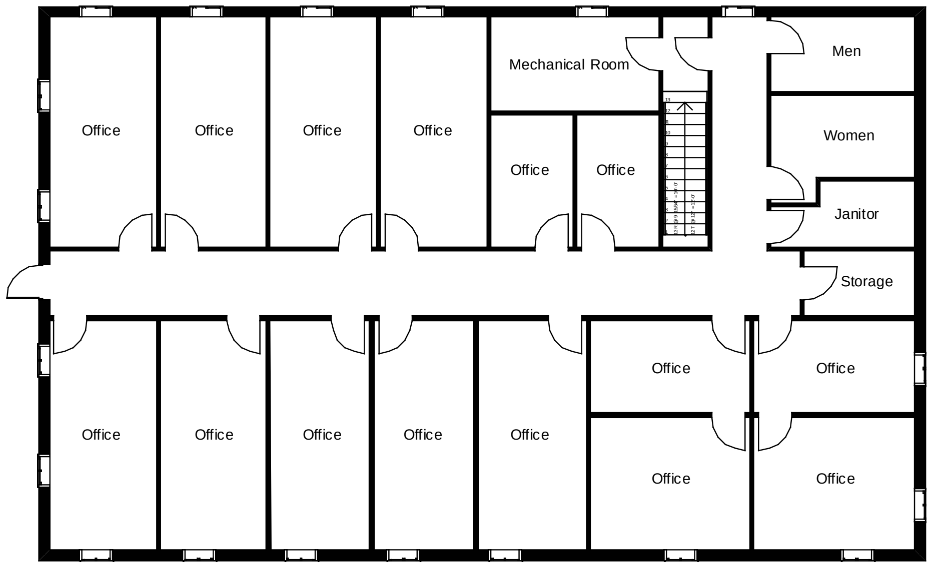

Figure 2. 2nd floor plan of PBF-632.

Figure 3. 1st floor plan of PBF-632.

3.2 BOTE Experimental Measurements

Three particle resuspension experiments consisted of the dissemination of *Bacillus atrophaeus* subsp. *globigii* (BG), which is used as a surrogate for *Bacillus anthracis.* During each of these three release experiments, 200 mg were released on the 1st floor and 0.5 mg were released on the second floor through the use of automated nebulizers placed on the downstream side of the filter banks of the recirculating air handling system. Releases took place in the early afternoon. The fans of the air handlers were left on for approximately two hours after release and then turned off for the remainder of each experiment. Particles were allowed to settle overnight, and sampling took place during the following days as detailed in **Table 1**.

Table 1. Release and Resuspension Information for Three Tests

Test	BG Release (2 mg)			Resuspension Period					
				Building Entry		Room 101A		Room 102	
	Date	Fan on	Fan off	Date	Time	Enter	Exit	Enter	Exit
Round 1	2011-04-16	13:18	15:18	2011-04-17	09:18	12:06	n/a	n/a	16:47
Round 2	2011-04-25	14:16	16:16	2011-04-26	08:09	09:28	11:31	11:59	13:38
Round 3	2011-05-10	15:22	17:22	2011-05-11	08:42	11:51	14:34	16:02	17:54

In addition to the three BG releases, a set of so-called building characterization tests was performed prior to the BG decontamination experiments. These characterization tests were performed by releasing 1 μm mono-dispersed fluorescent polystyrene latex (FPSL) particles in an attempt to establish target release levels for the BG experiments. While this simulation study does not address these FPSL particle releases, these particles did contribute to initial loadings of non-viable particles during the resuspension tests.

3.2.1 Particle Measurements

The BOTE study utilized two types of real-time aerosol monitors referred to as Ultraviolet Aerodynamic Particle Sizer (UVAPS) [37] and IBAC [38]. The UVAPS provides counts in 52 individual bins of particle diameter ranging from 0.5 μm to 20 μm at approximately one-minute intervals. The manufacturer of the UVAPS provides software to read the raw data files and export them to text files in units of number of particles per cubic centimeter, which were then imported into a spreadsheet for further analysis. The IBAC counter provides total counts of particles ranging from 0.7 μm to 10 μm in diameter at one-second intervals, and data are written to files in units of number of particles per liter. Note that the IBAC did not provide counts in individual particle size bins as did the UVAPS. Detailed descriptions of this equipment can be found in the original BOTE report [1].

Both the UVAPS and the IBAC are capable of distinguishing viable and non-viable particles based on fluorescence [39]. However, for the data collected during these experiments, the particles were not distinguished by fluorescence. Therefore, the BG data from these experiments do not distinguish the particles as viable or non-viable. UVAPS aerosol monitors measured real-time particle aerosol levels in two rooms. These rooms, 101A and 102, were both located on the first floor of the building as shown in **Figure 4**. Of these two rooms, only room 101A also contained a single IBAC sampler. The corresponding figures reveal that the total UVAPS count matches that of the IBAC count very well, indicating that particles sizes were well within the range of the IBAC counter. There was no real-time particle monitoring of the outdoor air.

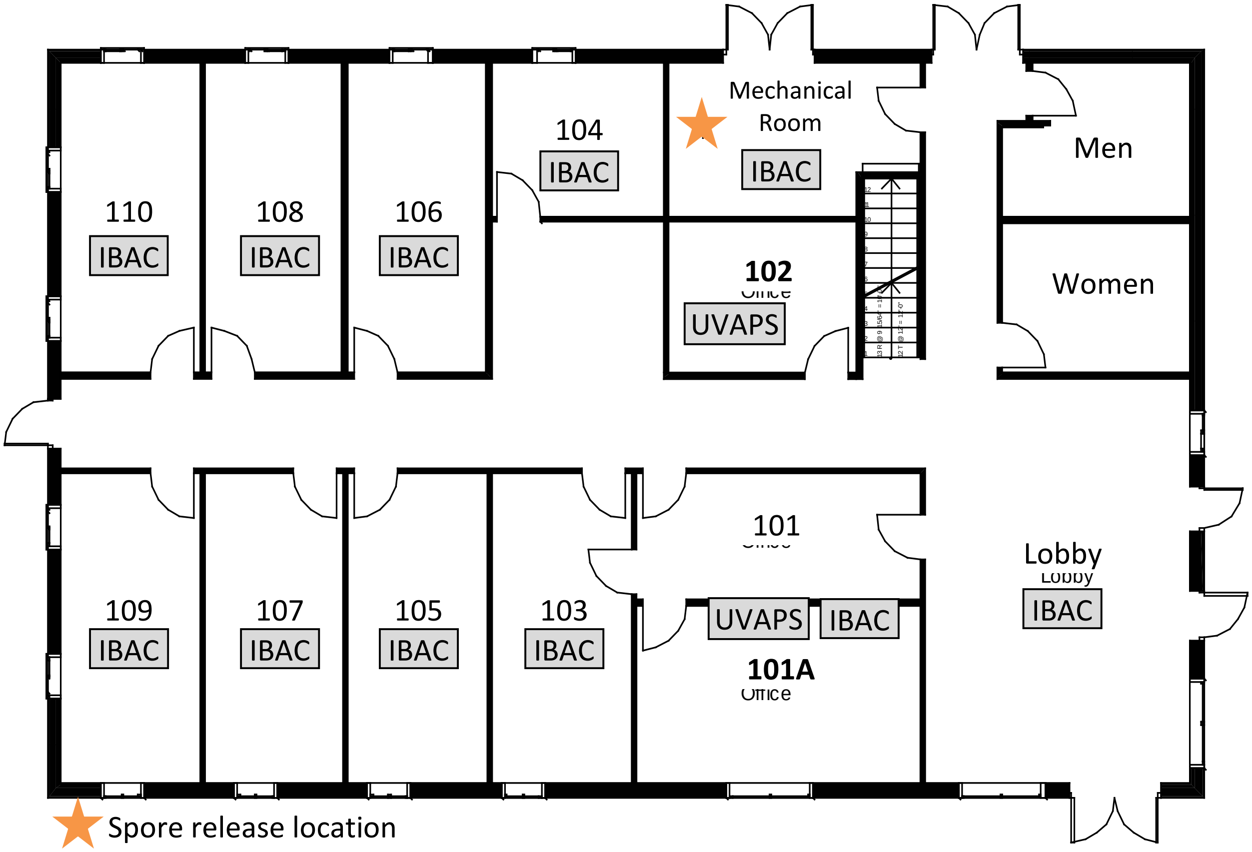

Figure 4. **1st floor plan of PBF-632 building shows locations of rooms 101A and 102, the UVAPS and IBAC devices, and the spore release.**

Plots of particle measurements reveal the time history over the range of particle sizes measured by the UVAPS and IBAC instruments during the simulant release phase through the resuspension phase. **Figure 5** through **10** show the plots for the three rounds of BG release for rooms 101A and 102. Each plot shows the release event occurring in the early afternoon, followed by the resuspension activity beginning the next morning between 6 a.m. and 12 noon. The time the building was first entered and the sampling period are provided in the title of each plot. To reduce clutter, only bins in the range from 0.5 μm to 5 μm are plotted for the UVAPS measurements (Also to reduce clutter, not all of the bins in this range are being shown, and particles larger than 5 μm were not elevated above background levels, as determined by observations of particle distributions made soon after the releases). The UVAPS curves include all one-minute data as obtained from the aforementioned data files. However, IBAC curves were obtained using one-minute data gleaned from the one-second raw data files. Both UVAPS and IBAC one-minute data were smoothed using ten-minute time averages to further improve legibility of the plots.

The plots reveal the significant increase in particle concentrations associated with the initial releases soon after the indicated times of release. Particles in the size ranges plotted (from 0.5 μm to 5 μm diameter) were all elevated by at least an order of magnitude above their respective background levels. This release period is followed by decay of concentrations until the times at which the buildings were entered for the performance of the sampling experiments. (The perfectly linear portions in some UVAPS plots indicate data missing from raw data files.) The plots reveal increased levels in both rooms 101A and 102 very close to the times reported as building entry even though building entry occurs typically an hour or more prior to entry into the two rooms. These elevations in concentrations were assumed to be the result of resuspension due to human activity elsewhere in the building and not in the specific rooms. These elevations are an indication that inter-zone particle transport was occurring within the building as a result of airflow and diffusion transport processes. More discussion on these measurement results is provided later when comparisons are made with simulation results.

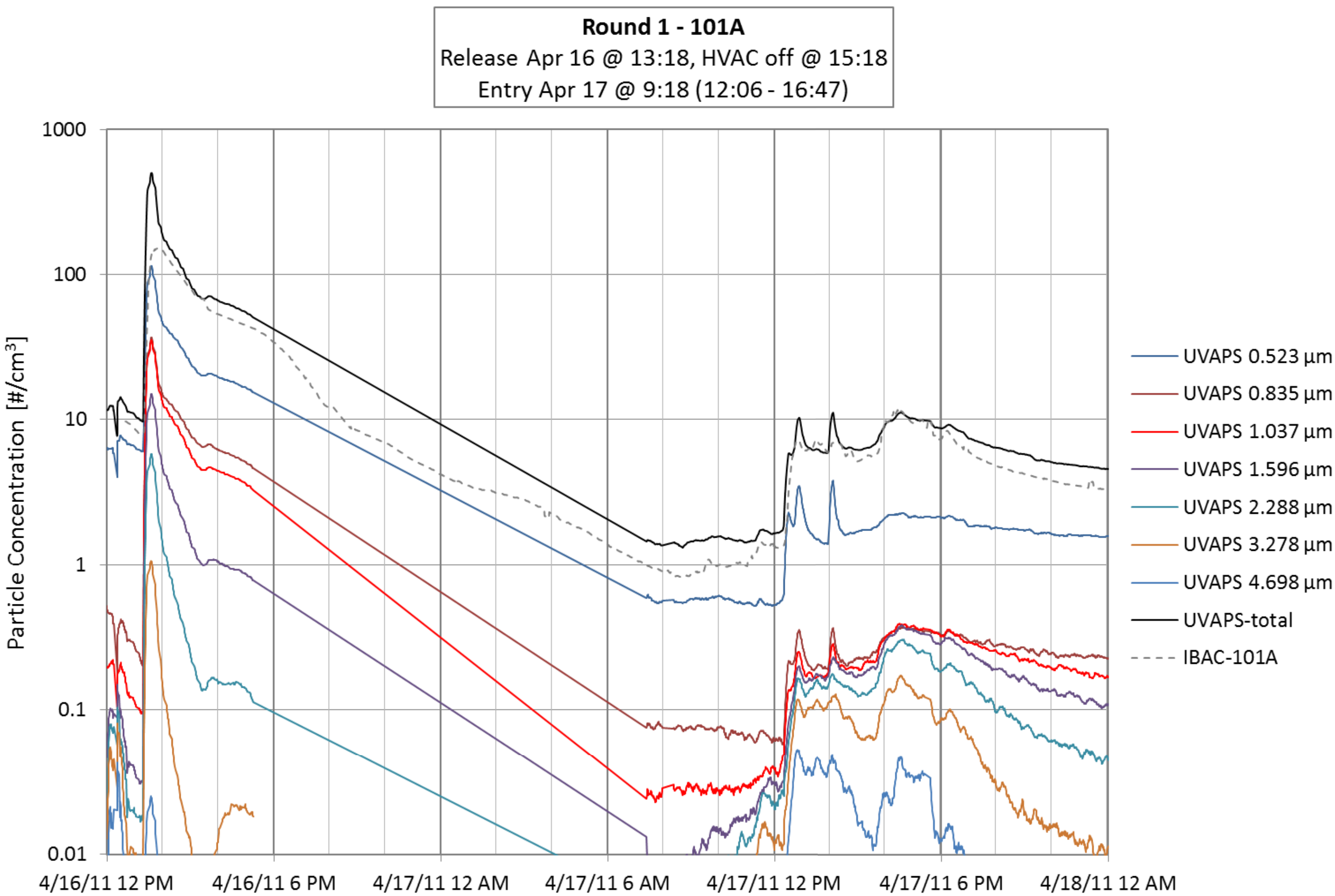

Figure 5. Particle measurements for Round 1, room 101A.

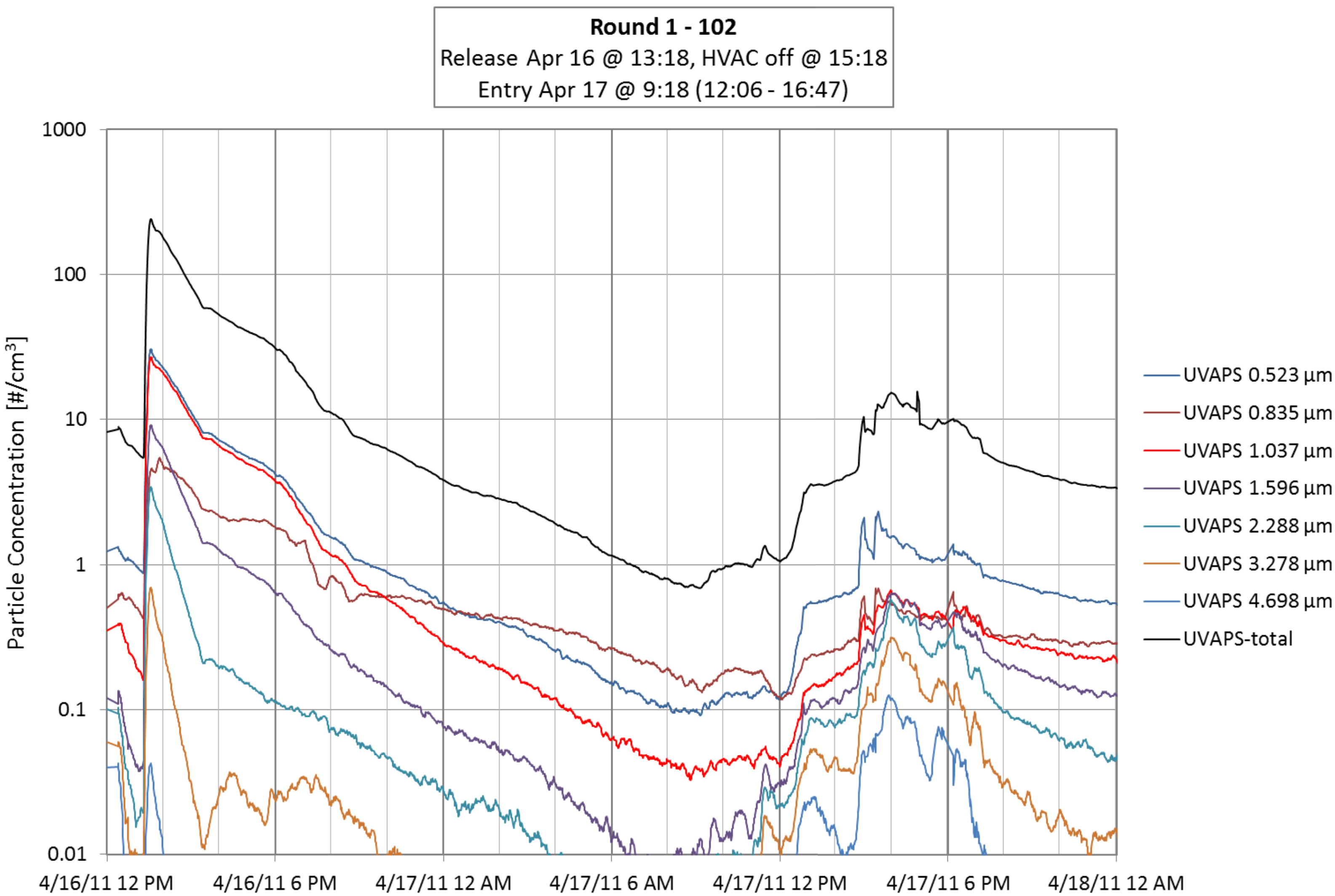

Figure 6. Particle measurements for Round 1, room 102.

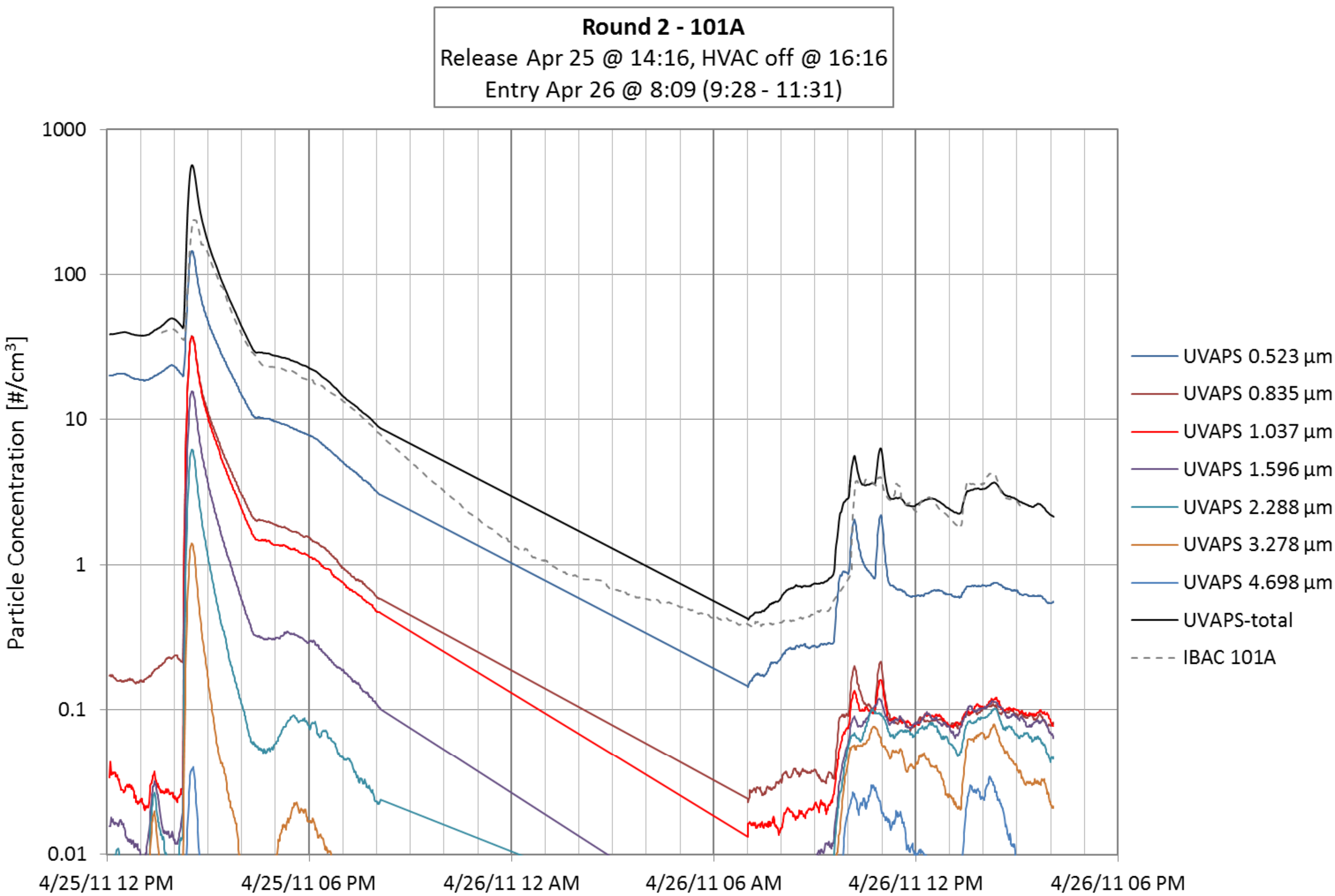

Figure 7. Particle measurements for Round 2, room 101A.

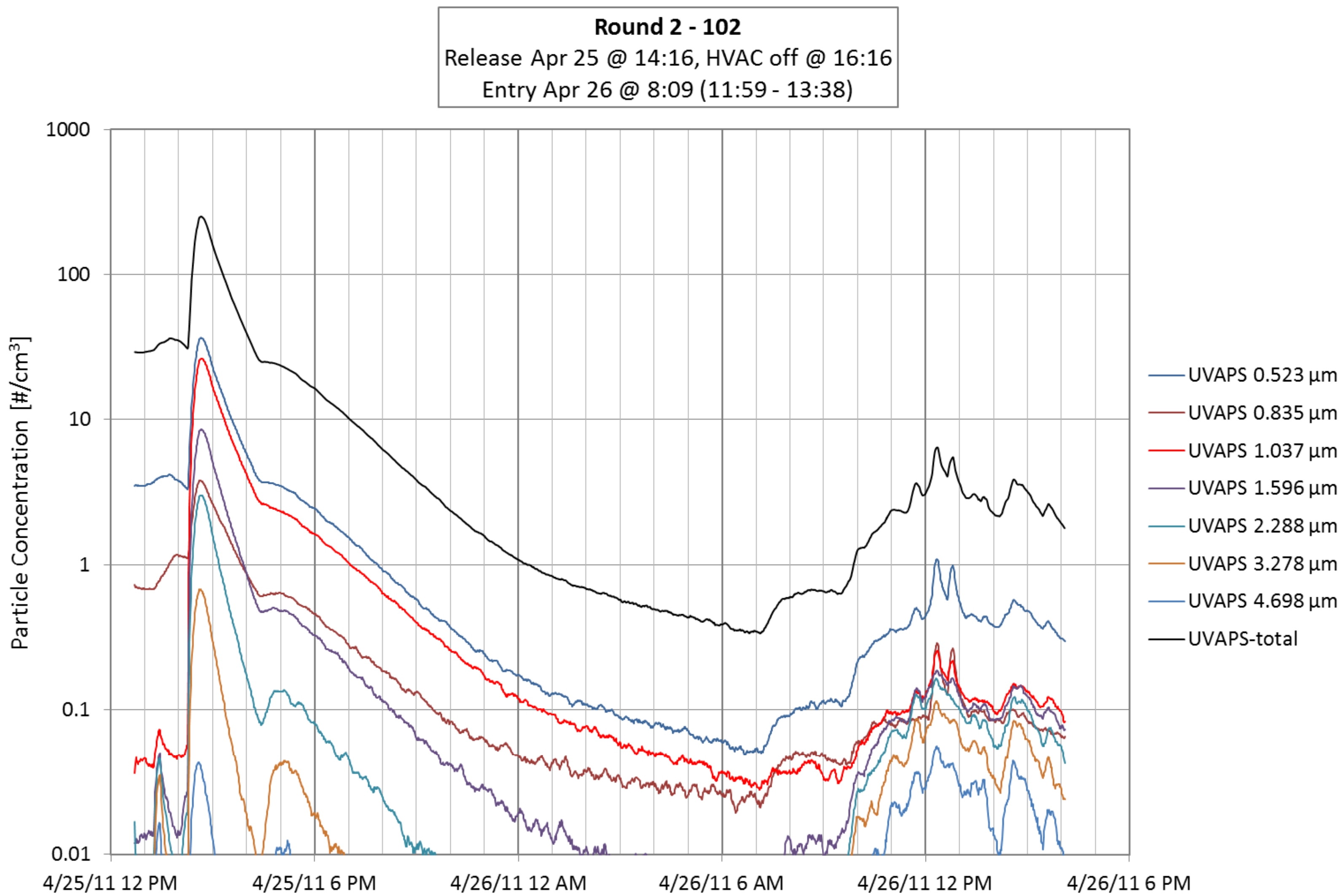

Figure 8. Particle measurements for Round 2, room 102.

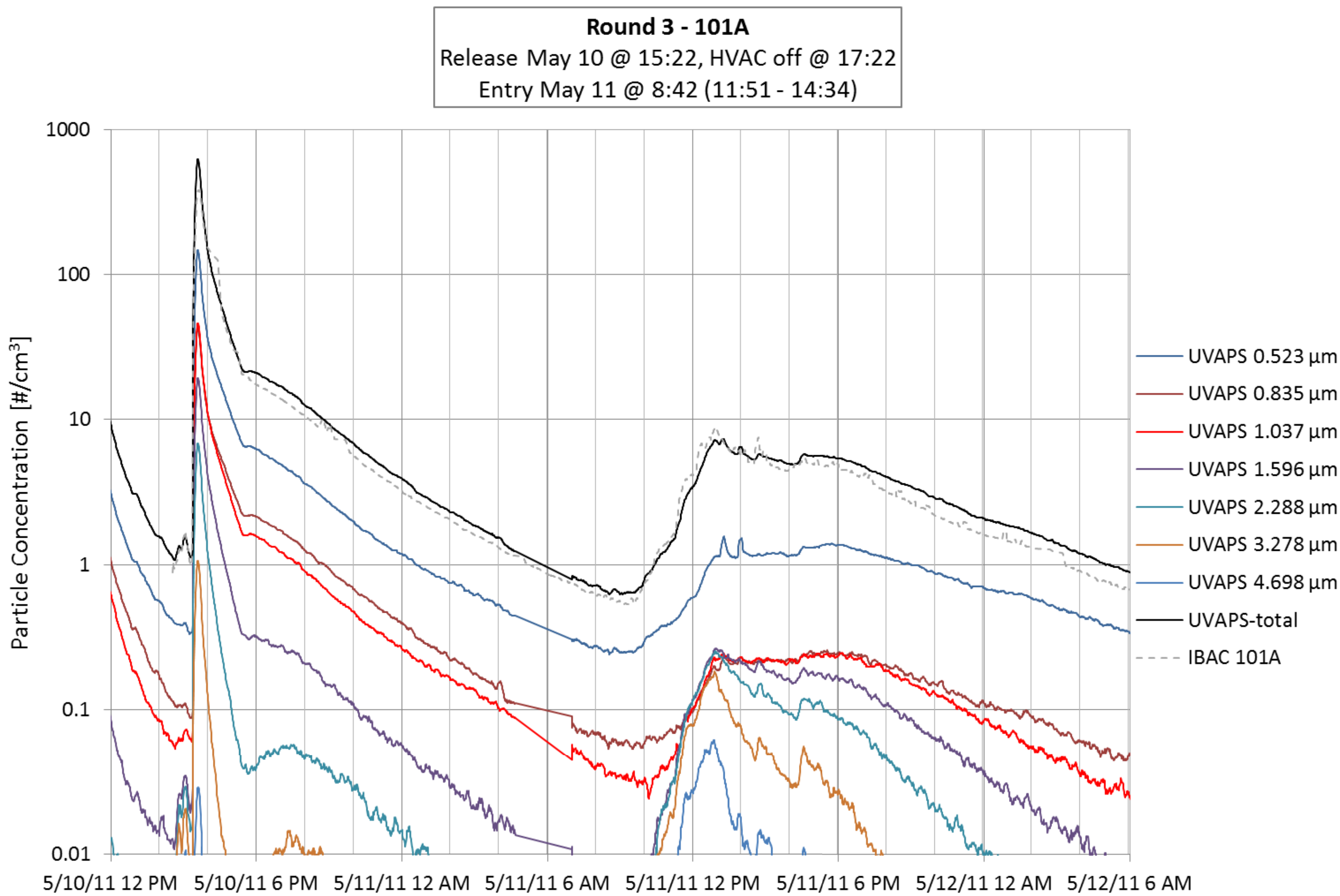

Figure 9. Particle measurements for Round 3, Room 101A.

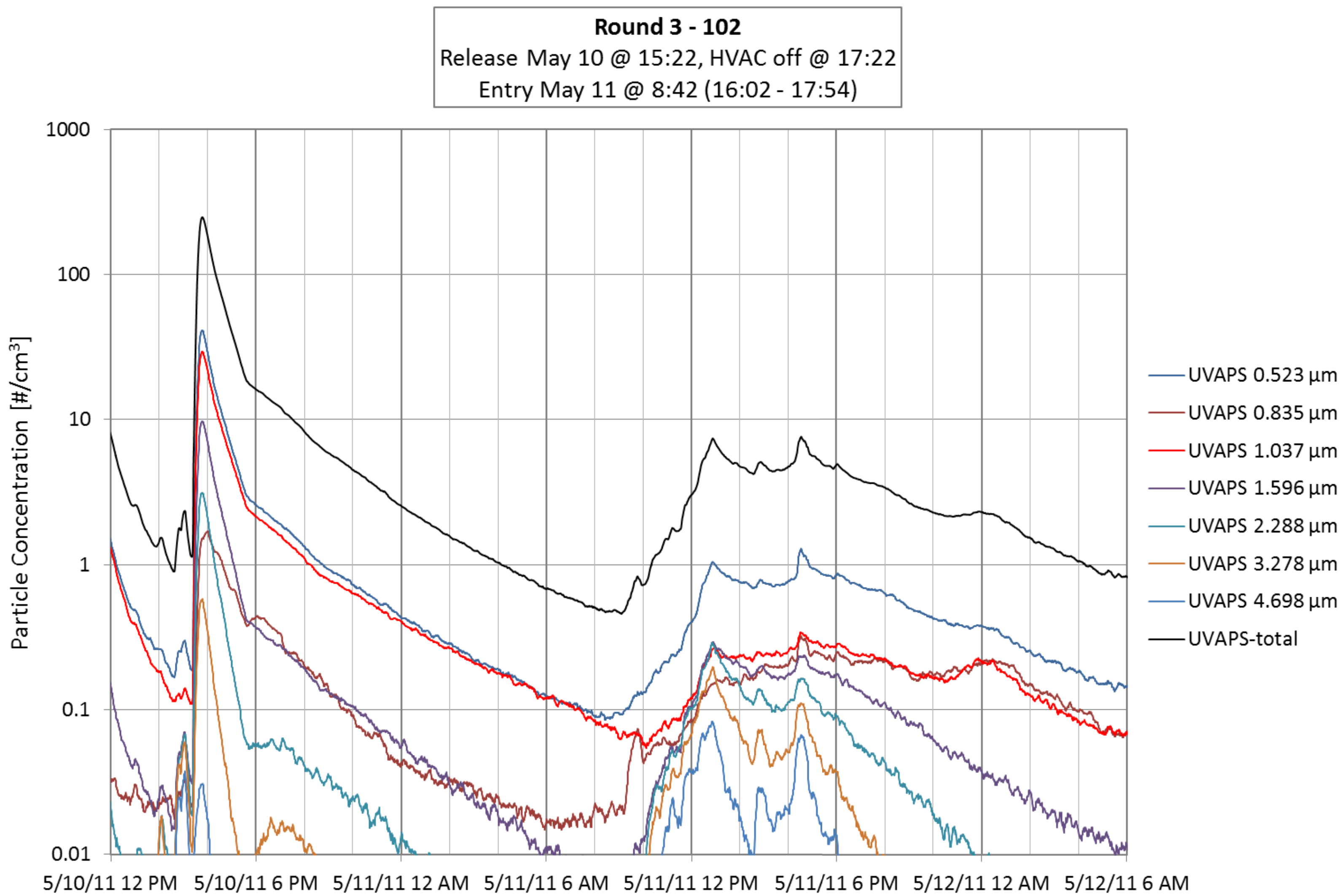

Figure 10. Particle measurements for Round 3, room 102.

3.2.2 Video of Sampling Activities

Video of the BOTE testing was analyzed to obtain detailed information on occupant activity to support the development of resuspension schedules for use in the CONTAM simulations. Seventeen video cameras were located throughout both floors of the building and at the building entrance through which the sampling personnel entered. Each camera continuously captured video during the three rounds of sampling. The three sampling periods covered between 5 hours to 9 hours each, for a total of approximately 23 hours of experimental time yielding approximately 380 hours of video.

The video was reviewed for the first round of sampling to determine the types of resuspension-related activities that were occurring during the post-contamination sampling periods. Video revealed multiple teams of sample collectors moving throughout the building simultaneously; utilizing carts to transport sampling equipment; performing multiple sampling-related activities including: vacuuming, climbing ladders and removing ceiling tiles, and shuffling papers. During the sampling period there were anywhere from one to five three-person teams within the building. Discerning the exact time and location of all members was ultimately determined not to be considered a critical issue due to the uncertainty in attributing resuspension rates to the wide range of occupant activities occurring within the building and the wide range of particle sizes that were resuspended into the air as a result of these activities.

4 Whole-Building Resuspension Simulations Results

Simulations were performed to compare the airborne particle concentrations provided by field sampling data collected during the BOTE study to simulated airborne concentrations calculated based on resuspension rates evaluated from the literature. The objective of these simulations was to determine if multizone building airflow and contaminant modeling can be used to predict resuspension of deposited/settled particles given relevant input data (building and system characteristics, particle size, deposition rates, initial loading, information on activities inducing resuspension, and resuspension rates) in support of estimations of potential human exposures to residual contaminations.

4.1 CONTAM Representation of PBF-632

The CONTAM representation of PBF-632 was based largely on a previous version developed for other studies carried out in the same building [34-36]. Each level of the building was represented in CONTAM by a schematic of the floor plan via the CONTAM sketchpad. The representation used in this study consisted of four levels – the 1st and 2nd floors and their respective plenums that contain the air distribution ductwork. CONTAM sketchpads are shown for each of the four levels in **Figure 11** and **Figure 12**. The nominal floor area of the building is 372 m^2 with a nominal volume of approximately 2610 m^3. Individual level properties are provided in **Table 2**.

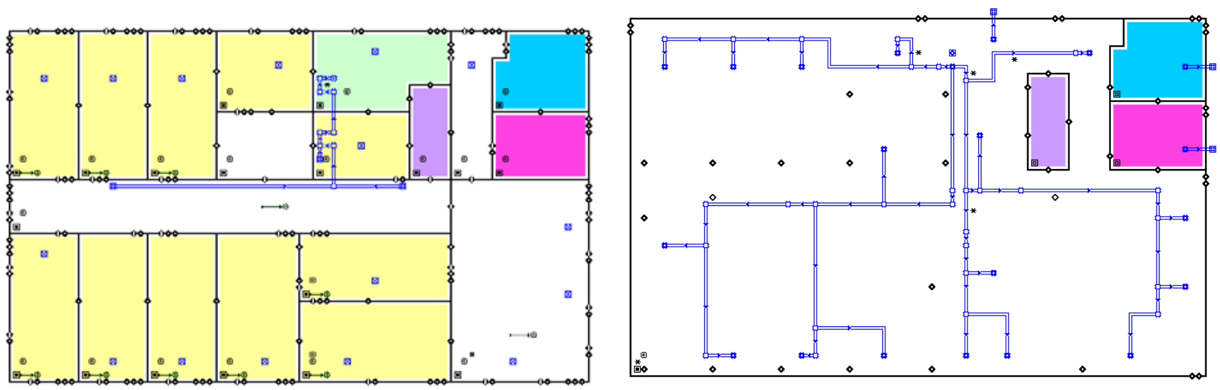

Figure 11. CONTAM representation of 1st floor and plenum.

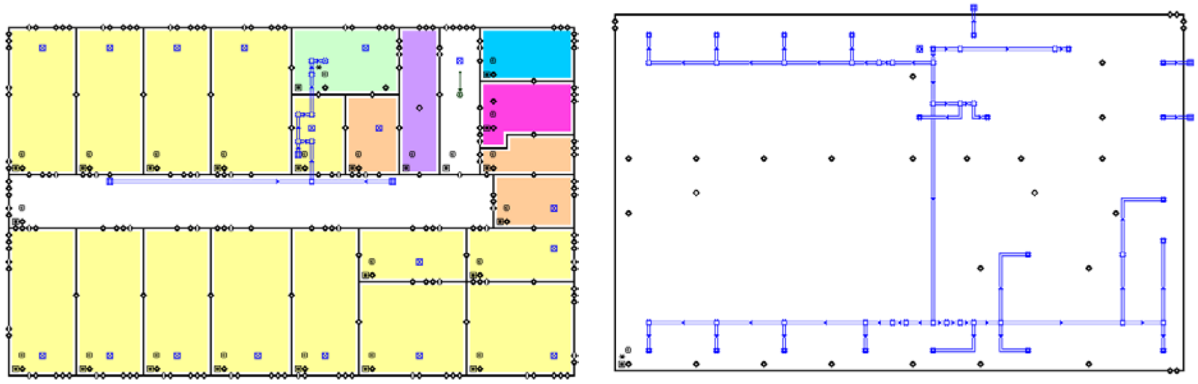

Figure 12. CONTAM representation of 2nd floor and plenum.

Table 2. Building Level Properties

Level	Nominal Height [m]	Nominal Volume [m^3]
1st floor	2.44	906
1^{st} floor plenum	0.61	227
2^{nd} floor	2.44	906
2^{nd} floor plenum/attic	1.22	570

The building representation was modified for the purposes of this project by utilizing the weather data for the BOTE test period, placing resuspension source/sinks in every zone depending on the type of flooring located in the zone, setting initial zone concentrations and surface loadings, and scheduling system airflows and resuspension activity. These modifications are described below.

4.1.1 Weather Data

The National Institute of Standards and Technology (NIST) obtained weather data from the "PBF" weather station of the National Oceanic and Atmospheric Administration (NOAA) INL Weather Center website [http://www.noaa.inel.gov/metgraph]. Weather data included barometric pressure, outdoor temperatures, wind speed and wind direction at five-minute intervals. These data were reformatted into the specific format required by CONTAM. There were no indoor temperature measurements available and the building was unconditioned, so indoor and outdoor temperatures were set to be the same leading to mostly wind-driven and two-way flows through interior doorways as described in [36]. The tent around the building was accounted for by utilizing a wind pressure modifier based on urban terrain to reduce the effect of wind pressure on the building [36].

4.1.2 Resuspension

Resuspension source/sinks were placed in each zone over the entire floor area of the two floors. Only the floor surfaces were modeled, either as carpet or laminate according to the type of flooring installed for the purposes of the BOTE study. It was assumed for the purposes of simulation that all deposition occurred onto the floors; deposition onto vertical surfaces was not considered.

Resuspension rates were selected based on the literature review presented previously. Baseline resuspension rates (r_{base}) for each floor type were selected from the rate-based PSU/CHPPM resuspension model [15] for 1 μm diameter particles, a walking rate of 114 steps/min and a resuspension surface area of 0.028 m^2 (the size of a single foot print). These baseline rates are:

Carpet = 1.06×10^{-2} h^{-1}

Laminate = 3.67×10^{-4} h^{-1}

These rates are referred to as baseline rates, because they are for a single person walking. As described below, they were adjusted in the simulations to reflect increased levels of activity.

4.1.3 Initial Loading

CONTAM is capable of simulating particle releases in units of mass or number per unit time over a schedule based on the contaminant source of interest. However, for the purposes of these simulations, the BG releases via nebulizers were not included as part of the analysis for two reasons. First, the rate of emission associated with the nebulizers as a function of particle size was not well characterized. Also, the surfaces accumulated particles throughout the entire set of experiments. Decontamination targeted the deactivation of viable particles but not removal of the BG (and other) particles. As previously mentioned, non-viable particles include FPSL and other unknown background particles. Therefore, simulations were performed only for the sampling phase with initial loadings estimated for all of the resuspension source/sinks prior to the start of the simulation. Surface sampling was performed using various methods to determine the number of viable particles, or colony forming units (CFU), but the total loadings (viable and non-viable) of particles were not measured. That latter quantity was required for the simulations. Therefore the initial loadings were estimated based upon known, intentional releases of BG during the BOTE project. These initial loadings did not include background particle loadings that may have been present prior to commencement of the BOTE release tests.

According to the BOTE Final Test Plan [40], FPSL particle releases were intended to determine the amount of BG that would be required to establish target floor loadings between 1×10^4 CFU/ft^2 (1.08×10^5 CFU/m^2) and 1×10^6 CFU/ft^2 (1.08×10^7 CFU/m^2) on the 1st floor and between 100 CFU/ft^2 (1 076 CFU/m^2) and 200 CFU/ft^2 (2 153 CFU/m^2) on the 2nd floor. Each of the three rounds of BG release consisted of 200 mg on the 1st floor and 0.5 mg on the 2nd floor (the assumed viability rate was not available). For the purposes of estimating initial floor loadings for simulations performed herein, all contaminant released was assumed to be dispersed evenly throughout the respective floor upon which it was released, contaminant released was all assumed to be deposited onto the floor before resuspension activity occurred, and contaminant released was all assumed to be viable. As a result, the initial particle loadings were calculated according to equation (8).

$$L_i = \frac{M_{rel}}{V_p \rho_p} \frac{1}{A_s} \tag{8}$$

where:

L_i = particle surface loading [particles/m²]
M_{rel} = mass released [kg]
V_p = volume of a single particle [m³]
ρ_p = density of a single particle [kg/m³]
A_s = deposition surface area [m²]

Initial loadings were characterized by particles/area as opposed to CFU/area. The release and loading assumptions used in the simulations are provided in **Table 3**.

Table 3. Release and Initial Loading Assumptions Used in Simulations

Floor Area	371.61 m^2 (4 000 ft^2)
Particle diameter	1.0 μm, corresponds to a particle volume, V_p = 5.236 x 10^{-19} m^3
Particle density	1 000 kg/m^3
BG mass release	1st floor = 200 mg, 2nd floor = 0.5 mg
1st floor loading (baseline value, L_{base})	1.03 x 10^9 particles/m^2 (9.55 x 10^7 particles/ft^2) 5.38 x 10^{-7} kg/m^2
2nd floor loading (baseline value, L_{base})	2.57 x 10^6 particles/m^2 (2.39 x 10^5 particles/ft^2) 1.35 x 10^{-9} kg/m^2

Note that the loadings in the last two rows of **Table 3** are approximately two orders of magnitude greater than the target loadings that were presented above in terms of CFU. This difference may be a function of assumed viability of the BG spores by experimenters when establishing release amounts or anticipated losses of particles through deposition to other surfaces, e.g., ducts and plenums, and/or removal by ventilation system filters.

4.1.4 Activity Schedule

For the purposes of comparing simulation results to measurements, a constant activity schedule and resuspension rate of ten times that of r_{base} (to roughly account for pre-existing particle loadings) were assumed throughout the two floors of the building and during the entire sampling period. The schedule activates the resuspension component of the source/sink models to simulate resuspension at the rate established by the source/sink properties. CONTAM does allow for very complex scheduling of resuspension, but as discussed previously, complex scheduling was not implemented in the study due to the uncertainty in associating resuspension rates with the various types and locations of activity, surface types and sizes of particles being resuspended.

4.2 Simulation Results and Comparison with Measurements

Simulations of the sampling period, during which resuspension would be occurring due to occupant activity, were run for the three rounds of BG release. Inputs were as described above.

The measurements used for comparison are based on a limited range of particle sizes as measured with the UVAPS, specifically the four bins of particle diameters between 0.835 μm and 1.037 μm. The comparisons between measured and simulated airborne particle concentrations focused on the results within rooms 101A and 102, primarily because the UVAPS measurements enable the consideration of a specific particle size range that showed the most significant increase above background levels and are close in size to the nominal 1 μm diameter of the BG particles. This consideration greatly simplified the simulation inputs to those for a single particle size as opposed to the wide range of particles whose properties can vary greatly, e.g., deposition rate and resuspension rate.

Figure 13 through **16** provide plots of the comparisons between measured and predicted airborne particle concentrations for the three rounds of BG sampling tests. The dashed lines provide the measured UVAPS airborne concentrations and the solid lines provide the simulation results. Chart titles provide information on resuspension rates and initial loadings used, i.e., ten times the base resuspension rate, r_{base}, and ten times the base loading, L_{base}.

In **Figure 14**, the measured concentrations of rounds 1 through 3 reveal that particle concentrations were clearly elevated in rooms 101A and 102 during the resuspension (sampling) periods. The review of the detailed occupancy video for round 1 revealed that a sampling team was working in room 101A from 12:00 to 14:30 and room 102 from 14:30 to 16:45. The plot of measured results for Round 1 reveals that the timing of the elevated airborne concentrations do not correspond directly to the time frames of the observed activity within rooms 101A and 102. The plot also reveals that the airborne concentration at the measurement locations was not indicative of a constant resuspension rate and a constant air change rate, i.e., a build-up in concentration to a steady level. This discrepancy between observed activity schedules and measured, elevated particle concentrations attributed to resuspension could be the a result of variations in resuspension rates due to various types of activity, a non-uniform room concentration due to airflow patterns or resuspension location within the rooms, or some combination thereof. These observations of variability and the lack of key input variables (e.g., activity-based resuspension rates) led to the decision not to pursue detailed modeling of the resuspension activities themselves. However, for the purposes of illustration, **Figure 13** provides simulation results obtained by assuming rooms were occupied during the periods obtained from the video analysis for Round 1 showing that CONTAM is capable of simulating such details if warranted.

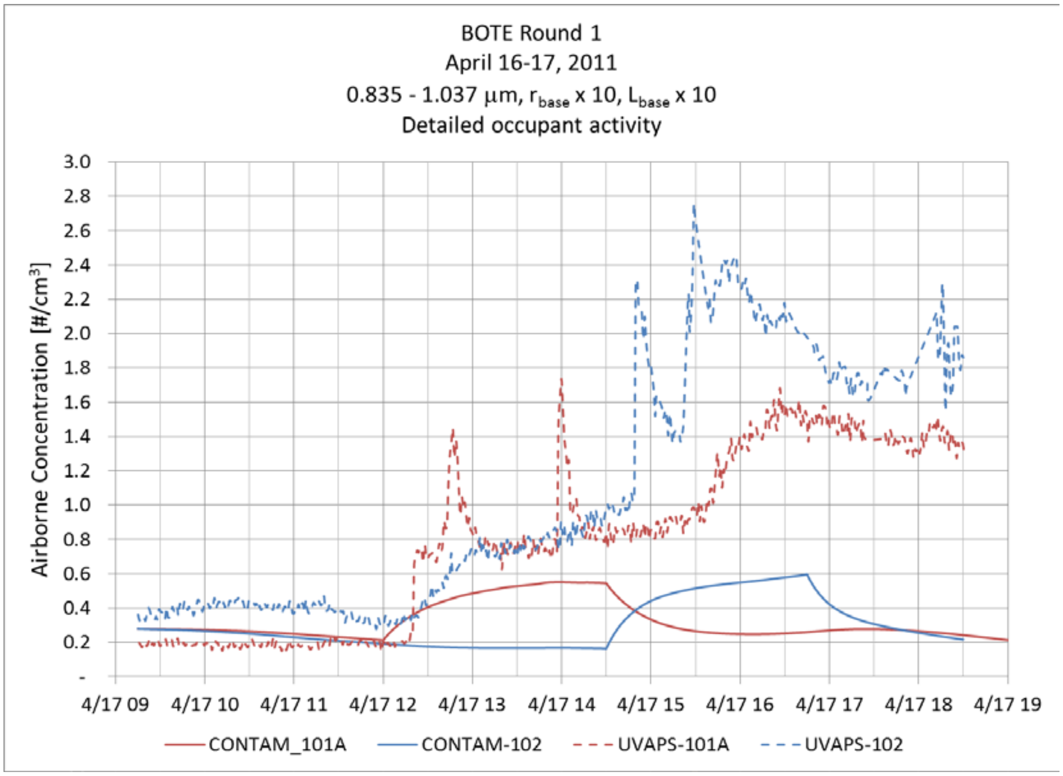

Figure 13. Simulation vs. measurement, Round 1, with detailed resuspension schedule.

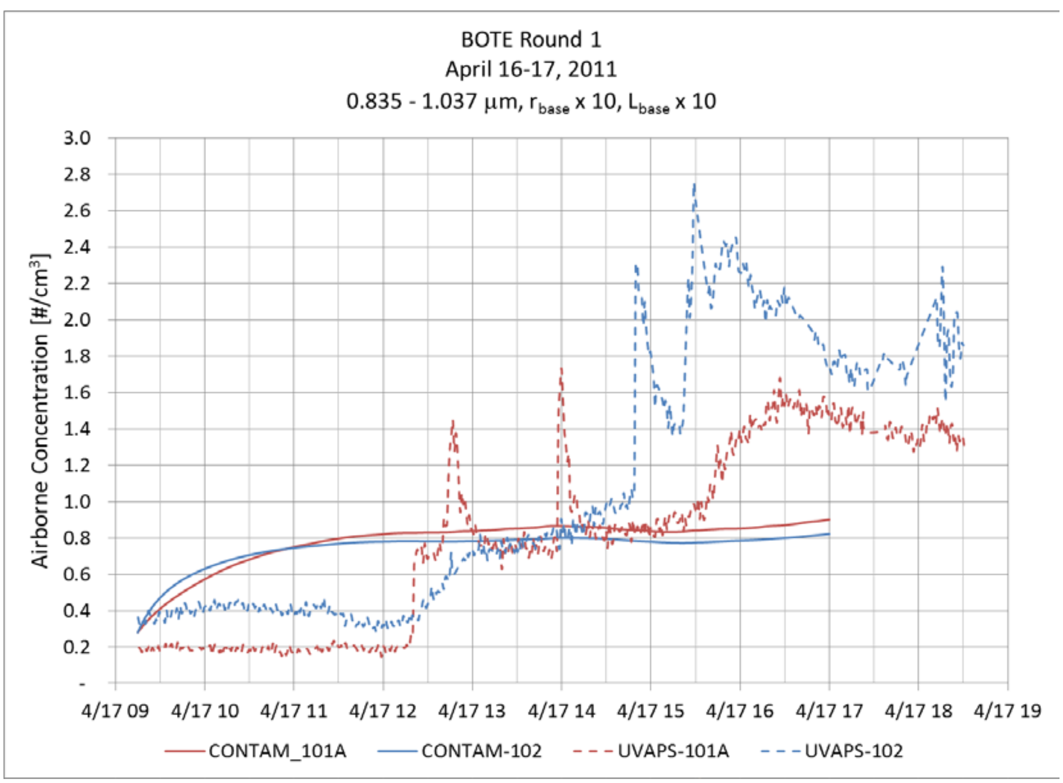

Figure 14. Simulation vs. measurement, Round 1, resuspension 10 x bases, loading 10 x base.

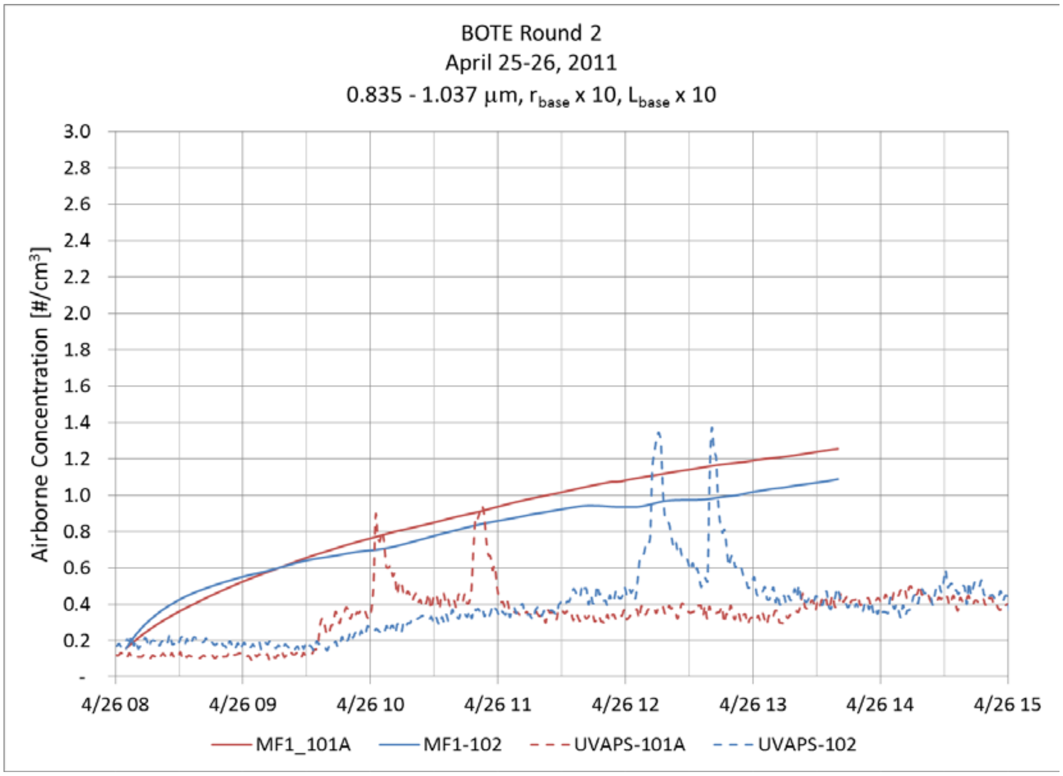

Figure 15. Simulation vs. measurement, Round 2, resuspension 10 x bases, loading 10 x base.

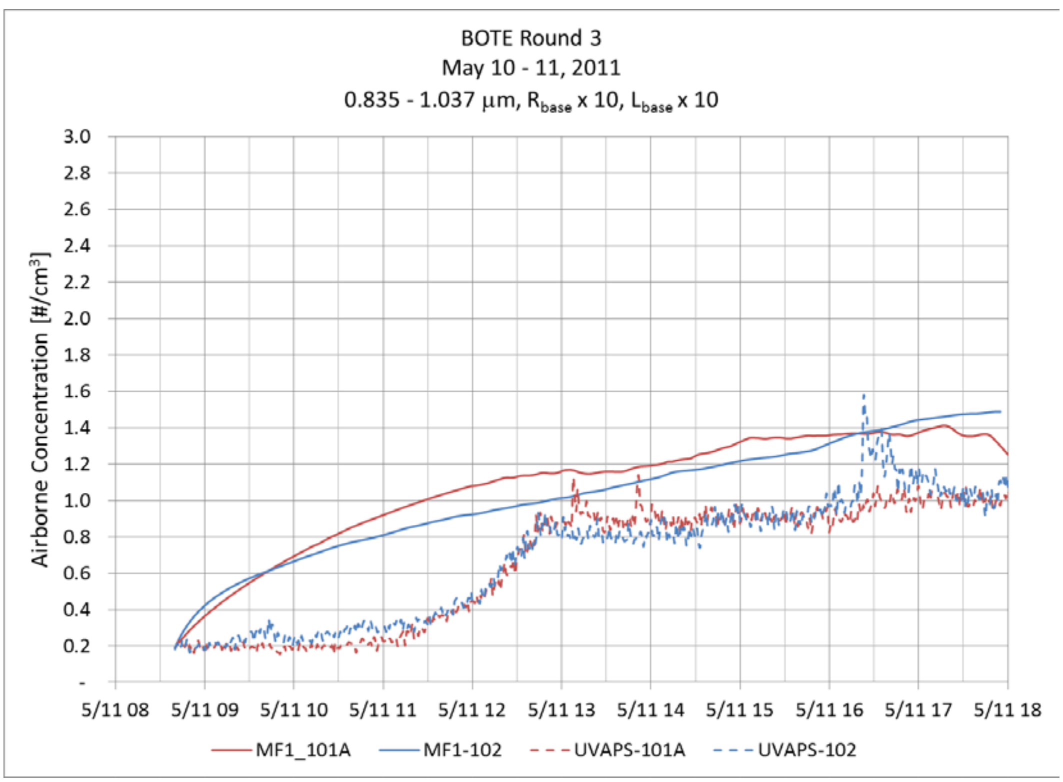

Figure 16. Simulation vs. measurement, Round 3, resuspension 10 x bases, loading 10 x base.

Table 4 provides a summary of comparisons between measurements and simulations for average airborne concentrations in rooms 101A and 102 based on data shown in **Figure 13** through **16**. Average and standard deviation of air change rates determined from the CONTAM simulation are presented. Decay rates in room 101A were also determined from measured IBAC data for several periods of each round during fan-off conditions. While these values are not directly comparable to the air change rate (and are not presented in the table), they ranged between 0.12 h^{-1} to 0.49 h^{-1}.

Table 4. Summary of Average Measured and Simulated Resuspended Airborne Concentrations

Test	Air Change Rate [h^{-1}]		Integration Period			Average Concentration [mg/m^3]					
						Measured		Simulation		Percent Diff.	
	AVG	STD	BEGIN	END	[h]	101A	102	101A	102	101A	102
Round 1	0.29	0.04	4/17/2011 9:15	4/17/2011 17:00	7.75	3.65E-04	4.63E-04	4.09E-04	3.91E-04	12	-16
Round 2	0.19	0.08	4/26/2011 8:05	4/26/2011 13:40	5.58	1.68E-04	1.93E-04	4.50E-04	4.10E-04	168	112
Round 3	0.08	0.03	5/11/2011 8:40	5/11/2011 18:00	9.33	3.46E-04	3.59E-04	5.64E-04	5.38E-04	63	50

The measured average concentrations ranged from approximately 1.7 x 10^{-4} mg/m^3 to 4.6 x 10^{-4} mg/m^3 (or assuming a 1 μm particle diameter, from 3 x 10^5 particles/m^3 to 9 x 10^5 particles/m^3), and simulated values were within about one order-of-magnitude of the measured values. One order-of-magnitude agreement is thought to be reasonable agreement considering the uncertainty in simulation inputs, e.g., activity-related resuspension rates, initial loadings and building airflows. Further, the variation in agreement between Rounds 1 through 3 (percent differences ranging from -16 % to 168 %) is indicative of the wide variation in concentration time histories as depicted in **Figure 13** through **16** and likely due to variation in activity-related resuspension rates and occupant movement patterns.

5 Sensitivity Analysis of Resuspension Exposure Model

The whole-building simulation results revealed that the potential exposure, i.e., average airborne concentration, was sensitive to the simulation inputs. Future prospects of establishing a means to predict potential exposure to spore resuspension should be based on a sound basis for modeling resuspension activity and establishing the inputs to such a model. Therefore, a simulation model is proposed herein to examine the sensitivity of potential exposure determined from this model. This resuspension model is then presented as a candidate for incorporation into a future software tool for resuspension exposure assessment.

In the discussion of resuspension simulations presented in Section 3, several inputs were identified as having a wide range of possible values that presumably led to some of the observed disagreement between measured and predicted values. Some inputs to the whole-building simulation were building-specific, e.g., building layout and occupancy schedules, that should not generally be associated with a high degree of uncertainty. However, other inputs are more difficult to estimate and are therefore more likely to be associated with a range of potential values, e.g., resuspension rates and particle loadings.

To examine the impact of the variations in these factors on the simulation results, a sensitivity analysis was performed by conducting a series of single zone simulations. This sensitivity analysis consisted of a two-level, full factorial analysis [41,42] based on the *Design of Experiments* methodology as presented in [42]. This analysis uses graphical methods to screen for main effects and interactive effects among factors or inputs affecting the outcome of an experiment, or in this case, a simulation. It provides a relatively simple method to qualify those input variables that have the most significant influence on the outcome of the calculation in question, which in this case will be the potential exposure due to resuspension for the model presented in the following section. This discussion uses several terms specific to the *Design of Experiments* methodology, and those terms are presented in italics below to make them easy to identify.

5.1 Single-zone Simulation Model

To focus on factors that are not building-specific, this sensitivity analysis employed CONTAM to model a single, well-mixed zone with deposition and resuspension. This model can be described by equations (1) and (2) with the added assumption that the outdoor concentration and the source terms are both zero leading to consider the following set of two equations:

For the air:

$$\mathrm{dC}_z/\mathrm{dt} = -(\frac{Q}{V} + v_d \frac{A_s}{V})C_z(t) + r\frac{A_r}{V}L_s(t) \tag{9}$$

For the surface:

$$\mathrm{dL}_s/\mathrm{dt} = v_d C_z(t) - r\frac{A_r}{A_s}L_s(t) \tag{10}$$

This initial value problem assumes that the initial zone concentration was zero, and the floor contained an initial loading of particles. Simulations were run for an eight-hour period. The average zone concentration, C_{avg}, was selected as the outcome or response factor to be representative of the potential exposure to which one performing sampling would be subjected.

5.2 Model Inputs

The inputs to the sensitivity analysis were selected to represent the ranges of values that might be found in realistic circumstances; however, most of the inputs can vary widely and cannot be known definitively. A set of five inputs was selected for consideration in the analysis including:

L_i = initial surface loading [kg/m^2]
Q = volumetric outdoor airflow rate [m^3/s]
r = particle resuspension rate [1/s]
v_d = deposition velocity [m/s]
A_s = deposition surface area [m^2]

Zone volume was set to 1,000 m^3 and resuspension area A_r was set to 0.028 m^2 (the size of a single foot print) for all simulations. **Table 5** provides the ranges of the five input values that were varied. The minimum value for initial loading is based on that which would occur for a single release of BG particles in a single BOTE experiment and the maximum was somewhat arbitrarily set to 100 times that. Minimum deposition surface area was based on the zone volume divided by a ceiling height of 2.44 m and allowed to vary by two times to vary the surface-to-volume ratio from 0.41 m^{-1} to 0.82 m^{-1}. The range of resuspension rates was selected based on the 25th and 75th quartiles of the data presented in **Figure 1** of Section 2.3. Volumetric airflow rates were selected to include air change rates between 0.25 h^{-1} and 3.0 h^{-1}, which cover a reasonable range of building air change rates. Deposition velocities were determined based on measured deposition rates for 0.5 μm to 2.5 μm diameter particles and presented in [43] and [44].

Table 5. Range of Input Values for Sensitivity Analysis

	L_i [kg/m^2]	A_s [m^2]	r [1/s]	Q [m^3/s]	v_d [m/s]
Minimum	5.38E-07	410.10	2.328E-08	250	2.5E-05
Maximum	5.38E-05	820.21	1.164E-05	3000	5.0E-03
Ratio	100:1	2:1	500:1	12:1	200:1

These minimum/maximum pairs of values are referred to in the sensitivity analysis as the two levels for each input. The pairs are depicted in the following discussion and graphs as “-” and “+” (and as “-1” and “+1”), respectively.

5.3 Results of Sensitivity Analysis

Five inputs with two levels each yields a set of 32 (2^5) simulations for which the resultant average airborne concentrations are presented in **Figure 17**. This *Ordered Data Plot* presents resultant values in order from smallest to largest and provides the combination of input levels that pertain to each result at the top of the chart. From this chart one can readily discern which combination of inputs yields the most significant results, i.e., higher average concentration.

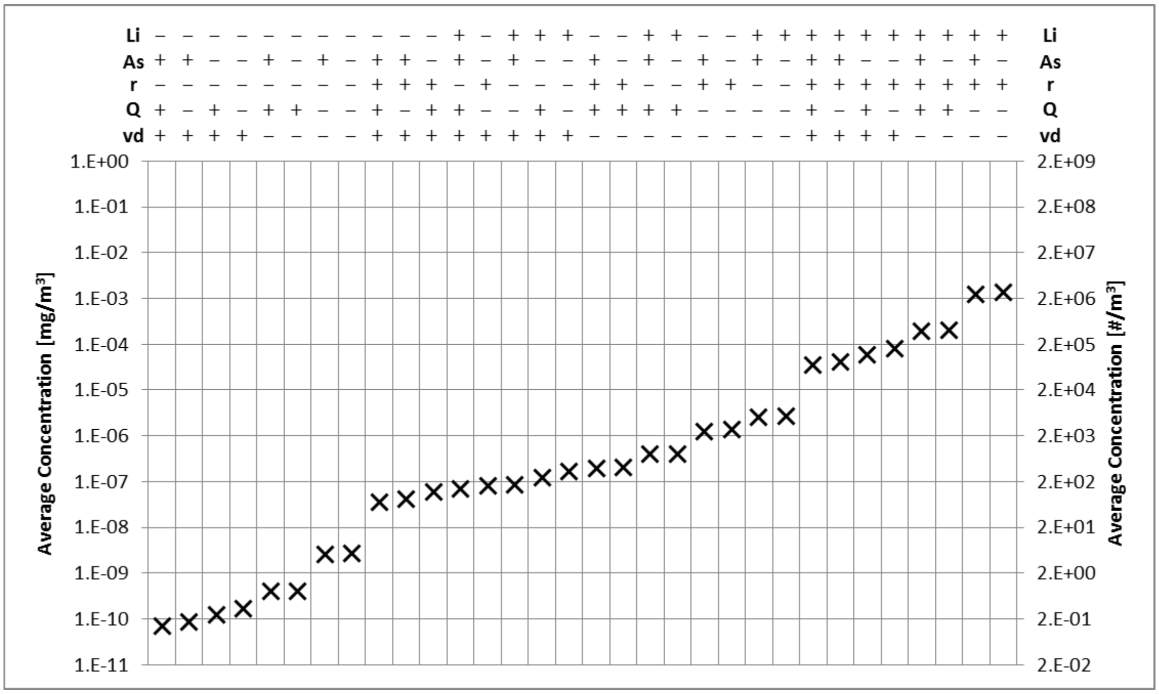

Figure 17. Ordered data plot.

One of the main purposes of this sensitivity analysis is to identify those factors that have the main effects on the outcome. **Figure 18**, *Main Effects Plot*, provides an indication of the effect a single variable has on the outcome by plotting the mean of the responses for each variable at the indicated levels, -/+. Those factors having the steepest slope are considered most significant to the outcome relative to others; those factors with flatter lines are less significant. This plot indicates that initial surface loading and resuspension rate have the most significant effect while deposition surface area has the least significant effect.

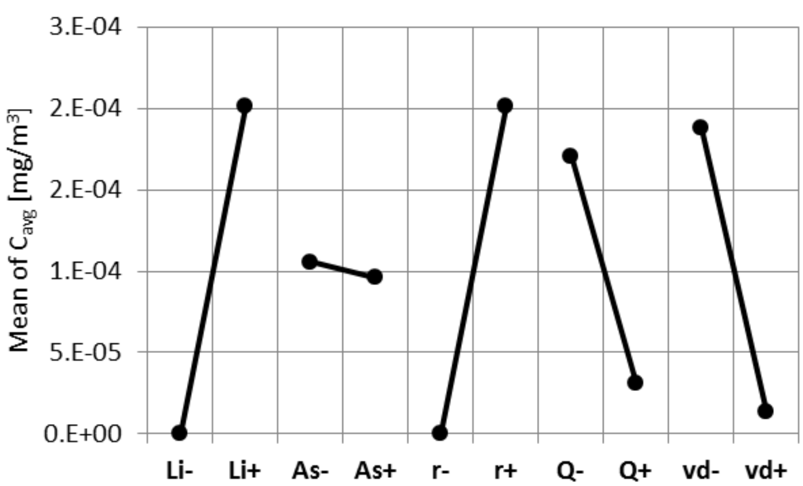

Figure 18. Main effects plot.

While the *Main Effects Plot* provides information on effects related to individual variables, the *Absolute Effects Plot,* (**Figure 19**) provides information on the interaction between pairs of inputs in conjunction with the main effects. Absolute effects, |Exy|, are determined by the absolute value of the difference between the means of the responses for those variables at the levels determined by the so-called multiplicative cross products as explained in Section 5.5.9.4. of [42]. For example, $|E_{LiQ}|$ as depicted in the *Absolute Effects Plot* is the absolute value of the difference between the "+1" and "-1" values of the corresponding *Interactive Effects Matrix* shown in **Figure 20**. These values of |Exy| provide a quantitative relationship among the main and interactive effects as depicted in **Figure 19**, which shows that the initial loading (Li), resuspension rate (r) and their interactive component (Li r) have nearly equal significant effects. Further, all factors not including the deposition surface area would appear to be relatively significant factors as demonstrated by the sharp drop-off in |Exy| at the "As" factor.

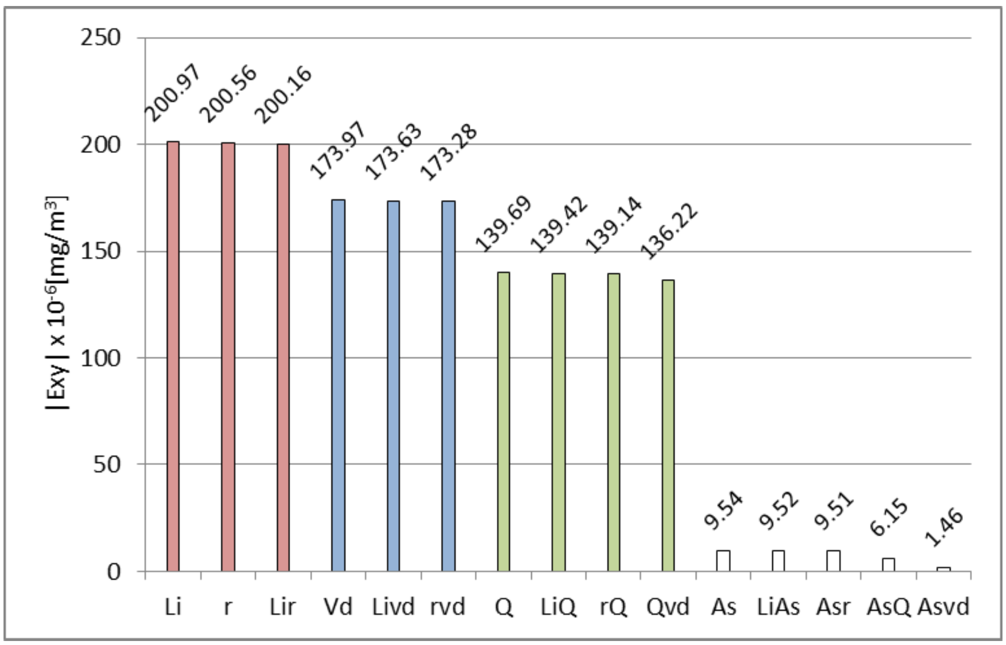

Figure 19. Absolute effects plot.

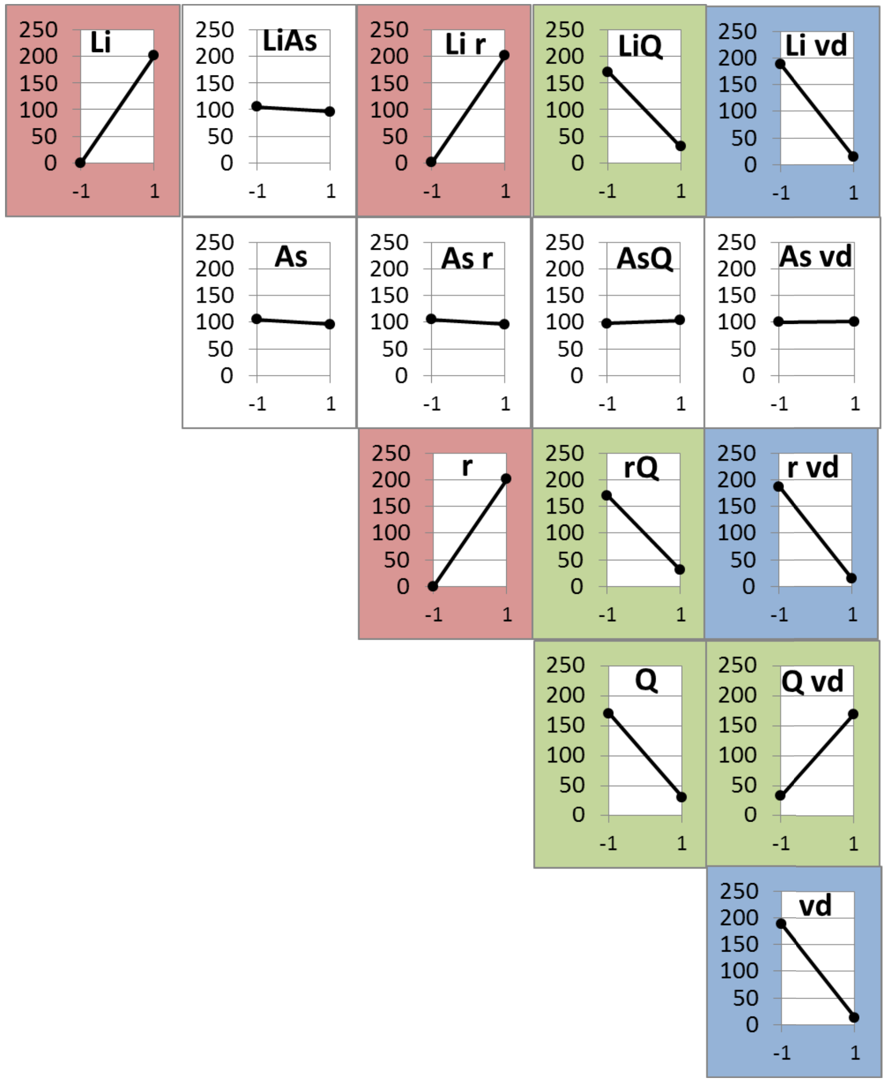

Figure 20. Interactive effects matrix (color-coded to match the *Absolute Effects Plot*).

This sensitivity analysis was based on the *Design of Experiments* methodology as presented in [42]. While this methodology is geared towards identifying those factors that have a significant effect on an outcome of an experiment, the methodology can also be used to develop a model of the experimental outcome based on the input levels utilized in the analysis, i.e., the "+" and "-" values for each factor (see Section 5.5.9.9.5 of [42]). However, this model would be for the specific ranges of inputs and assumptions under which this analysis was performed, e.g., fixed building volume and 8-hour exposure time. It would be more useful to develop a more flexible modeling tool that would allow for a broader range of inputs and outputs. This will be the topic of the following Section.

6 Proposed Resuspension Exposure Tool

A key objective of the EPA BOTE project was to provide first responders and others with techniques to estimate residual risks associated with biological agents remaining after releases and/or decontamination efforts. One technique would be a software tool that would allow users to estimate indoor agent concentrations and the resultant exposures due to resuspension. This Section describes a resuspension tool that would allow the user to select key inputs and provide estimates of potential exposure as a result of resuspension activities.

The whole-building simulations of the BOTE resuspension experiments and the sensitivity analysis of the inputs to the proposed single-zone resuspension model presented above provide insight into the development of such a tool. While a whole-building airflow and contaminant transport representation of a building with well-established and verified behavior would be ideal for addressing particle release/resuspension events, such a representation, i.e., a multizone resuspension model, would be difficult to develop quickly and accurately for situations as they arise. The whole-building simulations presented above (including work presented in the establishment of the building representation [36]) and the review of resuspension rate studies revealed several potential issues related to application of this type of simulation on a case-by-case basis including:

- establishing initial floor loadings
- establishing schedules of resuspension activity, i.e., number of occupants and walking rate
- associating resuspension rates with other activities, e.g., vacuuming and shuffling papers
- associating resuspension rates with flooring material (and other surfaces)
- establishing a building representation that captures building airflows (ventilation system, infiltration, and inter-zone) for multiple building operating conditions
- establishing boundary conditions that drive airflow, i.e., internal and external environmental parameters such as temperatures, wind speed and direction

Based on these issues, it would be more reasonable to develop a simpler model that could be used to perform quicker estimations based on a well-established set of inputs. The above sensitivity analysis provided such a set of inputs based on building-related information, e.g., volume and air change rate; the above literature review, e.g., walking-induced resuspension rates; and information related to release events, e.g., floor loadings based on release amounts and particle size.

The key inputs to calculating exposure due to resuspension are listed in **Table 6**, along with an assessment of the ability to determine reliable values for use in exposure calculations. The current view of the tool is that it would perform single-zone calculations of indoor agent levels assuming an initial loading on the interior surfaces and resuspension of that agent based on indoor activities. The first four parameters in the table, volume, air change rate, particle size and deposition rate, are fairly straightforward to specify. The tool could have default air change rates that vary by building type and operating conditions, which the user could select from a menu or other input scheme. Particle size could also be menu driven, and the deposition rate as a function of particle size could be provided by the tool with the ability to be overridden by the user if they desire.

The next three variables in **Table 6** are more challenging to estimate. The initial loading of the agent depends on the agent release itself, including the quantity released and the amount that enters the building in the case of an outdoor release or the amount that remains in the building if the agent release takes place indoors. If the user has this information, the loading value will be more reliable than it would be otherwise. If the user does not know the nature of the release, they will have to estimate the initial loading. The viable fraction of the agent that is available for resuspension is a key factor to determining the fraction of resuspended particles that contributes to the risk. If the user knows this fraction, the exposure estimate will be more accurate. Otherwise a conservative assumption of 100 % viability may be reasonable.

The resuspension rate is probably the most challenging input parameter to determine for this calculation. The discussion in Section 2 of this report presents the range of values that has been reported in the literature and describes the dependence on particle size, surface type and activity.

Table 6. Key Inputs for Resuspension Exposure Calculations

Input Parameter	**Assessment**
Building volume	Straightforward to determine; High accuracy is not critical
Building outdoor air change rate	Depends on building, ventilation system type and operating conditions; Existing data to support estimates
Particle size of agent	Key input that user must select
Particle deposition rate	Depends on size; Values exist in literature
Initial agent loading on surfaces	Challenging to determine but can be estimated from agent release information
Viable fraction of agent	Useful if need for risk assessment; Availability unclear
Resuspension rate	Depends on surface, particle size, activity type and activity level; Challenging to estimate
Exposure period	User input

As noted in the last row of **Table 6**, the user would need to specify the exposure period, which constitutes the start and stop time for the exposure calculation. This period may or may not include the period during which the resuspension activity occurs. Therefore, the user would need to specify the start and stop time of the resuspension activity and of the exposure period. The tool would then calculate and output the average airborne agent concentration over the exposure period.

Figure 21 shows a schematic of how the exposure tool screen could appear, with the inputs identified for user entry in the upper box. The outputs, including a plot of agent concentration over time, are shown in the bottom half of the screen. This presentation is only conceptual at this time, and if the tool is developed it will likely change as programming decisions are made and input is received from beta users.

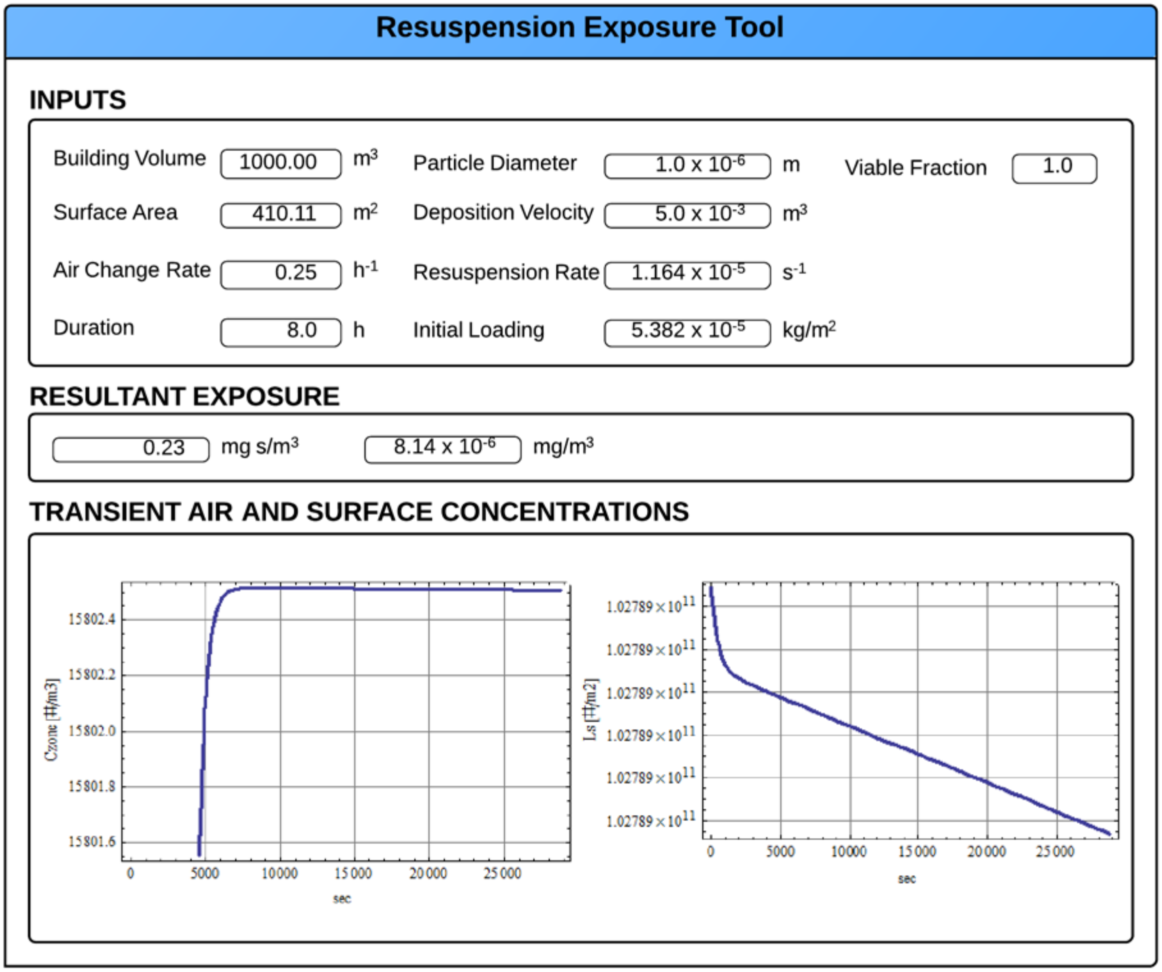

Figure 21. Exposure tool sample screen.

7 Summary and Conclusions

This modeling study was predicated on the availability of resuspension rate data that would be applicable for use in the CONTAM multizone airflow and contaminant transport simulation tool or other similar simulation tools. Further, the intent was to use the rates determined to simulate the conditions of the BOTE resuspension experiments, and then to compare the simulation results to those obtained from the BOTE experiments.

The literature review revealed one resuspension rate model that was easily applied for the modeling described in this report. This model is referred to as the PSU model and provides resuspension rates that could be directly applied within CONTAM based on the following set of inputs: particle size, particle type, flooring type, walking rate and resuspension surface area (area of a single foot print). However, it should be noted that the conditions measured in the PSU model did not necessarily represent the conditions during the BOTE study. Several other critical observations were made based on the literature review related to the applicability of resuspension rates determined from experimental results within CONTAM or other similar simulation models. The methods of reporting results varied widely and included multiple forms, e.g., resuspension factor, resuspension fraction and resuspension rate.

Simulation results compared favorably with experimental results in that order-of-magnitude agreement was obtained between average airborne concentrations of resuspended particles (the factor used as an indicator of potential exposure) over the period of resuspension activity for all three rounds of the BOTE experiments. This result was very encouraging due to the uncertain nature of resuspension rates that vary widely depending on particle size, resuspension activity type (walking, vacuuming, shuffling papers, etc.), resuspension activity schedules (number of occupants, location of occupants, etc.), particle surface loadings, and other environmental factors (airflow rate, relative humidity, etc.). It should be noted that to model the potential resuspension during BOTE, there were assumptions used as is indicated throughout this report that might have been incorrect. For example, it was assumed that no background particle loadings were present prior to commencement of the BOTE release tests; this assumption, if incorrect, could have caused the loading estimates used for the simulation modeling to have been lower than they actually were during the experiments.

Comparisons between the experimental results and simulations revealed the inherent difficulty in capturing the detailed nature of the range of activities and associated resuspension rates. Nevertheless, given a well-formed building representation and assuming one could associate resuspension rates with particle size, flooring surfaces, activity types and schedules, a building simulation could be carried to predict potential exposure to resuspension activities. However, development of such well-formed and detailed building models and associated resuspension-related inputs would be quite resource intensive and perhaps reserved for those buildings that warrant such attention. More work is needed to evaluate application of whole-building simulation for these more resource-intense analysis methods. Previous work has been performed related to simulation of building protection schemes with respect to CBR events [46,47], but there does not appear to have been as much done with respect to simulating resuspension due to decontamination-related sampling after such events.

The uncertain nature of the threat to which this study pertains makes it difficult to anticipate when and where the need for a detailed resuspension exposure tool would arise. Therefore, it would be more reasonable to develop a simpler tool that could be used to perform quick estimations based on a well-established set of inputs. A sensitivity analysis defined such a set of inputs based on building-related information, e.g., volume and air change rate; the literature review, e.g., walking-induced resuspension rates; and information related to release events, e.g., floor loadings based on release amounts and particle size. A relatively simple tool was proposed that would capture the main inputs and provide an estimate of potential exposure during a resuspension event. The preliminary design of the proposed tool could be modified or enhanced to accommodate additional requirements were development of such a tool to be undertaken.

8 References

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Appendix A. Summaries of Documents from Literature Review

This appendix lists the articles and reports considered as part of this literature review organized into the following categories: *Relevant resuspension models*, *Chamber measurements of resuspension rates*, *Other chamber measurements*, *Field measurements of resuspension rates or particle concentrations*, *Other model development and application*, and *Reviews*.

Relevant resuspension models

Bahnfleth, W.P., Freihaut, J.D., and Aumpansub, P. 2007. Implementation of re-suspension factors in building air flow simulations for cross contamination risk assessment in multi-zone buildings and determination of source strengths associated with given levels of risk reduction. U.S. Army Center for Health Promotion and Preventive Medicine, Phase III Task 7 Report.

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Chamber measurements of resuspension rates

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Other chamber measurements

Gomes, C.A.S. 2004. Resuspension of allergen-containing particles subject to mechanical and aerodynamic disturbance - introduction to an experimental controlled methodology. MS thesis, Architectural Engineering, Pennsylvania State University.

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Shaughnessy R., Vu, H. 2012. Particle loadings and resuspension related to floor coverings in chamber and in occupied school environments. *Atmospheric Environment*. 55: 515-524.

Field measurements of resuspension rates or particle concentrations

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