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VULNERABILITY AND THREAT BASED MEASURES OF BUILDING PROTECTION FROM AIRBORNE CHEMICAL AND BIOLOGICAL AGENTS

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ABSTRACT

To mitigate risk in the event of extraordinary incidents including chemical and biological attacks, risk assessment is a necessary process to identify threats and systems vulnerabilities. Most available risk assessment methodologies are qualitative and lack building specific components to assess building system protection level. It is important that quantitative or semi-quantitative methods are developed to evaluate building systems, control, and remediation measures. These methods require reliable building performance measures to determine occupant health consequences of a building attack. This research investigated available threat-based and vulnerability-based measures specific for building mechanical systems and determine their accuracy and usefulness in risk assessment.

Threat-based measures are event and agent specific measures indicating an absolute severity levels of building occupants in an attack event. Vulnerability-based measures are relative and non-agent specific measures which evaluate the impact of an event relative to a base event. Both approaches were carried out on a presumed contaminant release of 6×10^8 cfu of *Bacillus anthracis* inside or into an OA intake of a three-story, 16,791 ft^2 (1,560 m^2) residential building to determine the impact of mechanical system and event characteristics including filter efficiency, ventilation rate, mechanical system types, zoning strategy, and stack effect. The multizone modeling program CONTAM was used to simulate the spread of the contaminants after a release. The contaminant transport simulation was coupled with the appropriate epidemiological methodology to determine total infections and casualties which were used as reference measures. Vulnerability-based measures were also applied to the same scenarios and

compared their interpretation to reference measures. Uncertainty analysis was performed on three filter scenarios (MERV 6 filter, MERV 13 filter and no-filter) to determine the effects of variations in input parameters.

Total infections, total casualties, percent infections, and percent casualties provided absolute numbers of occupants that had health adverse consequences from contaminant exposure. These measures were easy to compare between cases. Fraction of building protection, another threat-based measure, were straightforward to compute and also easy to compare; however, it lacked ability to differentiate risk in some scenarios especially one with uniform air distribution.

A number of vulnerability-based measures (i.e., nondimensional building average concentration, transient concentration, and improvement score) were not complicated to obtain compared to the threat-based measures. They were suitable in identifying risk in scenarios with uniform contaminant distribution but different mechanical system characteristics. On the other hand, nondimensional occupancy dose curves and decile breakdown of nondimensional exposure dose indicated risk levels accurately for scenarios with uniform and non-uniform airborne contaminants. The nondimensional occupancy dose curve included only results in occupied space; while the decile breakdown of nondimensional exposure dose covered the contaminant distribution for the entire building.

Based on results from both measures, the impact of different mechanical system and release characteristics could be evaluated in a building attack event. A higher efficiency filter provides better protection than the less efficient one. For a release into an air handler, the DOAS system was worse than the CAV and VAV systems due to

much lower air change rates in contaminated spaces. However, for an interior release event, a DOAS system was much more protective than the CAV and VAV systems because of its ability to limit the spread of contaminant from recirculation. Also, the zoning strategy could contain the contaminants within zones connected to the mechanical system that the release occurred. Nonetheless, zoning created more possible release scenarios. A winter stack effect could reverse air direction in elevator shaft and lower air change rates in stairwell; its effect on severity level of building occupant were found to be minimal for this building.

In conclusion, the research evaluated each measure and discussed its application and usefulness. Sensitivity analysis indicated that uncertainties for most input parameters affected results in varying degree depending on the mechanical system and type of results. The confidence in the mitigation measure depends on the confidence in the risk assessment results. Future work would embody the development of risk assessment methodology using building-specific performance measure as a part of design procedure.

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Chapter 1

Introduction

1.1. Background

The October 2001 bioterrorism attacks that occurred in the USA have heightened concern regarding the vulnerability of buildings and building occupants to chemical and biological attack (Haas 2002). This has consequently increased interest in chemical and biological terrorism risk assessment for buildings. Several studies in the open literature show that building mechanical systems (i.e., heating, ventilation, and air-conditioning (HVAC) systems) are major contributors to the risk levels of building occupants to both intentional and accidental airborne contaminant releases due to their direct influences on airflow patterns in buildings (Kowalski 2003; Musser et al. 2002; Sextro et al. 2002)

To evaluate building protection level and determine control measures against building attacks for mechanical systems, risk levels of a building and building occupants follow an airborne contaminant release need to be accurately identified which requires appropriate risk assessment methodologies. Most available risk-assessment methodologies are qualitative or subjective published in government risk management guidelines. Therefore, building-specific quantitative or semi-quantitative methods are needed which require reliable performance measures to determine the severity of health consequences of an event on building occupants (Bahnfleth et al. 2006).

Building performance measures can be categorized as vulnerability-based or threat-based. Threat-based measures refer to the consequences of a particular event – a

release of a specific agent. Threat-based measures can provide absolute severity levels (i.e., numbers of casualties or infections) of building occupants to a chemical and biological (CB) release which require agent-specific performance criteria that define the health effects of individuals subjected to specified exposure or dose (Bahnfleth et al. 2006). Vulnerability-based measures are relative measures that describe how the building and its systems affect exposure without reference to a particular agent.

Application of threat-based measures requires knowledge in epidemiology, chemistry, or toxicology depending on the type of contaminant and methods in risk assessment which may be too complicated and time consuming to apply in a building mechanical system design process – or which require data that is not available. Therefore, it is beneficial to develop and identify performance measures that are easy to determine, accurately identify risk levels, independent of the released agent, and provide quantitative weighting to the protection levels among building mechanical system options for a presumed event of airborne contaminant release.

1.2. Objective, Scope, and End User

The objectives of this study are to investigate the impact of building and HVAC parameters on consequences of an assumed CB release, identify simple and reliable performance measures for risk assessment, provide ideas for mechanical system upgrades and reduce occupant risk levels, and examine the role of uncertainty in risk assessment modeling.

These objectives necessitate an investigation of both vulnerability-based and threat-based performance measures using parametric studies on a three-story residential building focused on building mechanical systems' characteristics (e.g., HVAC system

type and zoning) , release characteristics (e.g., location and type), and performance measures. Threat-based measures (e.g., distribution of casualties) will be used as reference measures since they are the clearest way to quantify health consequences of building occupants following a CB release. Airborne contaminants can be introduced to building occupants through absorption, ingestion, or inhalation, together or in combination. The numbers of infections and casualties in this study are calculated solely based on exposure through inhalation. However, the investigated measures are applicable to other types of exposure if they are included in the analysis.

Various vulnerability-based measures (e.g., contaminant concentration and exposure distribution) are investigated. Their accuracy in indicating risk levels is determined by comparing their results to that of the reference measure for a given scenario. Each performance measure's strengths and weaknesses are discussed and explored through analysis of its application in parametric studies. Parametric studies are based on several release scenarios of a selected biological agent. However, the use of performance measures can be implemented with some adaptation to a release of chemical agents as well.

The multi-zone airflow and contaminant transport modeling software, CONTAM 3.0.1 was used to create airborne contaminant release scenarios in simulated building models for both parametric studies and uncertainty analysis. The uncertainty analysis is performed to address the confidence of risk assessment and determine the significance of HVAC parameters. The application and limitations of the developed performance measures are discussed in order to provide ideas for future study.

The intended end users of this research include researchers, engineers, or building owners who would like to implement performance measures in indicating risk levels of building occupants exposed to airborne contaminants and comparing protective level of mechanical system options in a CB building attack.

Chapter 2

Literature Review

This chapter summarizes published research and guidelines to provide background of risk assessment, to review crucial building mechanical characteristics related to CB release responses, and to justify the selection of dose-response models. It also reviews threat and vulnerability basis in existing performance measures for both individual and group exposure, justifies the use of multi-zone modeling program, and shows the importance of uncertainty analysis.

2.1. Background of risk assessment

Risk assessment is an important procedure required to derive means to reduce vulnerability and improve security of buildings to terrorism attacks. Risk assessment is defined as the qualitative or quantitative characterization and estimation of potential adverse health effects associated with exposure of individuals or population to hazards (biological or chemical agents) (Haas et al. 1999; ILSI 2000; Reddy and Bahnfleth 2007).

Bahnfleth et al. (2008) performed a literature review on risk assessment frameworks proposed by various agencies (American Society of Mechanical Engineers (ASME), Federal Emergency Management Agency (FEMA), American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), National Research Council).

- ASME's RAMCAP (Risk Analysis and Management for Critical Asset Protection) framework was created for analyzing and managing risks associated

with terrorist attacks on critical infrastructures (ASME 2005). This framework comprises seven steps: (1) asset characterization and screening, (2) threat characterization, (3) consequence analysis, (4) vulnerability analysis, (5) threat assessment, (6) risk assessment, and (7) risk management.

- FEMA developed a risk assessment process model which is published in one of the publications in the Risk Management Series. This model is composed of five steps: (1) threat identification and rating, (2) asset value assessment, (3) vulnerability assessment, (4) risk assessment, and (5) consider mitigations options. Figure 2.1 shows the presented process that helps identify terrorism mitigation measures.

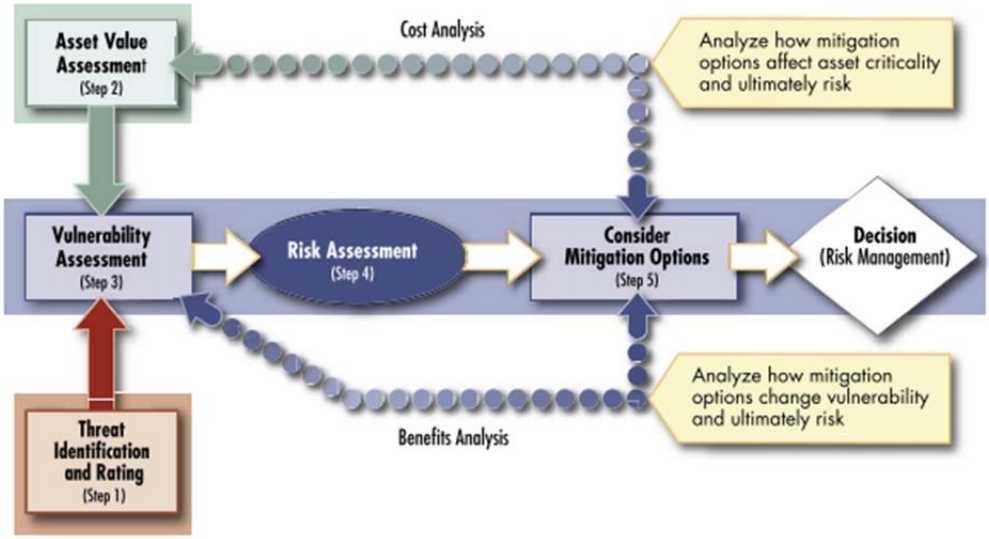

Figure 2–1: Risk assessment process model (FEMA 2005)

- ASHRAE also published guideline for risk management of public health and safety in buildings (ASHRAE 2009) which contains four steps risk management process including risk assessment, risk management planning, risk management plan implementation, and re-evaluation of the plan after implementation.

According to this guideline, risk assessment comprises the following 10 steps: (1) identify the decision maker, (2) conduct a threat assessment, (3) conduct a vulnerability assessment, (4) assign a risk category, (5) establish criteria, (6) calculate the loads imposed by threats, (7) develop and evaluate intervention (alternative solutions), (8) determine if the criteria are met, (9) select the intervention to use, (10) run the assessment using multiple threats. In addition to ASHRAE guideline 29, ASHRAE also published a position document on building safety and security to provide overall information regarding the impact of HVAC systems on building occupants in the event of "extraordinary incidents" exclusive of fire including explanation of risk management and listings of existing guidance for building safety and security.

- Bahnfleth et al. (2008) observed that the first four steps of The FEMA's five-step risk assessment process model have similar essence to the first two steps of the four-step risk management model recommended by the ASHRAE Presidential Ad Hoc Committee.

The European Collaborative Action (ECA) performed a comparison of three common risk assessment frameworks and selected a framework (Figure 2–2) for indoor air quality risk assessment composed of four main steps: (1) hazard identification, (2) exposure assessment, (3) dose-response assessment, and (4) risk characterization (ECA 2000).

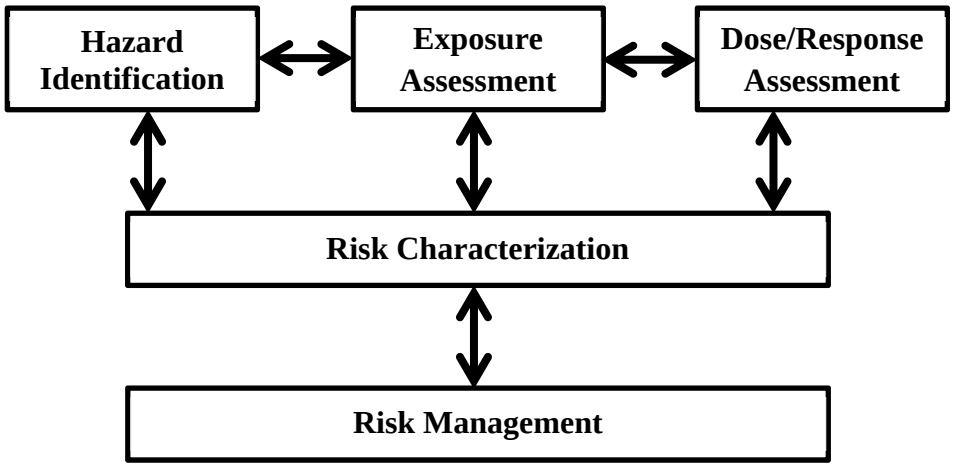

Figure 2–2: The European risk assessment framework for indoor air quality (ECA 2000)

In addition to all the above frameworks, the U.S. Environmental Protection Agency (EPA) offers a four-step risk assessment framework (Figure 2–3) for human health that comprises the four most generic steps in risk assessment framework: hazard identification, exposure assessment, dose-response assessment and risk characterization. This framework offers the simplest relation between each step of risk assessment which is described further in section 2.1.1 to section 2.1.4.

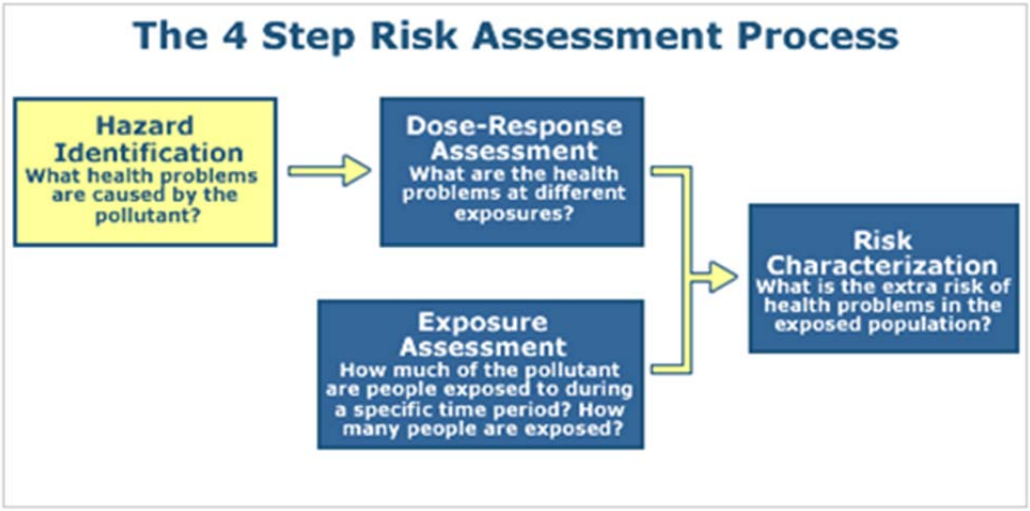

Figure 2–3: The four-step risk assessment process (EPA 2012)

2.1.1. Hazard Identification

Hazard identification is a step for determining hazard identity, location under concern, quantity, and nature of hazard (EPA 1987). Information derived from this step will be used in exposure and dose-response assessment. This step can be done through observation for a presence of a CB source, detection of a hazardous agent in the air, and observation of health effects (i.e., uncommonly high and persistent levels of symptoms and complaints or disease) within building occupants (ECA 2000).

Three common types of contaminants are briefly reviewed in this section: biological agents, chemical agents, and toxins. Similarities and differences between chemical agents and toxins are shown in Table 2–1. Chemical agents (e.g., tear gas, nerve agent) are man-made and can be gaseous or particulate, while toxins (e.g., saxitoxin, botulinum) are substances produced by living organisms (e.g., viruses, bacteria, plants, or animals). Microorganisms themselves can be biological weapons which act as particles that can die-off or re-growth over time, which consequently changes the distribution concentration. They can agglomerate into larger particles which increases the tendency of deposition and source strength for resuspension. Despite these differences, all types of agents are similar in that they can be airborne and fatal (Franz 1997). These agents can be transported and distributed easily via air-conditioning systems.

Table 2–1: Comparison of Toxins and Chemical Agents (Franz 1997)

Characteristics	Toxins	Chemical Agents
Origin	Natural	Man-made
Production	Difficult, small scale	Large-scale industrial
Volatility	None volatile	Many volatile
Relative Toxicity	Many are more toxic	Less toxic than many toxins
Dermal Activity	Not dermally active*	Dermally active
Use	Legitimate medical use	No use other than as weapons
Odor and Taste	Odorless and tasteless	Noticeable odor or taste
Toxic Effects	Diverse toxic effects	Fewer types of effects
Immunogenicity	Many are effective immunogens°	Poor immunogens
Delivery	Aerosol delivery	Mist/droplet/aerosol delivery

*Exceptions are trichothecene mycotoxins, lyngbyatoxin, and some of blue-green algal toxins. The latter two cause dermal injury to swimmers in contaminated waters, but are generally unavailable in large quanitites and have low toxicity, respectively.
°The human body recognizes them as foreign material and makes protective antibodies against them.
Adapted from Franz DR. *Defense Against Toxin Weapons*. Fort Detrick, Frederick, Md: US Army Medical Research Institute of Infectious Disease, 1996:6.

2.1.2. Exposure Assessment

The U.S. Environmental Protection Agency (EPA) published guidelines to provide general principles for exposure assessment in 1992 and defined exposure as the condition of chemical contacting the outer boundary of a human. The human outer boundary refers to the skin and openings of a human body (e.g.., mouth, nostril, punctures, and lesions of the skin). An exposure assessment is the quantitative or qualitative evaluation of that contact; it describes the intensity, frequency and duration of contact, and often evaluates the rates at which the chemical crosses the boundary (chemical intake or uptake rates), and the resulting amount of the CB agent that actually crosses the boundary (a dose) and the amount absorbed (internal dose) (EPA 1992).

Exposure over a period of time can be represented by a time-dependent profile of the exposure concentration which is contaminant concentration at the point of contact.

The magnitude of exposure can be determined from the integral of the time-dependent profile of the exposure concentration represented in Equation 2-1.

$$E = \int_{t_1}^{t_2} C(t)dt \qquad \text{Equation 2-1}$$

Where:

E = magnitude of exposure,

C(t) = exposure concentration as a function of time,

t = time,

and $t_2 - t_1$ = exposure time or t_e

Dose is a general term referring to the quantity of CB agents entering a human body. Potential dose is the amount of chemical or biological agents introduced to a human body via exposure routes: respiration, absorption, and ingestion (Figure 2-4). Applied dose is the amount of chemical in contact with the primary absorption boundaries (e.g., skin, lungs, gastrointestinal tract) and available for absorption. Internal dose is the amount of chemical penetrating across an absorption barrier or exchange boundary via either physical or biological processes. Delivered dose is the amount of chemical available for interaction with any particular organ or cell.

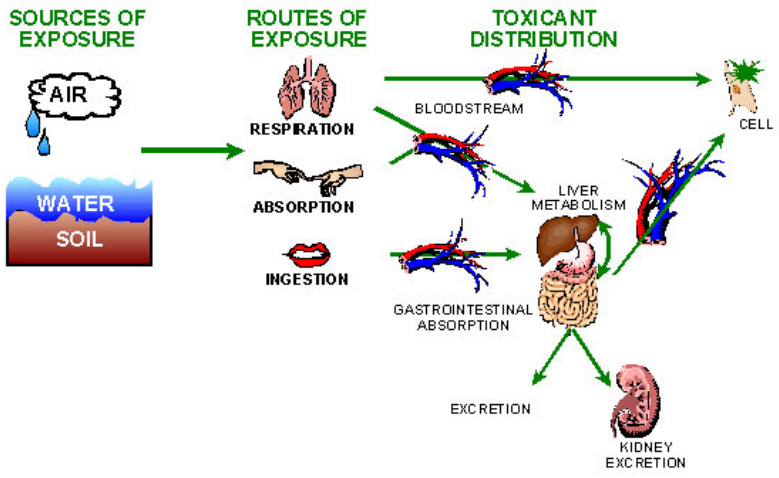

Figure 2–4: Schematic of exposure routes (Mclaughlin 2006)

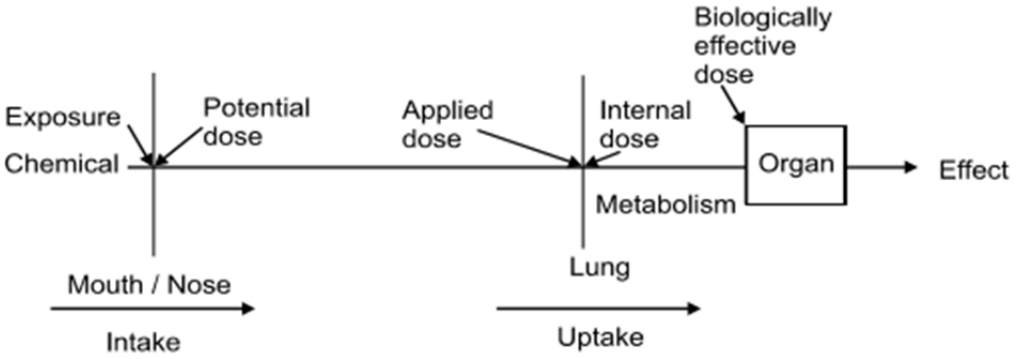

Figure 2–5: Schematic of doses via respiratory route (EPA 1992)

For the simplified illustrative purposes of this study, potential dose calculated based on exposure through inhalation is considered equivalent to delivered dose to determine health responses of individuals or populations exposed to CB agents. Figure 2-5 shows the schematic of doses via respiratory route. Haber's Law (Equation 2-2) is commonly used to determine potential dose or total dose of an individual exposed to CB agents. This equation represents a summation of doses over total exposure time (Heinsohn and Cimbala 2003; Kowalski 2003). Haber's Law assumes that concentration and time equally impact total dose which is commonly used with exposure assessment to biological agents where health effects responded to an accumulation of the agents in an individual's body

$$D(t) = k\int_{t_1}^{t_2} C(t)dt \qquad \text{Equation 2-2}$$

Where:

t = time (time),

$C(t)$ = airborne concentration as a function of time (mass of contaminants/volume for chemical agents and toxins and number of particles/volume for biological agents),

k = coefficient (e.g., breathing rate (volume/time) or absorption rate (volume/time).

However, for chemical agents that rapidly cause adverse health effects, Haber's law does not represent the effects of an exposure event accurately. For such agents, the intensity of response increases non-linearly with concentration compared to the effect of exposure duration – for example, doubled concentration for halved exposure time has more severe effects. Therefore, the nonlinear toxic load equation (Equation 2-3) calculated with toxic load exponent is used in determining effects of various chemicals.

$$D(t) = k\int_{t_1}^{t_2} C^n(t)dt \qquad \text{Equation 2-3}$$

Where:

t = time (time),

$C^n(t)$ = airborne concentration (mass of contaminants/volume of air containing chemical agents or number of particles/volume of air containing biological agents),

n = exponential factor,

k = coefficient

To determine total inhaled dose, coefficient k is the breathing rate of individual of interest, B_r (volume/time). Breathing rates depend on numerous factors such as age, gender, weight, health status, and the activity level of an individual. The U.S. EPA has summarized a number of studies on breathing rates and recommends using inhalation rates (EPA 1985; Layton 1993) in Table 2-2 for adults, children, and outdoor workers/athletes for both short-term and long-term exposure.

Table 2–2: Summary of recommended values for inhalation (EPA 1997)

Population	Mean	Upper Percentile
Long-term Exposure		
• Infants		
<1 year	4.5 m^3/day	-
• Children		
1-2 years	6.8 m^3/day	-
3-5 years	8.3 m^3/day	-
6-8 years	10 m^3/day	-
9-11 years		
Males	14 m^3/day	-
Females	13 m^3/day	-
12-14 years		
Males	15 m^3/day	-
Females	12 m^3/day	-
15-18 years		
Males	17 m^3/day	-
Females	12 m^3/day	-
• Adults		
Males	11.3 m^3/day	-
Females	15.2 m^3/day	-
Short-term Exposure		
• Adults		
Rest	0.4 m^3/hr	-
Sedentary Activities	0.5 m^3/hr	-
Light Activities	1.0 m^3/hr	-
Moderate Activities	1.6 m^3/hr	-
Heavy Activities	3.2 m^3/hr	-
• Children		
Rest	0.3 m^3/hr	-
Sedentary Activities	0.4 m^3/hr	-
Light Activities	1.0 m^3/hr	-
Moderate Activities	1.2 m^3/hr	-
Heavy Activities	1.9 m^3/hr	-
• Outdoor Workers		
Hourly Average	1.3 m^3/hr	3.3 m^3/hr
Slow Activities	1.1 m^3/hr	
Moderate Activities	1.5 m^3/hr	
Heavy Activities	2.5 m^3/hr	

2.1.3. Dose-Response Assessment

Dose-response assessment is a process that determines health consequences corresponding to administered doses in a human body. Mathematical dose-response models are developed to represent the relationship between the level of contaminant exposure and the likelihood of occurrence of an adverse health consequence (EPA 2012; Haas et al. 1999).

2.1.3.1. Dose-response (DR) Models for Biological Agents or Microorganism

In epidemiology and toxicology, many mathematical models categorized as empirical models and mechanism models are used to represent DR models for many toxins and biological agents such as log-normal, single hit exponential model, beta-poisson dose response models, etc. Most models are determined based on available experimental data for specific agents. Two commonly used dose-response models (i.e., poisson probability and normal distribution) are selected for a review in this section because there are dose-response data available for *Bacillus anthracis* which is the agent of interest in this study.

A Single-hit Exponential Model (Wells-Riley Equation)

A single hit dose response model refers to a probability that ingestion or inhalation of a single pathogen results in infection. A study by Haas (2002) showed that the exponential dose-response model (Equation 2-4) can represent an inhalation dose-response model for anthrax).

$$y_T = 1 - \exp(-k_T d) \qquad \text{Equation 2-4}$$

Where:

y_T = the expected proportion of exposed individuals with the mortality or infection,

d = average dose (cfu),

and k_T = the dose response parameter (1/cfu).

Equation 2-5 can be used to predict the proportion of mortality or infection in exposed individuals. However, the constant k_T has to be determined by fitting experimental data to the exponential equation. The Druett et al. (1953) data set of dose-response of Rhesus monkeys exposed to *Bacillus anthracis* for a one-minute exposure was fit to the exponential equation (Equation 2-5), giving an estimated k_T of 7.16×10^{-6} (1/cfu). This constant value k_T, corresponds to an LD_{50} of 96,800 cfu (Haas 2002). However, by fitting the exponential DR model to the daily risk dose-response data (Brachman et al. 1966), the k_T coefficient is 2.6×10^{-5} which leads to LD_{50} of 26,600 cfu.

A number of researchers have developed a similar equation to Equation 2-4 such as a disease transmission model or the Wells-Riley Equation (Equation 2-5) to determine the effect ventilation rates on airborne transmission of infectious respiratory disease for a well-mixed zone (Fennelly et al. 2004; Fisk et al. 2005; Nardell et al. 1991; Riley 1980).

$$\frac{C}{S} = 1 - \exp\left(-\frac{Iqtp}{Q}\right) \qquad \text{Equation 2-5}$$

Where:

C = the number of new cases,

S = number of persons susceptible to the infection,

I = number of infected individuals,

q_I = quanta or number of microorganisms needed to cause infection per source per unit of time,

and Q = ventilation rate.

The quantum of infection (q_T) is defined as the dose required to produce infection in 63 of susceptible members of population or 1.25 times the median infectious dose i.e., 1.25 x ID_{50} (Fennelly et al. 2004: Riley 1980; Wells 1955). Two other studies show the determination of a quantitative value of q_T by indirect measurement (Nardell et al. 1991; Riley 1980)

B Normal Distribution DR Model (Kowalski 2003)

A second dose-response model, Equation 2-6, was developed from a normal distribution of risk of infection by Kowalski (2003):

$$y = \frac{2}{LD_{50}\sqrt{2\pi}} e^{-2\left(\frac{x-LD_{50}}{LD_{50}}\right)^2} \qquad \text{Equation 2-6}$$

Where:

y = new casualties,

x = dose,

and LD_{50} = mean lethal dose

This normal distribution DR model (Equation 2-6) assumes that the standard deviation in risk is half the mean value. To determine the total number of casualties, Equation 2-6 is integrated through time, resulting in the fraction of casualties. This equation can also be used to determine total infections by substituting ID_{50} for LD_{50}. As an alternative to an integral of Equation 2-6, a Gompertz equation (Equation 2-7) can also be used to calculate total infections and casualties as well.

$$y_T = 0.5^{0.1\left(\frac{x-\mu}{\mu}\right)}$$ Equation 2-7

Where:

y_T = total infections or casualties,

x = contaminant doses,

and μ = mean lethal dose (LD_{50}) or mean infectious dose (ID_{50}) depends on the availability of LD_{50} and ID_{50} corresponding to each contaminant agent.

Kowalski (2003) presented data collected from disease and dose curves for both chemical and biological agents. anthrax was selected to use in this study; therefore, LD_{50} for anthrax extracted from Kowalski (2003) is 28,000 cfu. The normal distribution DR model is used to determine total infections and casualties in this study.

2.1.3.2.Dose-response Model for Chemical Agents and Toxins

For chemical agents or toxins, human responses to contaminant exposure are not equally impacted by concentration and time as described by the toxic load equation (Equation 2-3). Ten Berge (1986) shows that the method of probit analysis (Equation 2-8) composed of the toxic load exponent component can represent dose-response relationship very well. The coefficients associated with the dose-response model can be determined from experimental data (Ferguson and Hendershot 2000).

$$Y = a + b\ln(c^n t_e)$$ Equation 2-8

Where:

Y = the probit value, which can be converted to probability of fatality (percentage of fatality) using published Table 2-2,

a, b, and n = constants derived from experimental data for each agent,

C = airborne concentration (ppm),

and t_e = exposure time

Table 2-3 is used to convert the percentage of probability to probit values. The first column of Table 2-3 represents the tenth place of the probability percentage, while the first row represents the ones place of the probability percentage. The second row and second column to the eleventh column and eleventh row contain probit values. For example, if the percentage of probability is 15%, the probit value corresponding to this percentage is 3.96; the probit value of 4.36 is corresponding to 26% probability, etc. The last row from the second column to the eleventh column contains the probit values which correspond to 99.1 to 99.9 % of probability.

Table 2–3: Conversion probit to probability (Safety 1999)

%	0	1	2	3	4	5	6	7	8	9
0	—	2.67	2.95	3.12	3.25	3,36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

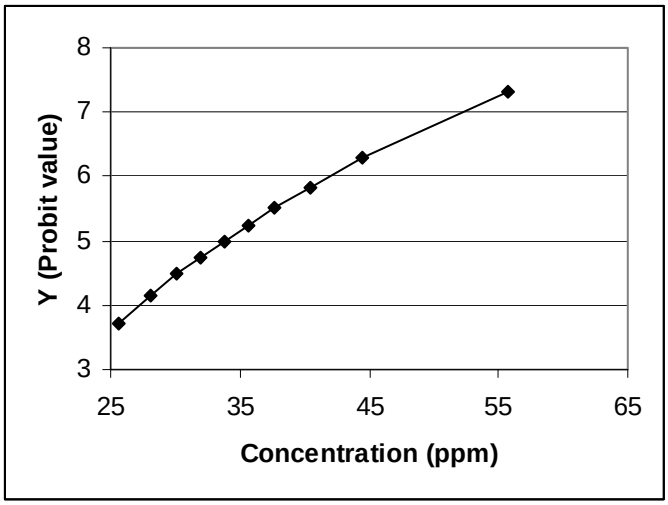

Figure 2–6: Probit distribution for Chlorine for 30-minute exposure

Ferguson and Hendershot (2000) and Ten Berg (1986) provide examples of published dose-response constants for probit equations (Equation 2-8) for several materials (e.g., Ammonia, Chlorine, and Hydrogen Chloride.) Figure 2-6 demonstrates the sample probit distribution for Chlorine corresponding to 30-minute exposure and probit constants i.e., a of -17.1, b of 1.69, and n of 2.75 (Eisenberg et al. 1975). The impact of using different dose-response relationships on the results of a quantitative risk analysis was investigated by Ferguson and Hendershot (2000). According to a sample study on an exposure to chlorine, they found that large differences in risk assessment are presented in an exposed population greater than five people, when the probit constants from different dose-response data are used in the risk assessment. Therefore, it is important to select an appropriate dose response model for risk assessment to determine accurate health consequences from contaminant exposure.

2.1.4. Risk Characterization

Many published articles provide definitions of risk characterization. The risk characterization is described in National Academy of Sciences' (NAS) National Research

Council (NRC) publication as “the process of estimating the incidences of a health effect under the various conditions of human exposure described in exposure assessment. It is performed by combining the exposure and dose-response assessments. The summary effects of the uncertainties in the preceding steps are described in this step”.

The U.S. EPA risk characterization handbook defines risk characterization as a step that integrates information from the preceding components of the risk assessment and synthesizes an overall conclusion about risk that is complete, informative, and useful for decision maker (EPA 2000). A good risk characterization will restate the scope of the assessment, express results clearly, articulate major assumptions and uncertainties, identify reasonable alternative interpretations, and separate scientific conclusions from policy judgments. In order to conduct a good risk characterization, the U.S. EPA recommends implementing four principles: transparency, clarity, consistency and reasonableness (TCCR). Criteria for each principle are also provided in this handbook.

2.2. Critical HVAC System Characteristics in a CB Building Attack

HVAC systems are commonly used in most buildings, both commercial and residential. The HVAC system is intended to provide thermal comfort and indoor air quality that are acceptable to a building’s occupants. The system is designed according to performance requirements, budget, and other factors including the engineer’s familiarity and owner’s preferences. The system also performs multiple interdependent functions including ventilation, pressurization, and filtration which affect distribution of airborne contaminants in buildings. This consequently makes the HVAC system arguably the most vulnerable engineering feature to a CB attack in a building. A basic HVAC system has three components: (i) outdoor air intake, (ii) air handling units, and

(iii) an air distribution system (Figure 2–.7). Three main parameters of HVAC system are reviewed in this section: HVAC system type, HVAC system zoning, and air cleaning technologies. To study performance measures of building protection to CB attacks, the effects of HVAC system types, zoning, and air cleaning technologies on contaminant distribution should be clearly understood.

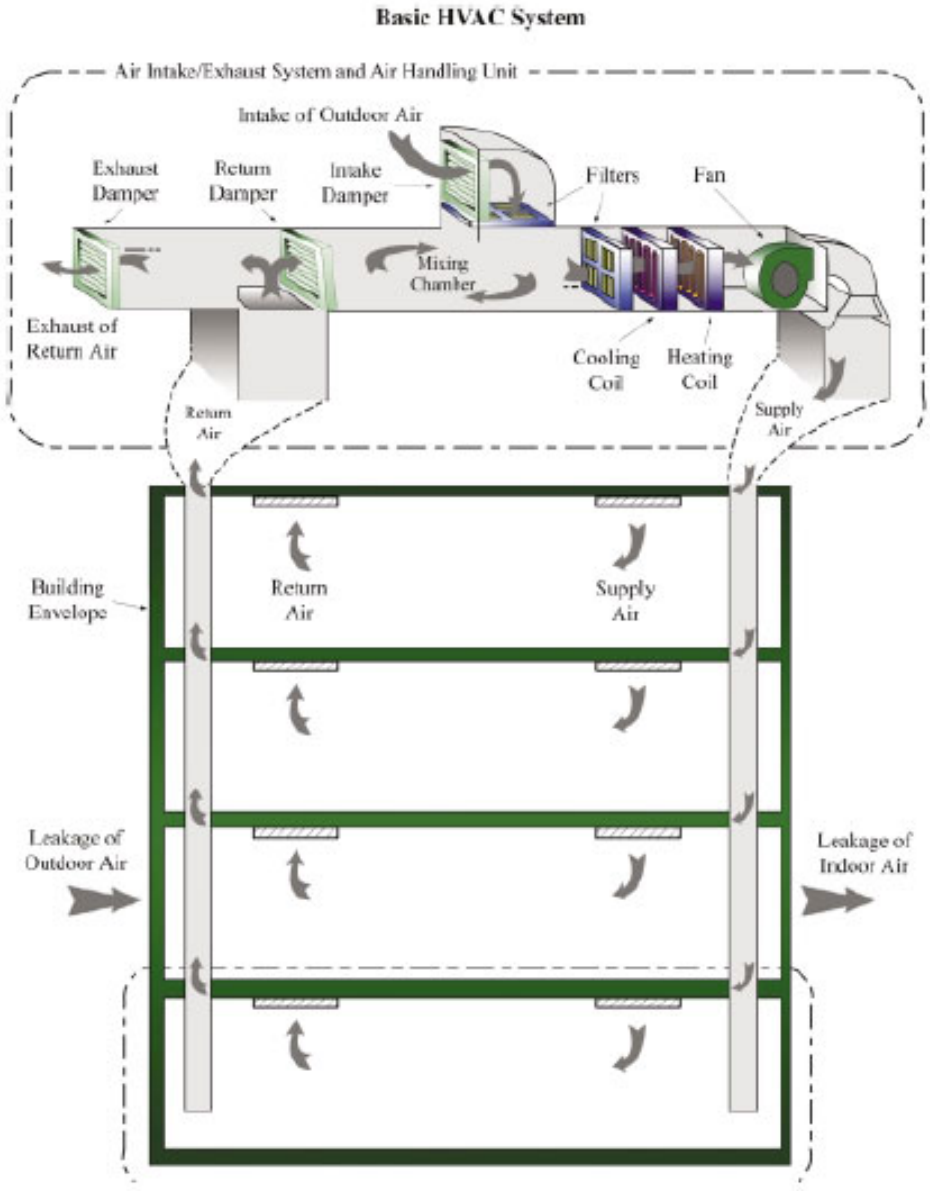

Figure 2–7: Basic HVAC system

2.2.1. HVAC System Type

Engineers can select and design the HVAC system type based on published guidelines (e.g., ASHRAE Standard 90.1, ASHRAE Standard 62.1). Three widely used HVAC system types—constant air volume systems (CAV), dedicated outdoor air systems (DOAS), and variable air volume systems (VAV)—are considered in this study.

2.2.1.1. CAV System

A CAV system provides a constant supply air flow rate to each conditioned space regardless of the heating or cooling load. The system changes the supply air temperature to maintain the desired room temperature by means of a reheat coil controlled by the space thermostat (ASHRAE 2011). A schematic of a typical CAV system is shown in Figure 2–8. Such systems typically have air-side economizer controls, which permit the amount of outside air brought in to increase as much as 100% of the supply air flow (i.e., no recirculation), when doing so will help to cool the building. When increasing the outdoor air flow rate would add to cooling load, it is maintained at the minimum value required for ventilation. This reduces the amount of energy consumed by the refrigeration plant serving the cooling coils.

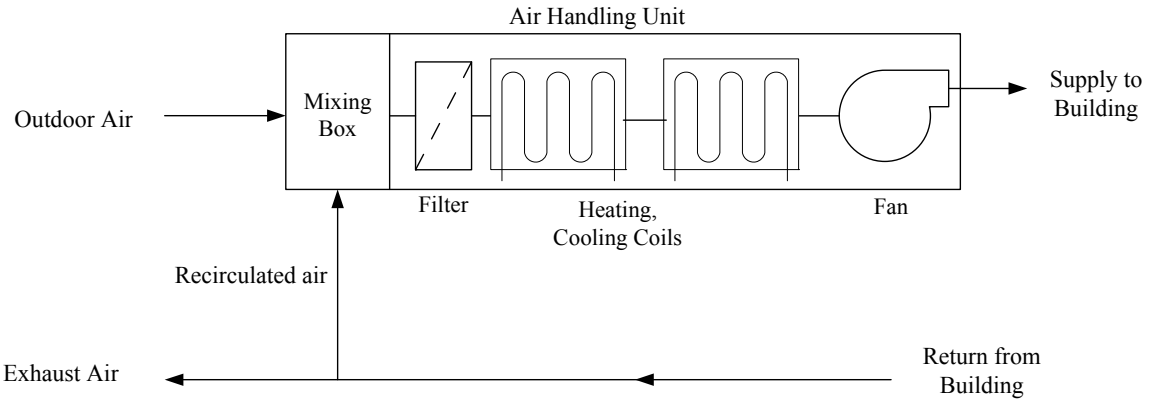

Figure 2–8: CAV system schematic

2.2.1.2. DOAS system

A dedicated outdoor air system (DOAS) is a constant air volume system that supplies 100% outdoor air to deliver the volumetric flow rate of ventilation air to each conditioned space in the building. Usually, the supply air flow rate is determined to at least meet minimum ventilation requirement based on ASHRAE Standard 62.1 or other design codes adopted by the city or county. In some application such as LEED buildings, the supply air flow rate also has to meet a required normal design standard and is increased to obtain certain LEED points. In an HVAC application, a DOAS usually handles the space latent load and is integrated with parallel systems (e.g., radiant cooling panels, chilled beams, etc.) which treat both sensible and latent loads in the space that are not accommodated by DOAS (Mumma 2001). Most DOAS applications require the use of total energy recovery (enthalpy wheel) to meet the requirements of ASHRAE standard 90.1. DOAS generally delivers approximately 20% as much air to space as a conventional all-air VAV system. This will affect the distribution of airborne contaminant differently than other system types. Figure 2-9 shows a schematic of DOAS system.

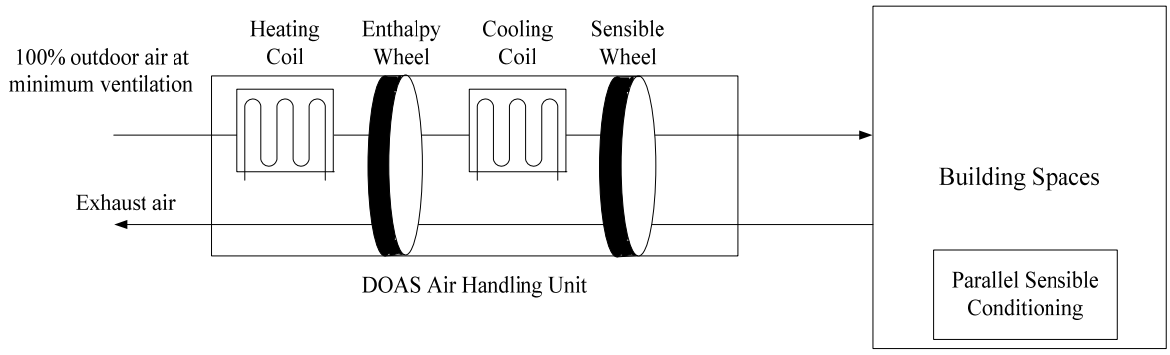

Figure 2–9: DOAS system schematic

2.2.1.3.VAV System

A VAV system supplies a constant temperature air stream to each air-conditioned space. The air flow to the space is varied by dampers in VAV boxes that are controlled by a space thermostat to maintain desired room temperature. In general, every VAV box may be at a different percentage of its full flow at a given time, because heat sources may vary from room to room as shown in Figure 2-10. Air-side economizer controls are also common in VAV systems. To meet heating and cooling loads, each system has its own way to regulate supply air flow to the space which directly influences the airflow pattern in the building. Consequently, this affects the airborne contaminant transportation.

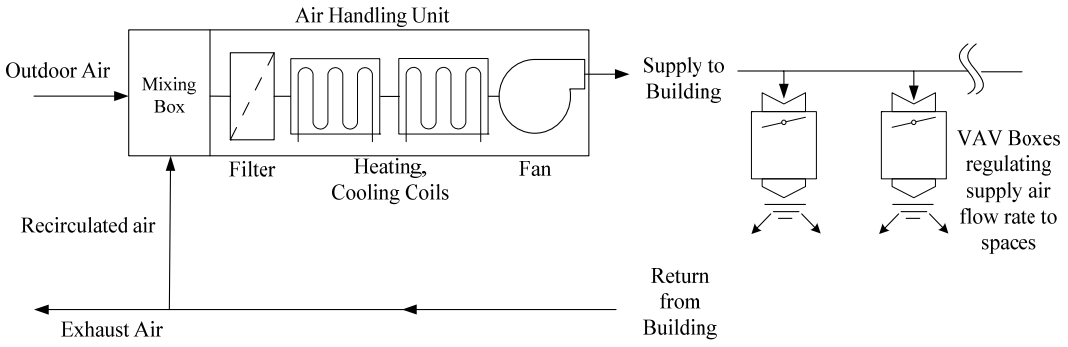

Figure 2–10: VAV system schematic

2.2.2. HVAC System Zoning

Many buildings are subdivided into multiple areas served by independent HVAC systems. Several zoning configurations, e.g., single rooftop air handling unit (AHU) zoning, floor-by-floor AHU zoning, core-perimeter zoning, etc. are commonly implemented in practice. When a contaminant release occurs, zoning tends to limit the spread of contaminants through mechanical system within the zone.

Given the ability of zoning to limit contaminant dispersion, it is one of the commonly recommended countermeasures to a CB weapon attack in building protection guidelines. This concept is also reflected in "shelter in place" strategies, in which a room with a separate, protected air distribution system, high airtightness, and low infiltration, is used to protect occupant against CBW attacks (Kowalski 2003; Mead and Gressel 2002; Price et al. 2003; USACE 2001).

Even though zoning can limit the spread of the contaminants, contaminant transportation between zones served by different air handling units can be induced by pressurization causing air flows through leakage paths or vertical shafts, e.g., stairwell and elevator shafts (Musser et al. 2002). Therefore, the effects of HVAC zoning on contaminant dispersion should be thoroughly explored.

2.2.3. Air Cleaning Technology

An air cleaning system can be one of the most effective defense mechanisms that protect buildings from CB attacks. Four common technologies are implemented to remove or mitigate the spread of CB agents: dilution ventilation, particulate filtration, gas phase filtration, and ultraviolet germicidal irradiation (UVGI).

2.2.3.1.Dilution Ventilation

Ventilation is the process that provides acceptable indoor air quality and personal comfort and usually represents the introduction of outside air into spaces. The minimum requirement of ventilation air is determined based on maximum number of occupants, floor area, and function of the space according to ASHRAE Standard 62.1-2010 or other standards and codes. In the event of an indoor contaminant release, increasing the amount of outside air to dilute indoor contaminant concentrations is an effective

protection strategy. This process is referred to as "dilution ventilation" (Kowalski 2003). This strategy requires an air conditioning system that can treat the increased amount of outside air. However, dilution ventilation will not offer protection against external release unless special filtration or air cleaning technology at the outdoor air intake is implemented.

In some HVAC applications such as CAV systems and air-side economizer controls are applied to utilize the low temperature outside air to provide free cooling. An economizer can increase the quantity of outside air up to 100% of the supply air flow rate when outside air is cool or has low enthalpy. This results in better dilution of indoor contaminants and also improves indoor air quality. An economizer system is found to provide benefits on reducing sick leave due to its contribution to improve indoor air quality because it brings more fresh air into spaces (Fisk et al. 2005).

2.2.3.2. Particulate Filtration

Filtration is a common air-cleaning technology for controlling particulates. Particulate air filters are made of fibrous media which have ability to capture particles including microorganisms or biological materials, and are used extensively in HVAC systems. The fibers may range in size from less than 1 μm to greater than 50 μm in diameter. This type of filter relies on four mechanisms (Figure 2-11): inertial impaction, interception, diffusion, and electrostatic effects to collect particles (NIOSH 2003). Impaction occurs when a particle deviates from the air stream and collides with a fiber. Interception occurs when a large particle collides with a fiber in the filter. Diffusion occurs when the random (Brownian) motion of a particle causes that particle to contact a fiber. Electrostatic attraction occurs when smaller particles are retained on the filter by a

weak electrostatic force. The first two mechanisms, impaction and interception, are the dominant collection mechanisms for particles larger than 0.2 µm, and diffusion is dominant for particles less than 0.2 µm. Figure 2-12 shows the combined effect of these three collection mechanisms results in the classic collection efficiency curve.

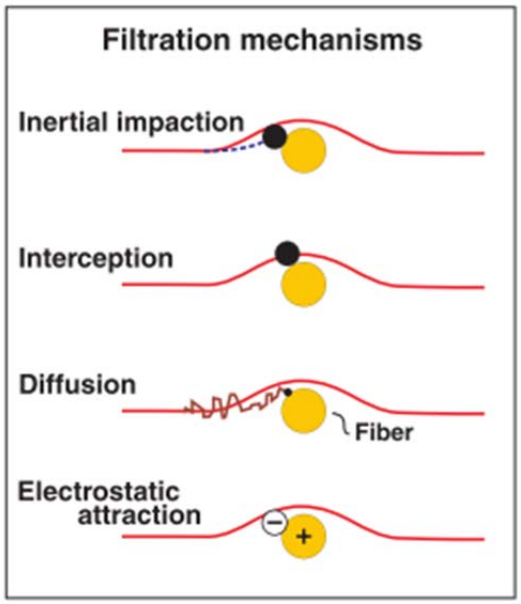

Figure 2–11: Four primary filter collection mechanisms (NIOSH 2003)

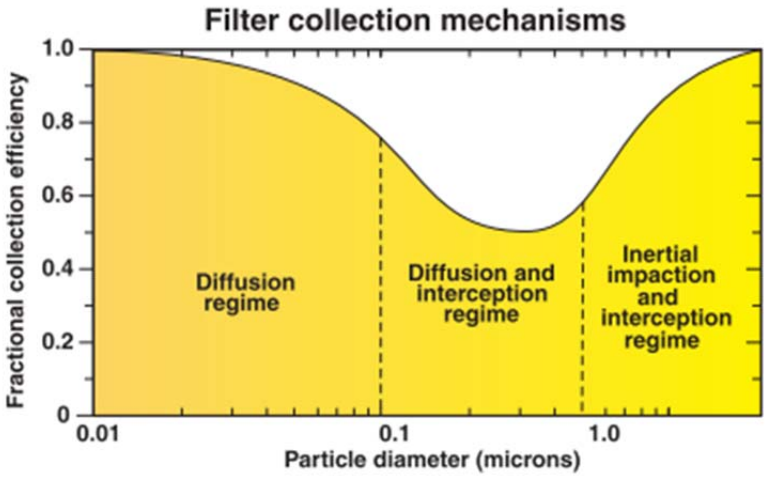

Figure 2–12: Fractional collection efficiency versus particle diameter for a mechanical filter. The minimum filter efficiency will shift based upon the type of filter and flow velocity. (Note the dip for the most penetrating particle size and dominant collection mechanisms based upon particle size) (NIOSH 2003)

In general practice, particulate filters are utilized to remove dirt and pollutant in order to provide certain level of indoor air quality. These filters efficiency is selected to meet minimum particulate filtration efficiency specified by ASHRAE Standard 62.1. The standard requires only a minimum efficiency reporting value (MERV) 6 filters which is generally too low to be effective against particles in the size range associated with CB particles which is usually smaller than 1 μm (Bahnfleth et al. 2008). Figure 2-13 shows relationship between fractional efficiency and particle mean diameter at various MERV filter models.

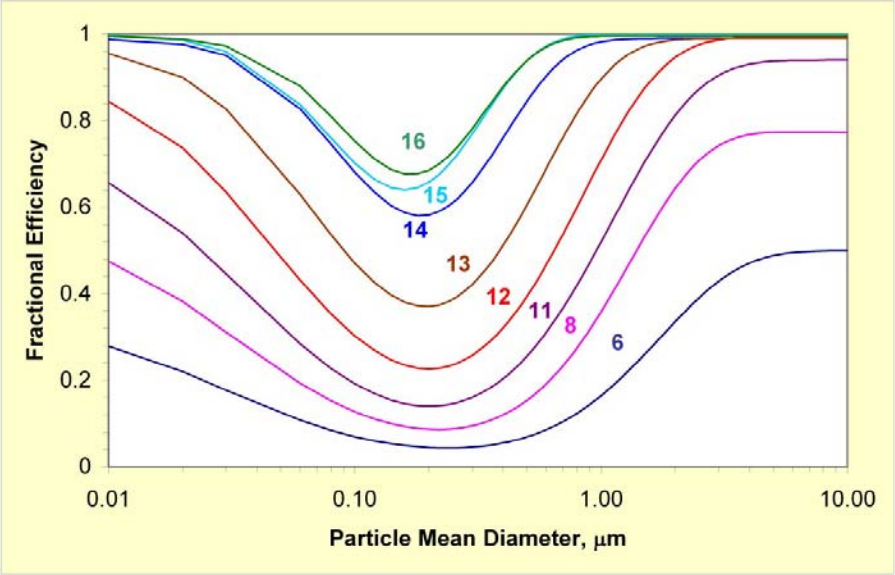

Figure 2–13: Representative efficiency of MERV filter models (Kowalski and Bahnfleth 2002)

In the context of CB weapons attacks, high efficiency particulate air (HEPA) filters and ultra-low penetration air (ULPA) filters can be implemented as a defense mechanism. HEPA filters are defined as having 99.97% or greater removal efficiency for 0.3 μm (DOE 1997) which is comparable to MERV rating greater than 17 according to ASHRAE Standard 52.2. ULPA filters are defined as 99.999% efficient in removal of

0.1 – 0.2 μm particles which is comparable to MERV 19. These high efficiency filters have major impact in increasing air-side pressure drop for a given air flow which may require larger size of supply fan. This consequently increases fan energy use. Selection of these types of filters requires knowledge of the particle size of interest. Table 2–4 shows approximate removal rates of representative agents as a function of filter MERV value (Kowalski and Bahnfleth 2002).

Table 2–4: Filter rating and typical fractional removal rates (Kowalski and Bahnfleth 2002)

Agent	**Mean size (μm)**	**MERV 6**	**MERV 7**	**MERV 8**
Smallpox	0.22	0.037	0.04	0.07
C. bunetti	0.283	0.037	0.04	0.08
L. pneumophila	0.52	0.058	0.08	0.14
Bacillus anthracis	1,12	0.16	0.22	0.37
Agent	**MERV 10**	**MERV 13**	**MERV 15**	**MERV 16**
Smallpox	0.40	0.40	0.68	0.71
C. bunetti	0.44	0.44	0.75	0.77
L. pneumophila	0.69	0.69	0.95	0.95
Bacillus anthracis	0.96	0.96	0.9998	0.9998

2.2.3.3. UVGI

Ultraviolet germicidal irradiation (UVGI) is an indoor air enhancement technology that uses UVC radiation to deactivate airborne microorganisms without removing them from the airstream. The UV spectrum has been subdivided into three different wavelength bands: UVA (long wavelengths range from 320 to 400 nm), UVB (midrange wavelengths range from 290 to 320 nm), and UVC (short wavelengths range from 100 to 290 nm). UV lamps used as UVGI devices are low-pressure mercury vapor lamps that radiate UV spectrum predominantly at a wavelength of 254 nm (Coker et al.).

UVGI systems including air-stream-disinfection and surface-disinfection applications are commonly implemented in healthcare facilities (Kowalski and Bahnfleth 2000). However, a wide range of airborne respiratory pathogens are susceptible to deactivation by UVGI. This grows an interest in utilizing UVGI as one of protective measures to bioterrorism building attacks. The destructive effect of UVGI on bacterial and viral DNA depends on the intensity of UVGI energy to which the infectious particle is exposed and the duration of the exposure. Several researchers have studied a spectrum of microorganism susceptibility dependent primarily upon the presence or absence of a cell wall and the thickness of cell wall. Brickner et al 2003 has summarized the UVGI radiant exposure necessary to inhibit colony formation in 90% (LD90) of organisms (10% survival) (Brickner et al. 2003).

In analogy to the MERV rating for particulate filters, UVGI Rating Value (URV) for any UVGI system has been proposed by Kowalski and Dunn (2002) and Kowalski (2003). The URV is based on the UV dose produced which is defined as the product of exposure time and irradiance and has units of $\mu J/cm^2$ (or $\mu W\text{-}s/cm^2$). Table 2–5 shows the proposed breakdown of UV doses used to define the URV and a sample of inactivation rates that would be obtained by the indicated URV.

Table 2–5: UVGI Rating Values and Typical Kill Rates (Kowalski and Bahnfleth 2004)

URV	**UV Dose $\mu J/cm^2$**	**Anthrax Kill, %**	**Influenza Kill, %**	**Small-pox Kill, %**	**TB Kill, %**
1	1	0	0	0	0
2	10	0	1	2	2
3	20	0	2	3	4
4	30	0	3	4	6
5	50	1	6	7	20
6	75	1	9	11	15
7	100	2	11	14	19

URV	UV Dose $\mu J/cm^2$	Anthrax Kill, %	Influenza Kill, %	Small-pox Kill, %	TB Kill, %
8	150	2	16	20	27
9	250	4	26	32	41
10	500	8	45	53	66
11	1000	15	69	78	88
12	1500	22	83	90	96
13	2000	28	91	95	99
14	3000	39	97	99	100
15	4000	49	99	100	100
16	5000	57	100	100	100
17	6000	63	100	100	100
18	8000	74	100	100	100
19	10000	81	100	100	100
20	20000	96	100	100	100
k ($cm^2/\mu J$)		1.67×10^{-4}	1.187×10^{-3}	1.1528×10^{-3}	2.132×10^{-3}

2.2.3.4. Gas-phase Filtration

A gas-phase filter is designed to remove pollutant gases and vapors. The physical mechanism utilized by typical gas-phase filters is adsorption, in which contaminant molecules are bound to surface sites on adsorbent medium by physical or chemical forces, or a combination of the two. Figure 2–14 shows the two types of gas-phase filters subdivided by their material: carbon absorber and non-carbon technologies.

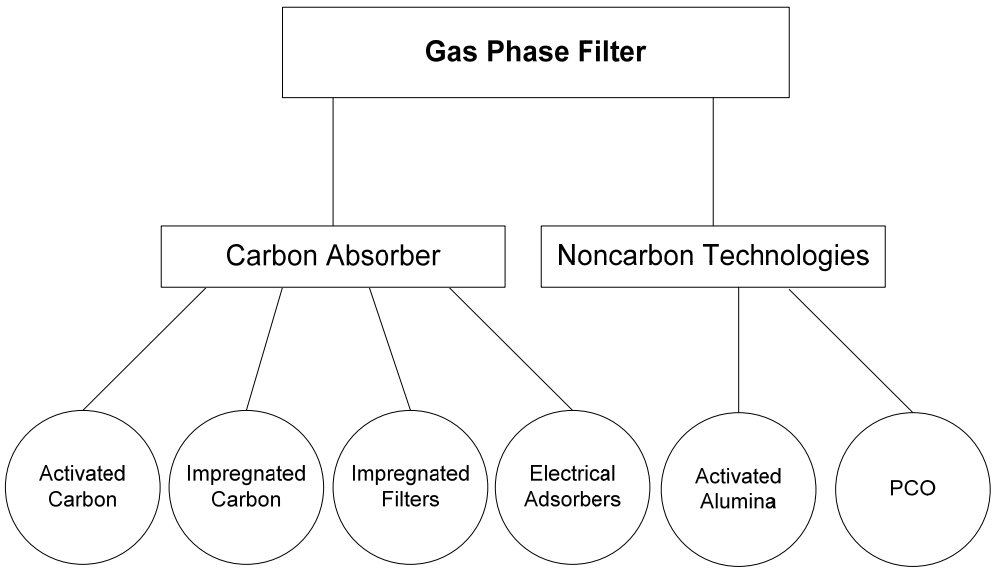

Figure 2–14: Breakdown of common gas-phase filtration technologies based on sorbent material (Kowalski 2003)

Carbon absorbers are used in the heating, ventilating, and air conditioning (HVAC) industry for controlling odors and volatile organic compounds (VOCs). In a study, carbon adsorption also has the capability to remove Botulinum toxin. Unlike the particulate filters, the performance of adsorption devices is usually rated in terms of "adsorption capacity" and "penetration time". The percent removal of chemical is dependent on residence time (Woods and Crawford 1983). The adsorption capacity of an activated carbon filter for a variety of chemicals is rated on a scale from 1 (low or no capacity) to 4 (high capacity). More than 70% of activated carbon materials have high adsorption capacity or are rated as 4 on the rating scale. A filter rating of 4 for a particular agent can absorb 20% to 40% of its mass. Table 2–6 is an example of adsorption capacity at 20 ºC of dry air in removing chemical agents and simulant.

Table 2–6: Some chemical weapon agent removal by carbon filter (ASHRAE 2003)

CW agent or simulant	Adsorption at 20ºC in dry air, % of Carbon Mass
Chlorine	10-25 % (rate 3)
Chloropicrin	20-40 % (rate 4)
Phosgene	10-25 % (rate 3)
Sulfur dioxide	Low (rate 2)
Sulfur trioxide	Low (rate 2)

However, there are several disadvantages regarding the use of gaseous filters: (i) there is no single adsorbent capable of removing all toxic chemicals; (ii) carbon filter system are relatively expensive; and (iii) operating and maintenance costs are relatively high (Bahnfleth et al. 2008).

2.3. Existing Performance Criteria

Bahnfleth et al. (2006) defined performance criteria as values assigned to performance measures to define an acceptable outcome. Where human health effects are concerned, criteria are defined in terms of the likelihood of a particular level of consequence to individuals subjected to a specified exposure or dose. Criteria may be defined in very specific terms or they may be quantitative but based on qualitative distinctions of severity.

A number of quantitative performance criteria have been developed mostly for occupational exposure to provide safe environment to workers by specifying the threshold for short-term (higher limit) and long-term (lower limit) exposure of workers to hazardous agents. In the US, four recognized agencies have established standards for occupational exposure that designers most likely encounter (Heinsohn and Cimbala 2003): the American Conference of Governmental and Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA), the American National

Standards Institute (ANSI), and the National Institute for Occupational Safety and Health (NIOSH). In addition to occupational exposure limits, performance criteria such as the US National Research Council (NRC) Acute Exposure Guideline Levels (AEGLs) are developed for an accidental exposure to a specific agent.

2.3.1.1. Threshold Limit Values (TLVs)

The American Conference of Governmental and Industrial Hygienists (ACGIH) has developed threshold limit values (TLVs) as concentration criteria for people exposure levels to contaminants. Three levels of TLV values are developed: threshold limit value-time-weighted average (TLV-TWA), threshold limit value-short term exposure limit (TLV-STEL), and threshold limit value-ceiling (TLV-C). The TLV-TWA (Equation 2-9) is the concentration that a person can repeatedly work in that environment for a normal 8-hour day, 40-hour a week, and week after week without health adverse effect.

$$TWA_{8hr} = \frac{1}{8hr}\int_{0}^{8hr} C(t)dt \qquad \text{Equation 2-9}$$

where:

$TWA_{8\text{-}hr}$ = 8 hour time-weighted average concentration,

t = time (time),

$C(t)$ = airborne concentration as a function of time (mass of contaminants/volume for chemical agents and toxins and number of particles/volume for biological agents).

The TLV-STEL is defined as a 15-min time-weighted average exposure concentration which causes minor symptoms such as irritation and chronic or irreversible tissue change.

$$STEL = \frac{1}{15\,\text{min}} \int_{0}^{15\,\text{min}} C(t)dt \qquad \text{Equation 2-10}$$

where:

STEL = 15-min time-weighted average concentration,

t = time (time),

C(t) = airborne concentration as a function of time (mass of contaminants/volume for chemical agents and toxins and number of particles/volume for biological agents).

The TLV-C is the contaminant concentration that people should not have exposed to, even instantaneously, during any part of the working exposure.

2.3.1.2. Permissible Exposure Limits (PELs) and Recommended Exposure Level (REL)

The permissible exposure limits (PELs) are standards published by OSHA to protect workers against the adverse health effects due to exposure to hazardous substances (OSHA 2006). PELs are based on an 8-hour time weighted average (TWA) exposure. The PELs are addressed in specific standards used for the general industry, shipyard employment, and the construction industry. Each hazardous substance is listed on the OSHA website at http://www.OSHA.gov/SLTC/pel.

Recommended exposure limit (REL) was adopted by National Institute of Occupational Safety and Health (NIOSH) to provide examples of criteria for preventing disease and hazardous conditions in the workplace (NIOSH 1992). NIOSH also published the adverse health effects of the human exposure to the substance at the RELs for selected hazardous agents and also recommends preventive measures including

engineering controls, safe work practices, personal protective equipment to reduce the health effects of these hazards.

2.3.1.3. Biological Exposure Indices (BEIs)

According to ACGIH, Biological Exposure Indices (BEIs) are guidelines to provide safe biological contaminant exposure levels found in workplace. Exposure below the level of BEI does not create an unreasonable risk of disease of injury.

2.3.1.4. Acute Exposure Guideline Levels (AEGLs)

To complement routine occupational exposure limits, the National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances (NAC) has developed acute exposure guideline levels (AEGLs) for high-priority, acutely toxic chemicals based on existing scientific and relevant toxicological data (NRC 2001). AEGLs are the representation of threshold exposure limits for the general public which are applicable to emergency exposure ranging from 10 min to 8 hr for rare or once-in-a-lifetime exposures. AEGLs are airborne concentrations (in ppm or mg/m3) and categorized into three levels (AEGL-1, AEGL-2, and AEGL-3) by varying degrees of severity of toxic effects. The effects of AEGL-1 exposure are notable discomfort, irritation, or certain asymptomatic non-sensory effects but not disabling and are transient and reversible upon cessation of exposure. AEGL-2 exposure can create irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. The highest level of exposure, AEGL-3, can cause life-threatening health effects in exposed population.

2.3.1.5. Dose-response Criteria

In toxicology and epidemiology, threshold or dose-response criteria are used in determining the health effects of human responding to specific level of exposure or dose. The following terms are commonly used as measures of infectiousness or toxicity of the CB agents (Kowalski 2003).

For biological agents, ID_{50} (mean infectious dose) means the dose or number of microorganisms that will cause infections in 50 percent of an exposed population. This term usually has unit of colony forming units/m^3 (cfu/m^3). LD_{50} (mean lethal dose) means the dose or number of microorganisms that will cause fatalities in 50 percent of an exposed population. LD_{50} has the same unit as ID_{50}.

For chemical agents, ID_{50} (mean incapacitating dose) means the dose of a chemical agent that will incapacitate 50 percent of an exposed population. The common unit is mg/kg. LC_{50} (mean lethal concentration) means the concentration of a chemical agent that will cause 50 percent fatalities of an exposed population. This term has the unit of mg/m^3. These values are usually determined based on experimental data.

These criteria can be applied to results of the parametric study to determine specific health effects based on exposure to specific agent.

2.4. Building Performance Measures

In evaluations of building CB security, many candidate building-level performance measures have been created to characterize the exposure level of the entire building and its occupants. However, there is no consensus as to which is most useful or appropriate (Bahnfleth et al. 2008). The available building measures can be mainly subdivided into two categories: threat-based and vulnerability-based measures. Threat-

based measures are performance measures that determine the adverse health consequences of exposed occupants following an assumed event. This requires the identification of the agent of concern as well as the quantity and manner of release. On the other hand, vulnerability-based measures are relative measures that focus on identifying the vulnerability level of a building and its occupants to airborne contaminants by comparing risk level to that of the baseline case without the identification of the distributed airborne contaminants, i.e., is exposure higher or lower and/or distributed differently from one case to another.

2.4.1. Casualties or Fatalities

One of the approaches in evaluation of building security is an estimation of casualties or fatalities resulting from a non-uniform exposure distribution of the building. This approach requires quantitative dose-response relationships (Section 2.1.3) for agents of concerns including chemical and biological agents. However, published data on these relationships for biological agents is not widely available or reliable (Bahnfleth et al. 2008). It is clear that the estimation of casualties and fatalities is categorized as a threat-based measure and also currently the most accurate measure regarding the determination of risk levels of building attacks.

2.4.2. Building Protection Factor (Kowalski 2003)

Kowalski (2003) proposed a whole building performance measure which is called the Building Protection Factor (BPF). The BPF is defined as the percent of occupants theoretically protected from infections during the release of airborne pathogens. The design basis is defined as an 8-hour continuous release of a quantity of an agent that will cause 99% infections in occupants of a building with a mechanical ventilated system that

is a CAV system and provides 15% outside air, 8 air change rates without any air cleaning system.

There is a sequence of steps to calculate the BPF. First, the building parameters including the air change rate (ACH) and filter removal efficiency (RE) and the design basis release rate (RR) are determined. Then the airborne concentration and 8-hour inhaled dose are determined using a model of the building (i.e., steady state models, transient single-zone complete mixing models, and multizone model). An epidemiological model is then used to compute the percent infections.

An agent is assumed as a generic microbe which has the mean lethal dose (LD_{50}) of 1. The design basis release rate (in cfu/min) for a generic microbe is determined to cause 99 percent infections in a single zone with complete mixing building model. Equation 2-11 is a result of transient modeling.

$$RR_T = 0.000373 \times Vol \qquad \text{Equation 2-11}$$

Where

Vol = building volume,

and RR_T = the basis release rate.

However, Kowalski used the equation 2-11 in a steady state equation to estimate the airborne concentration based on the clean air delivery rate (the sum of OA and the fraction of filters return air delivered by the air cleaner.) With an assumed breathing rate of 0.01 m^3/min and no filter, the 8-hour inhaled dose can be represented by Equation 2-12.

$$D_8 = 4.8\left(\frac{RR_T}{Q_{OA}}\right) \qquad \text{Equation 2-12}$$

Where

D_8 = 8-hour inhaled dose,

RR_T = the basis release rate,

And Q_{OA} = the quantity of OA.

Since the LD_{50} is normalized to unity, the percent of infections can be presented by Equation 2-13 which is the Gompertz equation. BPF or building protection factor is defined as the uninfected fraction of the building represented by Equation 2-14.

$$Inf = 0.5^{0.1^{(D_8 - 1)}} \quad \text{Equation 2-13}$$

Where

Inf = percent of infections,

$$BPF = 1 - Inf \quad \text{Equation 2-14}$$

Where

BFP = building protection factor.

This method is generally applicable to determine effects of air cleaning technologies for a single zone model. For the floor-by-floor building model, Kowalski recommends to use an area-weighted average of the zonal protection factor (ZPF) to estimate overall BPF (Equation 2-15). The ZPF can be calculated using the BPF method for the zone that is served by a single mechanical system.

$$BPF = \frac{1}{FA_{total}} \sum_{i=1}^{n} FA_i \left(ZPF_i \right) \quad \text{Equation 2-15}$$

Where

FA = floor area in ft^2 and m^2,

n = number of zones,

and ZPF_i = zonal protection factor for zone i.

2.4.3. Fraction of Building Exposed (FBE), Fraction of Building Protected (FBP) and Fraction of Occupants Exposed (FOE) (Bryden W. 2006)

Another building-level performance metric, the fraction of building exposed (FBE) and fraction of occupant exposed (FOE), were utilized by Immune Building Program. FOE is defined as Equation 2-16

$$FOE = \frac{Occupant\_Exposed}{Occupant\_Total} \qquad \text{Equation 2-16}$$

Where

Occupant_Exposed = the total number of occupants exposed to an agent after release,

Occupant_Total = the total number of occupants in building during incident.

Nakano et al. (2006) proposed a quantitative design assessment that will enable decision makers to assess building designs for CB protection. This methodology uses multizone simulation and the concept of fraction of building protected (FBP) to determine the level of building protection for each HVAC system design. The cost analysis of building HVAC upgrades versus FBP levels is also discussed.

$$FBE = \frac{\sum Area\_Exposed}{\sum Area\_Total} \qquad \text{Equation 2-17}$$

Where

FBE = fraction building exposed,

Area_Exposed = the total building area that is exposed to an agent,

and *Area_Total* = the total building area.

$$FBP = 1 - FBE \qquad \text{Equation 2-18}$$

Where

FBP = fraction building protection.

Several levels of health effects (mild, severe, and lethal) from available published values of dose-response data can be used to determine the level of exposure of interest in order to calculate FBE value. In the Nakano et.al. (2006) case study, the FBP is calculated based on lethal effects only which will be applied in this research as well.

2.4.4. Exposure Improvement Score (EIS)

DeGraw and Bahnfleth (2011) have proposed a single-value vulnerability-based metric, exposure improvement score (EIS), that represents overall good or bad rating of system design which is calculated based on cumulative, local exposure. Exposure dose, D, can be calculated using Equation 2–2 or 2–3 depending on whether or not one needs to take into account the toxic load exponent in the analysis. In the DeGraw and Bahnfleth (2011) study, a value of n = 1 is used to illustrate the application of exposure dose in a relative exposure metric. For a given release scenario, the exposure dose is determined for each zone and paired with the floor area of the zone. These results are sorted in order of increasing exposure dose as a fraction of cumulative area. A distribution between cumulative area fraction and exposure dose can be plotted as shown in the example in Figure 2–15.

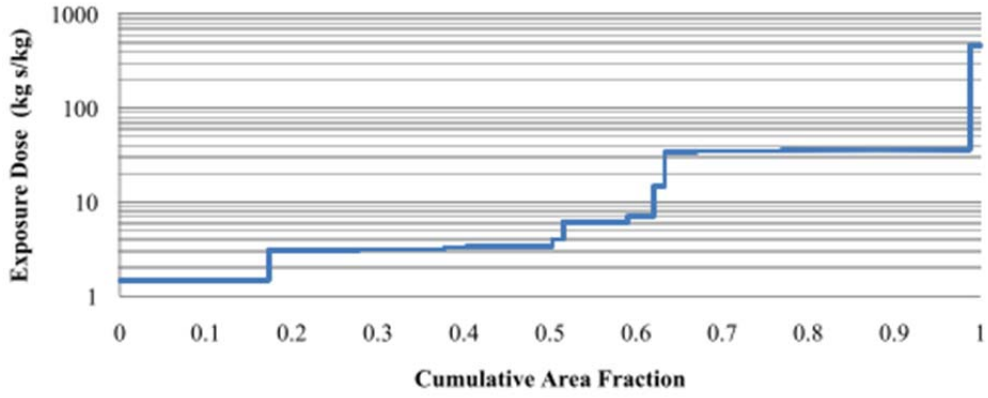

Figure 2–15: Ordered exposure dose as a function of cumulative area fraction of a single event (DeGraw and Bahnfleth 2011)

While the distribution as shown in Figure 2–15 could be considered the end point, further standardization and compression can be achieved if desired by binning the results in deciles. A decile based discretization of the results in Figure 2–15 is shown in Figure 2–16 where D1 is the 10% decile; D2 is the 20% decile, and so on. Simple averaging is used to compute an average response to the event in each bin by dividing the resulting exposure dose values by the worst-case building average exposure dose. The worst-case building average exposure dose is a value of the initial building-average concentration times total simulation time.

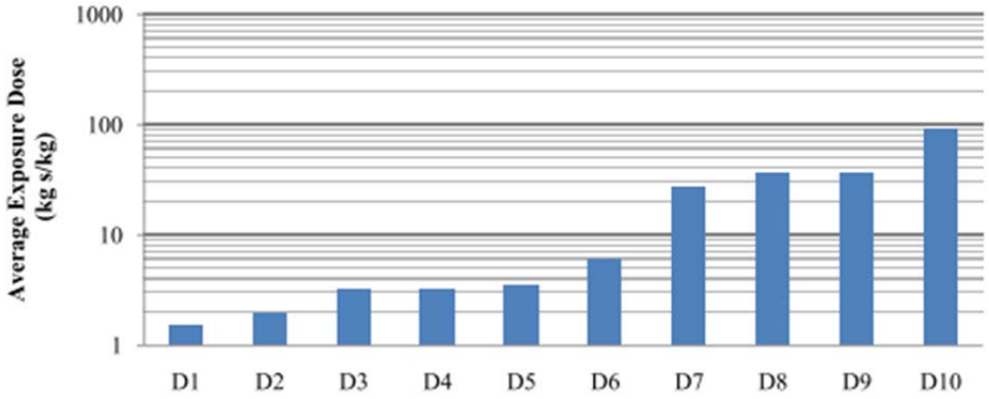

Figure 2–16: Decile breakdown of exposure dose results for a single event (DeGraw and Bahnfleth 2011)

EIS as defined by DeGraw and Bahnfleth provides a final degree of compression for the presentation of the results of a scenario relative to a baseline case by reducing the decile results portrayed graphically in Figure 2–16 to a single value. In DeGraw and Bahnfleth's example, exposure dose is calculated using Equation 2–2.

$$EIS_{10} = \sum_{k=1}^{10} \alpha_k \frac{D_{baseline,k} - D_k}{D_{baseline,k}} \qquad \text{Equation 2-19}$$

Where

EIS_{10} = exposure improvement score calculated based on a decile basis,

α_k = the decile weight,

$D_{baseline,k}$ = the baseline result in decile k,

and D_k = the candidate result in decile k.

DeGraw and Bahnfleth chose a weighting factor α_k of 10, which gives a maximum score of 100 for decile data. They applied this metric to the evaluation of two system design alternatives: envelope construction and percentage of outside air in the HVAC system. The EIS provides a consistent meaning of what system design would be better than the other following internal releases of contaminants.

In addition to aforementioned metrics, there are other options considered by various investigators and organizations including building average exposure or concentration over time, spatial and temporal distribution of building average concentration or exposure, etc.

2.5. Modeling Methods

In order to estimate occupant exposure in a CB event, it is necessary to determine the spatial and temporal distributions of contaminants in a building of interest. Sohn et al. (2004) have reviewed available tools including computational models for both internal and external dispersion. This research focuses on building occupant exposure to internal dispersion of contaminants. Therefore, two types of computational models are discussed in this section: computational fluid dynamic (CFD) modeling and multi-zone modeling.

2.5.1. Computational Fluid Dynamics (CFD) Modeling

Computational Fluid Dynamics (CFD) modeling provides detailed, potentially accurate predictions of the CB transport and the spatial concentration in the space by solving the partial differential equations governing mass, momentum, and heat transfer

on a fine grid with well-defined boundary conditions to determine fluid parameters such as velocity, temperature, pressure, turbulence, and contaminant concentrations (Bahnfleth et al. 2008; Sohn et al 2004). These equations represent a three-dimensional viscous fluid flow field which can be solved by an iterative procedure via CFD programs. Sohn et al (2004) has reviewed a number of of available CFD programs. Utilization of CFD modeling requires considerable time, tremendous computing power and also deep expertise in fluid dynamics; therefore, it is not practical to use the CFD approach on an entire building analysis and in this research.

2.5.2. Multizone Modeling

An alternative to CFD modeling is multizone modeling. Multizone model simulates an entire building as a collection of zones connected by paths representing flows between zones. Multizone airflow modeling programs such as CONTAM (Walton and Dols 2005) and COMIS (Warren 1996) are efficient and convenient tools to simulate CB attacks whereby parameters including HVAC system type and zoning as well as building and release characteristics are taken into account and easily varied (Stenner et al. 2001). Many researchers have used these multizone modeling programs extensively in their studies. For example, Arvelo et al. (2002) used estimates of of contaminant distribution provided by CONTAM to determine the optimization of CB weapon sensor placement. Ferreira (2002) and Klote (2002) used CONTAM in smoke control system design and management. Although both CONTAM and COMIS utilize the same governing equations, CONTAM is selected as a modeling tool for this project because of the author's familiarity with CONTAM and because of its widespread use.

CONTAM is designed to determine airflows and pressures, contaminant concentrations, and personal exposure (Walton and Dols 2005). CONTAM uses the basis of contaminant dispersal analysis i.e., the application of conservation of mass for all species in a control volume and implements mathematical relationships to model airflow and contaminant related phenomenon. The assumption of "a well-mixed zone" is utilized wherein the air has uniform conditions including temperature, pressure, and contaminant concentrations. Consequently, contaminant released in the zone will be uniformly distributed throughout the zone within a single time step. However, the conditions at a given point within a zone cannot be acquired from CONTAM.

Judging from the amount of time required for an analysis coupling with CONTAM's useful features, using CONTAM will improve the effectiveness of determining the exposure of the occupants in the building and an ability to do parametric studies on building and release characteristics for this research.

2.6. Role of Uncertainty

Results of any risk assessment or any engineering analysis may be impacted by the effects of uncertainty. Risk assessment comprises many steps relying on the usage of many sources of information and techniques which increase the effect of uncertainty in the assessment. Understanding and identifying the sources of uncertainty is the first step in determining the actions necessary to reduce the uncertainty. EPA (1992) describes the three typical types of uncertainties related to exposure assessment: scenario uncertainty, parameter uncertainty, and model uncertainty. Scenario uncertainty includes incomplete and/or error information and professional judgment needed to fully define exposure and dose in specific scenarios. Parameter uncertainty includes errors in parameters

(measurement errors, sampling errors, etc.) or inherent variability that is used to determine exposure and dose. Model uncertainty includes gaps or errors in scientific model or relationship required to make predictions or results in determining exposure.

In this study, severity level of a building attack associated with HVAC system design for a presumed release is the main focus; therefore, the parameter and model uncertainties are important. The main parameter uncertainty is uncertainty in the specification of building and HVAC parameters including filter efficiencies, envelope leakage, and HVAC air flows (Bahnfleth et al. 2006). Model uncertainty is in the accuracy of the simulation models and dose-response models used in parametric studies. Only the parameter uncertainty will be studied and discussed in this research. Since the scenarios in this study are all hypothetical; the building measure data is not available which is required to determine the accuracy of the models developed using multizone modeling program CONTAM. Therefore, an analysis on the model uncertainty will not be covered.

Most available approaches for analyzing uncertainty have focused on techniques that examine how uncertainty in parameter values translates into overall uncertainty in the assessment; for example, sensitivity analysis, analytical uncertainty propagation, probabilistic uncertainty analysis, and classical statistical methods (EPA 1992).

Sensitivity analysis is a common way to show effects of uncertainty in input variables in risk assessment. This process involves fixing each uncertain variable, one at a time, at its lower-bound and upper-bound (holding other variables at their medians), and then computing outcomes for each combination of values (EPA 1992). The sensitivity analysis, which will be performed in this research, will show which input

variable or parameter has the most or least impact in overall uncertainty for each selected scenario.

Chapter 3

Research Methodology

The objective of this research is to determine the effects of HVAC system characteristics on occupants' exposure severity levels following an assumed event of building attack and identify reliable performance measures. The research methodology involves performing a parametric study of mechanical system parameters on a dormitory building and evaluating them using a variety of metrics. To identify reliable performance measures, the numbers of infections and casualties are determined for each release scenario and used as a reference measure. The accuracy of the severity levels interpreted using each vulnerability-based measure will be determined by comparing its interpretation to the numbers of infections and casualties. The following sections describe the method and specific parameters used in a parametric study, performance measures, and a sensitivity analysis.

3.1. Parametric Study

The parametric study employs a CONTAM model of a typical three-story building with supply and return ducted systems using several types of HVAC systems, zoning, and release scenarios.

3.1.1. Building Information

The building is a three story (plus attic), 16,791 ft^2 (1,560 m^2) multi-unit residential structure. The building model is based loosely on a typical university residence hall. It is composed of dormitories and public areas which include one

recreation room and two foyer areas on the first floor, one study area, and one foyer area on the second floor, and one study and one foyer area on the third floor. The first three floors are occupied and nearly identical. The layout and room usage of the first floor are shown in Figure 3–1. Each dormitory room holds two people, giving a building occupancy of seventy-six (76).

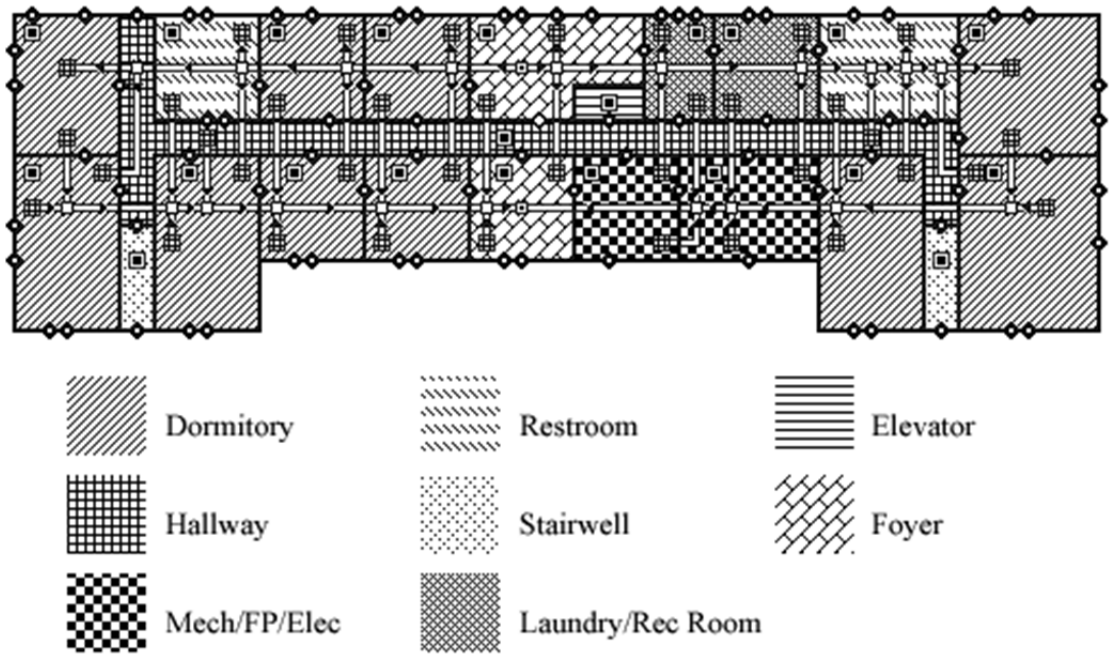

Figure 3–1: Model building first floor plan

During a release it is assumed that sixty-nine (69) people are located in dormitory rooms and the remaining seven (7) are in the public areas. Table 3–1 shows occupancy in each room.

Table 3–1: Building occupancy schedule during the release

Room	Function	Occupancy	Room	Function	Occupancy
112	Bedroom	2	213	Bedroom	2
R111	Bathroom	0	214	Bedroom	2
111	Bedroom	1	215	Bedroom	1
110	Bedroom	1	216	Bedroom	2

Room	Function	Occupancy	Room	Function	Occupancy
F102	Lobby	1	217	Study	1
109	Laundry	0	202	Bedroom	2
108	Rec Rm	1	203	Bedroom	2
R107	Bathroom	0	204	Bedroom	2
107	Bedroom	2	205	Bedroom	2
V101	Elevator	0	Z202	Stairs	0
Q101	Hall	0	Z201	Stairs	0
114	Bedroom	2	313	Bedroom	2
115	Bedroom	2	R312	Bathroom	0
116	Bedroom	1	312	Bedroom	2
117	Bedroom	2	311	Bedroom	1
F101	Vestibule	1	F301	Lobby	1
101	Elec/FP	0	309	Bedroom	2
103/102	Mech Rm	0	308	Bedroom	2
104	Bedroom	2	R307	Bathroom	0
106	Bedroom	2	307	Bedroom	2
Z102	Stairs	0	V301	Elevator	0
Z101	Stairs	0	Q301	Hall	0
212	Bedroom	2	318	Study	1
R211	Bathroom	0	315	Bedroom	1
211	Bedroom	1	316	Bedroom	2
210	Bedroom	2	317	Bedroom	2
F201	Lobby	1	310	Bedroom	2
208	Bedroom	2	302	Bedroom	2
207	Bedroom	2	303	Bedroom	2
R206	Bathroom	0	304	Bedroom	2
206	Bedroom	2	306	Bedroom	2
V201	Elevator	0	Z302	Stairs	0
Q201	Hall	0	Z301	Stairs	0
			ATTIC	Attic	0
			OA_deck	OA intake	0

The assumed building construction characteristics in Table 3–2 are used in simulation of the building model which affects the specification of building leakage characteristics.

Table 3–2: Building construction materials

Item	Description
Partitions	
Exterior Wall	Brick cavity wall
Interior Wall	CMU (concrete masonry unit)
Ceiling/Floor	Poured Concrete slab
Doors/Windows	
Exterior Doors	Metal Exit Doors, 3’ x 8’ (0.914m x 2.44m)
Interior Doors	Wooden Doors, 3’ x 8’ (0.914m x 2.44m)
Windows	Double Hung, Operable, 2.5’ x 4’ (0.762m x 1.22m)

3.1.2. Release Characteristics

In this research, *Bacillus anthracis* or anthrax is selected to use as a test contaminant in the parametric study. The localized short-duration releases into three different release locations are considered: releases into outdoor air intakes, in dormitory rooms, and in hallways. A one-minute release at the rate of 6×10^8 cfu/min into an outdoor intake of a single CAV system AHU is used as the base case. Anthrax spores are assumed to have an aerodynamic diameter of 1 μm and a density of 1100 kg/m^3 (68.7 lbm/ft^3). Results for other release rates could be calculated by applying a multiplier to this rate. In other words, if the release rate is doubled, exposure, concentration, and other quantities would also double. It is also assumed in all cases that the contaminant release would be undetected by occupants or protective systems during the time period of interest, so evacuation or other occupant-protective behaviors are not considered.

3.1.3. HVAC Parameters

3.1.3.1.Filtration

Since the selected contaminant is *Bacillus anthracis*, only particulate filters and normal ventilation are implemented in the model. However, the concept and results can also be applied with other types of filters since generic filters remove contaminants from

an airstream at a certain percentage of reduction depending on the efficiency of the filter. Three filter efficiencies were considered: the MERV 13 filter (ASHRAE 1992) specified in military standards at the time of the study, a MERV 6 filter required by ASHRAE Standard 62.1 (ASHRAE 2004), and no filter. For the assumed 1 μm anthrax spore size, a representative grade efficiency of 87.5% (0.875) was assumed for MERV 13 filter (Figure 2–13). The efficiency of removal of 1 μm particles by the MERV 6 filter was assumed to be 16.4% (Figure 2–13).

3.1.3.2. HVAC System Type

The three systems types considered, CAV, VAV, and DOAS, are all single duct systems (i.e., having one air stream leaving each AHU) with ducted return. Each system type has a different way of adjusting to variations in thermal loads and occupancy. The supply air flow rate to conditioned spaces and quantity of outdoor air brought into the building varies depending on the system type and operating conditions. All systems were modeled with a complete supply and return duct system (rather than a return plenum).

In scenarios involving a CAV or VAV system, the nominal supply air flow was 1.1 cfm/ft^2 (5.59 L/s-m^2) and the nominal return was 1 cfm/ft^2 (5.08 L/s-m^2). As is typical in air system design practice, supply was intentionally greater than return to pressurize the building relative to the outdoor ambient pressure. Actual return air flow rate is slightly less than supply air flow rate due to loss of some supply air by leakage through the building envelope to the outdoors. Individual supply air flows are randomly altered by an amount corresponding to typical balancing uncertainty in real buildings.

Based on ASHRAE Standard 62.1-2004, the required outdoor air flow per person is roughly 15 to 30 cfm/person (7 to 14 L/s per person). Based on the higher value and

assumed number of occupants, the minimum required ventilation quantity for the model building would be approximately 12%. This was rounded up to 15% to account for ventilation to other areas not explicitly included.

The CAV system alternative is shown schematically in Figure 2–8. The percentage of outside air is varied from 15% up to 100% (economizer operation). Table 3–3 summarizes air flow data for the CAV system with various outside air fractions.

Table 3–3: Supply air, outdoor air, recirculated air, and exhaust air flow rates for baseline ventilation and airside economizer operation.

Outside air flow (%)	Total supply air flow (cfm)	Outdoor air flow (cfm)	Recirculated air flow (cfm)	Exhaust air flow (cfm)
15 (Base line)	17,161	2,640	14,521	1,538
25	17,161	4,290	12,871	3,188
50	17,161	8,581	8,581	7,478
75	17,161	12,871	4,290	11,769
100	17,161	17,161	0	16,059

A Dedicated Outdoor Air System (DOAS) is another system that is considered in the study. Total supply air flow for the DOAS is the minimum ventilation rate for the building which translates to 2,640 cfm (approximately15% of the total supply air flow rate of a CAV system). With the effect of building envelope leakage, total exhaust air is reduced to 2,552 cfm.

The VAV system alternative is shown in Figure 3–2. To approximate the effect of VAV controls on air flow, the supply air flow to half of the occupied zones in the building model (all the zones on one side) was reduced to 60% of design supply air flow in order to simulate a part load condition while the other half was still served by full supply air flow. This condition roughly represents the situation on opposite sides of a building when the sun is shining on one side and not on the other. Because of the reduced flow to certain zones, the total supply air flow rate for the whole building was

reduced to 14,831 cfm, or 86% of full capacity. Outdoor air flow in this case was also reduced proportionately, as would happen in a VAV system without special controls designed to maintain outdoor air flow rate at a constant value when not in economizer mode.

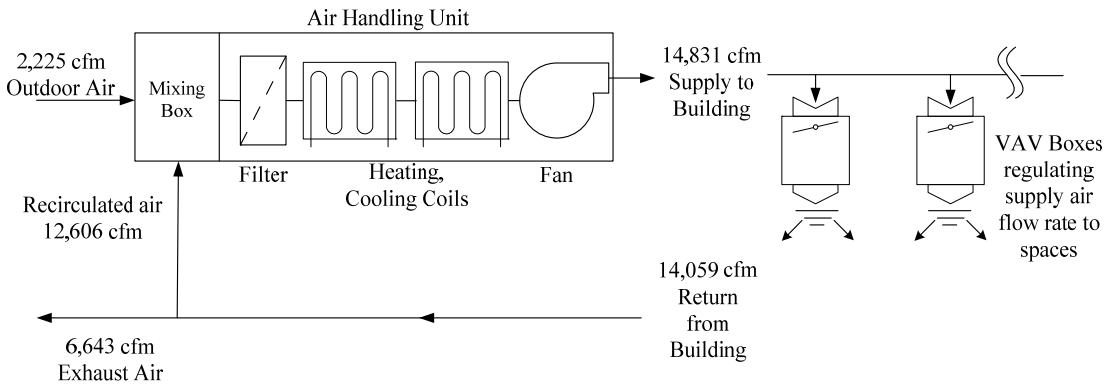

Figure 3–2: Variable air volume (VAV) system schematic

3.1.3.3. HVAC System Zoning

Zoning refers to how a building is subdivided into areas served by independent HVAC systems. Two common zoning approaches are tested. One is a single zone system with one AHU for the entire building. The other system is a floor-by-floor system with one AHU per occupied floor.

3.1.4. Test Scenarios

Parameters varied in test scenarios included release location, and duration, HVAC system type and zoning, outdoor air flow rate, filtration efficiency, and outdoor air conditions. Table 3–4 provides a comprehensive list of all scenarios and outlines the important aspects of each release. Each scenario has been given a concise name suggesting the type of system, level of filtration, release location, and other relevant details. Additional information about scenarios is given in the discussion of results.

The first letter in each scenario name represents the type of HVAC system. C denotes CAV, V denotes VAV, and D denotes DOAS. The second part of each name gives the number of air handling units and percentage of outside air. For example, 3A15 denotes a case with three air handling units and 15% outside air (OA). The last part of each name represents release location, i.e., OA represents outdoor air intake release, HW represents hallway release, and DM represents dormitory room release. In some scenarios, additional letter represents part load or full load dormitory room release location (VAV only) and weather condition as shown in Table 3.4.

Scenarios were simulated with steady-state air flow and transient contaminant concentration. A one-minute time step was used in all simulations. The total simulated time was 12 hours. Both re-suspension and deposition of the particles were not considered in this study.

The baseline scenario is the case "C-OA" in which the system is a constant air volume supplied by an air handling unit with 15% outside air and MERV 6 (16.4% efficiency for 1 μm particle) filters following an outdoor air intake release of anthrax. Outdoor air conditions were set at 68 °F (20 °C), which is identical to the indoor temperature, with no wind.

Table 3–4: Test scenarios

Name	Location of Release	Outdoor Airflow (% of Supply)	HVAC System Type	Filter Rating[1] (%)	Building Airflow[2]	Outdoor Temp (°F/°C)
Base Case						
C-OA	OA Intake	15	CAV	MERV 6 (16.4%)	Design	68/20
Release Location						
C-DM	Dorm Room	15	CAV	MERV 6 (16.4%)	Design	68/20
Filter Efficiency						
C-1A15-0F-OA	OA Intake	15	CAV	No Filter	Design	68/20
C-1A15-M13F-OA	OA Intake	15	CAV	MERV 13 (87.5%)	Design	68/20
HVAC System Type						
C-1A15-M6F-OA	OA Intake	15	CAV	MERV 6 (16.4%)	Design	68/20
C-1A25-M6F-OA	OA Intake	25	CAV	MERV 6 (16.4%)	Design	68/20
C-1A50-M6F-OA	OA Intake	50	CAV	MERV 6 (16.4%)	Design	68/20
C-1A75-M6F-OA	OA Intake	75	CAV	MERV 6 (16.4%)	Design	68/20
C-1A100-M6F-OA	OA Intake	100	CAV	MERV 6 (16.4%)	Design	68/20
C-1A25-M13F-OA	OA Intake	25	CAV	MERV 13 (87.5%)	Design	68/20
C-1A50-M13F-OA	OA Intake	50	CAV	MERV 13 (87.5%)	Design	68/20
C-1A75-M13F-OA	OA Intake	75	CAV	MERV 13 (87.5%)	Design	68/20
C-1A100-M13F-OA	OA Intake	100	CAV	MERV 13 (87.5%)	Design	68/20
D-1A-M6F-OA	OA Intake	100	DOAS	MERV 6 (16.4%)	Minimum ventilation	68/20
V-1A15-M6F-OA	OA Intake	15	VAV	MERV 6 (16.4%)	Design	68/20
D-1A-M6F-DM	Dorm Room 116	100	DOAS	MERV 6 (16.4%)	Minimum ventilation	68/20

[1] Denotes MERV rating and grade efficiency per W. J. Kowalski and Bahnfleth (2002)
[2] For constant volume and VAV systems, Design denotes the air flow delivered under maximum cooling load conditions. For VAV systems with reduced flow, the percentage given is a fraction of design flow. DOAS systems deliver only the air flow required for ventilation purposes.

Name	Location of Release	Outdoor Airflow (% of Supply)	HVAC System Type	Filter Rating[1] (%)	Building Airflow[2]	Outdoor Temp (°F/°C)
V-1A15-M6F-DM	Dorm Room 116	15	VAV	MERV 6 (16.4%)	60% Design	68/20
Zoning						
C-3A15-M6F-1OA	1st Floor OA Intake	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-2OA	2nd Floor OA Intake	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-3OA	3rd Floor OA Intake	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-1HW	1st Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-2HW	2nd Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-3HW	3rd Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	68/20
C-3A15-M6F-1HW-W	1st Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	25/-3.89
C-3A15-M6F-2HW-W	2nd Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	25/-3.89
C-3A15-M6F-3HW-W	3rd Floor Hallway	15	CAV	MERV 6 (16.4%)	Design	25/-3.89

3.2. Summary of Tested Performance Measures

Each scenario is analyzed using each performance measure to compare to the reference measure which provides the most accurate risk assessment of the scenario. The usefulness and interpretation of the implementation of each performance measure is shown and discussed. As mentioned before, there are two types of performance measures: vulnerability-based and threat-based.

Numbers of infections or casualties are clearly the most accurate means to determine the health adverse effects of CB attacks on building occupants; therefore, this measure is used as a reference measure. To provide an absolute number as a reference measure for each scenario, total infections are the sum of the percent infections multiplied by the number of occupants in each occupied zone. The percent of total infections are the percent of the total infections to the total number of building occupants.

The normal distribution dose response model (Equation 2–6) is selected to use in this research because it can be used to estimate infections and casualties for biological agents, chemical agents, and toxins. For anthrax, LD_{50} from Kowalski (2003) is 28,000 cfu; and ID_{50} is 10,000 cfu. It is assumed that all occupants are adults involved in sedentary activities; therefore, all exposure doses are calculated based on the breathing rate of 0.5 m^3/hr or 0.08333 m^3/min (see Table 2–1). A number of performance measures are selected to be tested in this study as listed in Table 3–5.

Table 3–5: Tested performance measures

Performance Measure		Description
Threat-based Measures	**Infections and Casualties (Reference Measure)**	$y = \frac{2}{LD_{50}\sqrt{2\pi}} e^{-2\left(\frac{x-LD_{50}}{LD_{50}}\right)^2}$ Where y = total infections or casualties, x = total inhaled dose, LD_{50} is mean lethal dose or ID_{50}. LD_{50} for anthrax is 28,000 cfu and ID_{50} is 10,000 cfu (Kowalski 2003).
	Fraction of Building Protection (FBP)	FBP = 1 – FBE Where: FBE = total area exposed/total building area where occupants were exposed to contaminants above mean lethal dose (LD_{50}). Only FBP based on lethal effects is performed in this study.
Vulnerability-based Measures	**Nondimensional Building Average Concentration**	A building average of contaminant concentrations over a period of time nondimensionalized using the worst case building average concentration.
	Nondimensional Building Average Transient Concentration	An average building transient concentration profile over a selected period of time nondimensionalized using the worst case building average concentration.
	Nondimensional Occupancy Exposure Dose Curve	A plot of the percent of occupants for which three-hour inhaled dose is exceeded from high to low nondimensionalized using the worst case twelve-hour inhaled dose.
	Nondimensional exposure dose as a function of cumulative area fraction and	A plot of the nondimensional exposure dose from low to high and cumulative area fraction.

Performance Measure		Description
Vulnerability-based Measures	**EIS (Exposure Improvement Score)**	$EIS_{10} = \sum_{k=1}^{10} \alpha_k \frac{D_{baseline,k} - D_k}{D_{baseline,k}}$ Where EIS_{10} = exposure improvement score calculated based on a decile basis, α_k = the decile weight, $D_{baseline,k}$ = the baseline result in decile k, and D_k = the candidate result in decile k.

3.3. Sensitivity Analysis

A sensitivity analysis is performed on the selected input parameters of the CONTAM simulations of selected scenarios to determine how uncertainty in each parameter impacts and contributes to overall uncertainty.

$$U[f] = \sqrt{\delta f_a{}^2 + \delta f_b{}^2 + \delta f_c{}^2 + \cdots} \qquad \text{Equation 3-1}$$

Where

U[f] = overall uncertainty,

and δf_a = a partial derivative of the response variable to parameter a

The following input parameters are selected at the presumed deviation for the sensitivity analysis.

Table 3–6: Estimated variances of each selected input parameter

Parameters	Estimated variances
% Filter Efficiency	±10%
Supply Airflow Rate	±15%
Outside Airflow Rate	±15%
Indoor-outdoor Air Temperature Difference	±0.4 °C
Breathing Rate	±10%
Mean Infectious Dose	±10%
Mean Lethal Dose	±10%

Chapter 4

Results of Parametric Study and Performance Measure Testing

This chapter presents results of the parametric study and also demonstrates how each performance measure represents the results. The results of the base case are first presented; then the results of the effects of each investigated parameter (i.e., filtration, ventilation, system type, system zoning, and stack effect) are discussed in relation to the base case results. Each parameter is also investigated using both threat-based and vulnerability-based measures. The results using threat-based measures will be discussed first and followed by each vulnerability-based measure.

4.1. Base Case (C-OA)

The base case (C-OA) is a one-minute release of 6 x 10^8 cfu of anthrax into the outdoor air intake of building served by a single zone constant air volume (CAV) AHU at same indoor and outdoor temperatures of 68 °F (20 °C). The base scenario filters are MERV 6 filters which have 16.4% grade efficiency for 1 μm particle and are also the minimum filter efficiency required per ASHRAE 62.1. The simulation is performed for a twelve-hour event. The characteristics of the base case results are discussed briefly in this section and are discussed more deeply in the following sections where the comparison to other scenarios are presented.

4.1.1. Calculated Threat-based Metrics for Base Case as Reference Measures

The threat-based measures implemented in this study are total casualties, total infections, percent casualties, percent infections, and FBP. The percent casualties and

infections and/or total number of casualties and infections are used as the reference measures because of their ability to provide absolute risk values. Table 4-1 shows the percent casualties and infections of each type of room in the base case. Due to the uniformity of the airflow distribution in the base case, the percent casualties and infections are similar in each type of room throughout the building. Therefore, the percent casualties and infections of the building occupants are 54.8% and 100% for the base case resulting in total casualties of 41.6 and total infections of 76. The percent casualties were determined based on a twelve-hour inhaled dose in each occupied room assuming occupants stay in the space for an entire simulated event. In this case, the entire building area is exposed to twelve-hour inhaled dose above the anthrax mean lethal dose (LD_{50}) of 28,000; therefore, FBE is 1 giving FBP of 0.

Table 4–1: Results in each type of room in the base case following an OA intake release

Room Type	Twelve-hour Inhaled Dose (cfu)	% Casualties	% Infections
Dorm Room	29,670	54.8	100
Hallway	29,671	54.8	100
Elevator Shaft	29,671	54.8	100
Stairwell	29,671	54.8	100

4.1.2. Baseline Results as a part of Vulnerability-based Measures

The vulnerability-based measures are non-agent specific and relative measures that compare each scenario's severity to baseline results. This section presents some results of the baseline case using non-threat based measures such as transient building average concentrations to which results from other scenarios can be compared. The airborne concentration profiles are nondimensionalized using the worst case building average concentration of 121,195 cfu/m^3. This concentration was calculated assuming

that the $6x10^8$ particles of contaminants were released and distributed evenly throughout the entire building and are not exhausted out of the building for an entire event (12 hours).

Figure 4–1 shows nondimensional transient concentrations in a typical dorm room, hallway, elevator shaft, and stairwell over twelve hours in base case. Contaminant concentrations in a dorm room and a hallway reach its maximum faster and also die off faster than that in the elevator shaft and stairwell. This is because both dorm room and hallway are directly served by the mechanical system while the contaminants are distributed to elevator shaft and stairwell through leakage and building pressurization. The air change rate of the dorm room is 6.5 and of the hallway is 7.1. On the other hand, the low air change rate of 3.7 in stairwell caused the clearance of airborne contaminants to be much slower than that in dorm room, hallway, and elevator shaft. As a result, the initial concentration in a dorm room and hallway are significantly higher than those in elevator and stairwell. Despite the differences in concentration profiles, the nondimensional twelve-hour average concentrations are 0.0408 in these four spaces.

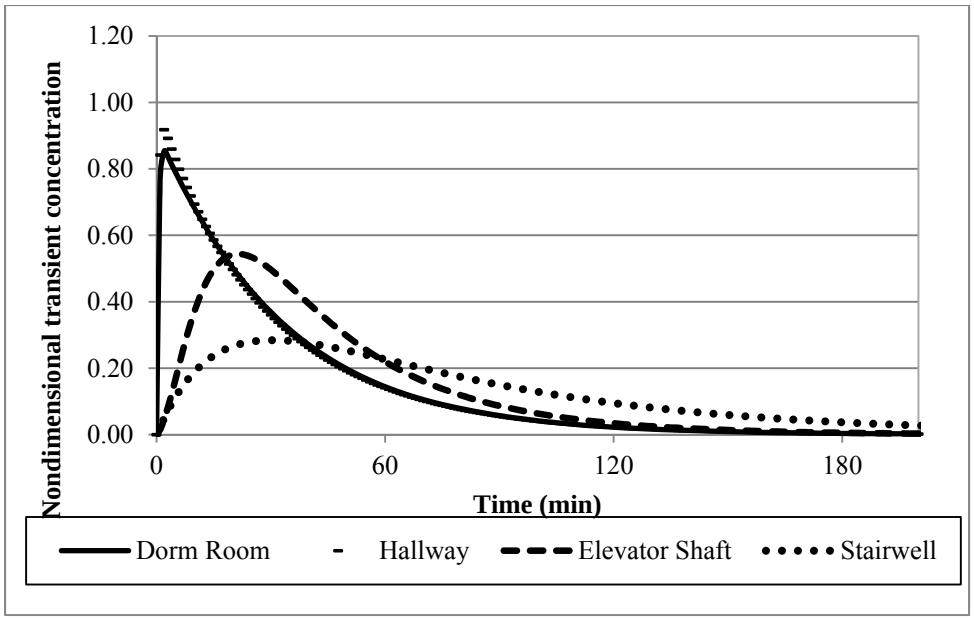

Figure 4–1: Nondimensional transient concentration in base case

4.2. Effect of release location

In addition to an OA intake release, a dorm room release scenario is also investigated for the single CAV system scenario.

4.2.1. Threat-based measures

For a dorm room release scenario (C-DM), the occupants in the release zone are exposed to the high level of inhaled dose which causes 100% casualties in the release zone. However, occupants in the rest of building encounter much less exposure resulting in 44.9% casualties and 99.9% infections in each occupied space. This resulted in 34.1 total casualties and 75.95 total infections. The FBE of the dorm room release scenario is 0.08 giving the FBP of 0.92 because 8% of building area is exposed to a twelve-hour inhaled dose above LD_{50}. Based on both casualties and FBP measures, the dorm room release caused slightly lower risk than that following the OA intake release scenario (C-OA) because a portion of contaminants is removed from the building via exhaust before re-entering the building via recirculation air. However, both dorm room and OA intake

releases caused the entire of population to be infected by the contaminants. This is mainly because all spaces are served by the same mechanical system.

4.2.2. Vulnerability-based measures

Two vulnerability-based measures are discussed in this section: nondimensional building average concentration and nondimensional occupancy dose curves. Figure 4–2 shows the nondimensional transient building average concentration of the dorm room release scenario (C-DM) compared to the base case (C-OA). The dorm room release scenario's concentration profile is higher than that of the base case because the contaminants are released inside the building and also included in the building concentration calculation. However, the clearance rate of the airborne contaminants for both cases is almost the same because of the similar filter efficiency and exhaust rate. Consequently, the nondimensional twelve-hour building average concentration for C-OA (0.041) is slightly lower than that of the C-DM scenario (0.049). Unlike the threat-based measures, the nondimensional building average concentration suggests that the dorm room release has higher risk than the base case.

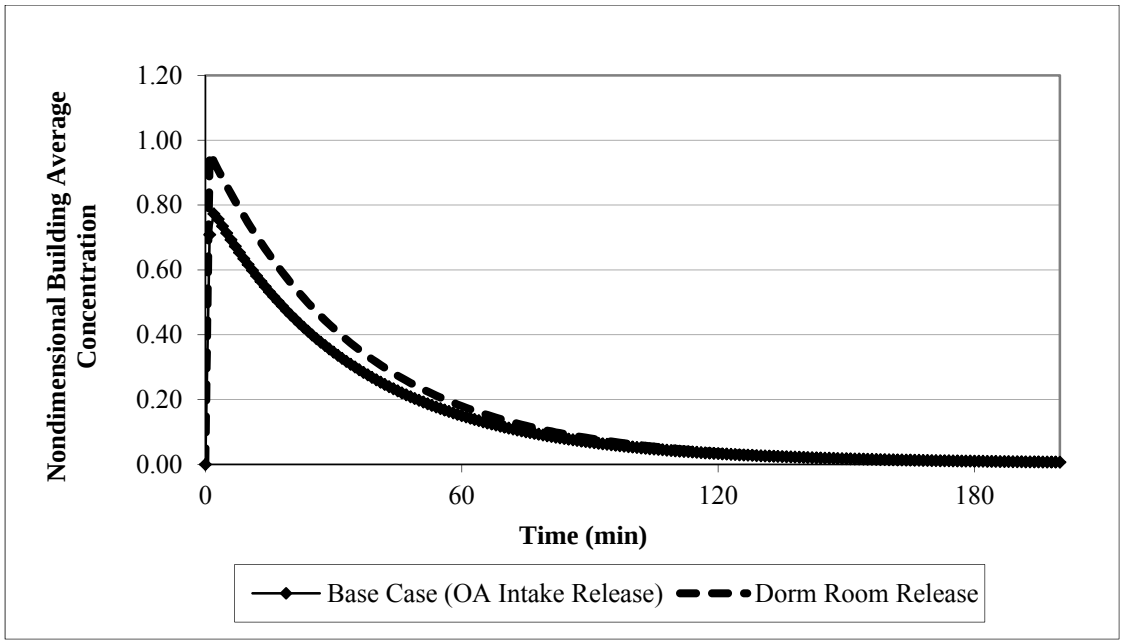

Figure 4–2: Nondimensional transient building average concentration for a CAV system with 15% OA and MERV 6 filter following OA intake and dorm room releases.

In addition to the nondimensional building average concentration, the nondimensional occupancy dose curves are also investigated. The occupancy dose curve is a plot representing the percent of occupants for which the level of dose is exceeded. The twelve-hour exposure dose is nondimensionalized by dividing each twelve-hour inhaled dose with the worst case twelve-hour inhaled dose of 727,170 cfu. The worst case twelve-hour inhaled dose is a twelve-hour inhaled dose calculated using the worst case building average concentration (121,195 cfu/m^3) and breathing rate (0.5 m^3/hr) assuming that the contaminants are released, distributed, and not exhausted from the space for the entire twelve hours.

As expected, Figure 4–3 shows that for the dorm room release scenario only 2% of occupants have one order of magnitude of inhaled dose higher than the rest of the building occupants' exposure dose which represents the inhaled dose in the release zone

in relative to the inhaled dose in the rest of the building. Once contaminants are distributed throughout the entire building, the C-DM occupancy dose curve is uniform. For the base case (C-OA), the entire population is exposed to the same level of inhaled dose. This is a result of the uniformity of the air distribution for a single zone CAV system. The nondimensional twelve-hour inhaled dose in the non-release zone for the dorm room release is slightly lower than that of the base case suggesting that the base case has slightly higher risk than the dorm room release. This agrees with the total infections and casualties measures.

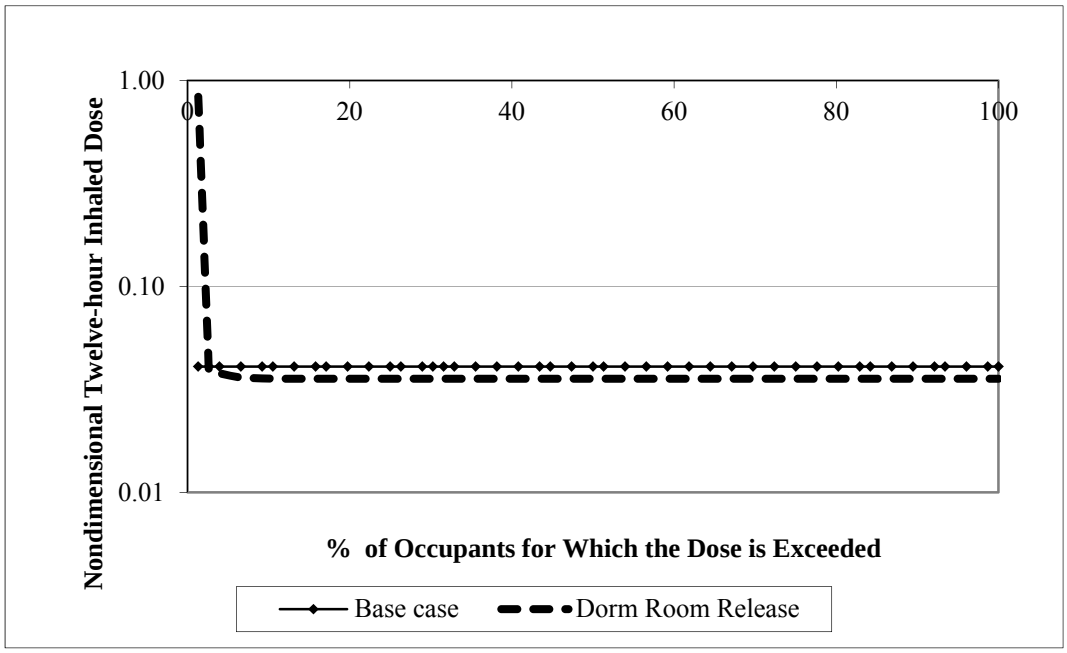

Figure 4–3: Nondimensional occupancy dose curves

4.3. Effect of Filtration

Three filter efficiencies are considered for the single CAV system building: no filtration (C-1A15-0F-OA), MERV 6 (C-OA), and MERV 13 filters (C-1A15-M13F-OA). Only scenarios following an OA intake release are investigated.

4.3.1. Threat-based Measures

Table 4–2 shows FBE, FBP, total casualties, percent casualties, total infections and percent infections for three filter efficiency scenarios following an OA intake release. The percent casualties and percent infections increase as the filter efficiencies decrease. The MERV 13 filter reduces total casualties by 39.5 and percent casualties by 52% compared to the MERV 6 filter (C-OA) because for 1 μm particle a MERV 13 filter has 87.5% grade efficiency; and MERV 6 filter has only 16.4% grade efficiency. On the other hand, the system without filtration increases the total casualties by 34.3 and percent casualties by 45%. The same effect is seen on total infections and percent infections.

For both MERV 6 (C-OA) and no filter (C-1A15-0F-OA) scenarios, the entire building area is exposed to twelve-hour inhaled dose above mean lethal dose (LD_{50}); therefore, FBP is 0 for both scenarios. The FBP measure shows that a usage of a filter does not guarantee a proper level of protection to building occupants. Filter has to have adequate of grade efficiency for the size and type of contaminants of interest to be effective in contaminant removal.

Table 4–2: FBE, FBP, percent total casualties, and percent total infections for a CAV system with various filter efficiencies following an OA intake release

Filter Efficiency	**MERV 6 Filter (Base Case)**	**MERV 13 Filter**	**No Filters**
FBE (Lethal)	1	0	1
FBP	0	1	0
Total Casualties	41.6	2.11	75.9
% Casualties	54.8%	2.77%	99.8%
Total Infections	76	2.96	76
% Infections	100.0%	3.89%	100.0%

4.3.2. Vulnerability-based Measures

Table 4–3 shows twelve-hour average building concentration, maximum building concentration, nondimensional twelve hour building average concentration, and nondimensional maximum concentration for three filter efficiency scenarios. Both the twelve-hour building average concentration and maximum building concentration are nondimensionalized by dividing their values with the worst case building average concentration mentioned in an earlier section. The increase of filter efficiencies lowers the nondimensional transient building average concentration shown in Figure 4–4 which consequently reduces both twelve-hour average concentrations and maximum building concentrations.

Table 4–3: Nondimensional twelve-hour and nondimensional maximum building average concentrations as a function of filter efficiency following an OA intake release

Filter Efficiency	**MERV 6 Filter (Baseline)**	**MERV 13 Filter**	**No Filters**
Twelve-hour average building concentration (cfu/m3)	4,947	197	11,460
Maximum concentration (cfu/m3)	93,655	10,494	115,101
Nondimensional twelve-hour average building concentration	0.0408	0.0016	0.0945
Nondimensional maximum concentration	0.7728	0.0866	0.9497

Figure 4–5 represents nondimensional occupancy dose curves which are flat for all three scenarios. The curves show that 100% of building occupants are exposed to the same level of exposure dose due to the uniformity of air distribution of a single zone CAV system. As before, a high-efficiency filter results in a lower exposure dose.

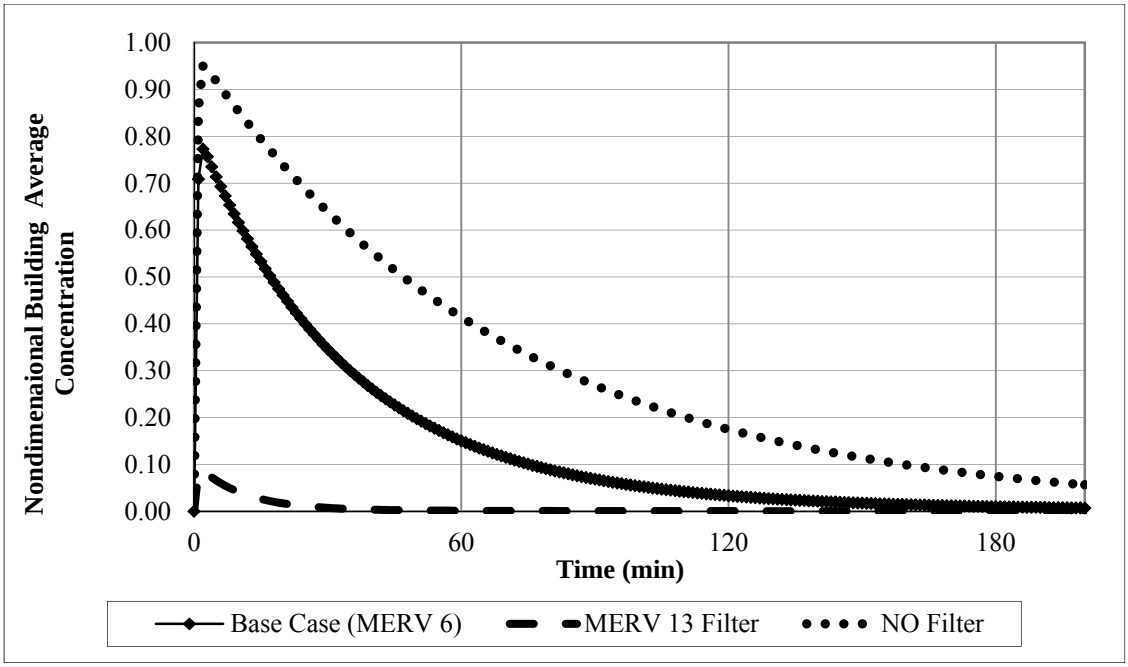

Figure 4–4: Nondimensional transient building average concentration for a single CAV system with various filter efficiencies following an OA intake release

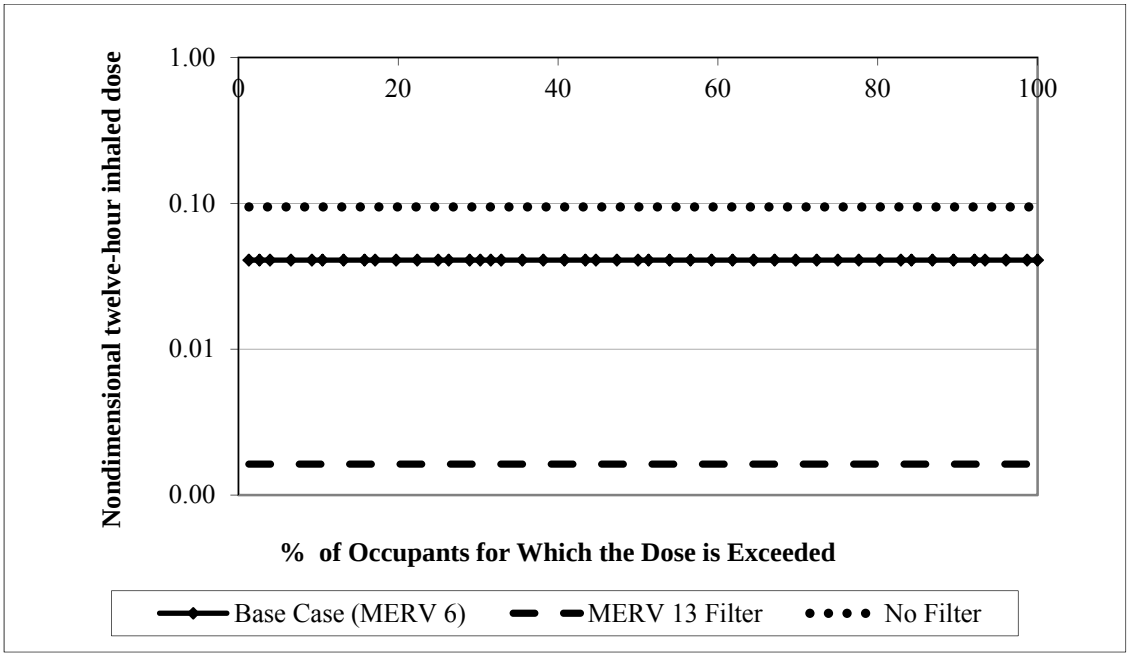

Figure 4–5: Nondimensional occupancy dose curves for three filter efficiency scenarios

Another vulnerability-based metric proposed by DeGraw and Bahnfleth 2011 is also evaluated for these three filters scenarios. For each event, the exposure dose is

computed for each zone and paired with the floor area of the zone. Each dose is also nondimensionalized by the worst-case building exposure dose. Then the results are plotted in the order of increasing exposure dose as a function of the cumulative area fraction. The cumulative area fraction is divided into ten decile-based bins (D1 to D10) representing the area fraction to the total building area ranging from 0.1 to 1. The average nondimensional exposure dose then is computed for each bin or decile. The exposure improvement score (EIS) is then computed for each scenario using Equation 2–19.

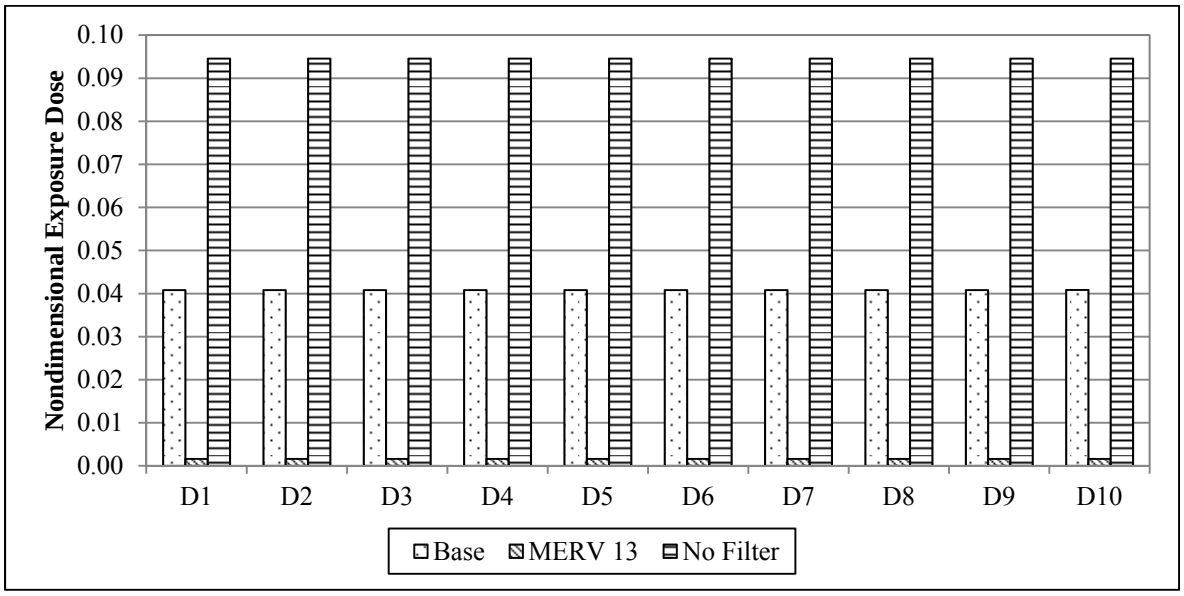

Figure 4–6: Nondimensional exposure dose metric results for three filter efficiency scenarios

Figure 4–6 demonstrates nondimensional exposure dose metric results for three filter efficiency scenarios. The exposure dose is similar in all deciles confirming that the entire building is exposed to the same level of contaminants confirming the uniformity of the air distribution of a single zone CAV system. The nondimensional exposure dose for the no-filter scenario is two times higher than that of the base case (C-OA). According to

how EIS is calculated, negative results suggest that the scenario of interest is worse than the baseline. Positive EIS indicates the opposite. Based on the calculated deciles, the MERV 13 filter scenario has EIS of 96 while the no-filter scenario has EIS of -132. This result confirms that MERV 13 filtration reduces occupant exposure dose significantly; therefore, is more protective than the MERV 6 filtration and without filter.

4.4. Effect of Ventilation Rate

Five percentages of outdoor air for a single CAV system with MERV 6 filters and MERV 13 filters were investigated: 15% OA (C-OA), 25% OA (C1A25-M6F-OA and C1A25-M13F-OA), 50% OA (C1A50-M6F-OA and C1A50-M13F-OA), 75% OA (C1A75-M6F-OA and C1A75-M13F-OA), and 100% OA (C1A100-M6F-OA and C1A100-M13F-OA). The supply airflow rates remain the same in every case. Only the fraction of outside air (and therefore, the fraction of recirculated air) in the supply air varies from case to case.

4.4.1. Threat-based Measures

Table 4–4 shows that the occupant risk levels to the exposure of airborne contaminants are reduced with respect to the increasing of the ventilation air fraction following an OA intake release. Supplying 100% of outside air at the design airflow rate, such as a mechanical system operating in economizer mode or purge mode, significantly reduces percent casualties (by 50%) and reduces percent infections (by 87%) compared to the base case (C-OA) for an OA intake release.

Except the base case (15% OA), the FBE is 0 for all four percentages of outside air (25% to 100%) which means none of the building area is exposed to inhaled dose

above mean lethal dose. Since the air distribution is uniform for a single zone system, FBP measures do not provide much differentiation in identifying risks.

Table 4–4: FBE, FBP, percent casualties, total casualties, percent infections, and total infections for a single CAV system with MERV 6 filters and five percentages of outdoor air following an OA intake release

Threat-based Measures	**15% OA (Base Case, C-OA)**	**25% OA (C1A25-M6F-OA)**	**50% OA (C1A50-M6F-OA)**	**75% OA (C1A75-M6F-OA)**	**100% OA (C1A100-M6F-OA)**
FBE (Lethal)	1	0	0	0	0
FBP	0	1	1	1	1
Total Casualties	41.6	27.9	13.2	8.48	3.48
% Casualties	54.8%	36.7%	17.4%	11.2%	4.6%
Total Infections	76	75.7	63.4	43.7	9.91
% Infections	100%	99.6%	83.5%	57.5%	13.0%

4.4.2. Vulnerability-based Measures

Similar to the threat-based measures, the increase of ventilation air decreases the nondimensional initial building concentration and transient building average concentration (Figure 4–7) resulting in lower twelve-hour building average concentration as shown in Table 4–5. The ventilation air fraction also raises the EIS values which suggest less contaminant exposure in overall building area compared to the baseline. As shown in Figure 4–8, the nondimensional occupancy dose curves also indicate the same conclusion. The nondimensional exposure dose as a function of area fraction are not shown here since it can be expected that the plots would demonstrate the same results that the entire building area is exposed to lower exposure dose as the ventilation air increases.

Table 4–5: Nondimensional twelve-hour, nondimensional maximum building average concentrations, and EIS as a function of ventilation rates for a single zone CAV system following an OA intake release

Ventilation rates	**15% OA (Base Case)**	**25% OA**	**50% OA**	**75% OA**	**100% OA**
Twelve-hour average building concentration (cfu/m^3)	4,947	3,872	2,478	1,825	730
Maximum concentration (cfu/m^3)	93,654	92,417	89,007	85,731	41,452
Nondimensional twelve-hour average building concentration	0.0408	0.0320	0.0204	0.0151	0.0060
Nondimensional maximum concentration	0.7728	0.7626	0.7344	0.7074	0.3420
EIS	N/A	22	50	63	70

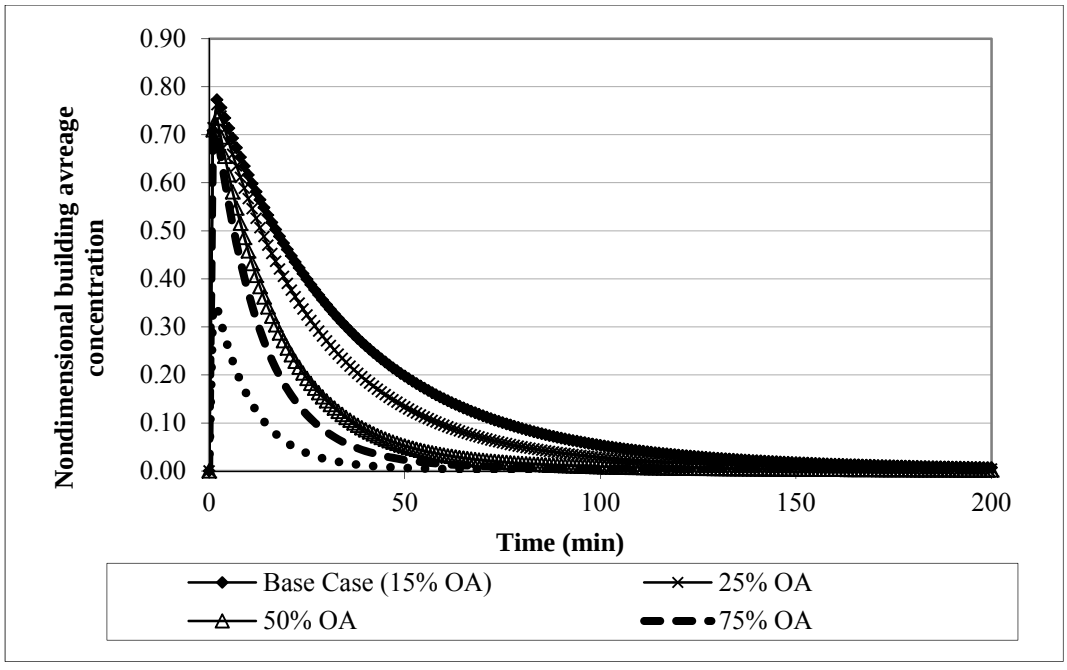

Figure 4–7: Nondimensional twelve-hour average building concentration for a single CAV system with various percentages of OA and MERV 6 filter following an OA intake release

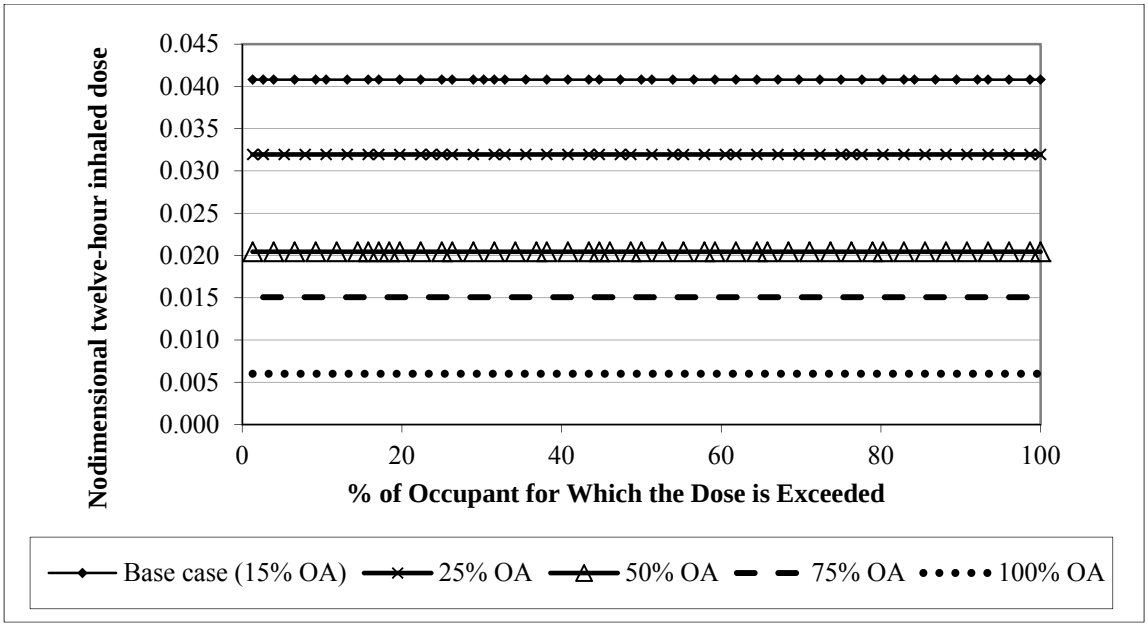

Figure 4–8: Nondimensional twelve-hour inhaled dose for a single CAV system with various percentages of OA and MERV 6 filter following an OA intake release

Filtration and ventilation have a complementary effect on contaminant removal. When filter efficiency is high, little recirculated contaminant returns to occupied spaces and the indoor concentration is less sensitive to the amount of outdoor air. Were it possible for a filter to have 100% efficiency, the effect on concentration would be the same as if the recirculated air had been exhausted. On the other hand, changing the amount of outside air has a strong effect on room contaminant concentrations when filter efficiency is relatively low. This can be seen by comparing the average concentration results with MERV 6 filters and MERV 13 filters shown in Figure 4–9.

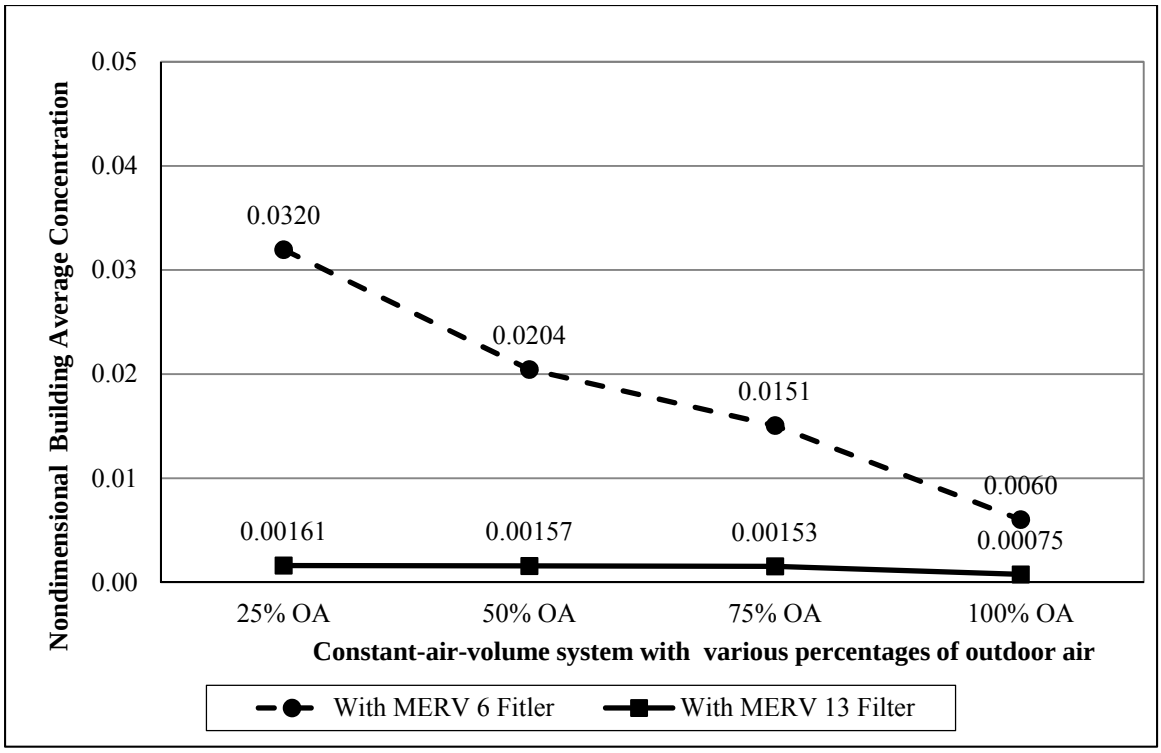

Figure 4–9: Nondimensional twelve-hour building average concentration for a single CAV system with various percentages of OA for MERV 6 filter and MERV 13 filter scenarios following an OA intake release

4.5. Effect of System Type

Mechanical system type may influence the quantity of supply air circulated in a building and the amount of recirculation. CAV, VAV, and DOAS systems which represent the most widely used centralized systems were investigated for a single air handling unit system.

From the perspective of contaminant distribution in a building, a CAV system delivers constant supply air flow while modulating supply air temperature to meet the required cooling or heating load in the space. A DOAS system is simply a CAV system that delivers 100% fresh air that meets the requirement of the minimum ventilation air per mechanical code and does not recirculate air within the building. For a VAV system, the supply air quantity delivered by a VAV system is a function of the heating or cooling

load while maintaining the supply air temperature for cooling or heating mode. The simulated scenario for a VAV system in this study represents the case where the load levels in the building vary slowly. Air flow was constant for the period of an entire event; but flow to part of the building was reduced by 40% relative to design conditions to approximate a part load condition in a real building.

Table 4–6 shows that for the DOAS system, average air change rates in each type of zone are much lower than that of the CAV (base case) and VAV systems due to the much lower supply air flow rate (approximately 20% of supply air flow rate in a CAV system). Additionally, VAV and CAV systems recirculate approximately 70% to 80% of the design supply air respectively while the DOAS system has no recirculation air.

Table 4–6: Average air change rates in zone according to each system

	Base case (CAV)	**DOAS**	**VAV**
Dormitory room	6.86	1.08	5.75
Hallway	10.32	1.52	9.42
Stairwell	2.11	0.24	1.69
Elevator Shaft	8.27	0.93	6.60

4.5.1. Outdoor Intake Release Scenario

The following section shows the effects of system types following an OA intake release including CAV (C-OA), VAV (V-1A15-M6F-OA), and DOAS (D-1A-M6F-OA) systems.

4.5.1.1.Threat-based Measures

For an OA intake release into a single zone system, the DOAS system scenario shows the highest total casualties and percent casualties compared to other system types. This is the result of the lowest air change rates in occupied zones in the building with the DOAS system as shown in Table 4–7. The VAV system scenario has total casualties and

infections slightly higher than those of the CAV system because half of the building is served by 60% of design supply airflow rate. The lower supply air flow reduces the average air change rates in occupied zones for the VAV system scenario which consequently lower the contaminant removal rate. The percent infections are 100% for all system type scenarios.

Table 4–7: FBE, FBP, total casualties, percent casualties, total infections, and percent infections for each system type following an OA intake release

System Type	CAV (Base Case, C-OA)	DOAS (D-1A-M6F-OA)	VAV (V-1A15-M6F-OA)
FBE (Lethal)	1	1	1
FBP	0	0	0
Total Casualties	41.6	74.14	51.1
% Casualties	54.8%	97.6%	67.2%
Total Infections	76	76	76
% Infections	100%	100.0%	100.0%

4.5.1.2.Vulnerability-based Measures

For the OA intake release, the differences in supply airflow rates from these system types do not have much effect on the nondimensional maximum building concentration because the contaminant introduction rate via the ventilation air in all system types are relatively the same. However, the transient building average concentration profiles demonstrate clearly that contaminants are removed from the building at the lower rate for the building with the DOAS system. The profile tapers off at an obviously slower rate compared to the other two systems. In addition to the lowest air change rates in occupied zones created by the DOAS system, the CAV and VAV systems do have recirculation air that cycles a portion of contaminants through filters in the mechanical systems before being reintroduced back to the building. As a result, the

nondimensional twelve-hour building average concentrations for the CAV and VAV systems are lower than that of DOAS. With the lower air change rates in occupied zones, the twelve-hour building average concentration in the building with a VAV system is higher than that of the CAV system building.

EIS values similar suggest that the DOAS system is overall the worst system among all three systems in the event of an OA intake release because the building is exposed to the highest exposure dose compared to the building with CAV and VAV systems. Due to the uniform air distributions for all three systems, both nondimensional occupancy dose curves and nondimensional exposure dose as a function of area fraction are not presented here since the entire building area and entire population are exposed to the same level of contaminants whereas all the profiles are simply straight lines and do not provide any more insight that the threat-based and other vulnerability measures do not already cover.

Table 4–8: Nondimensional twelve-hour, nondimensional maximum building average concentrations, and EIS for each system type following an OA intake release

System Type	**CAV (Base Case)**	**DOAS**	**VAV**
Twelve-hour average building concentration (cfu/m^3)	4,947	8,870	5,708
Maximum concentration (cfu/m^3)	93,655	94,848	93,983
Nondimensional twelve-hour average building concentration	0.041	0.073	0.047
Nondimensional maximum concentration	0.773	0.783	0.775
EIS	N/A	-84	-15

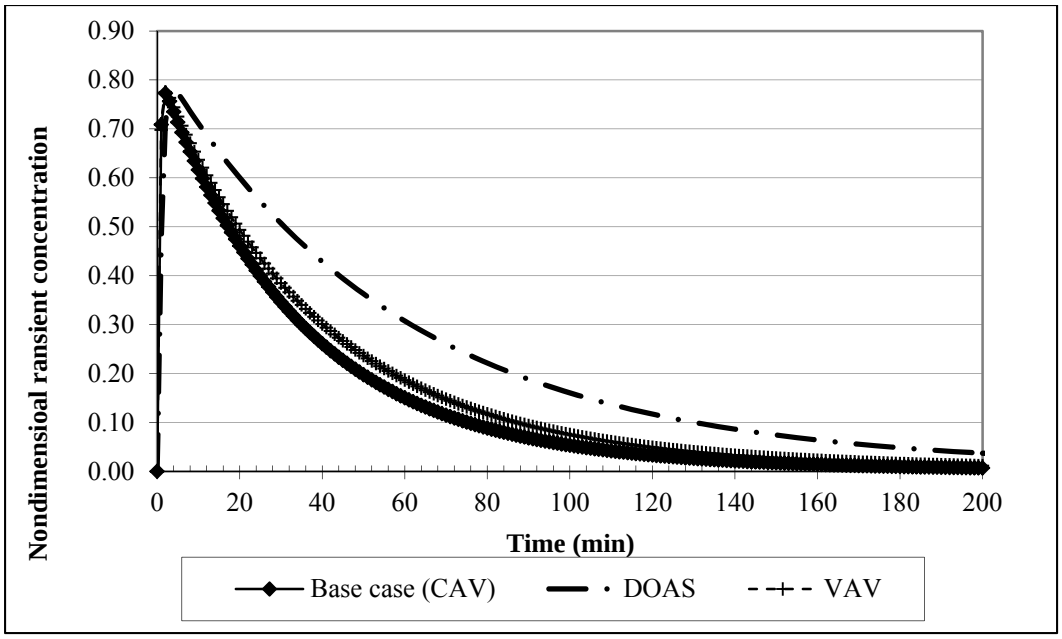

Figure 4–10: Nondimensional building average concentration in a single zone system with MERV 6 filter comparing between three system types following an OA intake release

In addition to the overall system type comparison, Figure 4–11 shows the nondimensional transient dormitory room concentration in part load and full load dormitory rooms in the VAV system scenario following an OA intake release (V-1A15-M6F-OA). The full load dorm room is exposed to higher maximum airborne concentration but is cleared from the contaminants faster compared to the part load dorm room. This can be explained by higher air change rates in the full load dorm room as presented in Table 4–9. Consequently, the nondimensional inhaled dose profiles show that the inhaled dose in the part load dorm room is slightly lower than that in the full load dorm room in the first three hours of the event. However, for the entire event of twelve hours, the accumulative inhaled doses are similar for the part load dorm room and full load dorm room. This suggests that the rate of contaminant introduction and the rate of

removal cancel each other effect out resulting in similar inhaled dose in the part load and full load dorm rooms for the entire event.

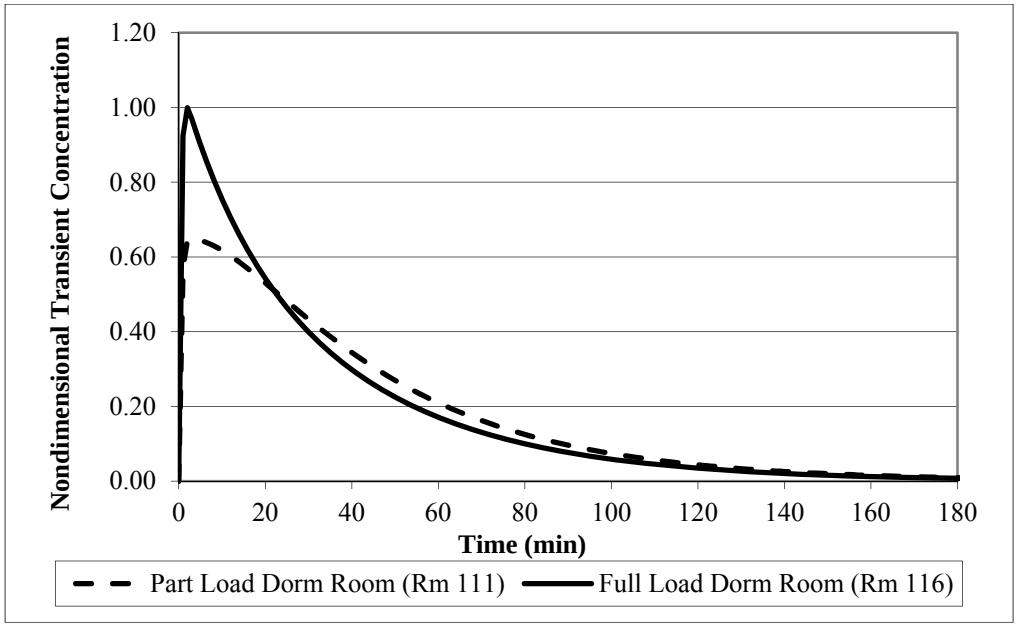

Figure 4–11: Nondimensional transient dormitory room concentration for the VAV system scenario following an OA intake release

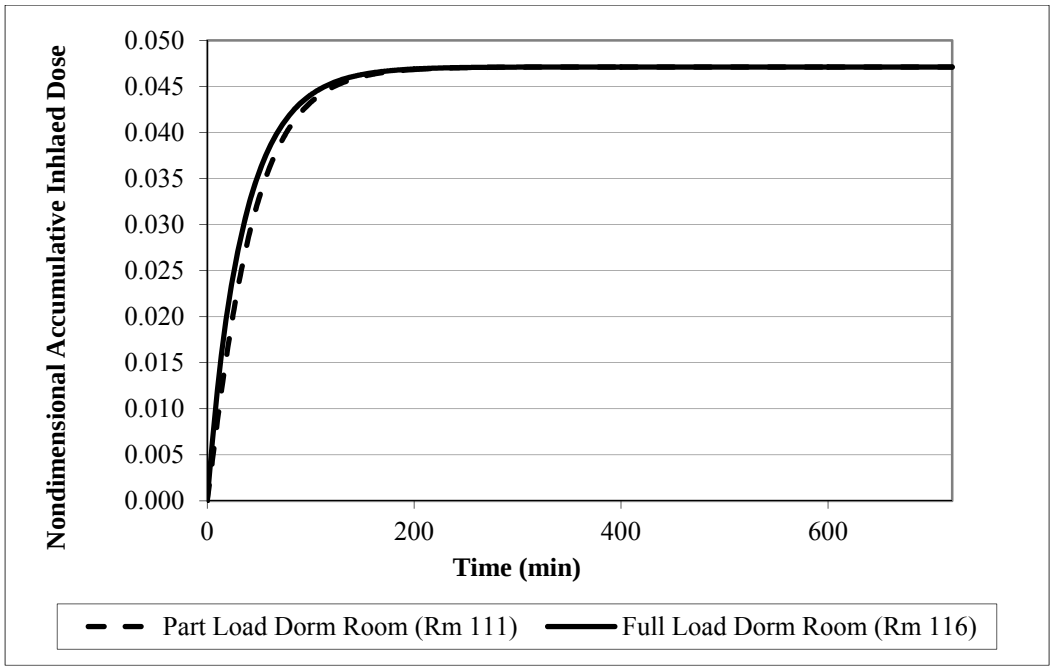

Figure 4–12: Nondimensional accumulative inhaled dose profile for the VAV system scenario following an OA intake release

Table 4–9: Average air change rates in a building with a VAV system (V-1A15-M6F-OA)

	Dorm room		Hallway	Stairwell	Elevator shaft
	Part Load 60% SA	Full Load 100%SA			
1st Floor	4.42	6.14	9.27	2.87	7.47
2nd Floor	4.85	6.72	9.29	1.52	7.47
3rd Floor	4.92	6.80	9.69	0.68	4.85
Average	4.73	6.56	9.41	1.69	6.60

4.5.2. Dorm Room Release Scenario

To further investigate the effects of system types, the dormitory room release for all three system types are also investigated including the following scenarios: C-DM, D-1A-M6F-DM, and V1A15-M6F-DM.

4.5.2.1.Threat-based Measures

In opposite to the results of an OA intake release, the DOAS system scenario reduces percent casualties by 41.2% and percent infections by 95.4% compared to the CAV system. The VAV system in part load operation has the highest percent casualties and infections among the three systems. Since the DOAS system does not have recirculated air like the CAV and VAV systems, the released contaminants are not re-circulated back into the building or distributed via mechanical system. This means that the contaminant distribution is via leakage paths connecting spaces. Therefore, for a single zone system building it can be concluded that the DOAS system has ability to limit the spread of the airborne contaminants for an interior release. FBE results do show some differences among system types and do agree with other threat-based measures and rate the DOAS system as the most protective system in a dorm room release event.

Table 4–10: FBE, FBP, total casualties, percent casualties, total infections, and percent infections for each system type following a dorm room release

System Type	CAV (C-DM)	DOAS (D-1A-M6F-DM)	VAV (V-1A15-M6F-DM)
FBE (Lethal)	0.08	0.02	1
FBP	0.92	0.98	0
Total Casualties	34.5	2.83	42.6
% Casualties	44.9%	3.73%	56.1%
Total Infections	75.95	3.4	76
% Infections	99.9%	4.5%	100%

4.5.2.2.Vulnerability-based Measures

The nondimensional building average transient concentration presents the same profiles as the OA intake release results as shown in Figure 4–12. The nondimensional maximum concentrations for the VAV and CAV systems are nearly the same and are lower than that of the DOAS system. The same trends can be seen in the nondimensional twelve-hour building average concentrations and EIS values. These results imply that occupants in the building with a DOAS system is subjected to more contaminant exposure following an indoor release compared to the buildings with VAV and CAV systems. This is because the building average concentrations are greatly influenced by the contaminant concentrations in the release zone; and their inability to differentiate the spatial distribution of the airborne contaminants. The interpretation is opposite to what threat-based measures indicate. For the interior release scenario, the building average concentration may not be an appropriate measure to determine risk levels.

Table 4–11: Nondimensional twelve-hour, nondimensional maximum building average concentrations, and EIS for each system type following a dorm room release

System Type	CAV (C-DM)	DOAS (D-1A-M6F-DM)	VAV (V-1A15-M6F-DM)
Twelve-hour average building concentration (cfu/m^3)	5,934	10,525	6,571
Maximum concentration (cfu/m^3)	116,518	119,277	116,271
Nondimensional twelve-hour average building concentration	0.0490	0.0868	0.0542
Nondimensional maximum concentration	0.9614	0.9842	0.9594
EIS	N/A	-127	-37

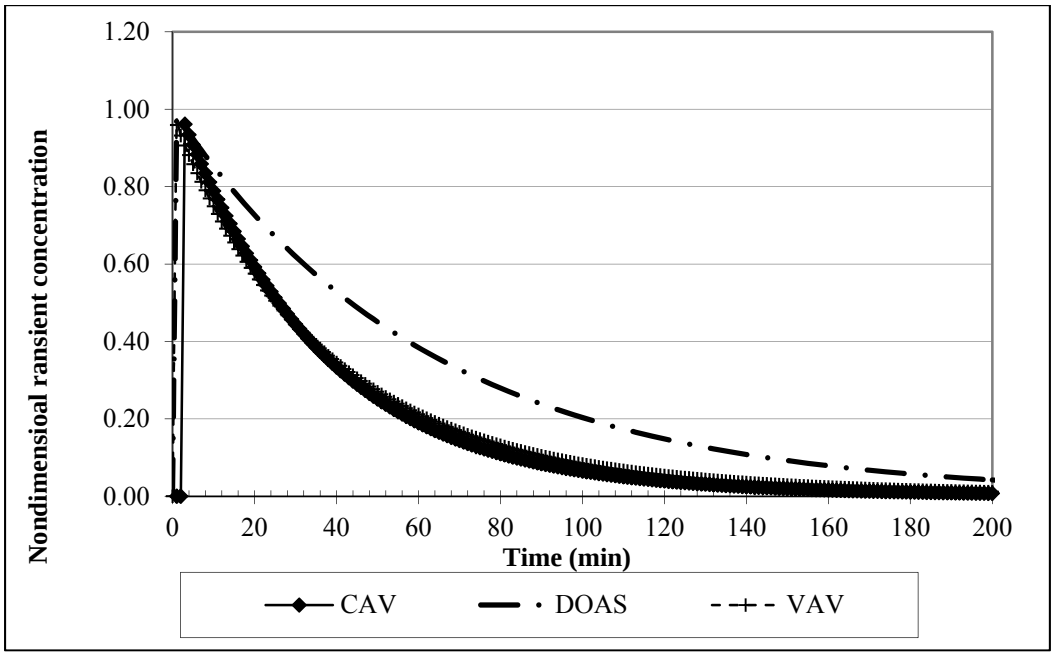

Figure 4–13: Nondimensional building average concentration in a single zone system with MERV 6 filter comparing between three system types following a dorm room release

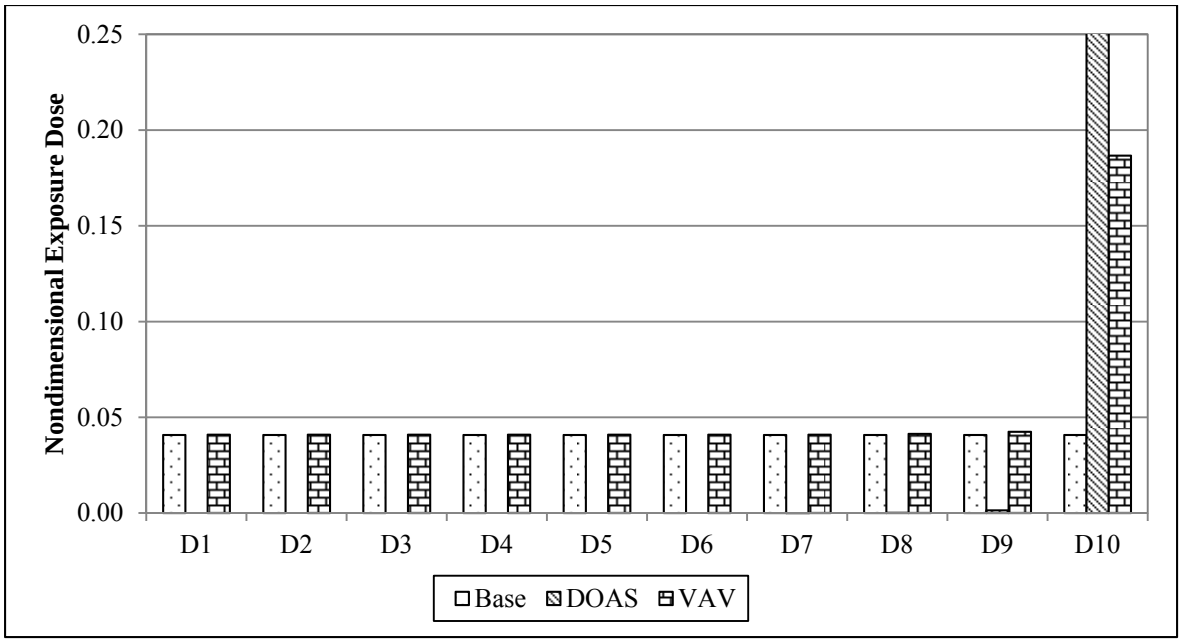

Figure 4–14: Decile breakdown of nondimensional exposure dose results for each system type

Since the EIS values suggest the same conclusion as the building average concentration, it is more beneficial to investigate the decile breakdown of nondimensional exposure dose results (Figure 4–14). These deciles do demonstrate clearly that the nondimensional exposure dose is almost zero for the first nine deciles (90% of building area) and is significantly higher on the tenth decile representing the exposure dose in the release zone. This supports the threat-based measure results that DOAS system has ability to limit the spread of the airborne contaminant for an interior zone release.

The nondimensional occupancy dose curves show that only 2% of occupants are exposed to maximum twelve-hour inhaled dose which are the occupants in the released zone. For the CAV and VAV system scenarios (C-DM and V-1A15-M6F-DM) following a dorm room release, over 90% of occupants are exposed to inhaled dose 2 orders of magnitudes higher than that of the DOAS system scenario (D-1A-M6F-DM).

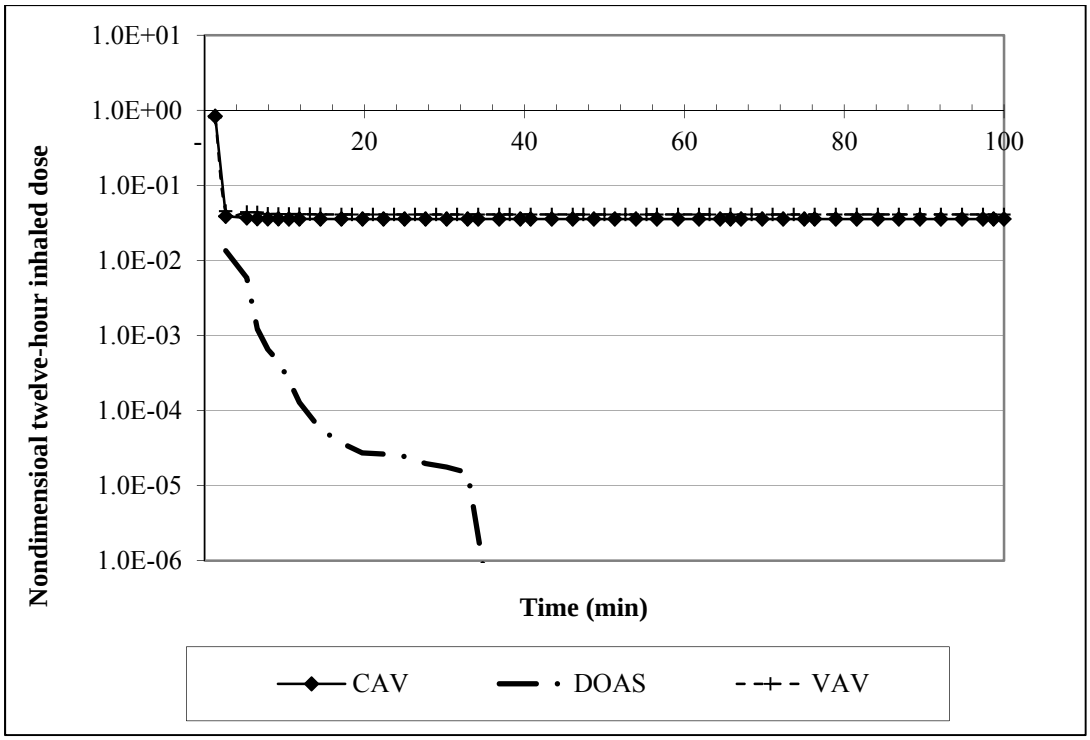

Figure 4–15: Nondimensional twelve-hour inhaled dose for a single CAV system with three system types following a dorm room release

4.6. Effect of System Zoning

HVAC zoning has the potential to change the impact of a contaminant release in a number of ways. Relative to a building with a single air-handling system that recirculates a portion of the return air, a building with multiple systems may limit the spread of the release. In these zoning scenarios, the three occupied stories of the model building were each served by their own CAV system. Other system characteristics were the same as the single-zone AHU system building (C-OA).

Air flow patterns created by the interaction of the three CAV systems (floor by floor zoning) are shown in Figure 4–16. The difference between supply and return flows was the smallest in the first floor hallway. This depressurized the first floor hallway relative to the second and third floor hallways. Therefore, the second and third floor hallways are at higher pressure than the elevator shaft and stairwell. Consequently, air

leaks from these hallways into both the elevator shaft and stairwell. The flow pressurizes the elevator shaft relative to the first floor hallway, so air flows from the elevator shaft into the hallway. Clearly, air contaminants entering the building on the third floor could be distributed to the first floor by this air flow pattern as well as a release on the second floor.

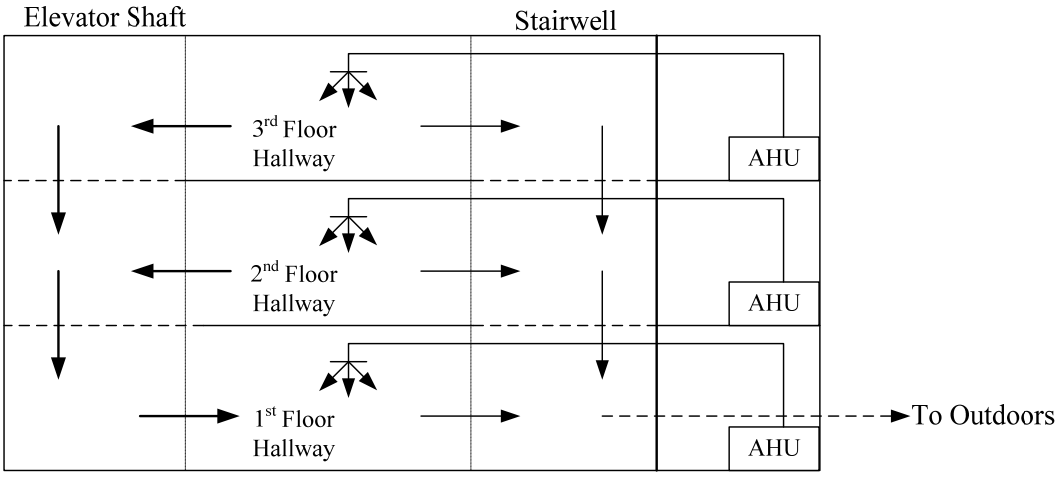

Figure 4–16: Elevator shaft and stairwell airflow schematic for the floor-by-floor AHU scenario

In addition to altering air flow patterns in a building, zoning also tends to increase the number of possible release scenarios. For example, an outdoor air intake release could be made into all intakes or a subset of the total. For the simulated building with floor-by-floor zoning, equal releases into all three AHUs are roughly equivalent to the outdoor air intake release for the single zone system (C-OA). In this study, a release into only one air handling unit were investigated, as was a release into the OA intake of each floor. The same amount of contaminant was released in each case. The following section shows results from the floor-by-floor zoning system for an OA intake release into each AHU.

4.6.1. Threat-based Measures

For the floor-by-floor zoning building, the total casualties and percent casualties are clearly lower than that of the single zone building; and the total infections are approximately one third of the total infections in the single zone building following an OA intake release. The second floor (C-3A15-M6F-2OA) and third floor (C-3A15-M6F-3OA) OA intake release scenarios show higher total casualties and infections than the first floor release scenario (C-3A15-M6F-1OA). This is mainly because there are 28 people occupying second floor; another 28 people on the third floor; and only 20 people occupying the first floor. The total casualties following the first floor OA intake release are 21.3 which are slightly more than the numbers of the occupants in the first floor. This confirms that although the release occurred in the first floor; there are occupants on other floors exposed to airborne contaminants as well. The contaminants were distributed through other floors basically through pressurizations and leakage paths.

FBE values indicates that approximately one third of the building area is exposed to the inhaled dose above LD_{50} for multi-zoning systems and the rest of the building is exposed to inhaled dose lower than LD_{50}. These values simply provide the evidence that the floor-by-floor zoning system can limit the airborne contaminant distribution within the spaces connected to the mechanical system that a release occurs.

Table 4–12: FBE, FBP, percent casualties, total casualties, percent infections, and total infections comparing between single zoning and floor-by-floor zoning systems following an OA intake release

Threat-based Measures	Base case (C-OA)	Floor by floor Zoning Scenarios		
	OA Intake Release	1st Floor OA Intake Release (C-3A15M6F-1OA)	2nd Floor OA Intake Release (C-3A15M6F-2OA)	3rd Floor OA Intake Release (C-3A15M6F-3OA)
FBE (Lethal)	1	0.32	0.35	0.37
FBP	0	0.68	0.65	0.63
Total Casualties	41.6	21.3	29.2	29.1
% Casualties	54.8%	28.0%	38.4%	38.3%
Total Infections	76	21.4	29.5	29.1
% Infections	100%	28.1%	38.8%	38.3%

4.6.2. Vulnerability-based Measures

Table 4–13 shows that the nondimensional twelve-hour building average concentrations are in the same order of magnitude for all three OA intake releases into the floor-by-floor zoning building and an OA intake release the single zone system building. However, there are some differences which are resulted from the effects of the air balance between floors, which is not perfect. The third floor OA intake release for the floor-by-floor zoning building has higher building average concentrations compared to other released scenarios because the contaminated air from the third floor do travel down to the second and first floor based on the airflow pattern shown in Figure 4–15; and therefore, stay in the building longer. The non-uniformity of contaminant distribution is not revealed by the average building results, which are similar for the base case and the OA intake releases in the floor-by-floor units.

Table 4–13: Nondimensional twelve-hour building average concentration and EIS for the single zone and the floor-by-floor zoning scenarios following alternate OA intake releases

Release scenarios	Base case	First Floor OA Intake Release (3AHU)	Second Floor OA Intake Release (3AHU)	Third Floor OA Intake Release (3AHU)
Twelve-hour average building concentration (cfu/m^3)	4,947	4,361	4,748	5,762
Nondimensional twelve-hour average building concentration	0.0408	0.0360	0.0392	0.0475
EIS	N/A	7	-1	-6

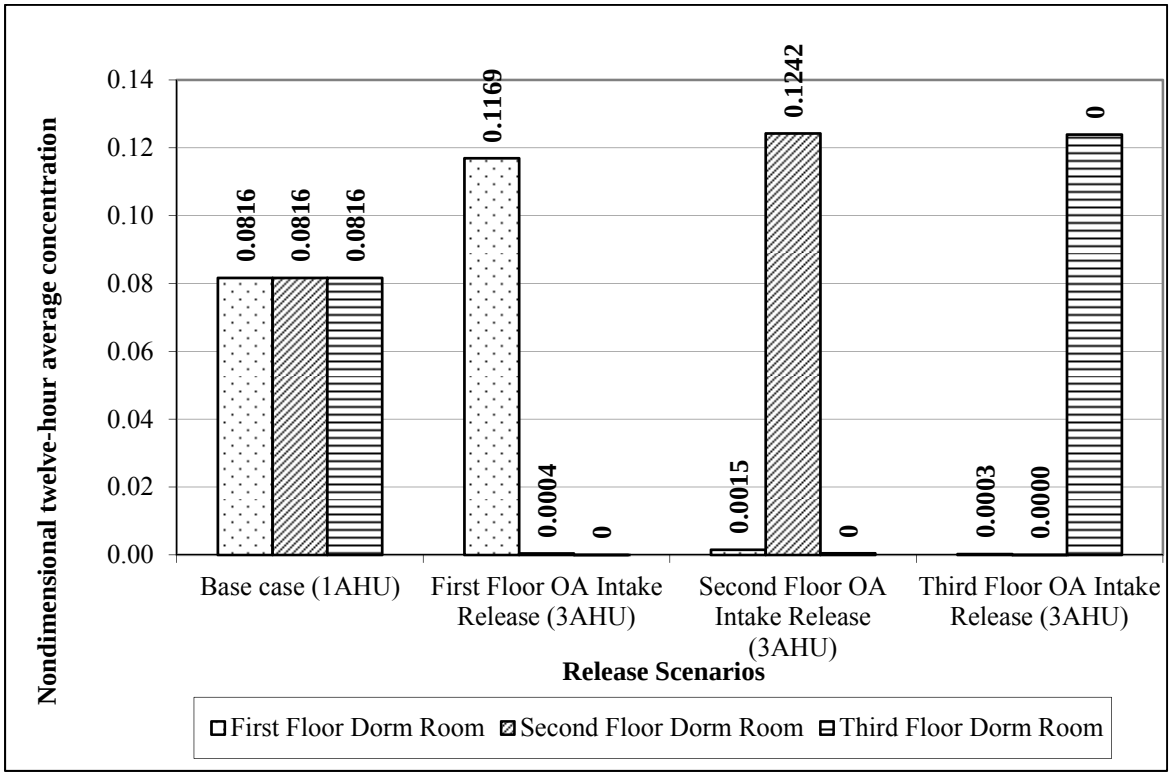

Figure 4–17: Nondimensional twelve-hour average dormitory room concentration for a single zone and floor by floor zoning following alternate OA intake releases

To better understand the effects of the floor-by-floor zoning, the nondimensional twelve-hour average dormitory room concentrations are plotted for each scenario in Figure 4–17. The outdoor air intake release for the single zone AHU scenario (base case) distributes the contaminant uniformly to all three floors. A release into one of the three air-handling units of the floor-by-floor model causes one and a half time more contaminant concentration to the floor it serves compared to the single zone system scenario; and very minimal concentrations to the other two floors. Thus, the averages are slightly different. The entire building population is directly and immediately affected in one case, while only one-third is affected immediately in the others. Since it is already established that the building average results cannot present the differences in risk levels for the floor-by-floor zoning scenarios; the nondimensional transient building average concentrations are not presented and discussed here.

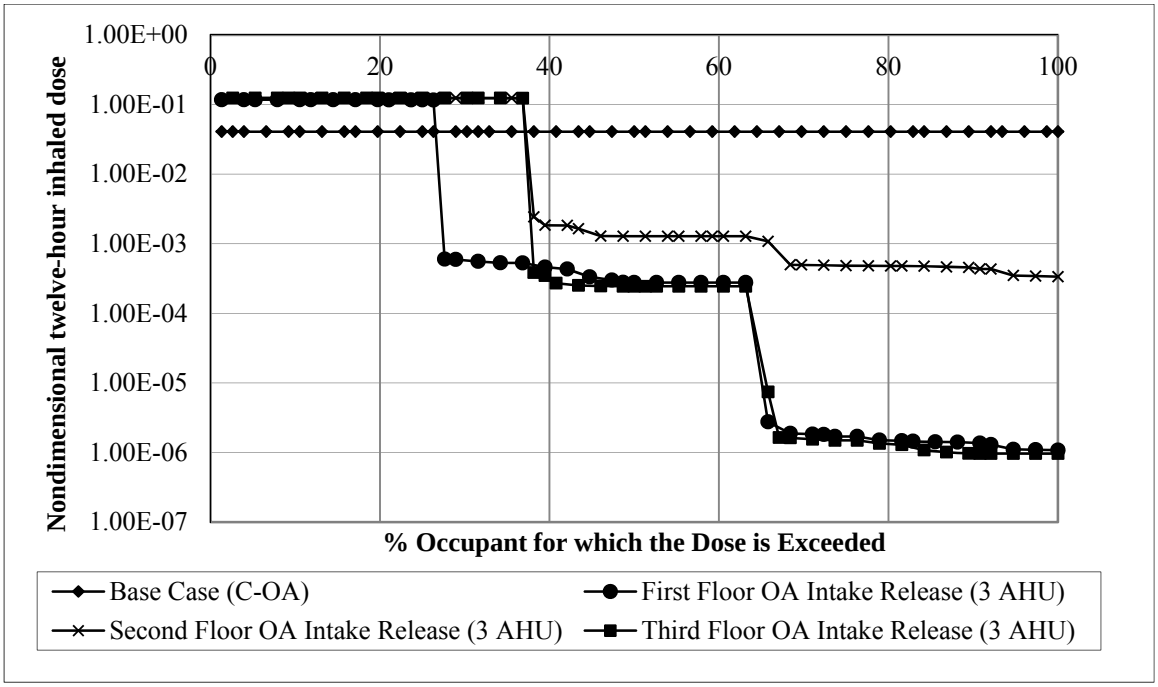

Figure 4–18: Nondimensional occupancy dose curves for a single zone system and floor-by-floor zoning systems following alternate OA intake releases

The nondimensional occupancy dose curves (Figure 4–18) for the floor-by-floor systems demonstrate that building occupants are exposed to 3 ranges of inhaled doses. For the floor-by-floor AHU system following the first floor OA intake release, the occupancy dose curve shows that 26.3% of the occupants are exposed to two orders of magnitude of inhaled dose higher than the rest of the building occupants. For both the second and third floor OA intake release scenarios, 36.8 % of the building occupants were exposed to 2 orders of magnitude of inhaled dose higher than the rest of the building occupants for the floor-by-floor AHU systems.

Although, the negative EIS values imply that the floor-by-floor zoning is worse that the baseline; it is better to examine the decile breakdown of the nondimensional exposure dose as well. The decile breakdown shown in Figure 4–19 suggests that 60% of the building area is exposed to a very minimal contaminant exposure dose; and only 30% of the building area exposed to substantially higher exposure dose. These results clearly validate the ability to limit the contaminant distribution for the floor-by-floor zoning system.

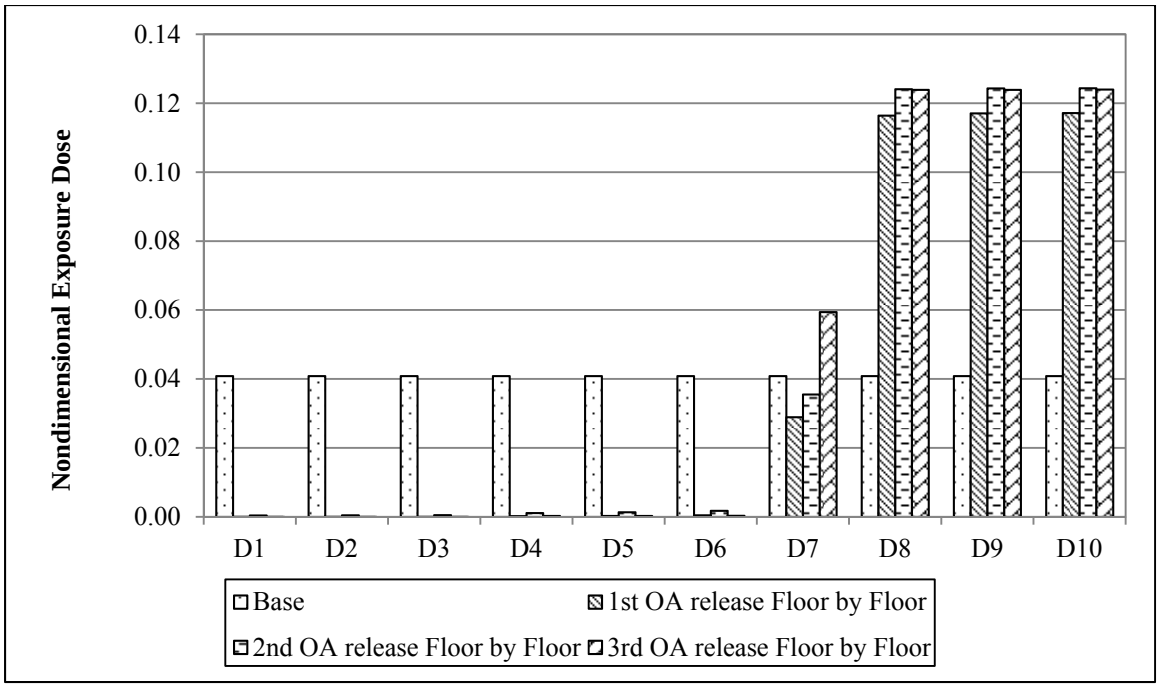

Figure 4–19: Decile breakdown of nondimensional exposure dose results for a single zone system and floor-by-floor zoning systems following alternate OA intake releases

4.7. Effects of Stack Effect

Imbalances in HVAC flows can cause unintentional flows between spaces in a building, from room to room and also from floor to floor. Environmental influences including wind and stack effects modify these flow patterns and, if sufficiently strong, can change the direction of flows. This possibility is investigated for the model building with floor-by-floor zoning by imposing a winter stack effect on the building following the second floor outdoor air intake release (C-3A15-M6F-2OA-W). In this scenario, the outside air temperature is set at 25 ºF (-3.89 ºC) to simulate winter condition.

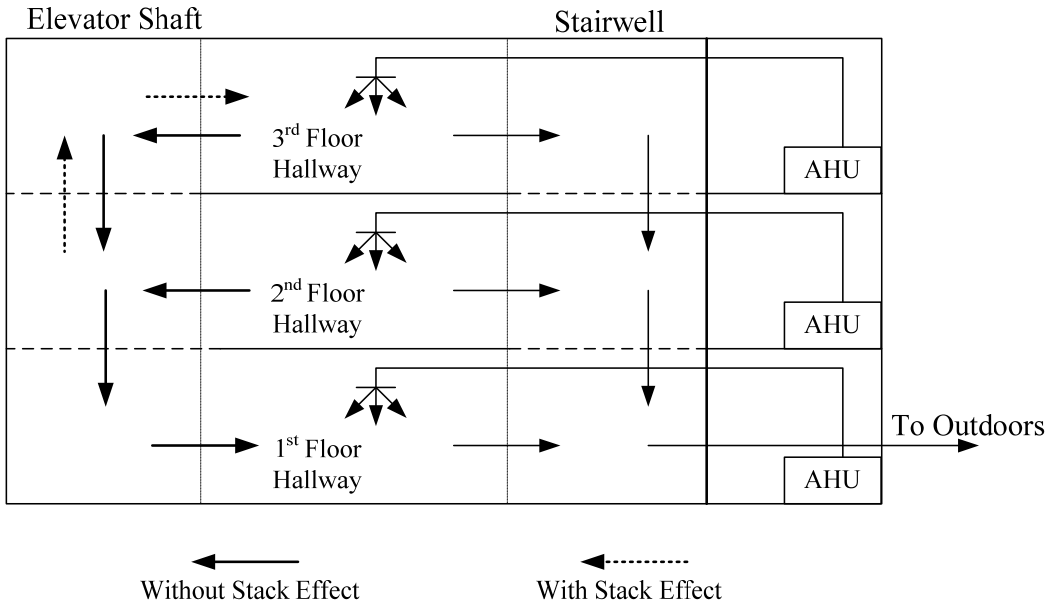

Figure 4–20: Elevator shaft and stairwell airflow direction schematic for the floor-by-floor zoning systems in winter condition

Winter stack effect tends to cause flow from the bottom of a building toward the top acting against the direction established by the relative pressurization of the AHUs. Figure 4–20 shows the resulting air flow patterns from stack effect. Although some flow directions were unchanged, the stack pressure on the elevator shaft was sufficient to reverse the direction of flow between the elevator shaft and the third floor hallway. Stack effect reduced air change rates (Table 4–14), and therefore, increased residence time of contaminants entering the stairwell.

Table 4–14: Stairwell air change rates for the floor-by-floor zoning scenario

Zone	**No Stack Effect (ACH)**	**Winter Stack Effect (ACH)**
1st Floor Stairwell	3.62	2.38
2nd Floor Stairwell	2.51	1.64
3rd Floor Stairwell	1.23	0.78
Average	2.45	1.60

4.7.1. Threat-based Measures

Table 4–15 presents threat-based building total and floor-by-floor dorm room results for the floor-by-floor zoning building with and without stack effect following a second floor OA intake release. For this building model, the stack effect does not have influence on the building total casualties and infections. However, FBE values do reflect a slight increase in the building area exposed to the twelve-hour inhaled dose that exceeds mean lethal dose from the stack effect. In addition to the entire building casualties and infections, the dormitory room total casualties and infections of each floor are investigated following a second floor OA intake release. The results show that the third floor dormitory room with the stack effect has higher total casualties and infections than that of the building without stack effect. This is because the reverse airflow direction in the elevator shaft and the reduction in air change rates in the stairwell extend the residence time of the contaminants in the building as a result of the stack effect.

Table 4–15: FBE, FBP, percent casualties, total casualties, percent infections, and total infections comparing between with and without stack effect for the floor-by-floor zoning systems following a second floor OA intake release

Threat-based Measures	**Without Stack Effect**			
	Entire Building	**1st Floor Dorm Room**	**2nd Floor Dorm Room**	**3rd Floor Dorm Room**
FBE (Lethal)	0.353	0.07	1	0
FBP	0.647	0.93	0	1
Total Casualties	29.2	0.54	28	0.68
% Casualties	38.4%	2.71%	100%	2.42%
Total Infections	29.5	0.74	28.0	0.75
% Infections	39%	3.68%	100%	2.69%

Threat-based Measures	With Stack Effect			
	Entire Building	1st Floor Dorm Room	2nd Floor Dorm Room	3rd Floor Dorm Room
FBE (Lethal)	0.356	0.07	1	0.01
FBP	0.644	0.93	0	0.99
Total Casualties	29.2	0.52	28	0.69
% Casualties	38.4%	2.62%	100%	2.48%
Total Infections	29.5	0.67	28.0	0.81
% Infections	76%	3.34%	100%	2.89%

4.7.2. Vulnerability-based Measures

The nondimensional twelve-hour building average concentrations for the scenarios with and without stack effect are slightly different as well as the EIS values as shown in Table 4–16. The stack effect increases the nondimensional third floor dormitory room average concentration but decreases the nondimensional first floor dormitory room average concentration similar to the results of total casualties and infections.

Table 4–16: Nondimensional twelve-hour building average concentration and EIS for the single zone and the floor-by-floor zoning scenarios following a second floor OA intake release

Vulnerability-based Measures	Without Stack Effect			
	Entire Building	**1st Floor Dorm Room**	**2nd Floor Dorm Room**	**3rd Floor Dorm Room**
Twelve-hour average building concentration (cfu/m^3)	28	187	15,054	58
Nondimensional twelve-hour average building concentration	0.00023	0.0015	0.1242	0.0005
EIS	-1.37	N/A	N/A	N/A
Vulnerability-based Measures	**With Stack Effect**			
	Entire Building	**1st Floor Dorm Room**	**2nd Floor Dorm Room**	**3rd Floor Dorm Room**
Twelve-hour average building concentration (cfu/m^3)	29	151	15,043	82
Nondimensional twelve-hour average building concentration	0.00024	0.0012	0.1241	0.0007
EIS	-2.64	N/A	N/A	N/A

Figure 4–21 shows the nondimensional building average concentration for floor-by-floor zoning system compared between with and without stack effect scenarios following a second floor OA intake release. The stack effect raises the overall nondimensional building concentrations corresponding to the longer contaminant residence time induced by lower air change rates.

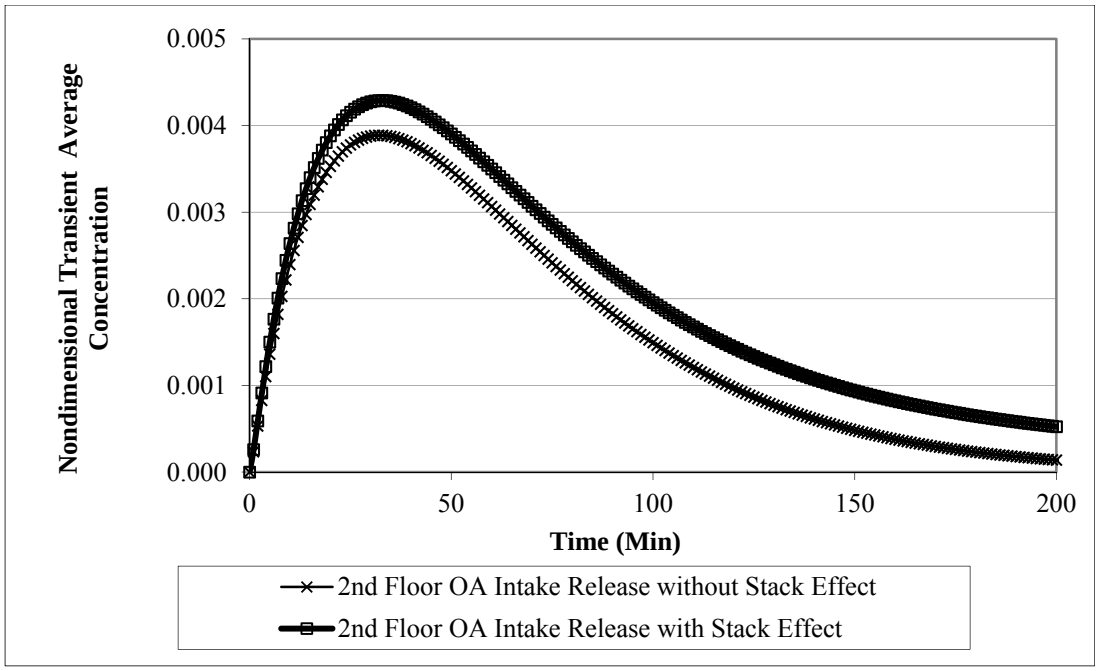

Figure 4–21: Nondimensional building average concentration for floor by floor zoning systems following a second floor OA intake release with and without stack effect

The decile breakdown of nondimensional exposure dose (Figure 4–22) shows minor difference in exposure dose in each decile compared between floor-by-floor zoning building with and without stack effect. The exposure dose for the stack effect scenario is slightly greater than that without stack effect for decile 1 to 3 which, in this case, represents areas that are not served by the mechanical system that connects to the release zone.

Similar to the decile breakdown, the nondimensional occupancy dose curves are not presented because they do not show much consequence from the stack effect.

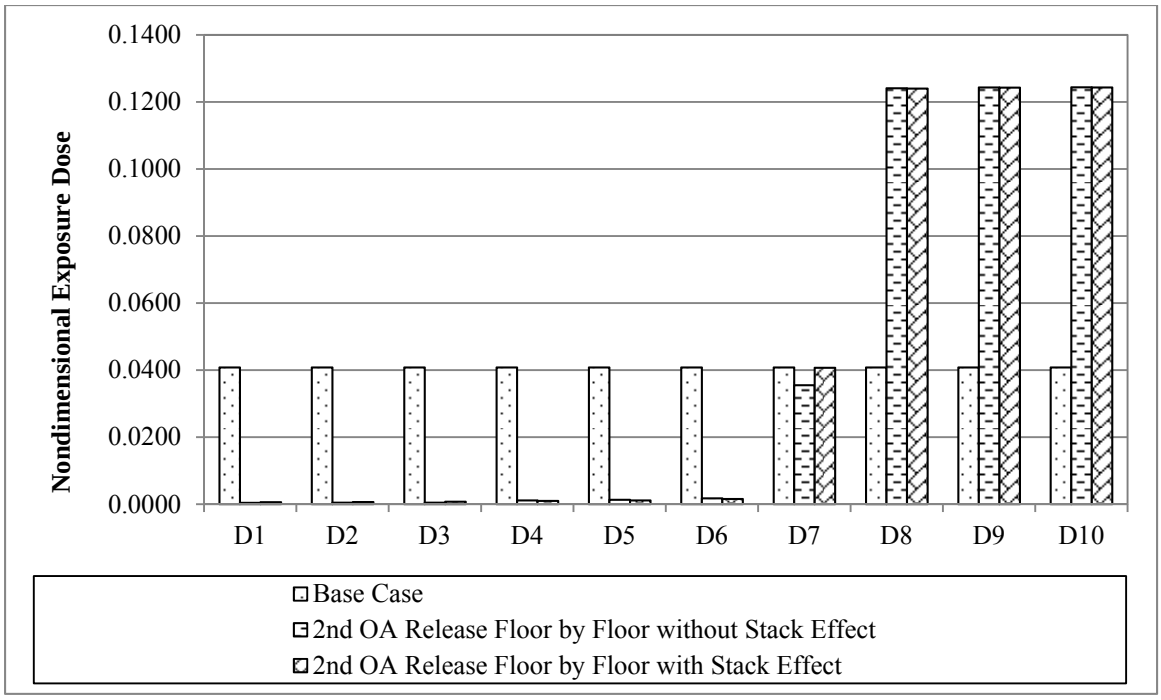

Figure 4–22: Decile breakdown of the nondimensional exposure dose results for the floor-by-floor zoning with and without stack effect following a second floor OA intake release

Chapter 5

Results of Sensitivity Analysis

The sensitivity analysis was performed to determine impact of uncertainties for the single CAV cases. This section shows the uncertainty of twelve-hour inhaled dose, percent infections, and percent casualties for the three different filter efficiencies: none, MERV 6 and MERV 13 filters. The following results are based on the assumed variances of each selected input parameter including supply airflow rate, outside airflow rate, percent filter efficiency, indoor-outdoor air temperature difference, breathing rate, mean infectious dose, and mean lethal dose as listed below.

- % Filter Efficiency: ±10%
- Supply Airflow Rate: ±15%
- Outside Airflow Rate:±15%
- Indoor-outdoor Air Temperature Difference: ±0.4 °C
- Breathing Rate: ±10%
- Mean Infectious Dose: ±10%
- Mean Lethal Dose: ±10%

Table 5–1 summarizes the results of the uncertainty analysis for the single CAV system following an OA intake results for dose, percent infections, and percent casualties. Uncertainties increase for all three types of results as the filter efficiency increases. For a building with MERV 13 filters, the contaminant is mostly removed before entering the building which causes the lowest inhaled dose, percent infections, and

percent casualties. Therefore, small changes in input parameters create the largest overall uncertainty in percentage compared to the base inhaled dose values. With the larger values of inhaled dose, percent infections, and percent casualties for MERV6 filter and no filter scenarios, the overall uncertainties are significantly small in percentage compared to the base values.

Table 5–1: Summary results of uncertainty analysis for single CAV system following an outdoor air intake release

		Twelve-hour Inhaled Dose	**% Infections**	**% Casualties**
No Filtration	Absolute Value	68,759.89 ± 24,155.50	100.0 ± 0	99.82 ± 2.25
	% Uncertainty	68,759.89 ± 35.1%	100.0 ± 0	99.82 ± 2.25%
MERV 6 Filter	Absolute Value	29,682.09 ± 6,859.98	99.96 ± 0.043	54.78 ± 19.6
	% Uncertainty	29,682.09 ± 23.1%	99.96 ± 0.04%	54.78 ± 35.7%
MERV 13 Filter	Absolute Value	1,183.96 ± 1,227.94	3.89 ± 2.27	2.77 ± 0.58
	% Uncertainty	1,183.96 ± 103.7%	3.89 ± 58.4%	2.77 ± 20.9%

Table 5–2 shows the percentage of each component uncertainty contributing to overall uncertainty for a single CAV system with various filter efficiencies following an OA intake release. The impact of filter efficiency on overall uncertainty for inhaled dose, percent infections, and percent casualties increases in relative to the filter efficiency. At the highest efficiency, uncertainty in filter efficiency has the most impact in overall uncertainty for all results. For a building without filtration, the twelve-hour inhaled dose in all occupied spaces are fairly larger than the mean infectious dose of 10,000 cfu; therefore, the percent infections are 100% in all cases. Consequently, there are no

changes in percent infections despite the uncertainties in the input parameters which results in 0 percent contribution in the overall uncertainty of percent infections

Table 5–2 – Distribution of uncertainty for a building with a single CAV system following an OA intake release

Fraction of Total Uncertainty (%)	Dose			% Infections		
	MERV 6 Filter	No Filter	MERV 13 Filter	MERV 6 Filter	No Filter	MERV 13 Filter
Supply airflow rate	41.5	17.51	2.10	16.58	0.00	1.75
% Outside air	7.9	18.31	12.18	2.51	0.00	9.15
% Filter efficiency	8.5	0.00	84.79	2.58	0.00	87.55
Indoor-outdoor air temperature difference	23.4	56.08	0.00	62.35	0.00	0.00
Breathing rate	18.7	8.10	0.93	8.42	0.00	0.77
Mean infectious dose	-	-	-	7.56	0.00	0.78

Fraction of Total Uncertainty (%)	% Casualties		
	MERV 6 Filter	No Filtration	MERV 13 Filter
Supply airflow rate	40.59	3.66	1.95
% Outside air	7.71	3.87	10.85
% Filter efficiency	8.48	0.00	86.23
Indoor-outdoor air temperature difference	22.55	90.44	0.00
Breathing rate	18.32	1.82	0.86
Mean lethal dose	2.35	0.22	0.11

For the MERV 6 filter scenario (base case), supply air flow rate has the most contribution in overall uncertainty in both inhaled dose and percent casualties.

Indoor-outdoor air temperature differences create the airflow imbalances between indoor and outdoor environment; therefore, affecting on airborne contaminant transfer between indoor and outdoor. Since there is no filter removing the contaminant

introduced to the building, the uncertainty in indoor-outdoor air temperature differences has the most significant effect on both inhaled dose and percent casualties.

Chapter 6

Conclusions and Recommendations

The objectives of this research were to investigate the effects of building and mechanical system characteristics on consequences of an assumed CB release, evaluate the usefulness of both vulnerability-based and threat-based building performance measures in risk assessment of building protection to airborne contaminant, and examine the role of uncertainty on risk assessment.

A parametric study was performed to investigate effects of selected and common mechanical system characteristics on a residential building. A residential building is a three-story (including attic) university residence hall occupied by seventy six (76) students. A multizone modeling program (CONTAM) was used in building simulations for all scenarios. The tested scenarios include three different filter efficiencies (MERV 13 filter, MERV 6 filter, no filter), five percentage of OA, HVAC system types (i.e., CAV, VAV, and DOAS), HVAC zoning, and stack effect.

Results of the parametric study were evaluated with threat-based (agent, release, and population-specific) and vulnerability-based (relative) performance measures. Threat-based measures involve total infections, total casualties, percent infections, percent casualties and FBP. Vulnerability-based measures include nondimensional average building concentration, nondimensional transient concentration, nondimensional occupancy dose curve, decile breakdown of nondimensional exposure dose, and exposure improvement score. Percent infections and casualties were selected as reference measures. The accuracy of the vulnerability-based measures was discussed by comparing

their interpretations to the reference measures. Impact of uncertainty on three filter efficiency scenarios following an OA intake release was investigated using a sensitivity analysis.

6.1. Parametric Study

The base case is a one-minute release of 6 x 10^8 cfu of anthrax into the OA intake of the building served by a ducted supply and return, recirculating forced-air, CAV system with MERV 6 filter. Effect of each parameter was compared to the base case using both threat-based and vulnerability-based measures. The effect of interior release does not differ much from the OA intake release when it occurs in the single zone building with a CAV system. This is because the system recirculates contaminated air and distribute evenly to other spaces.

Filter efficiency and ventilation are two common mechanisms in airborne contaminant removal. When the filter efficiency increases, the airborne contaminant is removed more substantially. The impact of ventilation was evaluated based on five percentages of OA with MERV 6 filter on a single zone CAV system. Similar to filtration, the increment in ventilation rate raises the ability to eliminate the contaminant from the building even though ventilation is also the mean to introduce the airborne contaminant into the building for an OA intake release. To determine the complementary effect of filtration and ventilation, the five percentages of OA with MERV 13 filter scenarios were also examined. With the high efficiency (MERV 13) filter, the dilution effect of ventilation is diminished because contaminant is significantly removed by the filter with a single pass.

Each mechanical system has unique characteristics and effects on air distribution. Three mechanical system types (CAV, VAV, and DOAS) were considered in a single-zone building. These systems influence the quantity of supply air circulated in the building and the amount of recirculation differently. In a building served with a CAV system, occupants were uniformly exposed to the same level of airborne contaminant following an OA intake release since a CAV system supplies constant air volume to the building with a portion of recirculated air. For an interior release, a CAV system also recirculates the contaminated air and distributes contaminant into other spaces uniformly.

Unlike the DOAS system which does not recirculate the air, the DOAS system has ability to limit the spread of the contaminant following an interior release. However, the clearance time of the building contaminant is much longer for the DOAS system compared to both CAV and VAV systems; because airborne contaminant is mainly removed via filter from recirculated air. Additionally, the DOAS system delivers only minimum airflow required for ventilation (approximate 20% of a CAV system) which contributes to longer clearance time of contaminant removal. This is shown in results of the OA intake release scenario as well as the interior release scenario.

A VAV system's supply air flow rate varies based on the space heating and cooling load. In some event, some areas of the building have full cooling or heating load which requires supply air flow rate at design (100%); some spaces require lower supply air according to part load condition. For the part load space, the supply air flow rate is reduced to 40% of the design supply air flow rate which also lower air change rates. Consequently, the nondimensional initial contaminant concentration is lower in the part load room but contaminant removal rate is higher for the full load room.

HVAC zoning has impact on contaminant distribution in a number of ways. A floor-by-floor system was selected and simulated to explore the effect of zoning. The three distribution systems created unique air flow patterns due to pressurization characteristic in each floor. For the selected building model, the first floor is de-pressurized compared to the second and third floor. The air flows from the second and third floor via elevator shaft and stairwell to the first floor. Consequently, when the contaminant was released in the second or third floor, it can be leaked to the elevator shaft and stairwell before being distributed to the first floor. In addition to air flow pattern alteration, zoning increases the possible release scenarios. However, when the release occurred on one of the floors, zoning can limit the spread of the contaminant into other floors.

Zoning is not the only parameter that causes air flow imbalances in the building. Environmental influences such as wind or winter stack effect can modify these flow patterns and, if sufficiently strong, can change the direction of the air. Therefore, the winter stack effect was investigated for the building with the floor-by floor zoning system. Winter stack effect tends to cause flow from the bottom of a building toward the top, acting against the original air flow direction created by three mechanical systems. For this building, it is strong enough to reverse the air direction in the elevator shaft from the second floor to the third floor. As a result, it reduced the air change rates in stairwell; therefore, increased residence time of contaminants entering the stairwell.

6.2. Building Performance Measures

Both threat-based and vulnerability-based measures were investigated. To compute the threat-based measures, agent-specific information and proper dose response

models are required. In contrary, vulnerability-based measures do not the identification of contaminant but are relative metrics requiring a base event. Threat-based measures include total infections, total casualties, percent infections, percent casualties, and fraction of building protection.

- The total infections, total casualties, percent infections, and percent casualties are straightforward calculation and able to indicate health consequences of the building occupants impacted by contaminant exposure accurately. However, due to the greater numbers of required parameters (building, human, and agent) to compute threat-based measures, it increases the numbers of uncertainties compared to vulnerability-based measures. Therefore, for decision making of mechanical system upgrades, the impact of uncertainties should be addressed to obtain accurate conclusion.
- Fraction building protection, another threat-based measure, is the simplest spatial threat-based measure. It can be determined easily for any scenario as long as the level of concern for the agent of interest is identified, in this study, the mean lethal dose (LD_{50}). However, it cannot differentiate the level of building security between the scenarios if an entire building area was uniformly exposed to contaminant under or over the level of concern. Therefore, this measure is better applied to a scenario with non-uniform air distribution or using zoning strategy than a scenario with uniform air distribution like a single zone system.

Several vulnerability-based measures were investigated including nondimensional twelve-hour building average concentration, nondimensional transient building average

concentration, nondimensional occupancy dose curves, decile breakdown of nondimensional exposure dose, and exposure improvement score.

- Nondimensional time average building concentration is the first vulnerability-based measure that was applied to the results of the parametric study. It is uncomplicated and does not require any knowledge in epidemiology to calculate the value. For the scenarios that evenly distribute air contaminant such as an OA intake release in a single CAV system, it can show how protective of the mechanical system characteristic like filtration or ventilation to building occupants in a CB attack. However, this measure can be misleading and cannot provide clear picture of risk levels for scenarios with non-uniform distribution of contaminants e.g., mechanical system types or zoning strategy.
- Nondimensional transient concentration, the second vulnerability-based measure, is a plot of nondimensional airborne concentration as a function of time. This measure is also not complicate to obtain. The profile shows how airborne contaminant presents in a space or a building per each time step. This measure can show how long it takes for the airborne contaminant is removed from the space or building. Similar to the nondimensional building average concentration, it can show differences in risk levels of the mechanical system parameters such as filter efficiency or ventilation in a single zone building. For example, these profiles show that the higher ventilation rate helps raising the contaminant removal rate. However, it has similar shortcomings to the time average concentration in the non-uniform contaminant distribution in the zoning and system type scenarios.

- Nondimensional occupancy dose curve is a plot of the percent of occupants for which the nondimensional twelve-hour inhaled dose is exceeded from high to low. These curves can demonstrate the level of contaminant exposure of each occupant in the building with an assumption of the occupancy schedule and locations in the building. They can show the impact of mechanical system characteristics on occupant exposure for both uniform and non-uniform release scenarios in the better details and more accurate than the nondimensional time average concentrations and transient building concentrations. For example, the curves can clearly show that at higher filtration efficiency and ventilation rate, 100 percent of the occupants were exposed to the lower level of inhaled-dose. For the floor-by-floor system following an OA intake release into one of the systems, the curves indicate that one-third of the building occupants were exposed to the twelve-hour inhaled dose three orders of magnitude higher than the rest of building occupants. However, the results are based on a presumed location of each occupant; the exposure of the unoccupied spaces was excluded in the result.
- The decile breakdown of nondimensional exposure dose is a plot of the nondimensional exposure dose from low to high as a function of cumulative area fraction in decile based. This measure can provide the same level of accuracy in risk assessment to the nondimensional occupancy dose curve for all scenarios; however, it demonstrates the distribution of risk levels to contaminant exposure in terms of the percent of the building area instead of the percent of occupants. Evidently, the profiles can indicate the risk levels of each mechanical system characteristics for both uniform and non-uniform contaminant distribution. With

the uniform distribution scenario such as the OA intake release into a single zone building, the curve is flat indicating the uniformity of the inhaled-dose each space; however, is easily compared to other scenarios' results. The advantage of this distribution is that it includes the level of inhaled dose for the entire of building area.

- The exposure improvement score (EIS) can estimate an overall risk computed from the decile breakdown of nondimensional exposure dose compared to a base event. This measure is straightforward and easy to calculate, and independent of the agent. For a comparison of the mechanical system upgrades such as effectiveness of filters or an increase in ventilation rates, EIS values can provide accurate interpretation of how better or worse of each scenario is compared to the baseline. However, for the scenarios resulting in non-uniform air distribution, the improvement score results are not clear.

In conclusion, threat-based measures can provide clear insight of risk levels; however, they are agent specific and require agent-related information including dose-response models. The selected threat-based measures except FBP are more complicated to compute compared to other measures. On the other hand, vulnerability-based measures are easy to obtain but harder to interpret. A number of vulnerability-based measures i.e., nondimensional building average, nondimensional transient concentration, and improvement score, can identify risk on cases with uniform air distribution correctly; however, they sometime can inaccurately indicate risk or are unclear especially scenarios resulting in non-uniform contaminant distribution. Nonetheless, a few vulnerability-based measures including nondimensional dose curves and decile breakdown of

nondimensional exposure dose can accurately compare risk levels for both uniform and non-uniform air distribution cases to a base case. Based on this study, it is recommended that the decile breakdown of nondimensional exposure dose should be used in vulnerability-based risk assessment to compare the building protection levels of mechanical systems in relation to a selected base case because of its ability to accurately provide a complete picture of inhaled dose distribution in a building.

6.3. Impact of Uncertainty

In risk assessment, there are many uncertainties imbedded in input parameters used in the modeling for a CB event. A simple sensitivity analysis was performed to determine the impact of uncertainty in input parameters and the level of confidence of results in risk assessment. Uncertainties of dose and infections were investigated for the three efficiency filter scenarios: no filter, MERV 6 filter, and MERV 13 filter. Uncertainty in each input parameter affects the results differently depending on the scenarios. For example, the filter efficiency has the most impact in the MERV 13 filter while other parameters (i.e., indoor-outdoor air temperature difference and percent of OA) have no impact on overall uncertainty. It is essential that the sensitivity analysis or statistical analysis is performed to provide non-biased risk assessment which is used in decision making of control measures to a CB event.

6.4. Further Work

This study has reviewed the literature available on important mechanical system characteristics to airborne contaminant distribution and available performance measures determining risk levels for an assume building attack, performed a parametric study on

selected mechanical parameters, tested accuracy of performance measures, and investigated impact of uncertainty.

Several mechanical system parameters were investigated; however, the parameters such as control systems or building constructions or other parameters (e.g., deposition and re-suspension) were not included in the parametric study or sensitivity analysis. The effect of these parameters should be further analyzed and discussed in the future study.

The selected contaminant in this research is a biological agent which the exposure is a linear function of the airborne contaminant concentration. For the chemical agent, the exposure can be a function of time, concentration, and the toxic load exponent (non-linear toxic load equation). It will be very useful to investigate the effect of toxic load exponent on the risk level of building occupants in the aspect of mechanical system.

A few relative metric performance measures such as nondimensional occupancy dose curves, decile breakdown of nondimensional, and EIS were investigated found to be accurate and very useful. Future work should develop the methodology implementing these metrics to quantitatively assess the risk levels of occupant exposure to airborne contaminant according to effects of mechanical systems so that it can be implemented as a design procedure.

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