MODELING INDOOR EXPOSURES TO OUTDOOR PARTICULATE MATTER ACROSS THE U.S. RESIDENTIAL BUILDING STOCK

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Symbol	Definition
α	Deposition rate multiplier during periods of low window opening (-)
β	Deposition rate multiplier during periods of high window opening (-)
ε	Correction factor for inhomogeneity (-), ε =1.6 for polyester filters
λ	Long term air exchange rate (AER, 1/hr)
$\lambda_{closedwindows}$	Air exchange rate in a home with doors and windows closed (1/hr)
λ_{gas}	Gas molecule mean free path, 0.067 μm
$\lambda_{openwindows}$	Average air exchange rate during periods of window opening (1/hr)
$\lambda_{openwindows,low}$	Air exchange rate during periods of low window opening (1/hr)
λ_{HVAC}	Recirculation rate through HVAC system (1/hr)
μ	Particle mobility (N-s/m)
η	Absolute gas viscosity (N-s/m^2)
$\eta_{i,HVAC}$	Size resolved particle removal efficiency of a filter installed in the HVAC system (-)
ρ	Particle density (g/cm^3)
a	Filter media volume fraction (m^3/m^3)
C_h	Cunningham slip factor (-)
$C_{i,in}$	Size-resolved indoor particle matter concentration (#/cm^{-3})
$C_{i,in,inhaled}$	Size-resolved dose inhaled by an average individual indoors (#)

$C_{i,out}$	Size-resolved outdoor particle matter concentration (#/cm^{-3})
D_d	Particle diffusion coefficient (m^2/s)
d_f	Fiber diameter (mm)
d_i	Correction factor (-)
$d_{p,i}$	Particle diameter (m)
f_{HVAC}	Long-term average fractional operation time of the HVAC system (-)
f_i	Correction factor (-)
f_{mild}	Fraction of time when mild weather is experienced (-)
$f_{openwindows}$	Fraction of time when windows are open (-)
$f_{openwindows,mild}$	Fraction of time when windows are open during mild weather (-)
$F_{i,inf}$	Long-term average size-resolved infiltration factor (-)
F_K	Kuwabura hydrodynamic factor (-)
k	Boltzman's constant, k = 1.3708 * 10^{-23} J/K
$k_{i,dep}$	Long term average size-resolved particle deposition rate (1/hr)
$k_{i,dep,closedwindows}$	Size-resolved deposition rate in a home with doors and windows closed (1/hr);
$k_{i,dep,openwindows}$	Size-resolved deposition rate with windows open (1/hr)
$k_{i,dep,openwindows,low}$	Size-resolved deposition rate with windows open a small amount (1/hr)
$k_{i,dep,openwindows,high}$	Size-resolved deposition rate with windows open a large amount (1/hr)
L	Length of the filter media in the direction of the airflow (m)
L_u	Maximum value for the filter efficiency (-)
$m_{openwindows,low}$	Air exchange rate multiplier during periods of low window opening (-)

$m_{openwindows,high}$	Air exchange rate multiplier during periods of high window opening (-)
$M_{i,indoors}$	Size-resolved mass concentration indoor fine particles ($\mu g/cm^3$)
N_r	Interception parameter (-)
$p_{openwindows,low}$	Probability of low window opening (-)
$p_{openwindows,high}$	Probability of high window opening (-)
P_e	Peclet number (-)
P_i	long-term average size-resolved envelope penetration factor (-)
$P_{i,closedwindows}$	Closed windows size-resolved envelope penetration factor in a home (-)
$P_{i,openwindows}$	Size-resolved average particle penetration factor during periods of window opening (1/hr)
$P_{i,openwindows,low}$	Size-resolved particle penetration factor with windows open a small amount (1/hr)
$P_{i,openwindows,high}$	Size-resolved particle penetration factor with windows open a large amount (1/hr)
$PM_{2.5,\ inhaled}$	Total dose of indoor fine particulate matter inhaled by an individual over one year (mg)
S_i	Fiber projected area (-)
T	Air temperature (K)
U	Media face velocity (m/s)
$UFP_{inhaled}$	Dose of ultrafine particles (UFP) inhaled by an average individual indoors (#)

ABSTRACT

Elevated ambient concentrations of fine and ultrafine particulate matter are consistently linked with adverse health effects in epidemiological studies. However, because people spend most of their time indoors (particularly at home) and outdoor particles can infiltrate into buildings with varying efficiencies, much of human inhalation exposure to outdoor particles actually occurs inside residences. Consequently, relying on ambient measurements of particulate matter can result in a significant exposure misclassification in epidemiological studies. To address the range of this misclassification in U.S. residences, this work predicts the statistical distribution of long-term average size-resolved indoor proportions of outdoor particles (from 0.001 to 10 μm) across the entire U.S. single-family residential building stock by means of Monte Carlo simulations. Best available data was used for distributions of important building-related model inputs (e.g., air exchange rates, penetration factors, deposition rates, and others).

Overall, results suggest that infiltration factors (i.e., the indoor-outdoor particle concentration ratio in the absence of indoor sources) vary highly among residences across the U.S. residential building stock. Long-term average size-resolved infiltration factors are estimated to vary by a factor of 20-100+ from the least protective of single-family homes in the U.S. (99th percentile) to the most protective (1st percentile), depending on particle size. Long-term average infiltration factors are predicted to be within a factor of 2-4 in the majority of homes (between the 25th and 75th percentiles of homes). A regression analysis further shows that parameters such as deposition rates, air exchange rates, penetration factors, and filter removal efficiencies are the most influential parameters for predicting infiltration factors.

Finally, the predicted distributions of size-resolved infiltration factors were used to map to archetypal outdoor particle size distributions to estimate absolute concentrations and ultimately inhalation doses of both ultrafine particles (UFPs) and $PM_{2.5}$ in an adult male. Inhalation doses of UFPs and $PM_{2.5}$ were estimated to be 43-49 and 21-22 times higher, respectively, in the least protective homes (99th percentile) versus the most protective homes (1st percentile). Taken together, these results suggest that a wide variability in size-resolved infiltration factors among U.S. residences leads to large variations in the dose of particles inhaled in indoor environments, which should be accounted for in future epidemiological studies.

CHAPTER 1

INTRODUCTION

Elevated ambient concentrations of particulate matter, including $PM_{2.5}$, PM_{10}, and ultrafine particles (UFPs), are consistently linked with adverse health effects (Andersen et al., 2010; Brook et al., 2010; Miller et al., 2007; Peters, Wichmann, Tuch, Heinrich, & Heyder, 1997; Pope III C, 2002; Stölzel et al., 2006; von Klot et al., 2002; Wellenius et al., 2012). Such studies usually use ambient concentration measurements from outdoor site monitors, assuming that every person in a study area is exposed to the same concentration. However, since Americans spend the majority of their time indoors (and most of that time in their homes) (N E Klepeis et al., 2001) and particles of outdoor origin can infiltrate and persist in buildings with varying efficiencies (Chen & Zhao, 2011; Diapouli, Chaloulakou, & Koutrakis, 0; Kearney et al., 2011; Rim, Wallace, & Persily, 2010a; B. Stephens & Siegel, 2012; Thatcher, Lunden, Revzan, Sextro, & Brown, 2003; Zhu et al., 2005), relying on ambient measurements alone can result in significant exposure misclassification for a large portion of the population (Baxter et al., 2009, 2013a; Hodas et al., 2013; Meng et al., 2005).

Several recent studies have attempted to address this exposure misclassification and elucidate the important determinants of the infiltration and persistence of outdoor particulate matter into residential indoor environments. One approach involves measuring indoor and outdoor particulate matter in a large number of residences, gathering information on home characteristics and occupant behaviors by questionnaires and building assessments, and using regression analyses and mass balance principles to identify predictors of indoor-outdoor ratios (Allen et al., 2012; Baxter, Clougherty, Laden, & Levy, 2006; Hystad, Setton, Allen, Keller, & Brauer, 2009; MacNeill et al., 2012). Another approach involves estimating indoor exposures to ambient particulate matter using mass balance models that incorporate fundamental particle transport and control mechanisms, such as particle penetration factors through building envelopes, air exchange rates, particle deposition rates, and removal by air-conditioning systems, as well as human activity patterns and behaviors (Baxter et al., 2013b; Burke, Zufall, & Ozkaynak, 2001a; Chen, Zhao, & Weschler, 2012a; Hering, Lunden, Thatcher, Kirchstetter, & Brown, 2007; Hodas et al., 2012a).

Both approaches have shown that large variations in indoor exposures to ambient particulate matter can result from differences in both building characteristics and human activities. However, these approaches are often limited in their representative sample sizes, their assumptions for important building input parameters (e.g., air exchange rates, penetration factors, or deposition rates), or in their focus on a limited range of constituents or sizes of particulate matter. Few investigations on the most fundamental, size-resolved indoor concentrations of outdoor particles across a wide range of particle sizes exist.

In this context, this study integrates a time-averaged size-resolved particle balance on the indoor environment with the best available data on influential building-related parameters to estimate long-term average indoor proportions of outdoor particles in U.S. single-family residences. A Monte Carlo simulation method was used to account for a variety of home types and characteristics (e.g., envelope air tightness, various filter efficiencies, and HVAC system and filter ownership), and of human behaviors (e.g., window opening, which increases particle infiltration). This work attempts to improve previous modeling approaches by using a wide particle size range (0.001 to 10 μm), larger sample sizes (100,000 modeled homes), and by using the best available data to build statistical distributions for building parameters. Additionally, we assumed size-resolved statistical distributions for deposition rates, penetration factors, and filter efficiencies, in order to obtain accurate size-resolved infiltration factors.

Given the wide particle size range the present study reports, results from this work were also used to address human exposure and inhalation doses of other classes of particulate matter, including ultrafine particles (UFP) and fine particles ($PM_{2.5}$) in three archetypal outdoor environments, for which health endpoint studies utilizing outdoor measurements are well known. Additionally, results from this work were also used to determine what relevant input parameters most impact resulting size-resolved infiltration factors, which can be used to inform future experimental studies for the most appropriate parameters to evaluate in homes.

Results are intended to demonstrate the likely statistical bounds and distributions of size-resolved indoor-outdoor infiltration factors across the US building stock. This work also provides a model framework for others to use in similar work. Using outdoor particle size distributions, these results will translate into distributions of long-term average indoor concentrations of any class of particulate matter encountered across the building stock. Additionally, this work highlights the importance of particular building characteristics and identifies several important data gaps and existing research needs.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of the relevant literature to this study. It is divided in four sections. The first section introduces the reader to the known health effects associated with outdoor particulate matter pollution and describes the establishment and evolution of U.S. air quality standards over the last few decades. Particular attention in the first subsection is paid to the adverse health effects associated with the inhalation of outdoor fine particulate matter ($PM_{2.5}$) and ultrafine particles (UFPs). The second section describes the importance of indoor airborne exposures to the same outdoor particulate matter pollutants. The third section presents various modeling methods for predicting the infiltration of outdoor particulate matter into buildings and the most important influencing parameters. Finally, a fourth section describes the objectives of the current study.

2.1 Health effects associated with air pollution and air quality standards

Many epidemiologic studies show a relationship between human exposure to particulate matter and adverse health effects. For example, one research group (Zeka, Zanobetti, & Schwartz, 2005) studied the short-term effects of particulate matter on mortality. They showed evidence that short-term increases in the mass of particles less than 10 µm (PM_{10}) (one or two days prior to the peak in mortality) increased deaths due to respiratory or heart disease.

While many epidemiologic studies mostly focused on the short term health effects of particulate air pollution, one study over a decade ago also linked long term effects of air pollution with cardiopulmonary disease (Pope III C, 2002). Using survey and mortality data associated with outdoor air pollution information, they determined that outdoor fine particulate matter ($PM_{2.5}$) and sulfur dioxide (SO_2) were associated with increased all-cause, cardiopulmonary mortality, and lung cancer risk. They reported that the risk of all-cause, cardiopulmonary mortality, and lung cancer mortality increased by 4%, 6% and 8% for a $10\mu g/cm^3$ elevation of $PM_{2.5}$, respectively. Recently, another research group published a study comparing the risks of both short-term and long-term exposure to outdoor $PM_{2.5}$ (Brook et al., 2010). While short-term exposures to particulate matter increased the risk of developing cardiovascular disease and non-fatal cardiovascular events, long-term exposures increased the human risk of cardiovascular mortality.

Another relevant study conducted by Miller et al. on a representative sample of postmenopausal women showed an association between outdoor $PM_{2.5}$ and risk of cardiovascular and cerebrovascular disease and death; an increase of $10\mu g/m^3$ in $PM_{2.5}$ was linked with a 24% increase in the risk of having a cardiovascular event (Miller et al., 2007). However, while many previous studies have focused on the exposure differences between cities, this study showed the exposure variability even within cities although still relying on outdoor concentrations alone.

Ultrafine particles (particles less than 100 nm in diameter, or UFPs) also play an important role in the adverse health effects of particulate matter pollution. UFPs are mostly emitted from combustion processes such as the ones occurring in motorized traffic (Hoffmann et al., 2006). Due to their small sizes, such particles do not contribute much to the total particulate matter mass ($PM_{2.5}$ or PM_{10}); however, they are present in a very large numbers in the atmosphere and typically have a very large surface area associated with them. Therefore, number concentrations or surface area concentrations are typically the most appropriate measure for ultrafine particles.

Outdoor number concentrations of UFPs have also been associated with adverse health effects. Elevated number concentrations of this range of particles is associated with increases in cardiovascular and cerebrovascular diseases (Andersen et al., 2010; Penttinen et al., 2001; von Klot et al., 2002; Wellenius et al., 2012). Additionally, the combined effects of fine and UFP concentrations on asthma symptoms have been demonstrated by a few studies in the past decades. For instance, von Klot et al. observed a correlation between fine and ultrafine mass and number concentrations and asthma symptoms and medication use (von Klot et al., 2002). In a study on German adults with a history of asthma, Peters et al. found associations between the number concentrations of fine and ultrafine particles with a decrease in the patient's peak expiratory flow and an increase in the feeling of illness (Peters et al., 1997).

In a more recent study, Andersen et al. showed a correlation between short-term exposures to outdoor UFPs and the occurrence of ischaemic strokes in Copenhagen, Denmark (Andersen et al., 2010). Since UFPs are mostly traffic-generated, this study showed a direct link between traffic-related pollution and the occurrence of cerebrovascular attacks.

Many epidemiologic studies suggest the existence of a link between high levels of $PM_{2.5}$ or UFP and cardiovascular or cerebrovascular diseases. Some fundamental biological studies have also attempted to prove this as a causal, biologically plausible relationship. For example, a group of researchers (Sun Q, 2005) compared the effect of inhaling filtered air versus polluted air on a number of mice. They showed that the mice that had been exposed to $PM_{2.5}$ had a larger composite plaque area in their thoracic and abdominal aorta than the ones exposed to “clean” air (19.2% of the area versus 13.2%). Therefore, these mice were more subject to vascular inflammation and were more likely to develop atherosclerosis. Brook et al. attempted to elucidate the mechanisms by which fine particulate pollution causes health disease (Brook et al., 2002). They showed that adults who had been subject to a 2-hour high exposure (150 $\mu g/m^3$) to fine particulate matter and ozone had more brachial artery vasoconstriction than the ones who had inhaled filtered air. The artery diameter change was about -0.09 ± 0.15 mm versus $+0.01 \pm 0.18$ mm. Subjects who were exposed to acute short term level of outdoor pollution were more subject to artery vasoconstriction.

Additionally, UFPs may be particularly important because they have been shown to be able to translocate to the brain via the nasal region. A group of researchers generated a peak concentration of ^{13}C particles and traced the air path in rats’ organs particles (Oberdörster et al., 2008); they found increased particle concentration in the rats’ nasopharyngeal region (50% increase) olfactory bulbs (20% increase in concentration) and brains. These results demonstrate that UFPs can translocate to the brain, which could help explain the impact of not only UFPs on cerebrovascular disease, but possibly the role that UFPs play in $PM_{2.5}$ exposure. However, such a link is still to be determined.

Given the adverse effects of outdoor air pollution on human health, in the past decades, many government agencies in Europe and in the USA have imposed standards on outdoor particulate matter levels. For instance, the Clean Air Act was set in 1975 in order to authorize the EPA to establish National Ambient Air Quality Standards (NAAQS). Through the use of State Implementation Plans (SIP), the EPA encouraged each state to establish air pollutant limits. The state of California, for example, developed numerous air pollutant levels in the past two decades.

However, even such regulations on $PM_{2.5}$ levels do not appear stringent enough to decrease pollution to a level that adverse health effects would be negligible. For example, a recent study showed that the current EPA standards for $PM_{2.5}$ were not sufficient to eliminate the risk of increased cerebrovascular or cardiovascular diseases (Wellenius et al., 2012). According to this study, ischaemic stroke risk was specifically 34% higher during days with “moderate” levels of $PM_{2.5}$ compared to days with “good” levels of $PM_{2.5}$ according to the U.S. Environment Protection Agency (EPA) standards.

2.2 Importance of outdoor particle infiltration into indoor environments

Most of the aforementioned studies on air pollution and adverse health effects were focused on concentrations of pollutants in outdoor air. However, people spend most of their time inside buildings and, specifically, inside their homes. In this context, and in response to an exposure assessment mandated by the Clean Air Act, Klepeis et al. conducted the National Human Activity Pattern Survey (NHAPS), a long term telephone based survey (N E Klepeis et al., 2001). Results of this study showed that Americans spend an average of 87% of their time in buildings, and around 69% of their time in their homes. Therefore, given that outdoor pollutants infiltrate and persist in buildings by various mechanisms and with various efficiencies, it turns out that much of human exposure to outdoor pollutants actually often occurs indoors.

However, epidemiologic studies typically use outdoor concentrations in order to determine human exposures to particulate matter. One reason for this is that robust indoor exposure studies, which involve a large series of measurements in homes and other buildings, are extremely expensive and invasive to perform. However, given that most of human exposure occurs indoors, better knowledge of the mechanisms of particle infiltration and persistence and of modeling methods can also be used to help determine with more accuracy human exposure to outdoor air pollution and how it varies across the building stock. Therefore, it is essential to have a better knowledge on infiltration factors – the indoor to outdoor concentration ratio in the absence of any indoor sources – in order to accurately address exposure misclassification in previous studies and to be able to link more accurately the infiltration of particles to the health effects observed in a population.

As Chen and Zhao (2011) described in a recent published study on indoor and outdoor particulate matter (Chen & Zhao, 2011), it is important to understand three main different parameters to understand indoor exposures to outdoor particulate matter: (i) indoor/outdoor concentration ratios, (ii) infiltration factors, and (iii) envelope penetration factors. These values can be characterized for particular sizes and/or classes of particulate matter, including size-resolved particles, UFPs, submicron particles, or $PM_{2.5}$ or PM_{10} mass, although each of these is fundamentally a function of the basic size-resolved values from 1 nm to 10 µm.

In the absence of indoor sources, the ratio between the indoor and outdoor concentration of particles is called the infiltration factor (F_{inf}). This ratio represents the ability a building to buffer or protect from the infiltration and persistence of outdoor particulate matter. An infiltration factor of 1 means that particles infiltrate and persist indoors with 100% efficiency and no losses occur at the building envelope or indoors. Conversely, an infiltration factor of 0 means that no particles can infiltrate and persist due to a combination of building envelope losses and indoor losses, including deposition to surfaces or control by HVAC filters or stand-alone air cleaners. Thus, the infiltration factor depends on various fundamental parameters, including the building's air exchange rate, envelope penetration factor, deposition rate, and filtration efficiency, among others.

Numerous studies have attempted to measure infiltration factors (F_{inf}) in residential buildings and some have also tried to determine penetration factors and deposition rates based on these measurements. For example, Zhu et al. determined freeway-generated UFP transport into indoor environments by conducting measurements of indoor/outdoor ratios in the absence of indoor sources (Zhu et al., 2005). They observed that the highest infiltration factors (0.6 to 0.9) were observed for the largest UFP size range (70 to 100 nm). Zhu et al. also showed that typically, lower infiltration factors were associated with smaller particles (10 to 20 nm).

Similarly, Rim et al. measured infiltration factors of ultrafine particles in a test house (Rim et al., 2010a). They reported values of F_{inf} ranging from 0 to 0.3 in this size range (< 100 nm) when the windows were closed and values ranging from 0.2 to 0.6 when the windows were open. This shows that the combined effects of increased values for air exchange rates, penetration factors, and deposition rates due to the window opening increase infiltration factors consequently.

In another recent study, Wallace and Ott (2011) showed that UFPs penetrate in homes with lower quantities than other particle size ranges, and therefore, ultrafine particles number concentrations indoors are more driven by indoor sources than are other particle sizes (L. Wallace & Ott, 2011). However, because people spend such a large amount of their time indoors and at home, much of their exposure to outdoor UFPs still often occurs indoors.

2.3 Modeling methods and important influencing factors on infiltration factors

Because of the expensive and invasive nature of large field studies, several recent studies have attempt to model or predict infiltration factors in residential indoor environments. For example, MacNeill et al. conducted an exposure study on approximately 40 participants in homes in Canada and determined the day to day variability in infiltration factors for $PM_{2.5}$ and UFPs (MacNeill et al., 2012). They reported daily median values of 0.26 to 0.36 for F_{inf} values for $PM_{2.5}$ and 0.15 to 0.26 for F_{inf} for UFP, albeit with a wide range among the most and least protective homes (from as low as ~0.01 to as high as 1.0). Importantly, MacNeill et al. also explored some predictors of infiltration factors, showing that window opening behaviors, home age, and air conditioning appeared to have significant impacts on F_{inf}. In general, infiltration factors were higher in homes with higher frequency of window opening, older homes, and in homes without central air conditioning.

Other studies have developed modeling approaches incorporating more fundamental particle motion mechanisms in order to determine accurately infiltration factors. For instance, Allen et al. recently developed a model predicting infiltration factors in residential buildings based on measurements of indoor and outdoor $PM_{2.5}$ in various communities and during all seasons. They reported an annual mean F_{inf} across 353 homes of 0.62 ± 0.21. Values for F_{inf} were generally higher during the summer season and window opening behaviors were more significant predictors of F_{inf} than the use of air conditioning during those periods (Allen et al., 2012). In the winter, however, infiltration factors were more predicted by outdoor distributions and forced air heat.

Overall, knowing the parameters that affect human exposure is essential to be able to quantify exposures more accurately and reduce exposure misclassification. Therefore, these studies provide insight into the need for the Monte Carlo simulation developed herein, which can more fundamentally, rapidly, and inexpensively estimate the likely statistical distribution of size-resolved infiltration factors across the residential building stock.

2.4 Objectives of this study

A large number of previous studies have demonstrated adverse health effects associated with outdoor fine and ultrafine particle pollution. However, although much of human exposure to outdoor particle pollution occurs inside buildings, and particularly inside homes, few studies have fundamentally explored size-resolved infiltration factors in homes. Important determinants of size-resolved infiltration factors, including envelope penetration factors, indoor deposition rates, filtration removal efficiencies, and outdoor particle size-distributions have been measured in only a relatively small number of buildings and/or locations in the world. Large samples of measurements remain limited in part because of the expensive and invasive nature of measurements. However, recent size-resolved measurements of these important determinants reported in the literature have allowed for a modeling study whereby the likely distribution of size-resolved infiltration factors can be modeled across the building stock. Therefore, in this study, we use the best available size-resolved data available as input parameters to model the likely distribution of size-resolved infiltration factors across U.S. homes. These input parameters include penetration factors, deposition rates, HVAC filtration removal efficiencies, outdoor particle size distributions, and several other building-related parameters that are not dependent on particle size (including HVAC system ownership, operation times, ownership of HVAC filtration, air exchange rates, window openings, and others).

Therefore, this study contributes to the field by:

1) Combining a literature review of the most important parameters necessary to conduct a study on exposure to particulate matter (e.g., deposition rates, penetration factors, air exchange rates, HVAC recirculation rates, HVAC runtimes, the effect of window opening on these parameters in residential homes, and others);
2) Providing an estimate of the likely statistical distribution of long-term average infiltration factors over a wide range of particle sizes (from 0.001 to 10 μm) using a Monte Carlo simulation of 100,000 single-family homes in the U.S.;
3) Assessing the likely distribution of long-term average particle exposure and dose inhaled by an adult U.S. citizen living in a specific environment (i.e., urban, rural, or near a highly trafficked roadway) based on the simulation results.

CHAPTER 3

METHODOLOGY

The simulations herein utilize a time-averaged number balance on the proportion of outdoor particles 0.001-10 μm in diameter found inside residences. The long-term averaging takes into account both natural infiltration through closed doors and windows as well as elevated infiltration factors during periods of natural ventilation (i.e., window opening for ventilation air). Similar approaches have been used in other studies (Riley, McKone, Lai, & Nazaroff, 2002; J. Thornburg et al., 2001), but this approach differs by incorporating more recent improvements in data availability for important building factors and by incorporating statistical distributions of window opening behaviors, HVAC ownership, and HVAC filter ownership. The model framework and relevant input parameters are described in the next sections.

3.1 Model framework

The long-term time-averaged number balance on indoor particles of diameter *i* of outdoor origin in a well-mixed space used for each modeled home is shown in Equation 1 below.

$$F_{i,\inf} = \frac{C_{i,in}}{C_{i,out}} = \frac{P_i \lambda}{\lambda + k_{i,dep} + \lambda_{HVAC} f_{HVAC} \eta_{i,HVAC}} \tag{1}$$

where

$C_{i,in}$	=	size-resolved indoor particle concentration (#/cm^{-3});
$C_{i,out}$	=	size-resolved outdoor particle concentration (#/cm^{-3});
$F_{i,inf}$	=	long-term average size-resolved infiltration factor (-);

P_i = long-term average size-resolved envelope penetration factor (-);

λ = long-term average air exchange rate (AER, 1/hr);

$k_{i,dep}$ = long-term average size-resolved particle deposition rate (1/hr);

λ_{HVAC} = recirculation rate through HVAC system (1/hr);

f_{HVAC} = long-term average fractional operation time of the HVAC system (-); and

$\eta_{i,HVAC}$ = size-resolved particle removal efficiency of a filter installed in the HVAC system (-).

Statistical distributions for each parameter in U.S. residences are taken from existing literature as shown in the next sections. Parameters that are defined on a long-term average basis take into account both basic building characteristics with doors and windows closed and periods when the building is influenced by human interaction (i.e., by opening windows). Values for those parameters unaffected by human interaction and appropriate for periods of closed doors and windows are termed 'closed-window' values in this work. Values for long-term averages of air exchange rates, penetration factors, and deposition rates, however, are made by adjusting the closed-window values from the literature to account for likely window opening by occupants. Window opening will increase air exchange rates, deposition rates, and penetration factors. For example, the long-term average air exchange rate is calculated by accounting for its value during times of window opening and its natural value, given the probabilities of window opening, as shown in Equation 2.

$$= {}_{closedwindows}(1 \quad f_{openwindows}) + {}_{openwindows} f_{openwindows} \tag{2}$$

where

$\lambda_{closedwindows}$	=	air exchange rate in a home with doors and windows closed (1/hr);
$\lambda_{openwindows}$	=	average air exchange rate during periods of open windows (1/hr);
$f_{openwindows}$	=	fraction of time windows are open (-).

The fraction of open windows ($f_{openwindows}$) was adjusted to account for window opening only during times of mild weather, as shown in Equation 3 (Chen et al., 2012b). Windows are not assumed to be open during any non-mild weather conditions (i.e., summer and winter), largely because of a lack of existing data on window opening behavior during heating and cooling periods across the U.S.

$$f_{openwindows} = f_{mild} f_{openwindows,mild} \quad (3)$$

where

f_{mild}	=	fraction of time mild weather is experienced (-);
$f_{openwindows,mild}$	=	fraction of time windows are open during mild weather (-).

$\lambda_{openwindows}$ is based on $\lambda_{closedwindows}$ for each home but is adjusted for the fraction of time that windows are open either a low or high amount ($p_{openwindows,low}$ or $p_{openwindows,high}$) using a constant air exchange rate multiplier for each opening condition ($m_{openwindows,low}$ or

$m_{openwindows,high}$) as shown in Equation 4. Air exchange rate (AER) multipliers are quantified in a later section.

$$_{openwindows} = {}_{closedwindows}\left(p_{openwindows,low}m_{openwindows,low} + p_{openwindows,high}m_{openwindows,high}\right) \qquad (4)$$

where

$p_{openwindows,low}$	=	probability of low window opening (-);
$p_{openwindows,high}$	=	probability of high window opening (-);
$m_{openwindows,low}$	=	air exchange rate multiplier during periods of low window opening (-);
$m_{openwindows,high}$	=	air exchange rate multiplier during periods of high window opening (-).

Similarly, long-term size-resolved envelope penetration factors are estimated based on size-resolved penetration factors during closed-window periods and the fraction of time windows are open (with higher penetration factors), as shown in Equation 5.

$$P_i = P_{i,closedwindows}(1 \quad f_{openwindows}) + P_{i,openwindows}f_{openwindows} \qquad (5)$$

where

$P_{i,closedwindows}$	=	closed windows size-resolved envelope penetration factor in a home (-);
$P_{i,openwindows}$	=	average size-resolved penetration factor with windows open (1/hr).

Values for $P_{i,openwindows}$ are estimated by taking into account separate values for low and high window opening conditions as well as the probability of each opening condition, as shown in Equation 6.

$$P_{i,openwindows} = P_{i,openwindows,low} p_{openwindows,low} + P_{i,openwindows,high} p_{openwindows,high} \tag{6}$$

where

$P_{i,openwindows,low}$ = size-resolved penetration factor during periods of low window opening (-);

$P_{i,openwindows,high}$ = size-resolved penetration factor during periods of high window opening (-).

For high window opening conditions, $P_{i,openwindows,high}$ is assumed to be equal to 1 for all particle sizes. For low window opening conditions, $P_{i,openwindows,low}$ is estimated by taking into account both closed window penetration factors through infiltration and assuming a penetration factor of 1 for any additional air exchange provided by excess natural ventilation, as shown in Equation 7.

$$P_{i,openwindows,low} = P_{i,closedwindows} \frac{{}_{closedwindows}}{{}_{openwindows,low}} + (1) \frac{{}_{openwindows,low} \qquad {}_{closedwindows}}{{}_{openwindows,low}} \tag{7}$$

where

$\lambda_{openwindows,low}$ = air exchange rate during periods of low window opening (1/hr);

Long-term values for $k_{i,dep}$ are adjusted in a similar manner to account for greater particle removal during times of window opening (He, Morawska, & Gilbert, 2005), as shown in Equation 8.

$$k_{i,dep} = k_{i,dep,nat}(1 \quad f_{openwindows}) + k_{i,dep,openwindows} f_{openwindows} \qquad (8)$$

where

$k_{i,dep,closedwindows}$	=	size-resolved deposition rate in a home with doors and windows closed (1/hr);
$k_{i,dep,openwindows}$	=	size-resolved deposition rate with windows open (1/hr).

Values for $k_{i,dep,openwindows}$ are adjusted in a similar manner as $P_{i,openwindows}$ by taking into account separate values for low and high window opening conditions as well as the probability of each opening condition, as shown in Equation 9.

$$k_{i,dep,openwindows} = k_{i,dep,openwindows,low} p_{openwindows,low} + k_{i,dep,openwindows,high} p_{openwindows,high} \qquad (9)$$

where

$k_{i,dep,openwindows,low}$	=	size-resolved deposition rate with windows open a small amount (1/hr);
$k_{i,dep,openwindows,high}$	=	size-resolved deposition rate with windows open a large amount (1/hr).

$k_{i,dep,openwindows,low}$ is adjusted for all sizes by a constant deposition rate multiplier, α:

$$k_{i,dep,openwindows,low} = \alpha k_{i,dep,closedwindows}$$

Similarly, $k_{i,dep,openwindows,high}$ is adjusted for all sizes by a constant deposition rate multiplier, β:

$$k_{i,dep,openwindows,high} = \beta k_{i,dep,closedwindows}$$

Values for α and β are quantified in a subsequent section. The following sections describe how statistical distributions were gathered for each of the input parameters described above.

3.2 Input parameters

Accurate distributions of each of these input parameters are required to complete the simulations herein. This section first describes the collection of inputs that are independent of particle size, including air exchange rates due to infiltration alone ($\lambda_{closedwindows}$), recirculation rates through HVAC systems (λ_{HVAC}), fractional operation times of HVAC systems (f_{HVAC}), window opening behavior and associated elevations in air exchange rates. The subsequent section describes particle-size-dependent input parameters, including envelope penetration factors (P_i), indoor deposition rates ($k_{i,dep}$), and filter removal efficiency ($\eta_{i,HVAC}$), which is also based on information on central HVAC system and filter ownership. These values are taken from a wide variety of sources in order to establish a best estimate of the statistical distribution for each input parameter in single-family homes across the U.S. Both of these sections will also describe the multiplier values used to account for each level of window opening on air exchange rates, indoor deposition rates and envelope penetration factors, as well as the number of simulations completed for this Monte Carlo study.

3.2.1 Input parameters independent of particle size

3.2.1.1 Air exchange rate due to infiltration alone ($\lambda_{closedwindows}$). Infiltration AERs have been measured in thousands of buildings worldwide and have been shown to vary widely both across buildings and temporally within individual buildings (Murray & Burmaster, 1995; Offermann, 2009; L A Wallace, Emmerich, & Howard-Reed, 2002). Most recently, Persily et al. (2010) reported a statistical distribution of infiltration AERs in a representative sample of the U.S. residential building stock (Persily, Musser, & Emmerich, 2010). A lognormal distribution was fit based on the percentiles reported by Persily et al. We minimized the sum of the squared errors between their reported cumulative distribution function and a model of a lognormal cumulative distribution function, resulting in a geometric mean AER of 0.44 hr^{-1} (μ = -0.821 and σ = 0.713). Knowing that a typical median air exchange rate value is 0.5 hr^{-1} in residential buildings (Murray & Burmaster, 1995), we were able to validate the normal distribution used for the Monte Carlo simulation. The distribution used in this study is shown in Figure 1 below.

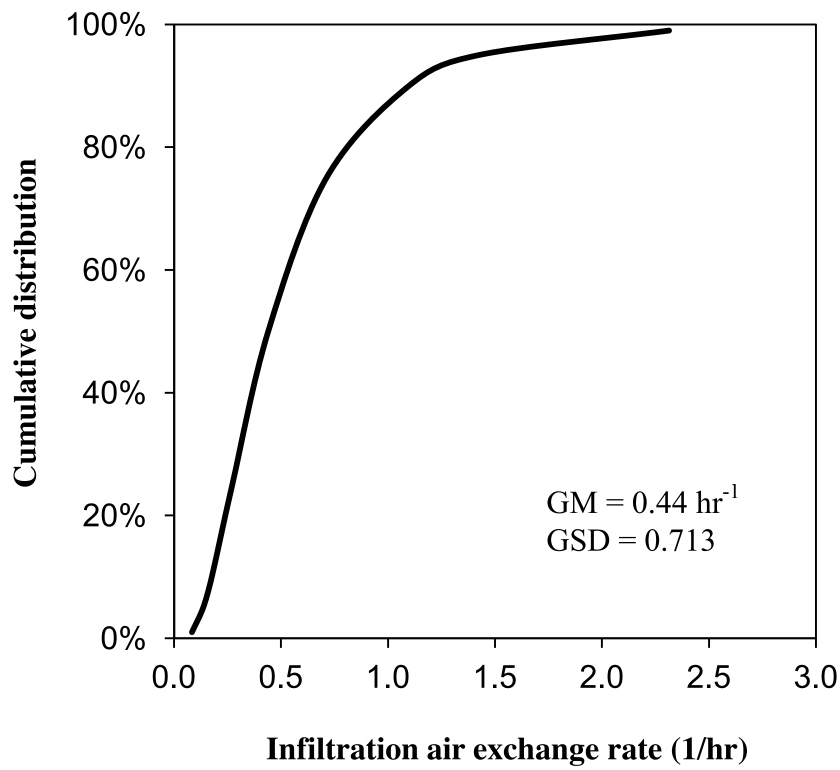

Figure 1. Distribution of infiltration air exchange rates ($\lambda_{closedwindows}$)

3.2.1.2 Recirculation rate through HVAC systems (λ_{HVAC}). For the homes that were assumed to have a central HVAC system, it is important to quantify the rate of airflow through the HVAC system relative to the volume of the space it serves (i.e., its recirculation rate with the HVAC system on). Unfortunately, there is surprisingly little information about recirculation rates in residential buildings in the existing literature. Previous studies have typically assumed values of λ_{HVAC} (Riley et al., 2002; Waring & Siegel, 2008). However, we rely on a distribution of actual recirculation rates measured with systems operating 17 residential and small commercial buildings (all of which utilized typical residential HVAC equipment) reported in Stephens et al. (2011) (Brent Stephens, Siegel, & Novoselac, 2011). A lognormal distribution of recirculation rates was fit with a geometric mean of 5.7 hr^{-1} (μ = 1.740 and σ = 0.228); one extreme outlier was excluded because it represented an atypical indoor environment. This distribution is shown in Figure 2 below. These values are not yet adjusted for fractional runtime.

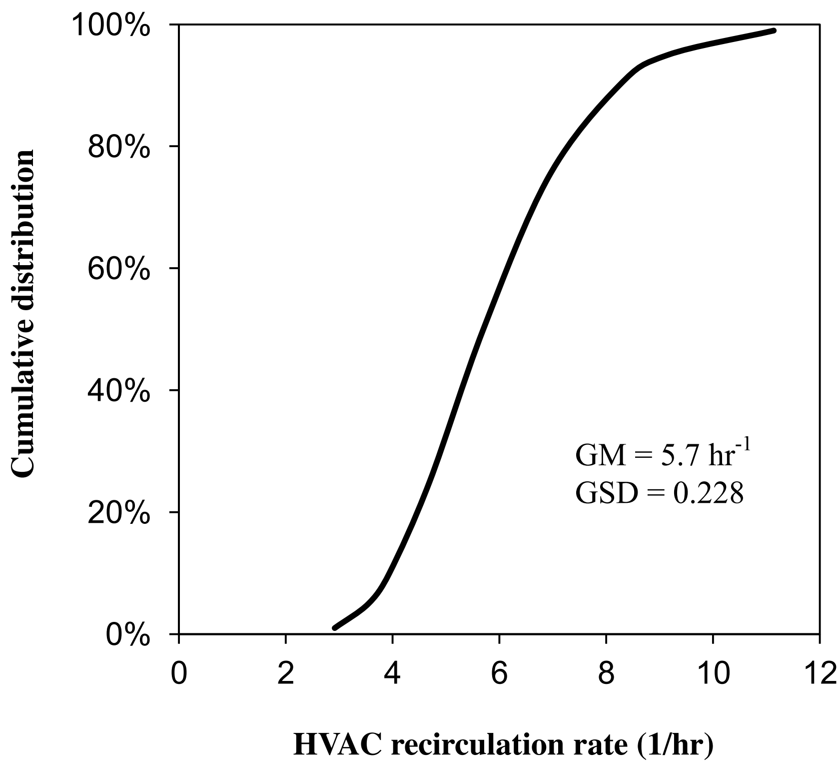

Figure 2. Distribution of HVAC system recirculation rates (λ_{HVAC})

3.2.1.3 Fractional runtime of HVAC system (f_{HVAC}). Previous similar investigations have either assumed values for fractional operation times (Neil E. Klepeis & Nazaroff, 2006; J. Thornburg et al., 2001; Waring & Siegel, 2008) or estimated them from building energy models (MacIntosh et al., 2009). Conversely, we compiled a database of previously measured fractional operation times in residences that were made during a variety of heating, cooling, and mild weather seasons for use in the simulations of homes assumed to have a central HVAC system. We used data from 37 homes in North Carolina

(J. W. Thornburg, Rodes, Lawless, Stevens, & Williams, 2004), 17 homes in Florida (J. W. Thornburg et al., 2004), and 17 homes and light-commercial buildings Texas (Brent Stephens et al., 2011) to build a statistical distribution that may be considered as generally representative for the residential building stock. The data were log-normally distributed with a geometric mean of 0.246, or 24.6% of the time (μ = -1.401 and σ = 0.615). This distribution is shown in Figure 3.

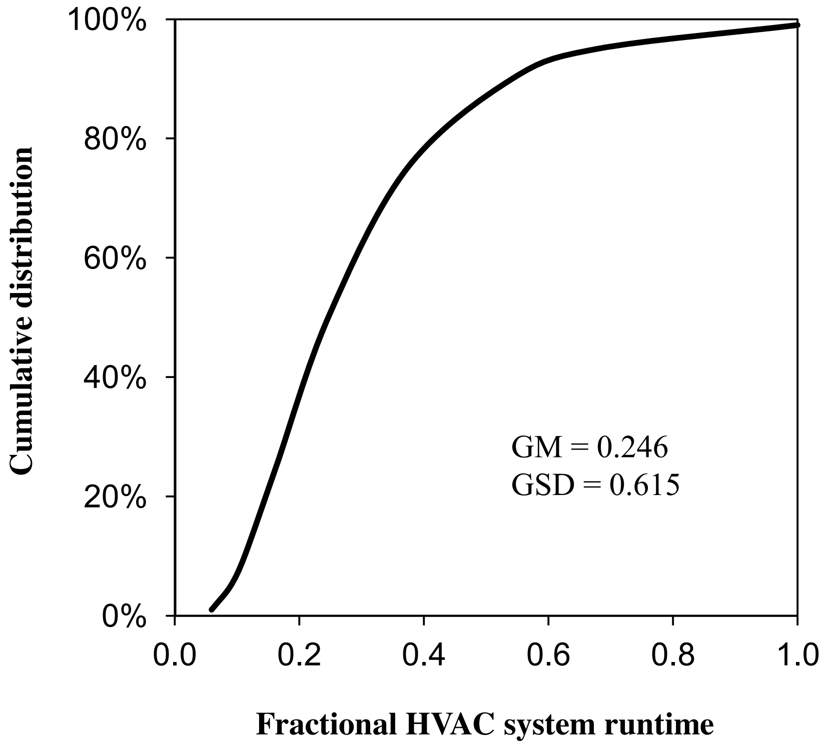

Figure 3. Fractional HVAC system runtimes (f_{HVAC})

3.2.1.4 Fraction of window opening ($f_{openwindows}$). Window opening is an important behavior to capture accurately for exposure modeling because values of air exchange rates, penetration factors, and particle deposition rates will all increase relative to periods of infiltration only. Therefore, we culled existing literature on window opening behaviors in homes, giving priority to large sample sizes. We also assumed that window opening occurred only during mild weather in the homes; therefore, we fit a nationwide distribution of fractions of the year that mild weather occurs using data reported in Chen et al. (2012), as shown in Figure 4 (Chen et al., 2012b). This data represented the fraction of mild weather measured in 83 cities in the U.S.

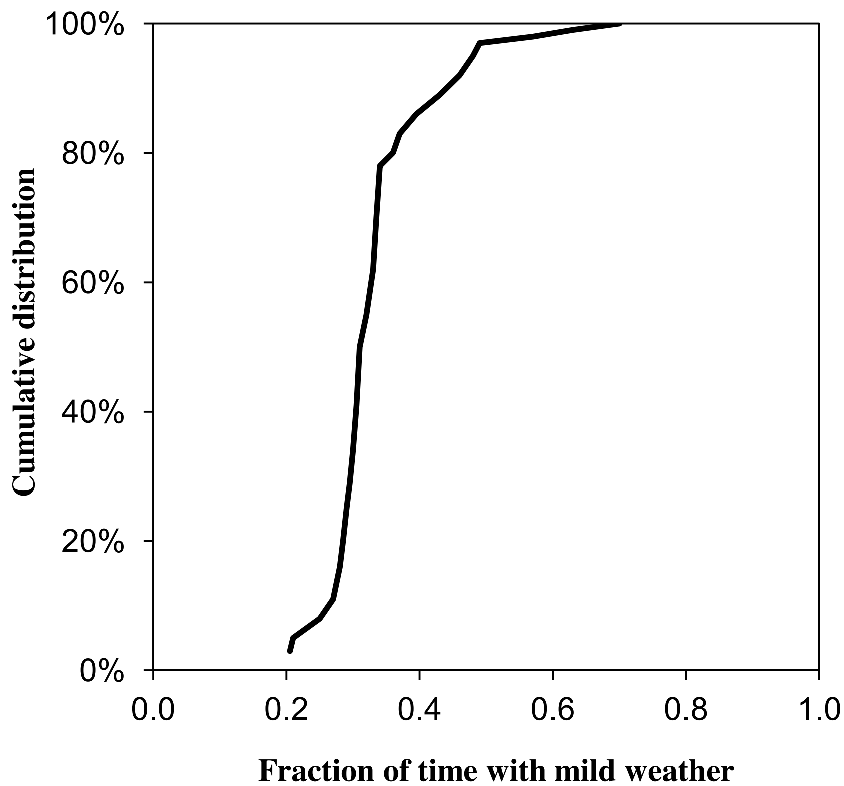

Figure 4. Cumulative distribution of the fraction of time with mild weather (f_{mild})

To assess the statistical distribution of window opening behaviors during periods of mild weather, we culled data primarily from a large study of single-family homes across the state of California (Price & Sherman, 2006). We limited use of their data only to mild weather times (i.e., spring seasons). For window opening fractions, we combined their ‘low’ and ‘medium’ opening characterizations into one ‘low’ window opening behavior class, which includes anywhere from only one or two windows opened slightly to as much as one or two windows open several inches. The ‘high’ window opening scenario was used to characterize homes with at least some windows or doors open fully. The distribution of the fraction of time windows are open during mild weather is shown in Figure 5.

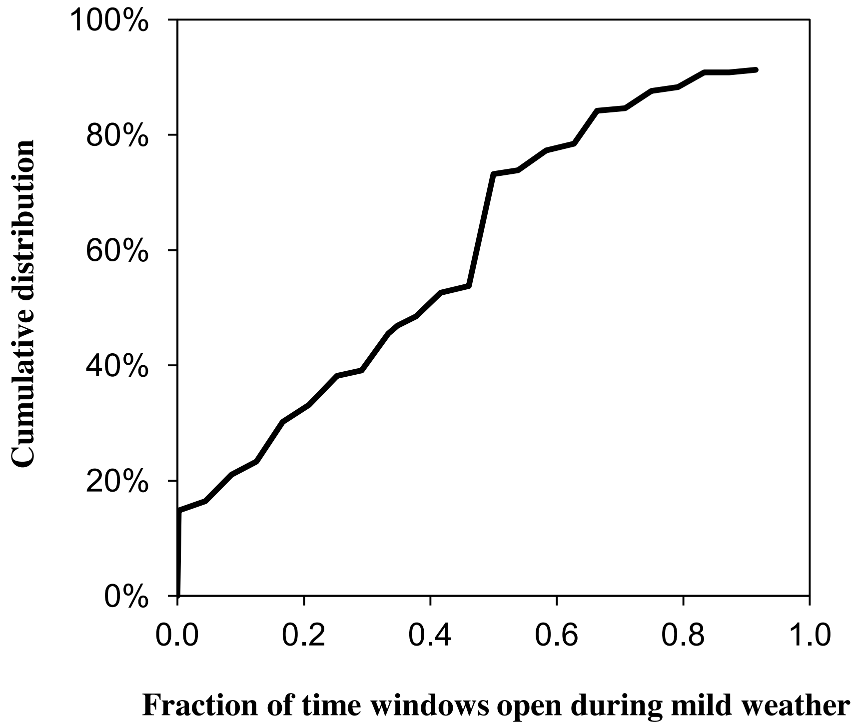

Figure 5. Cumulative distribution of the fraction of time the windows are open during periods of mild weather ($f_{openwindows,mild}$)

Because of the irregular shapes of the distributions for mild weather and window opening during mild weather, data from Figures 4 and 5 were used to create step-wise functions instead of continuous distributions. The median fraction of time with mild weather across the U.S. was shown to be around 31%. The median fraction of time with windows open during mild weather was around 40% of the time. Therefore, the median long-term average fraction of time that windows were open was approximately 13%, which is in a similar range as other studies on window opening behavior (Johnson & Long, 2004). A table summarizing the step-function used to determine window opening is shown below.

Table 1. Step function for the fraction of mild weather

Percentile	**Fraction of mild weather, f_{mild}**
0 - 3	0.205
3-5	0.210
5-8	0.250
8-11	0.270
11-16	0.280
16-20	0.285
20-25	0.290
25-29	0.295
29-34	0.300
34-41	0.305
41-50	0.310
50-55	0.320
55-62	0.330
62-70	0.335
70-78	0.340
78-80	0.360
80-83	0.370
83-86	0.395
86-89	0.430
89-92	0.460
92-95	0.480
95-97	0.490
97-98	0.570
98-99	0.630
99-100	0.700

A table summarizing the step-function used to determine window opening is shown below.

Table 2. Step function for the fraction of window opening

Percentile of homes	**Fraction of window opening during mild weather, $f_{openwindows,mild}$**
0-15	0.000
15-21	0.065
21-23	0.105
23-30	0.146
30-33	0.187
33-38	0.230
38-39	0.272
39-46	0.312
46-47	0.340
47-48	0.362
48-53	0.397
53-54	0.438
54-73	0.480
73-74	0.519
74-77	0.561
77-78	0.605
78-84	0.645
84-85	0.686
85-88	0.729
88-100	0.832

3.2.1.5 Air exchange rates during window opening ($\lambda_{openwindows}$). Using data from Price and Sherman (Price & Sherman, 2006), we assumed that when windows are open in a home, 20% of the time they are open to a large extent (i.e., 'high' window opening) and 80% of the time they are open to a low or moderate amount (i.e., 'low' window opening). These fractions were assumed to be constant across all homes due in part to the findings in Price and Sherman (Price & Sherman, 2006) and in part to a lack of more detailed distribution data. We then assumed values for an air exchange rate multiplier for each window opening scenario ($m_{openwindows,low}$ and $m_{openwindows,high}$). We assumed that the AER during times of low window opening was two times higher than the home's closed-window infiltration AER and four times higher during times of high window opening; therefore $m_{openwindows,low}$ = 2 and $m_{openwindows,high}$ = 4. These multipliers are assumed constant in each home and were derived from measurements reported Wallace et al. (2002) (L A Wallace et al., 2002), who measured AERs during moderate and high window opening, as well as Marr et al. (2012) (Marr, Mason, Mosley, & Liu, 2012), who measured AERs during moderate window opening. Values for AER multipliers are also similar to the mean values measured in Johnson et al. (2004) (Johnson, Myers, Kelly, Wisbith, & Ollison, 2004) with one window open and three or more windows open, as well as those utilized in Chen et al. (2012) (Chen et al., 2012b). Similar values for AER multipliers were also used in Chen et al. (2012). After accounting for window opening behavior during times of mild weather, the median air exchange rate (0.44 hr^{-1}) increased to a long-term average of 0.50 hr^{-1} (a 14% increase). The bottom percentile of window opening increased infiltration AERs by <5% while the top increased long-term AERs by 25% or more relative to infiltration only.

3.2.2 Particle size-resolved input parameters

3.2.2.1 Penetration factors (P_i). Chen and Zhao (2011) provide an extensive review of previous measurements of size-resolved particle infiltration factors and penetration factors in residences (Chen & Zhao, 2011). Infiltration factors are helpful for understanding exposures, but cannot distinguish between envelope sources or losses by deposition to surfaces, control by HVAC systems, and other mechanisms. Penetration factors are a more useful fundamental parameter for elucidating the relative impact of building envelopes on indoor exposures. Studies that have measured particle penetration factors in homes vary widely in their particle sizes over which the values were measured, as well as in their estimates of uncertainty and number of homes measured. We have not been able to identify a particular study that investigated the full range of particle sizes of interest (0.001-10 μm), so we have relied on a combination of all of the previous studies reported in Chen and Zhao (Chen & Zhao, 2011), which summarized penetration factors of 0.01 to 10 μm measured in approximately 10 homes in several other studies (Chao, Wan, & Cheng, 2003; Long, Suh, Catalano, & Koutrakis, 2001; Thatcher et al., 2003; Vette A. F. et al., 2001; Zhu et al., 2005). We also included another recent study in our summary, which also measured penetration factors of ~10-100 nm particles in a test house.

There is considerable variability in these measured values of penetration factors, depending on both individual homes and particle sizes of interest. However, because sample sizes are small and we lack more robust data, we rely on an estimate of the midpoint of the size-resolved penetration factors across any and all applicable homes included in the review in Chen and Zhao (2011) (Chen & Zhao, 2011) with the addition of Rim et al. (2010) (Rim, Wallace, & Persily, 2010b) to estimate mean values of $P_{i,closedwindows}$ for each particle size. We have also extrapolated results from 1-10 nm, assuming a log-linear decrease toward zero for 1 nm particles.

Additionally, we have included a measure of likely variability in size-resolved values for $P_{i,closedwindows}$ using relative standard deviations from the two largest previous studies of particle penetration factors of which we are aware. Williams et al. (2003)

reported mean (± s.d.) values for penetration factors of $PM_{2.5}$ of 0.72±0.21 in 37 homes in North Carolina (and thus a relative standard deviation of ~29%) (Williams et al., 2003). Similarly, Stephens and Siegel (2012) reported mean (± s.d.) values of penetration factors for submicron particles (20-1000 nm) of 0.47±0.15 in 19 homes in Texas (with a relative standard deviation of ~32%) (B. Stephens & Siegel, 2012). We have therefore used a relative standard deviation of 30% for all of the size-resolved penetration factors utilized in this study, which provides a reasonable estimate of the statistical bounds on $P_{i,closedwindows}$ in the absence of better information. We also assume that values for every particle size increase or decrease together in the same direction and the same relative magnitude. Thus, the mean (± one standard deviation) size-resolved penetration factors used in the simulations is shown in Figure 6.

Penetration factors during periods of window opening are estimated according to Equations 5-7. In this procedure, we assume that when windows are open a small amount (i.e., low opening), some fraction of outdoor air still enters through the envelope ($\lambda_{closedwindows}/\lambda_{openwindows,low}$) with the closed-window penetration factor($P_{i,closedwindows}$). Any additional amount of outdoor air ($1 - \lambda_{closedwindows}/\lambda_{openwindows,low}$) is assumed to enter through open windows with a penetration factor of 1. Therefore the long-term average envelope penetration factor will always be greater than or equal to the closed-window envelope penetration factor. When windows are open a large amount, we simply assume that the penetration factor for every particle size is equal to 1.

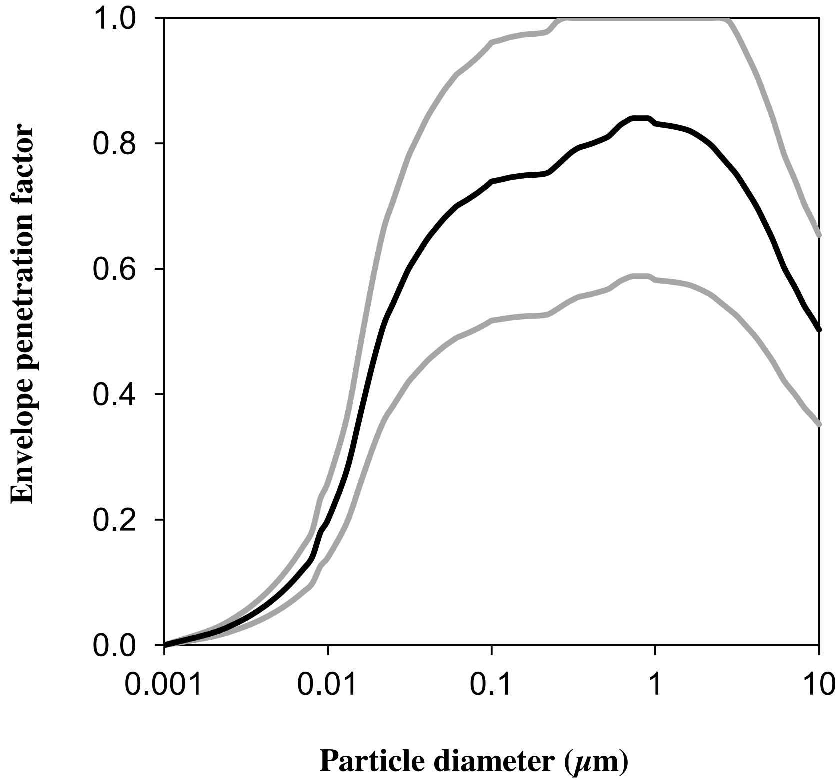

Figure 6. Size-resolved particle penetration factors ($P_{i,closedwindows}$). Black lines represent mean values and gray lines represent ± one standard deviation

3.2.2.2 Indoor deposition rates ($k_{i,dep}$). Another important size-resolved loss mechanism in indoor environments is particle deposition to indoor surfaces ($k_{i,dep}$). Previous modeling studies have estimated deposition rates using physical models (Riley et al., 2002), but we rely on a range of size-resolved deposition rates measured in real residential environments. In one of the largest investigations of size-resolved particle deposition rates, He et al. (2005) reported size-resolved measurements of $k_{i,dep}$ in 14 homes in Australia under two different ventilation conditions: doors and windows closed (infiltration AER) and with some doors and windows open (natural ventilation) (He et al., 2005). Increased ventilation rates with windows open will increase indoor air speeds, which will in turn increase particle deposition rates. The same study reported size-resolved deposition rates measured in several other residential studies (mostly in the U.S.), and noted large differences between their measured values and others, due perhaps to differences in estimation methods and/or the type of aerosol source utilized (deposition rates also vary according to particle density and shape). Given these issues, we used a polynomial curve to fit the shape of size-resolved deposition rates from He et al., but adjusted the mean values downward to the midpoints of the other reported studies in order to better reflect results from other studies in U.S. homes. The resulting polynomial curve yields $k_{i,dep,closedwindows} = 1.06 + 1.83\times(\log D_p) + 1.65\times(\log D_p)^2$, where D_p is in µm. We also used the relative standard deviations (mean RSD ~68% across all particle sizes) reported in He et al. (2005) (He et al., 2005) to establish bounds on the likely statistical distribution of deposition rates in homes across the building stock. These values are shown in Figure 7.

Finally, increased AERs with windows open will increase indoor air speeds, which will in turn increase particle deposition rates (K. Lai & Nazaroff, 2000). Therefore, we estimated size-resolved deposition rate multipliers with windows open (α and β) using the same data from He et al. (2005). We used their polynomial fits for mean size-resolved deposition rates from Figures 3 and 4 in their manuscript for periods of windows closed and windows open, respectively. We then calculated the ratio between $k_{i,dep,openwindows}$ and $k_{i,dep,closedwindows}$ and averaged the ratio across all particle size bins. The resulting value was approximately 1.7; that is, with windows open, the mean deposition rate increased approximately 70% over that measured during periods with windows closed. Thus we assume that β = 1.7 with windows open a large amount. Additionally, we estimated that α = 1.23 for periods with windows open a small amount, based on an assumed linear relationship between deposition rates and air exchange rates (AERs were estimated as 2 times higher with windows open a low amount and 4 times higher with windows open a large amount; thus $\alpha = (2-1)/(4-1)\times\beta = 1.23$).

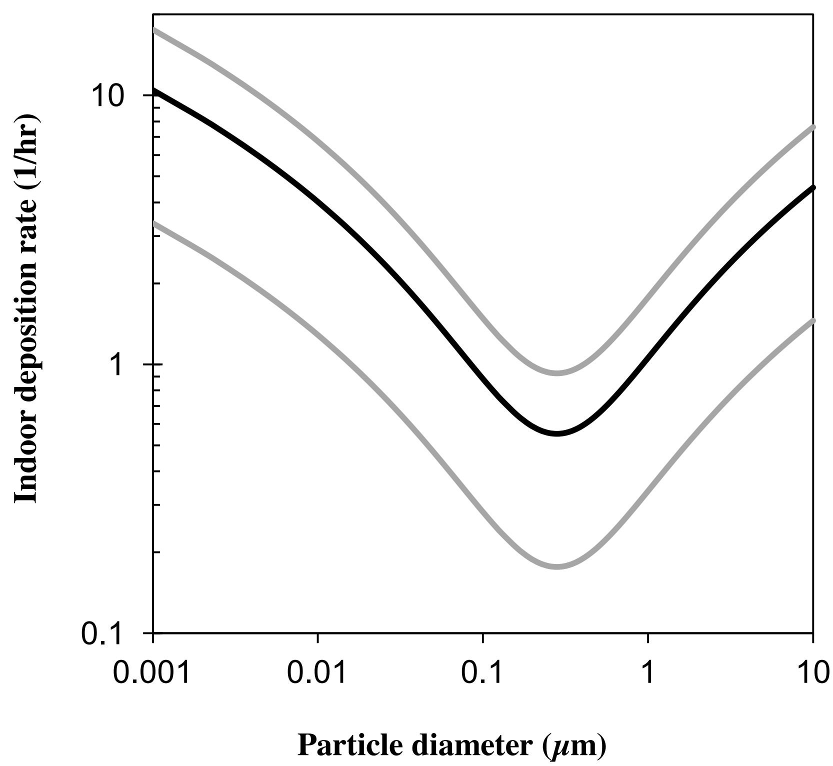

Figure 7. Size-resolved deposition rates during periods of closed-window infiltration ($k_{i,dep,closedwindows}$). Black lines represent mean values and gray lines represent ± SD.

3.2.2.3 Filter removal efficiency (η_i). The presence and use of air-conditioning and forced-air heating has been shown to be a significant predictor for particulate matter infiltration factors in field studies (Allen et al., 2012; Clark et al., 2010; Hystad et al., 2009; Meng et al., 2005). This decrease is most likely attributed to particle filters installed in HVAC systems; even if a very low efficiency filter is used, HVAC filters can increase indoor particle loss rates due to typically larger recirculation rates through HVAC systems (MacIntosh et al., 2008, 2009). Higher efficiency filters intuitively have a greater effect (Hanley, Ensor, Smith, & Sparks, 1994; B. Stephens & Siegel, 2012, 2013). A wide range of particle filters exist in the residential market, so it is necessary to understand both (i) the removal efficiency of a range of commonly available HVAC filters and (ii) HVAC filter ownership across the building stock in order to estimate the impacts that HVAC filtration likely has on size-resolved particle infiltration factors in U.S. residences. We ignore deposition to HVAC ductwork surfaces for lack of more robust data (Sippola & Nazaroff, 2004; Lance A. Wallace, Emmerich, & Howard-Reed, 2004).

HVAC filters are typically tested for particle removal efficiency only in laboratory settings. ASHRAE Standard 52.2 is the most commonly used test standard in the U.S. The standard assigns filters a minimum efficiency reporting value (or MERV) according to the ability of the filter to remove 0.3-10 μm particles. However, to extend the particle size range below 0.3 μm, we utilize polynomial fits for recent measurements of size-resolved particle removal efficiency reported for a range of commercially available HVAC filters in Hecker and Hofacre (2008) (Hecker, Hoffacre, 2008), which reported removal efficiencies for as low as 30 nm particles. Using these polynomial fits, we were able to calculate filter removal efficiencies for most of the filter categories we studied (MERV 6, MERV 8, MERV 12, and MERV 16), covering the particle size range we studied.

Therefore, polynomials for each of the categories from MERV 6 to MERV 16 were approximated as follows:

$$Y = a + bx + cx^2 + dx^3 \tag{10}$$

Parameters a, b, c and d are filter dependant and are reported in Table 3 below.

Table 3. Coefficients used to determine size-resolved filter removal efficiencies

Filter Category	Coefficients			
	a	b	c	d
MERV 6	1.9311	-0.1441	-0.1243	-0.0234
MERV 8	0.5839	0.1675	0.1289	0.0188
MERV 12	1.3943	-0.908	-0.624	-0.0404
MERV 16	0.3855	-2.0698	0.5326	1.3895

Additionally, particle removal efficiency values for the lowest efficiency filters (MERV <5) were taken from Waring and Siegel (Waring & Siegel, 2008). However, since the measurements made by these authors only covered particles with a diameter as small as 10nm, we completed the filter efficiency values using a model developed by Kowalski and Bahnfleth (Kowalski & Bahnfleth, 2002). The previous model is explained below.

Assuming that each filter is mainly constituted by three media sizes, the filter removal efficiency is:

$$E = L_u . \left(1 - e^{-\sum_{i=1}^{3}(d_i . E_{Di} + f_i . E_{Ri}) S_i}\right) \tag{11}$$

where

L_u	=	maximum value for the filter efficiency (-);
d_i, f_i	=	correction factors (-);

S_i = fiber projected area (-).

According to Kowalski et al., the fiber projected area can be defined as:

$$S_i = \frac{4*10^6.L.a}{\pi*d_f} \tag{12}$$

where

L = length of the filter media in the direction of the airflow (m);

a = filter media volume fraction (m^3/m^3);

d_f = fiber diameter (mm).

Kowalski et al. defined the single fiber diffusion efficiency E_{Di} as the following:

$$E_{Di} = 1.6125(\frac{1-a}{F_K})^{1/3}.P_e^{-\frac{2}{3}} \tag{13}$$

where

F_K = Kuwabura hydrodynamic factor (-), defined as:

$$F_K = a - \frac{a^2+2.\ln(a)+3}{4} \tag{14}$$

and P_e = Peclet number (-), defined as:

$$P_e = \frac{1*10^{-6}.U.d_f}{D_d} \tag{15}$$

where

U = media face velocity (m/s);

D_d = particle diffusion coefficient (m^2/s) ;

The particle diffusion coefficient can be calculated as follows:

$$D_d = \mu.k.T \tag{16}$$

where

μ = particle mobility (N.s/m);

k = Boltzman's constant, k = 1.3708 * 10^{-23} J/K;

T = temperature (K).

Kowalski et al. defined the particle mobility defined as:

$$\mu = \frac{C_h}{3*10^{-6}.\pi.\eta.d_p} \tag{17}$$

η = absolute gas viscosity (N.s/m^2);

C_h = Cunningham slip factor (-).

The Cunningham slip factor is defined as:

$$C_h = 1 + \frac{\lambda_{gas}}{d_p}.(2.492 + 0.84e^{-\frac{0.435d_p}{\lambda}})$$

(18)

where

λ_{gas} = gas molecule mean free path, 0.067μm.

According to Kowalski et al., the single-fiber interception efficiency E_R is:

$$E_R = \frac{\frac{1}{\varepsilon}.(1-\alpha)}{F_K}\frac{(N_r^2)}{(1+N_r)} \tag{19}$$

where

N_r = interception parameter (-);

ε = correction factor for inhomogeneity (-), ε =1.6 for polyester filters.

And the interception parameter is defined by:

$$N_r = \frac{d_p}{d_f} \tag{20}$$

Size-resolved HVAC filter removal efficiencies for five broadly representative classes of filters are summarized in Figure 8.

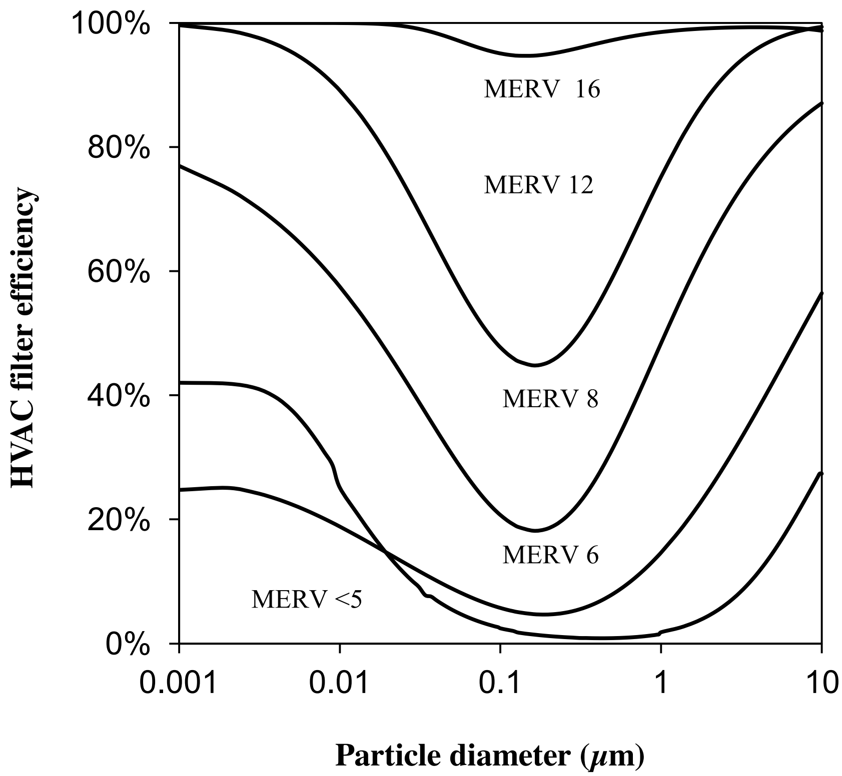

Figure 8.Size-resolved particle removal efficiency ($\eta_{i,HVAC}$) for the 5 classifications of filters used in this study: MERV<5, MERV 6, MERV 8, MERV 12, and MERV 16

3.3 HVAC system and filter ownership.

According to an American housing survey conducted by the U.S. Census Bureau, approximately 65% of residences in the U.S. utilize central HVAC systems. Since the sample size used in this study is large enough (representative of 111 million residential homes), we can easily assume that 65% of all residential U.S. buildings own an HVAC system that includes filtration. In this study, we decided to use 5 different filter categories: MERV <5, 6, 8, 12 and 16 (similar to HEPA), which cover a range of filters used in residential homes. However, very little information exists on the distribution of types of filter across the residential building stock. In a survey of 17 homes in Austin, TX with central HVAC systems, Stephens and Siegel (2012) observed the following distribution of installed HVAC filter types: 5 homes utilized MERV <5; 9 homes utilized MERV 6-8; 2 homes utilized MERV 11-12; and 1 home utilized MERV 16 . In a survey of three pilot test homes, Offermann (2009) reported that two utilized MERV 6 filters and one utilized a MERV 8 filter (Offermann, 2009). A conversation with an anonymous contact in the residential filtration industry confirmed that ~75% of their filter sales were MERV 7 or lower. Therefore, we assumed a distribution of HVAC filter ownership in U.S. single-family residences, as shown in Table 4.

Table 4. Estimate of HVAC filter ownership across the building stock (for homes with HVAC systems)

Filter type	% ownership
MERV <5	25%
MERV 6	30%
MERV 8	30%
MERV 12	10%
MERV 16	5%

3.4 Monte Carlo simulations

A Monte Carlo approach was used to estimate the likely distribution of size-resolved ratios of indoor particles of outdoor origins in single-family residences across the U.S. building stock using the aforementioned statistical distributions of each input parameter. A total of 100,000 simulations were performed for 102 individual particle diameters between 0.001 and 10 μm. Because approximately 65% of residences in the U.S. have central HVAC systems (HUD, 2007), 65,000 simulation cases were assigned an HVAC system; the other 35,000 were assumed to have no central HVAC system.

3.4.1 Number of simulations. One of the main parameters to account for in a Monte Carlo simulation is the total number of simulations. Performing such a simulation with a too few simulations would result in unstable results, which would vary with the sampled parameters. Hence, it is essential to determine the minimum number of simulations required to ensure that the overall results (i.e., infiltration factors, in our case) do not vary when other random parameters are pulled throughout the simulation. Usually, 10000 to 20000 simulations are performed in order to guarantee a stabilization of the results, but this number depends on the type of simulation that is run.

Given the distribution of filter categories shown in Table 4, we can notice that, if we assume to simulate 20,000 houses, only 600 cases would be attributed to the MERV 16 filter category. This number being the lowest subset, we performed a sensitivity analysis that showed that 600 cases were not sufficient to obtain consistent results for this MERV category. Therefore, we needed to increase the number of simulations of the MERV 16 category until we reached a stabilization of the results obtained from these random simulations, as shown in Figure 9 below. Consequently, the number of simulations was chosen such that the smallest group of simulated homes (those with MERV 16 HVAC filters) was still large enough to capture a wide range in predicted values (n_{MERV16} = 3,250). A total of 100,000 simulations were performed for 102 individual particle diameters between 0.001 and 10 µm.

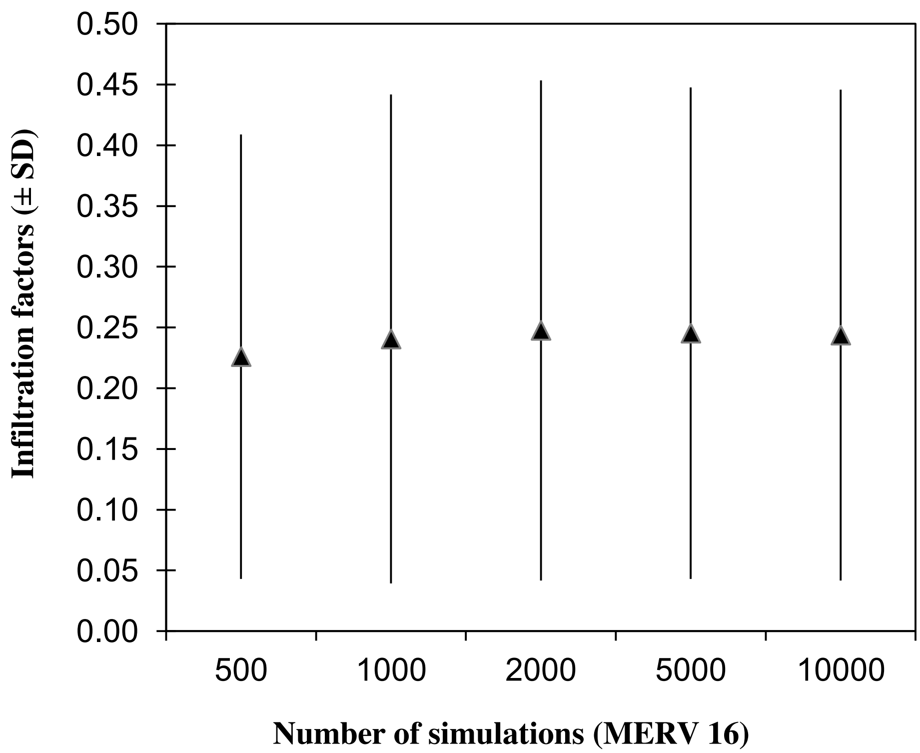

Figure 9. Sensitivity on the number of simulations performed on the MERV 16 category

3.4.2 Methodology of the simulations. Simulations began by drawing size-independent parameters randomly from the aforementioned distributions (Figures 1, 2 and 3). Simultaneously, closed-window values for size-resolved deposition rates and penetration factors were also randomly drawn from the individual distributions in Figures 6 and 7 (and scaled in the same direction and relative magnitude for each particle size). Values for penetration factors, filter removal efficiencies, and HVAC system runtimes were limited to values between 0 and 1. Deposition rates were limited to values greater than zero. At this point, each home was uniquely identified in the simulations with this range of closed-window building characteristics.

Subsequently, the long-term average fraction of mild weather, fraction of window opening, and type of filter used (if the home had an HVAC system) were all selected at random according to the inputs in Figures 4 and 5 and Table 4. Each parameter was assumed to be independent of all other parameters, which may not be entirely realistic. For example, closed-window envelope penetration factors were recently shown to be correlated with air exchange rates (AERs) (B. Stephens & Siegel, 2012); however, the relationships between many of these parameters are not yet well known. Additionally, there is some evidence that occupants may be more likely to open windows in homes without central HVAC systems during a wider range of seasons (Marr et al., 2012). However, we do not account for this herein, largely because we are not aware of existing data on these relationships.

From there, long-term average AERs, penetration factors, and deposition rates were estimated according to Equations 3-9. Finally, each sampled long-term input parameter was used to estimate the long-term average indoor proportion of outdoor particles of diameter i in each simulated home according to Equation 1. Results were then explored in order to describe the likely distribution of size-resolved infiltration factors (in the absence of indoor sources) across the entire U.S. single-family residential building stock. Simulations were performed in MATLAB R2012a. The model code is included in Appendix A in its entirety.

3.5 Multiple regression analysis for influential parameters

In order to explore the most influential input parameters for predicting size-resolved infiltration factors, a multiple linear regression was performed on all 100,000 modeled values of $F_{i,inf}$ for each of the 102 particle size bins. Seven model input parameters are used as possible predictor variables, including closed-window penetration factors ($P_{i,closedwindows}$), deposition rates ($k_{i,dep,closedwindows}$), and air exchange rates ($\lambda_{closedwindows}$); HVAC filter efficiency ($\eta_{i,HVAC}$); HVAC recirculation rate (λ_{HVAC}); HVAC system runtime (f_{HVAC}); and the fraction of time windows are open ($f_{openwindows}$). Only the closed-window values were used for the relevant input parameters because their long-term average values are a function of another predictor variable ($f_{openwindows}$). The multiple regression analysis followed the format in Equation 21.

$$F_{i,inf} = x_1 + x_2 \;{}_{closedwindows} + x_3 f_{openwindows} + x_4 f_{HVAC} + x_5 \;{}_{HVAC} + x_6 \;{}_{i,HVAC} + x_7 k_{i,dep,closedwindows} + x_8 P_{i,closedwindows} \tag{21}$$

The regression was performed using Stata Version 11 using (i) results from all of the 100,000 simulated homes, (ii) results from the 35,000 simulated homes without HVAC systems, and (iii) results from the 65,000 simulated homes with HVAC systems. Standardized regression coefficients were used to normalize the strength of each predictor variable.

3.6 Estimating indoor inhalation doses of fine and ultrafine particulate matter

After predicting size-resolved infiltration factors, we also determined the dose of particulate matter inhaled during one year by a 30 – 40 year old male if he were living in the simulated homes over the course of a year. According to Klepeis et al., we considered that this individual spent in average 69% of his time is his house (252 days), and we only took into consideration the exposure resulting from the time spent in his home (Neil E. Klepeis et al., 2001). We based our calculations on a size-resolved urban outdoor distribution reported by Costabile et al. in Leipzig, Germany (Costabile et al., 2009). (Accurate long-term average outdoor particle distribution data were not available from any relevant sites in the U.S.). Based on the Environmental Protection Agency's (EPA) Exposure Factors Handbook (EPA, 1997), we assumed that the mean breathing rate of a 30-40 years old male is equal to 16.88 m^3/day. Using these outdoor distributions, breathing rates, and time activity patterns, we were able to assess the dose inhaled indoors by the average individual both in terms of fine particulate matter ($PM_{2.5}$) and of ultrafine particles (UFP).

The indoor size-resolved mass concentration $M_{i,indoors}$ (assuming spherical particles with a diameter d_p) is calculated as follows (we assumed a particle density of 1 g/cm^3):

$$M_{i,indoors} = C_{i,in} \; x \; \rho \; x \; \pi \; x \; \frac{dp,i^3}{6} \tag{22}$$

where

ρ = particle density, ρ = 1 g/cm^3;

$d_{p,i}$ = particle diameter (µm).

Therefore, the total dose of indoor fine particulate matter inhaled over the course of one year, $PM_{2.5,\,inhaled}$ is given by the following equation:

$$PM_{2.5,inhaled} = \sum_{d_p=0.001\mu m}^{d_p=2.5\mu m} M_{i,indoors} \; x \; Q_b \; x \;\; T \tag{23}$$

where

Q_b = breathing rate of an average individual (m^3/day);

T = exposure time (day).

Similarly, we were able to summarize the average human exposure in terms of UFPs. The size-resolved number concentration inhaled by an average individual indoors $C_{i,in,inhaled}$ is:

$$C_{UFP,in,inhaled} = C_{UFP,in}\ x\ Q_b\ x\ T \qquad (24)$$

The dose of UFP inhaled by an average individual indoors $UFP_{inhaled}$ is:

$$UFP_{inhaled} = \sum_{d_p=1nm}^{d_p=100nm} C_{i,in,inhaled} \qquad (25)$$

CHAPTER 4

RESULTS

Estimates of the likely distribution of long-term average size-resolved infiltration factors ($F_{i,inf}$) across the U.S. single-family residential building stock are shown in Figure 10. Seven percentiles are shown based on the results from the 100,000 simulations herein: from the 1st percentile to the 99th percentile. Minimum and maximum values are excluded for clarity.

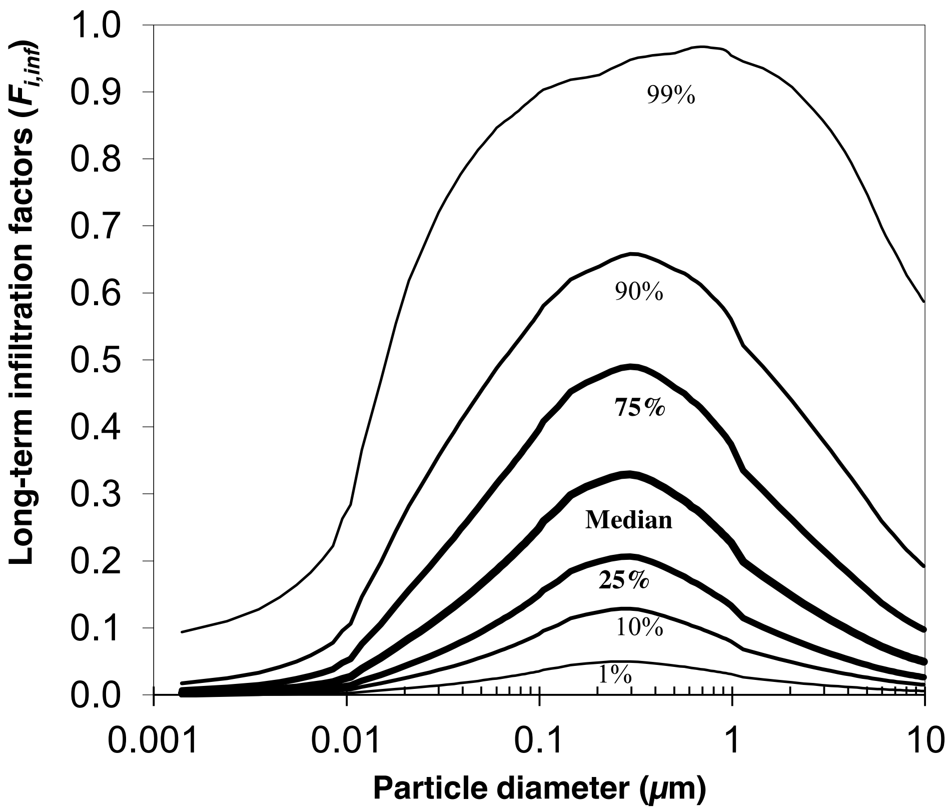

Figure 10. Estimate of the distribution of long-term averaged size-resolved infiltration factors ($F_{i,inf}$) across the U.S. single-family residential building stock

For some particle sizes in Figure 10, long-term average infiltration factors ($F_{i,inf}$) are estimated to vary by a factor of ~20 to more than 100 from the 99th percentile to the

1st percentile (with an average of ~60 across all particle sizes between these two percentiles). Differences within the interquartile range are not as stark but are still meaningful; the 75th percentile $F_{i,inf}$ is typically between a factor of 2-4 greater than the 25th percentile (with a mean of ~3.1 across all particle sizes). Overall, these results suggest that indoor concentrations of (and indoor exposures to) outdoor particles can vary highly among residences across the U.S. building stock, particularly between the most protective homes and the least protective homes.

To better summarize the size-resolved results, these same data are also shown averaged over seven particle size bins in Figure 11. The size bins included: <0.01 μm, 0.01-0.05 μm, 0.05-0.10 μm, 0.1-0.5 μm, 0.5-1 μm, 1-5 μm, and 5-10 μm.

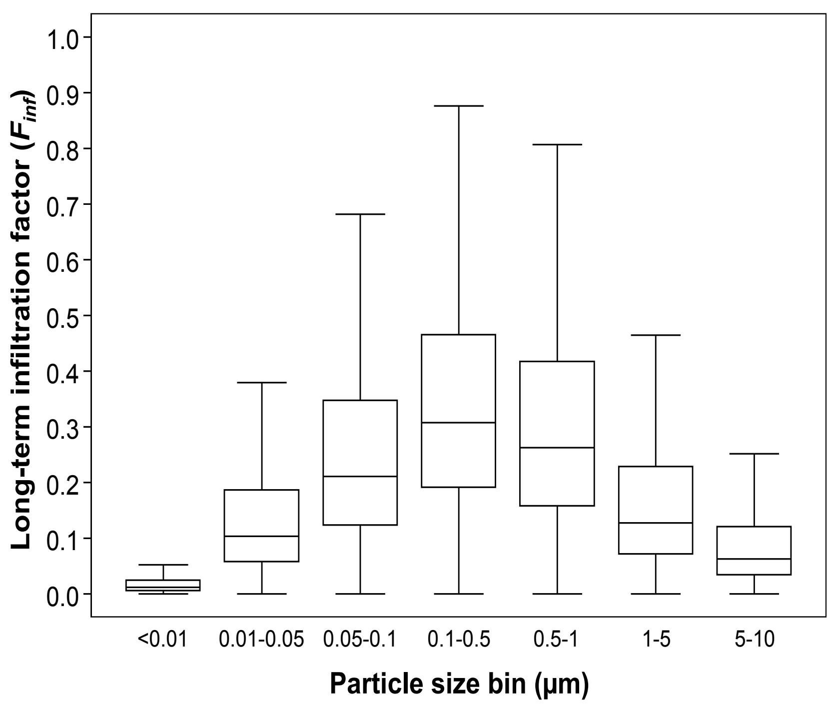

Figure 11. Box plots of predicted long-term averaged infiltration factors (F_{inf}) across the U.S. single-family residential building stock, averaged over seven particle size bins. Boxes represent the interquartile range (IQR) and whiskers represent adjacent values (i.e., those within 1.5 times the IQR). Outliers are excluded for clarity.

According to Figure 11, we estimate that 0.1-0.5 µm particles of outdoor origin are most likely to exist indoors in the greatest numbers (geometric mean (GM) $F_{0.1\text{-}0.5,inf}$ = 0.29; geometric standard deviation (GSD) = 0.287), followed by 0.5-1 µm particles ($F_{0.5\text{-}1,inf}$: GM = 0.25 and GSD = 0.312). This is intuitive because most of the fundamental forces that govern particle transport and control are typically lowest for 0.1-0.5 µm particles (Hinds, 2012; Riley et al., 2002). Larger particles (i.e., 1-5 µm and 5-10 µm) are estimated to have lower long-term average values of $F_{i,inf}$ ($F_{1\text{-}5,inf}$: GM = 0.13 and GSD = 0.377; $F_{5\text{-}10,inf}$: GM = 0.06 and GSD = 0.420). Finally, values of $F_{i,inf}$ for ultrafine particles are also estimated to be lower than 0.1-1 µm particles ($F_{0.05\text{-}0.1,inf}$: GM = 0.20 and GSD = 0.327; $F_{0.01\text{-}0.05,inf}$: GM = 0.10 and GSD = 0.375; and $F_{0.001\text{-}0.01,inf}$: GM = 0.01 and GSD = 0.465). Estimates of $F_{i,inf}$ in both Figure 10 and Figure 11 also show that in some homes indoor proportions of outdoor particles are very small or even negligible, particularly for the bottom percentiles. Conversely, values of $F_{i,inf}$ for some particle sizes may approach unity for some homes in the 99th percentile or above.

For comparison, other studies have measured similar distributions of $F_{i,inf}$ in homes, although large samples seldom include size-resolved measurements. Kearney et al. (2011) measured values of F_{inf} for submicron particles ranging from ~0.03 to ~0.9 with a median of ~0.19-0.27 depending on season and estimation method (Kearney et al., 2011). Our estimates appear generally in line with these measurements. The 25th to 50th percentile size-resolved UFP estimates also follow a similar pattern to those measured in Rim et al. (2010) inside a test house with closed windows; the ~75th to 90th percentiles follow a similar profile to those in the same study measured with windows opened (Rim et al., 2010b). Size-resolved 10-200 nm particles also follow a similar profile to those in

Zhu et al. (2005) in several homes operating under different ventilation conditions (Zhu et al., 2005).

4.1 Mapping to outdoor particle size distributions

The size-resolved estimates of long-term average infiltration factors herein can also be used to estimate the absolute size-resolved indoor number concentrations based on particle size distributions in any outdoor environment. If particle densities are also known, estimates of absolute indoor proportions of outdoor particulate matter mass (e.g., $PM_{2.5}$ or PM_{10}) can also be made. However, data are quite limited for long-term size-resolved outdoor size distributions and particle densities in many locations in the U.S. Therefore, we rely on previous measurements of outdoor particle size distributions in a variety of archetypal outdoor environments from one of the longer term studies of which we are aware in order to illustrate the likely bounds on distributions of indoor particulate matter of outdoor origin (specifically $PM_{2.5}$ and total UFPs) (Costabile et al., 2009). This includes long-term outdoor data from three sites in and around Leipzig, Germany, including: (1) a rural background site approximately 50 km from Leipzig; (2) an urban background site on the roof of a university building within the city approximately 100 m from highly-trafficked roads; and (3) an area near a moderately-trafficked roadway near the city center (carrying approximately 12,000 vehicles per workday). These particle size distributions thus makeup three distinct representative locations: (1) rural, (2) urban background, and (3) urban traffic. We are not aware of similar long-term measurements in locations in the U.S., other than some shorter term measurements in Los Angeles, CA and Pittsburgh, PA that were made during sampling campaigns at two EPA Supersite locations (ASDC, 2012).

Mean and standard deviation particle size distributions reported in Costabile et al. (2009) were fit using three modal distributions. Only the mean distributions are utilized herein for the long-term average. Distribution statistics are shown in Table 5 and the long-term average outdoor particle size distributions are also shown graphically in Figure 12. Estimates of $PM_{2.5}$ mass concentrations for each outdoor location are made by assuming spherical shape particles and a particle density of 1.0 g/cm^3 (Brook et al., 2010; Riley et al., 2002; Waring & Siegel, 2008).

Table 5. Lognormal characteristics of the ambient particle size distributions used in this study as representatives for typical rural, urban background, and traffic environments

		Mode 1			Mode 2			Mode 3			Est. $PM_{2.5}$	Total
		N_i	D_{pi}	log σ_i	N_i	D_{pi}	log σ_i	N_i	D_{pi}	log σ_i	mass	UFPs
Location		cm^{-3}	μm	-	cm^{-3}	μm	-	cm^{-3}	μm	-	μg m^{-3}	# cm^{-3}
Rural	mean	2200	0.014	0.30	2800	0.070	0.30	600	0.200	0.23	13.2	4204
	s.d.	5000	0.011	0.28	2500	0.050	0.40	650	0.230	0.17	15.2	6944
Urban Background	mean	2600	0.014	0.30	8200	0.048	0.36	700	0.170	0.20	15.0	9340
	s.d.	3600	0.010	0.27	6200	0.048	0.36	600	0.170	0.20	11.8	8709
Traffic	mean	11500	0.013	0.24	10000	0.050	0.35	1400	0.150	0.18	17.5	19780
	s.d.	13500	0.012	0.27	5000	0.050	0.35	1200	0.150	0.23	13.6	17787

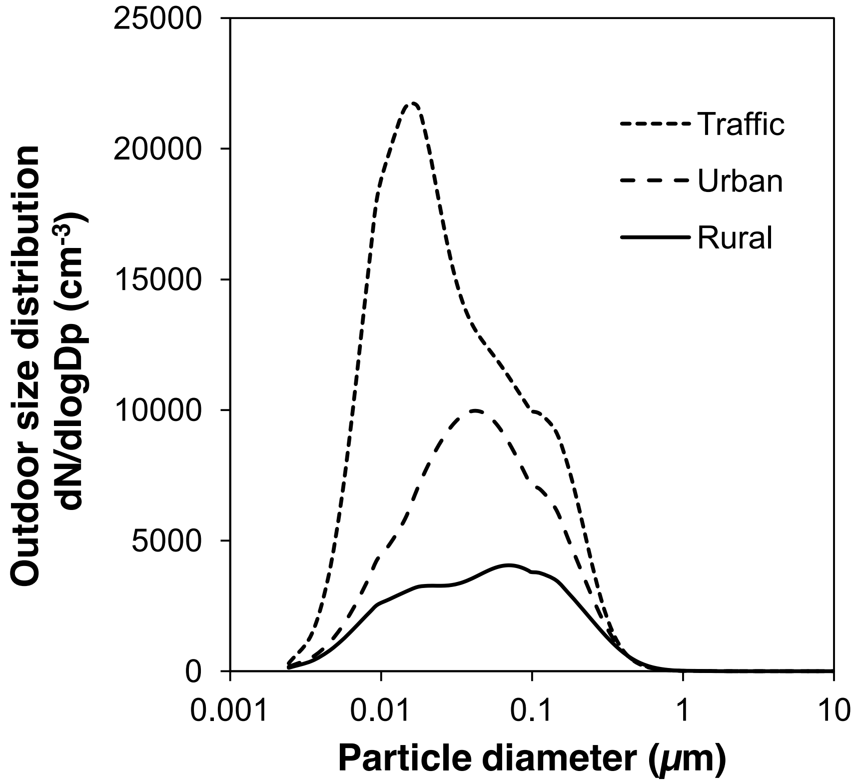

Figure 12. Mean outdoor particle size distribution from three different environments in and around Leipzig, Germany reported in Costabile et al. (2009)

The outdoor particle size distributions from each of the three locations are then used alongside the predictions of $F_{i,inf}$ distributions in Figure 10 to predict the distribution of long-term average indoor concentrations of outdoor size-resolved particles assuming each home is subject to the same outdoor size distribution, as shown in Figure 13. The results in Figure 13 are instructive for exploring how much indoor concentrations of outdoor particles can vary according to differences in outdoor particle size distributions. We did not attempt to assign rural, urban, and traffic environments to particular subsets of the predicted distributions based on geographical distributions.

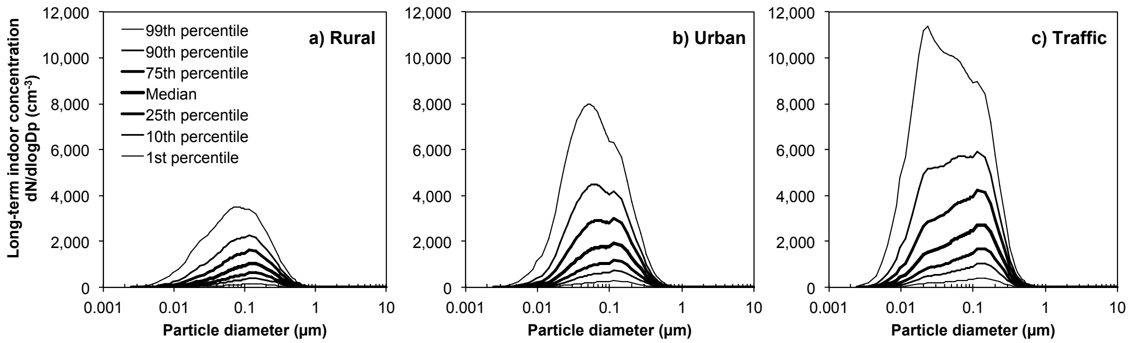

Figure 13. Distributions of long-term indoor concentrations of outdoor particulate matter estimated using values of $F_{i,inf}$ from Figure 10 and outdoor size distributions from Figure 12. Estimates are made assuming all homes are located in (a) rural, (b) urban, or (c) highly-trafficked locations.

In addition to size-resolved estimates, data from Figure 13 can also be used to estimate indoor concentrations of $PM_{2.5}$ and total UFPs (< 100 nm) on an absolute basis in each location, as shown in Figure 14. Estimates of $PM_{2.5}$ mass are made using the same assumptions for particle shape and density as in Table 5. The predicted distributions of absolute indoor $PM_{2.5}$ and total UFP concentrations are also used alongside long-term average outdoor estimates (made using the same assumptions) to estimate infiltration factors for $PM_{2.5}$ and UFPs. The intent is to explore sensitivity of the results to widely varying assumptions of outdoor particle size distributions.

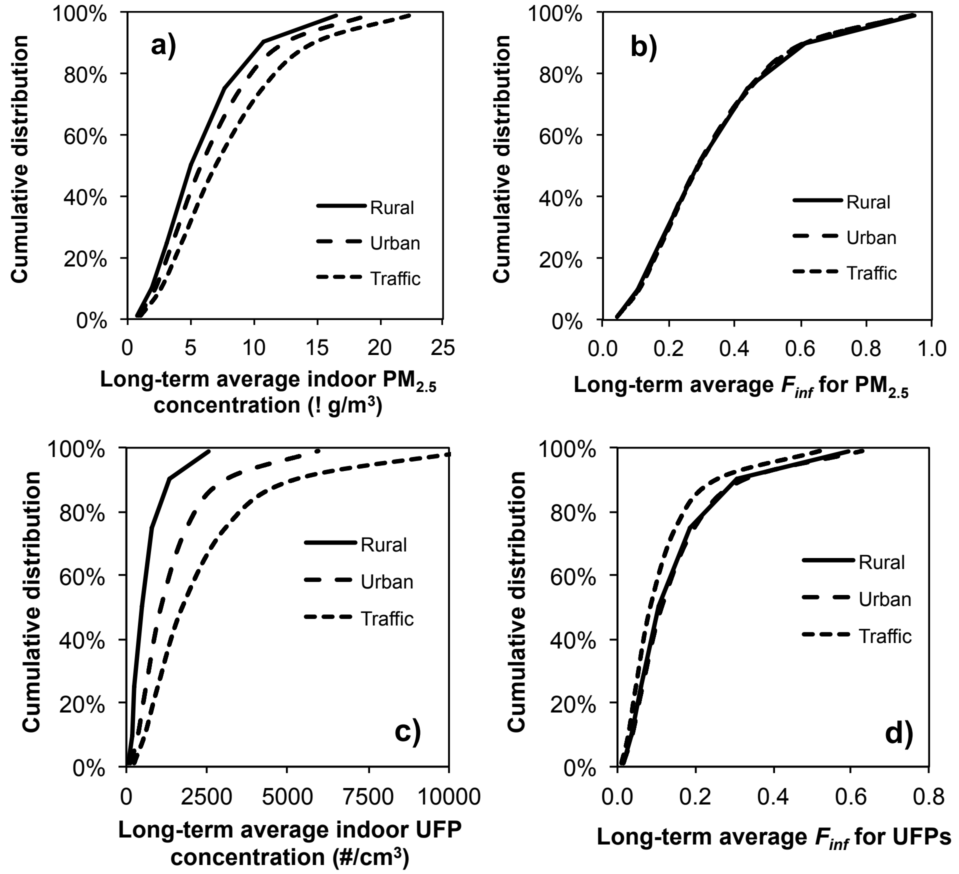

Figure 14. Estimated cumulative distributions of (a) indoor $PM_{2.5}$ concentrations, (b) F_{inf} for $PM_{2.5}$, (c) indoor UFP concentrations, and (d) $F_{i,inf}$ for UFPs using the modeled indoor size distributions in Figure 13 and assuming spherical particles with density of 1 g/cm^3 for estimating $PM_{2.5}$ mass.

According to Figure 14a, long-term average indoor $PM_{2.5}$ concentrations are not predicted to vary greatly between each environment, although highly-trafficked areas are estimated to have higher indoor concentrations than urban or rural locations. The median predicted indoor concentration of $PM_{2.5}$ of outdoor origin in the high traffic environment is approximately 7 μg/m^3 compared to 5.8 μg/m^3 in the urban environment and 5 μg/m^3 in the rural environment. Conversely, absolute concentrations of UFPs are predicted to vary widely depending on environment, as shown in Figure 14c. For example, if the median home is located in a highly trafficked environment, long-term indoor UFP concentrations of outdoor origin would be ~1730 #/cm^3 compared to ~1070 #/cm^3 and ~460 #/cm^3 in the urban and rural locations, respectively (a factor of almost 4 between traffic and rural).

On the other hand, indoor-outdoor ratios of both $PM_{2.5}$ and UFPs do not appear to be affected greatly by assumptions for particle size (see Figures 14b and 14d). Outdoor particle size distributions have almost no impact on the cumulative distributions of $F_{i,inf}$ values for $PM_{2.5}$ while $F_{i,inf}$ values for UFPs are actually somewhat smaller for the highly trafficked environment, most likely because a greater number of UFPs are smaller than 50 nm and predicted infiltration factors are smaller for <50 nm particles than for 50-100 nm particles (Figure 11). While this analysis is instructive, we should note that results are limited to assumptions for both outdoor particle size distributions and particle shape and density. For example, although we use a density of 1.0 g/cm^3 herein, other recent studies have shown that actual particles densities can range from 0.1 to 2.5 g/cm^3, depending on geographic location and characteristics of nearby particle sources (Geller, Biswas, & Sioutas, 2006; Khlystov, Stanier, & Pandis, 2004; Neusüss et al., 2002; Shen, Jaques, Zhu, Geller, & Sioutas, 2002; Stanier, Khlystov, & Pandis, 2004). These assumptions could be explored further using the size-resolved predictions of $F_{i,inf}$ in Figure 10.

4.2 Multiple regression analysis for influential parameters

Table 6. Mean ± standard deviation of the standardized multiple linear regression coefficients for each input variable for (i) all homes, (ii) only homes without HVAC systems, and (iii) only homes with HVAC systems

	Mean ± s.d. standardized regression coefficients across all particle sizes (Beta)		
Input parameter	**All homes**	**No HVAC**	**HVAC**
Closed-window deposition rate, $k_{i,dep,closedwindows}$	-0.56 ± 0.03	-0.65 ± 0.03	-0.53 ± 0.03
Closed-window air exchange rate, $\lambda_{closedwindows}$	0.42 ± 0.06	0.35 ± 0.07	0.49 ± 0.04
Closed-window penetration factor, $P_{i,closedwindows}$	0.30 ± 0.09	0.30 ± 0.10	0.31 ± 0.08

HVAC filter efficiency, $\eta_{i,HVAC}$	-0.21 v 0.05	omitted	-0.20 v 0.07
Fraction of time windows are open, $f_{openwindows}$	0.09 ± 0.05	0.08 ± 0.05	0.11 ± 0.06
HVAC system runtime, f_{HVAC}	-0.06 ± 0.01	omitted	-0.10 ± 0.01
Recirculation rate, λ_{HVAC}	-0.04 ± 0.00	omitted	-0.06 ± 0.01

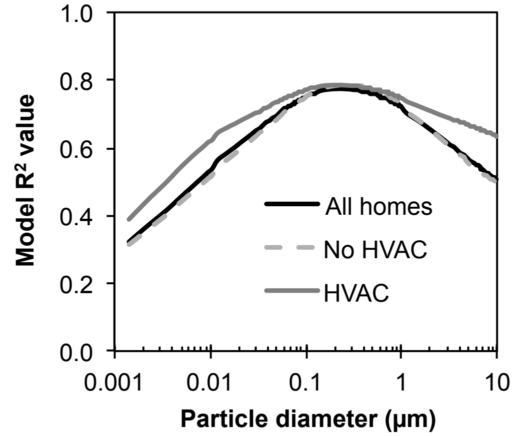

Figure 15. Model R^2 values for the multiple linear regressions for each particle size

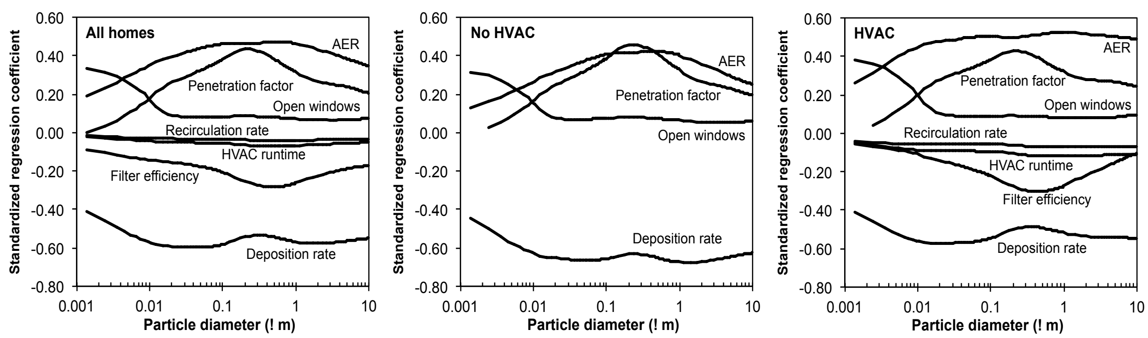

Figure 16. Size-resolved standardized regression coefficients for predictor variables in multiple regression analyses: (i) all homes, (ii) homes without HVAC systems, and (iii) homes with HVAC systems

Size-resolved closed-window deposition rates ($k_{i,dep,closedwindows}$) were shown to be the most influential parameter for predicting size-resolved infiltration factors in these simulations for all three regression analyses (mean Beta = -0.56 for all homes; -0.65 for homes without HVAC systems; and -0.53 for homes with HVAC systems), followed closely by closed-window air exchange rates ($\lambda_{closedwindows}$). Closed-window envelope penetration factors ($P_{i,closedwindows}$) were the next most important predictor across all particle sizes for all three regression analyses. HVAC filter removal efficiency ($\eta_{i,HVAC}$) was the next most important predictor for homes with HVAC systems and across all of the homes. The fraction of time that windows are open ($f_{openwindows}$), HVAC system runtime (f_{HVAC}), and recirculation rates (λ_{HVAC}) were all only minor predictors for all three cases, with standardized regression coefficients less than ±0.11. Each parameter was found to influence infiltration factors in a logical manner; that is, deposition rates (a loss term) were negatively associated with values of $F_{i,inf}$, while penetration factors (a source term) were positively associated with values of $F_{i,inf}$. These results suggest that in order to better estimate size-resolved infiltration factors in field studies and to incorporate into future epidemiological studies, accurate characterization of deposition rates, air exchange rates, and envelope penetration factors should be prioritized, followed by HVAC filter efficiencies for homes with HVAC systems and window opening for homes without HVAC systems.

4.3 Estimating inhalation dose based on simulation results

Using the previous simulation results and assumptions for outdoor particle size distributions, breathing rates, and time activity patterns, we estimated the dose inhaled by an average adult male individual spending 69% of his time inside the simulated homes for both fine particulate matter ($PM_{2.5}$) and of ultrafine particles (UFP). Figure 17 first shows the distributions of size-resolved particle dose estimates (in terms of particle number, #) across the simulated homes if they were all located in a rural outdoor environment. Doses are normalized by particle size for graphical clarity.

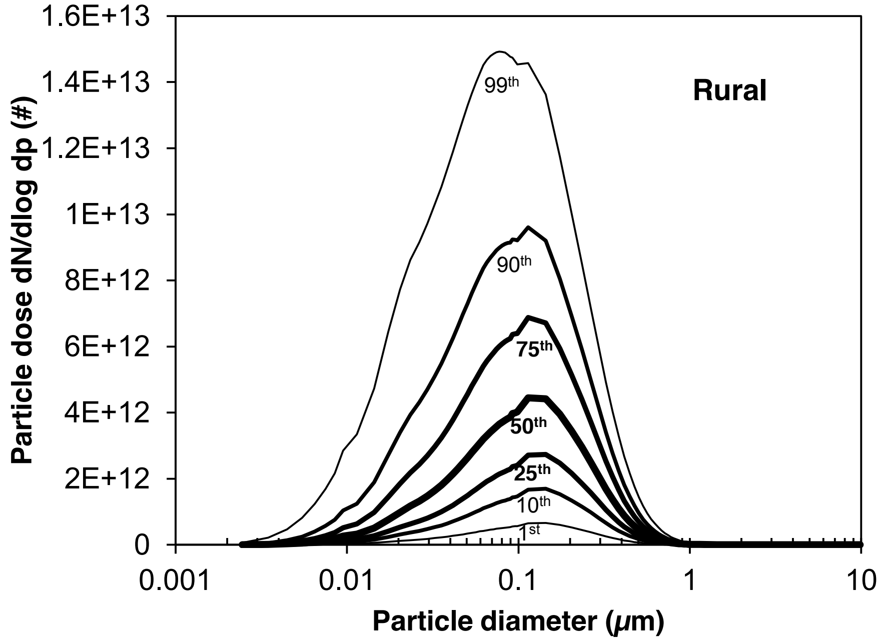

Figure 17. Size-resolved particle dose inhaled in a rural environment

Similarly, Figure 18 shows the distribution of size-resolved inhalation dose estimates assuming all homes are located in an urban outdoor environment. Last, Figure 19 shows similar results assuming homes are located near highly trafficked roadways. Note the differences in scales on each figure.

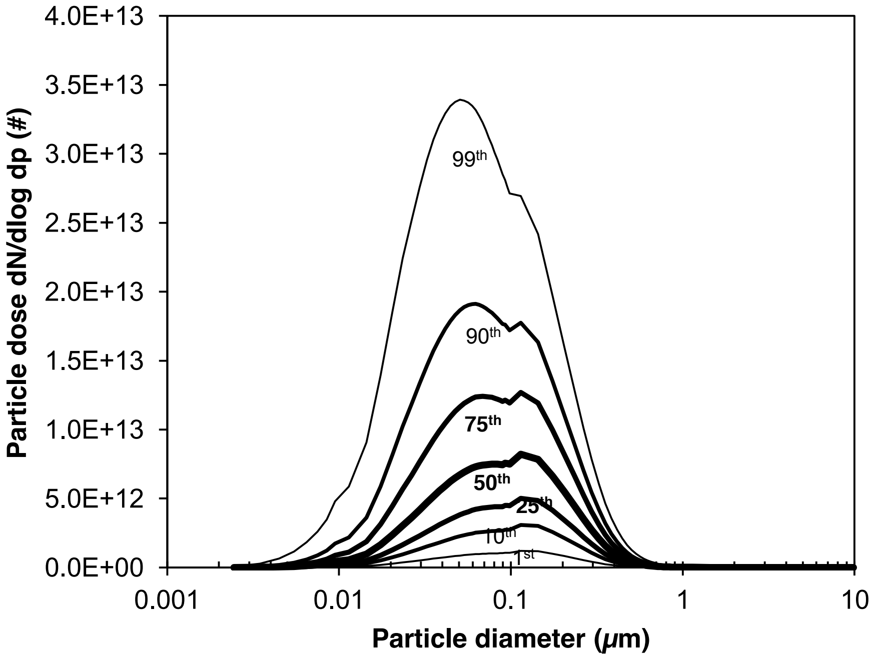

Figure 18. Size-resolved particle dose inhaled in an urban environment

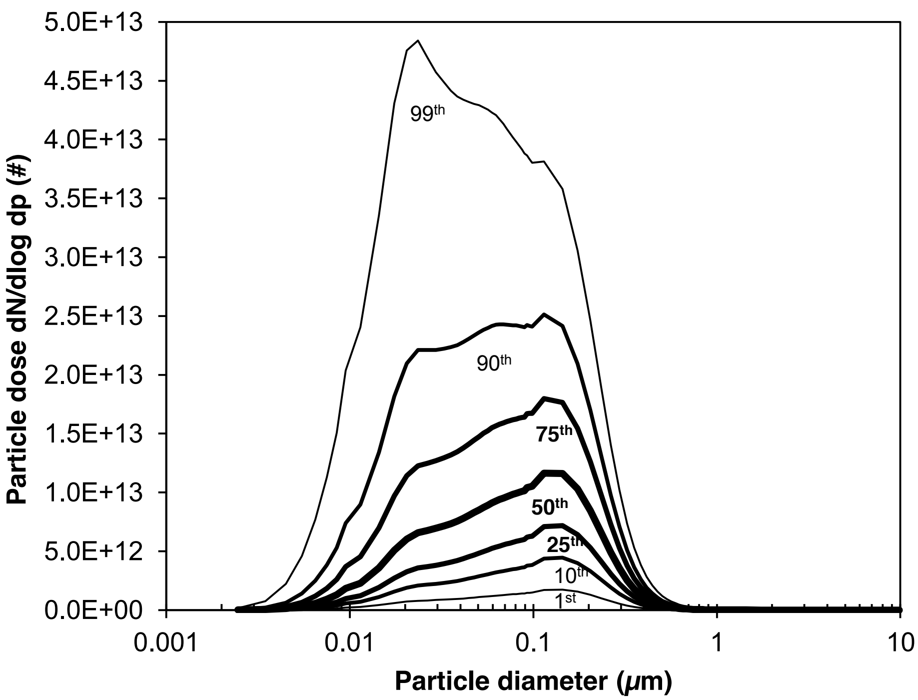

Figure 19. Size-resolved particle dose inhaled in a traffic environment

There is a large range of estimated inhaled doses in each environment represented (Rural, Urban, Traffic), especially in urban and traffic environments (Figures 17, 18 and 19). As expected, doses of fine and ultrafine particle numbers inhaled appear to be the highest in a highly trafficked environment, followed by the ones in an urban environment. The lowest inhaled dose values were predicted in a rural environment, which are all consistent with assumptions for outdoor particle size distributions. Because there is little information in the existing literature on size-resolved particle doses in other environments, the size-resolved dose estimates were then used to estimate the distribution of inhaled doses for both UFPs and $PM_{2.5}$, which are more relevant for epidemiological studies.

Figure 20 first shows the estimated cumulative distribution of inhaled UFP doses across the building stock, split by the same three outdoor environments. Doses across the outdoor environments followed similar trends according to the assumed outdoor UFP concentration (traffic > urban > rural). The median total indoor UFP dose for the assumed individual was $\sim 4.6\times10^{12}$ particles in an urban environment. However, the 99th percentile of UFP dose, which is associated with the homes with the highest infiltration factors, is estimated to be approximately 5 times this value. Similarly, the highest inhalation doses observed in a suburban environment (99th percentile) are more than 5 times as high as the median estimated doses, the latter being $\sim 7.4\times10^{12}$ particles. Median values of UFPs inhaled in the traffic environment are more than 3 times higher as in the rural environment. Overall, doses of inhaled UFPs were 43-49 times higher in the least protective house (99th percentile) versus the most protective house (1st percentile) depending on the environment. These results reveal that the combination of parameters such as deposition rates, penetration factors, filter removal efficiencies, and air exchange rates across the U.S. residential building stock can have large implications for the dose of UFPs inhaled by an average individual.

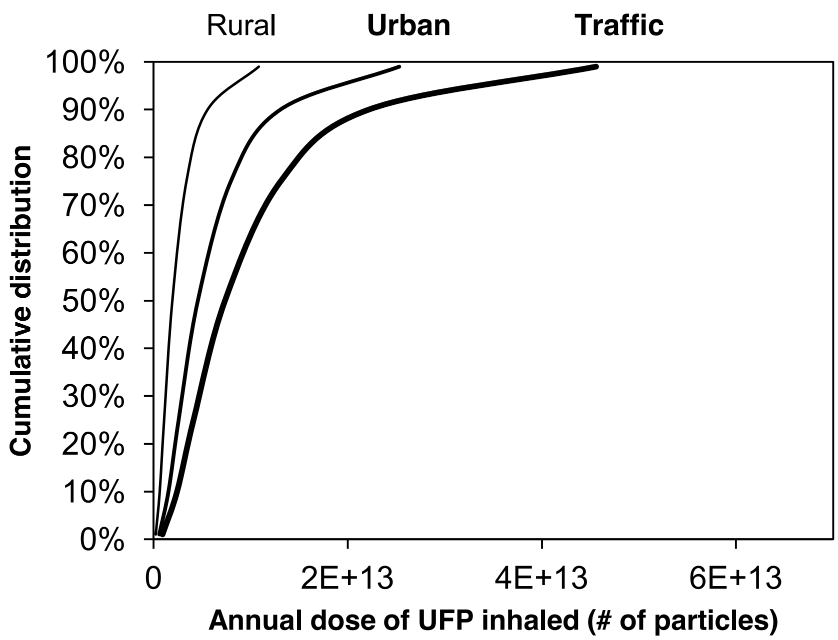

Figure 20. Distribution of the annual inhaled dose of UFPs across the building stock

Similarly, Figure 21 shows the estimated cumulative distribution of inhaled $PM_{2.5}$ doses across the building stock, split by the same three outdoor environments. Doses across the outdoor environments followed similar trends according to the assumed outdoor $PM_{2.5}$ concentration. That is, the distribution of the mass of $PM_{2.5}$ inhaled is also the highest in highly trafficked environments, followed by urban and rural environments. However, the values represented in all environments are less variable than the UFP values. The median mass of fine particulate matter inhaled estimated in a suburban environment (most polluted) is only about 1.5 times higher than the one calculated in a rural environment. The differences observed between the $PM_{2.5}$ results and the UFP results calculated may be due to the fact that "traffic" environments are composed by a very large proportion of UFPs. Less obvious differences are observed in the overall fine particle range between each environment.

However, we do observe that a large range in inhaled doses across the building stock is captured in each environment. For example, in an urban environment, depending on the type of house where an average individual lives, he is estimated to inhale masses of particulate matter as low as 3.6 mg over the course of a year (1st percentile) or as high as 81.4 mg (99th percentile). Doses of $PM_{2.5}$ inhaled were estimated to be 21-22 times higher in the least protective homes (99th percentile) versus the most protective homes (1st percentile), depending on the outdoor environment. Therefore, building specific parameters have a very importance influence on the doses inhaled by individuals, as expected from the concentration results. We can then conclude that differences in inhalation doses of outdoor $PM_{2.5}$ in indoor residential environments should be accounted for in exposure- and dose-response studies, and that window opening behaviors, deposition rates, HVAC ownership, types of HVAC filters, air exchange rates, and envelope penetration factors all influence human exposure and inhalation dose of fine and ultrafine particulate matter.

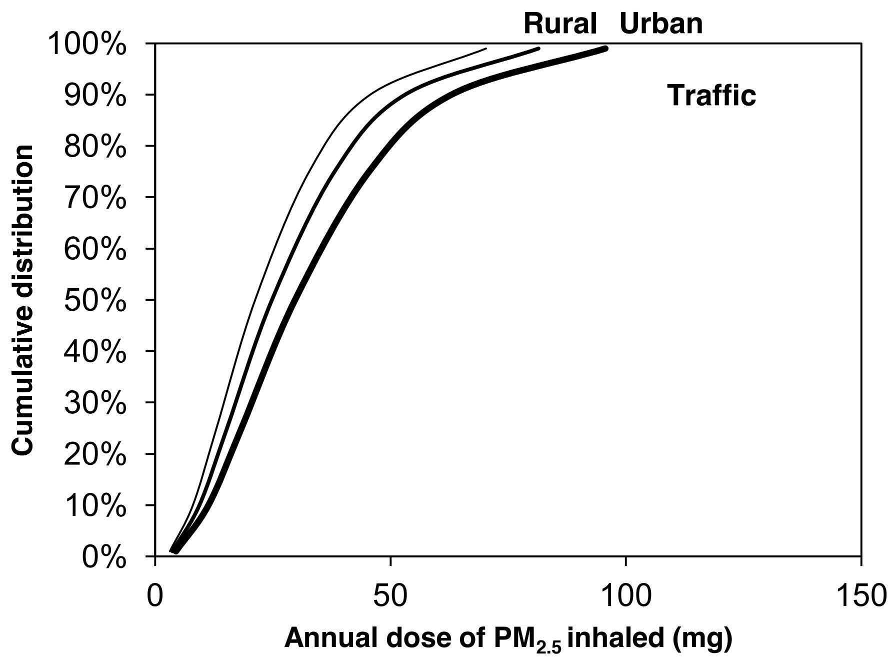

Figure 21: Distribution of the annual mass of fine particles inhaled ($PM_{2.5,inhaled}$)

CHAPTER 5

DISCUSSION

Overall, results from the Monte Carlo simulations herein reveal that indoor proportions of outdoor particles can vary widely from home to home based on a range of fundamental building characteristics. However, we should note that there are several important limitations to this work. For one, actual measured values of both size-resolved envelope penetration factors and particle deposition rates are quite limited to date. More research should be conducted to measure size-resolved particle penetration factors and deposition rates across the widest size range possible and in a larger number and variety of residential buildings. Results from the multiple regressions confirm the importance of both of these variables, as well as air exchange rates. Additionally, data for HVAC system runtimes, size-resolved filter efficiencies, filter ownership, window opening behaviors, and AERs during window opening all remain limited and warrant further study.

We should also note that there may be considerable uncertainty in the shape of the outdoor particle size distributions we used in the latter portions of this analysis. More information may be needed on long-term average outdoor particle size distributions in urban, rural, and highly trafficked environments in the U.S. to fully explore the impacts of outdoor size distributions. We should also note that the simple particle number balance in Equation 1 ignores other loss mechanisms such as loss of small particles by phase change of volatile compounds, which can alter indoor size distributions (Hodas et al., 2012b; Lunden, Thatcher, Hering, & Brown, 2003; Zhu et al., 2005). However, the wide range in deposition rates used herein should capture much of the variability that would be introduced by particle volatility. Additionally, this work explicitly ignores indoor sources of size-resolved particles to focus only on outdoor sources. There are many indoor sources such as cooking, smoking, or burning candles, of a wide range of particle sizes inside homes that lead to significant exposure (Afshari, Matson, & Ekberg, 2005; L. Wallace, 2006). Further modeling should incorporate size-resolved source strengths and time activity patterns.

Additionally, further modeling on inhalation exposures and doses on a wider variety of individuals with different breathing rates and body masses could be integrated with wider varieties of activity patterns using a Monte Carlo approach to improve the analysis. Regardless, results herein suggest wide variations in indoor particle exposures across the building stock that should be accounted for in epidemiology studies. More information is needed on a wide range of parameters, although the modeling effort described herein can also be used to explore hypothetical changes to the building stock, such as widespread decreases in AERs or increases in HVAC filtration efficiency.

CHAPTER 6

CONCLUSIONS

To conclude, this study reviewed the literature regarding many of the important parameters essential to model and predict exposures to particulate matter in residential buildings (e.g., deposition rates, penetration factors, air exchange rates, HVAC operational and filtration parameters, among others). Parameters culled from the review were then used in a detailed modeling approach to estimate the likely distribution in size-resolved infiltration factors in the U.S. single-family residential building stock. The size-resolved nature of some input parameters (e.g., penetration factors, deposition rates, and filter removal efficiencies) allowed for size-resolved outputs (infiltration factors, exposures, and doses) in a way that has not been conducted previously. The large variations in modeled concentrations, exposures, and doses, as well as the modeling approach used in this research, will all help inform the epidemiology field and help correct exposure misclassification that are present in numerous epidemiology studies.

APPENDIX A

Matlab Mote Carlo Simulation Code

```
% Number of particle diameters
N_particle_diameters = 102;

% Number of simulations
N_Simulations = 100000;

% Calculation of the number of houses (out of 100,000) that have each
% different type of filters.
% These values are cumulative for programming convenience.
N_MERV5_Simulations = 0.65*N_Simulations*0.25;
N_MERV6_Simulations = N_MERV5_Simulations+0.65*N_Simulations*0.3;
N_MERV8_Simulations = n_merv6+0.65*N_Simulations*0.3;
N_MERV12_Simulations = N_MERV8_Simulations+0.65*N_Simulations*0.1;
N_MERV16_Simulations = N_MERV12_Simulations+0.65*N_Simulations*0.05; %%
ADD comments

% Creation of the matrix variables: deposition and pentration rates for
the
% 100,000 simulation cases

k_dep_Closed_Windows = zeros(N_particle_diameters,N_Simulations);
P_Closed_Windows = zeros(N_particle_diameters,N_Simulations);
P_Open_Windows = zeros(N_particle_diameters,N_Simulations);
k_dep_Open_Windows = zeros(N_particle_diameters,N_Simulations);

Summary_Table = zeros (415,N_Simulations);

% Creation of the Air exchange rate variables, the HVAC runtime, and
the
% HVAC recirculation rate
AER_Open_Windows = zeros(1,N_Simulations);
AER_Closed_Windows = zeros(1,N_Simulations);
f_HVAC = zeros(1,N_Simulations);
Recirculation_Rate_HVAC = zeros(1,N_Simulations);

% Creation of the infiltration rate matrix
F_inf = zeros(N_particle_diameters,N_Simulations);

% Creation of the filter removal efficiency vector
Efficiency = zeros(N_particle_diameters,1);

% Assignment of the different filter removal efficiencies to Matlab
% variables based on Excel files.

filter_Eff_5 = 'm5.xlsx';
Filter_Eff_5 = xlsread(filter_Eff_5);

filter_Eff_6 = 'm6.xlsx';
```

```
Filter_Eff_6 = xlsread(filter_Eff_6);

filter_Eff_8 = 'm8.xlsx';
Filter_Eff_8 = xlsread(filter_Eff_8);

filter_Eff_12 = 'm12.xlsx';
Filter_Eff_12 = xlsread(filter_Eff_12);

filter_Eff_16 = 'm16.xlsx';
Filter_Eff_16 = xlsread(filter_Eff_16);

% Creation of the probability of low and high window opening variables
p_open_windows_low = 0.8;
p_open_windows_high = 0.2;

% Creation of the air exchange rate multipliers during periods of low
and high window opening
m_open_windows_low = 2;
m_open_windows_high = 4;

% Creation of the deposition rate multipliers during periods of low and
high window opening
Alpha = 1.23;
Beta = 1.7;



for j = 1 : N_Simulations


     % Sampling of a random percentile (between 0 and 1)
     Random_Percentile_Mild_Weather = rand(1);

     % Based on a step function (if statements), we obtain a random
fraction of
     % mild weather associated to this percentile
     if ( Random_Percentile_Mild_Weather >= 0) && (
Random_Percentile_Mild_Weather <= 0.03)
      f_mild = 0.205;

     elseif ( Random_Percentile_Mild_Weather > 0.03) && (
Random_Percentile_Mild_Weather <= 0.05)
      f_mild =0.21;

     elseif ( Random_Percentile_Mild_Weather > 0.05) && (
Random_Percentile_Mild_Weather <= 0.08)
      f_mild =0.25;

     elseif ( Random_Percentile_Mild_Weather > 0.08) && (
Random_Percentile_Mild_Weather <= 0.11)
      f_mild =0.27;

     elseif ( Random_Percentile_Mild_Weather > 0.11) && (
Random_Percentile_Mild_Weather <= 0.16)
```

```
      f_mild =0.28;

    elseif ( Random_Percentile_Mild_Weather > 0.16) && (
Random_Percentile_Mild_Weather <= 0.20)
      f_mild =0.285;

    elseif ( Random_Percentile_Mild_Weather > 0.20) && (
Random_Percentile_Mild_Weather <= 0.25)
      f_mild =0.29;

    elseif ( Random_Percentile_Mild_Weather > 0.25) && (
Random_Percentile_Mild_Weather <= 0.29)
      f_mild =0.295;

    elseif ( Random_Percentile_Mild_Weather > 0.29) && (
Random_Percentile_Mild_Weather <= 0.34)
      f_mild =0.3;

    elseif ( Random_Percentile_Mild_Weather > 0.34) && (
Random_Percentile_Mild_Weather <= 0.41)
      f_mild =0.305;

    elseif ( Random_Percentile_Mild_Weather > 0.41) && (
Random_Percentile_Mild_Weather <= 0.5)
      f_mild =0.31;

    elseif ( Random_Percentile_Mild_Weather > 0.5) && (
Random_Percentile_Mild_Weather <= 0.55)
      f_mild =0.32;

    elseif ( Random_Percentile_Mild_Weather > 0.55) && (
Random_Percentile_Mild_Weather <= 0.62)
      f_mild =0.33;

    elseif ( Random_Percentile_Mild_Weather > 0.62) && (
Random_Percentile_Mild_Weather <= 0.70)
      f_mild =0.335;

    elseif ( Random_Percentile_Mild_Weather > 0.70) && (
Random_Percentile_Mild_Weather <= 0.78)
      f_mild =0.34;

    elseif ( Random_Percentile_Mild_Weather > 0.78) && (
Random_Percentile_Mild_Weather <= 0.80)
      f_mild =0.36;

    elseif ( Random_Percentile_Mild_Weather > 0.80) && (
Random_Percentile_Mild_Weather <= 0.83)
      f_mild =0.37;

    elseif ( Random_Percentile_Mild_Weather > 0.83) && (
Random_Percentile_Mild_Weather <= 0.86)
      f_mild =0.395;
```

```
    elseif ( Random_Percentile_Mild_Weather > 0.86) && (
Random_Percentile_Mild_Weather <= 0.89)
     f_mild =0.43;

    elseif ( Random_Percentile_Mild_Weather > 0.89) && (
Random_Percentile_Mild_Weather <= 0.92)
     f_mild =0.46;

    elseif ( Random_Percentile_Mild_Weather > 0.92) && (
Random_Percentile_Mild_Weather <= 0.95)
     f_mild =0.48;

    elseif ( Random_Percentile_Mild_Weather > 0.95) && (
Random_Percentile_Mild_Weather <= 0.97)
     f_mild =0.49;

    elseif ( Random_Percentile_Mild_Weather > 0.97) && (
Random_Percentile_Mild_Weather <= 0.98)
     f_mild =0.57;

    elseif ( Random_Percentile_Mild_Weather > 0.98) && (
Random_Percentile_Mild_Weather <= 0.99)
     f_mild =0.63;

    elseif ( Random_Percentile_Mild_Weather > 0.99) && (
Random_Percentile_Mild_Weather <= 1)
     f_mild =0.7;

    end



    % Sampling of a random percentile (between 0 and 1)
    Random_Percentile_Window_Opening_Mild = rand(1);

    % Based on a step function (if statements), we obtain a random
fraction of
    % window opening during times of mild weather associated to this
percentile
    if (Random_Percentile_Window_Opening_Mild >= 0) &&
(Random_Percentile_Window_Opening_Mild <= 0.15)
     f_Open_Windows_Mild =0;

    elseif (Random_Percentile_Window_Opening_Mild > 0.15) &&
(Random_Percentile_Window_Opening_Mild <= 0.21)
     f_Open_Windows_Mild =0.065;

    elseif (Random_Percentile_Window_Opening_Mild > 0.21) &&
(Random_Percentile_Window_Opening_Mild <= 0.23)
     f_Open_Windows_Mild =0.105;

    elseif (Random_Percentile_Window_Opening_Mild > 0.23) &&
(Random_Percentile_Window_Opening_Mild <= 0.3)
     f_Open_Windows_Mild =0.146;
```

```
    elseif (Random_Percentile_Window_Opening_Mild > 0.3) &&
(Random_Percentile_Window_Opening_Mild <= 0.33)
      f_Open_Windows_Mild =0.187;

    elseif (Random_Percentile_Window_Opening_Mild > 0.33) &&
(Random_Percentile_Window_Opening_Mild <= 0.38)
      f_Open_Windows_Mild =0.230;

    elseif (Random_Percentile_Window_Opening_Mild > 0.38) &&
(Random_Percentile_Window_Opening_Mild <= 0.39)
      f_Open_Windows_Mild =0.272;

    elseif (Random_Percentile_Window_Opening_Mild > 0.39) &&
(Random_Percentile_Window_Opening_Mild <= 0.46)
      f_Open_Windows_Mild =0.312;

    elseif (Random_Percentile_Window_Opening_Mild > 0.46) &&
(Random_Percentile_Window_Opening_Mild <= 0.47)
      f_Open_Windows_Mild =0.340;

    elseif (Random_Percentile_Window_Opening_Mild > 0.47) &&
(Random_Percentile_Window_Opening_Mild <= 0.48)
      f_Open_Windows_Mild =0.362;

    elseif (Random_Percentile_Window_Opening_Mild > 0.48) &&
(Random_Percentile_Window_Opening_Mild <= 0.53)
      f_Open_Windows_Mild =0.397;

    elseif (Random_Percentile_Window_Opening_Mild > 0.53) &&
(Random_Percentile_Window_Opening_Mild <= 0.54)
      f_Open_Windows_Mild =0.438;

    elseif (Random_Percentile_Window_Opening_Mild > 0.54) &&
(Random_Percentile_Window_Opening_Mild <= 0.73)
      f_Open_Windows_Mild =0.480;

    elseif (Random_Percentile_Window_Opening_Mild > 0.73) &&
(Random_Percentile_Window_Opening_Mild <= 0.74)
      f_Open_Windows_Mild =0.519;

    elseif (Random_Percentile_Window_Opening_Mild > 0.74) &&
(Random_Percentile_Window_Opening_Mild <= 0.77)
      f_Open_Windows_Mild =0.561;

    elseif (Random_Percentile_Window_Opening_Mild > 0.77) &&
(Random_Percentile_Window_Opening_Mild <= 0.78)
      f_Open_Windows_Mild =0.605;

    elseif (Random_Percentile_Window_Opening_Mild > 0.78) &&
(Random_Percentile_Window_Opening_Mild <= 0.84)
      f_Open_Windows_Mild =0.645;
```

```
     elseif (Random_Percentile_Window_Opening_Mild > 0.84) &&
(Random_Percentile_Window_Opening_Mild <= 0.85)
      f_Open_Windows_Mild =0.686;

     elseif (Random_Percentile_Window_Opening_Mild > 0.85) &&
(Random_Percentile_Window_Opening_Mild <= 0.88)
      f_Open_Windows_Mild =0.729;

     elseif (Random_Percentile_Window_Opening_Mild > 0.88) &&
(Random_Percentile_Window_Opening_Mild <= 1)
      f_Open_Windows_Mild =0.832;
    end


    % Geomean and GeoSD for a Closed Windows AER
    Geomean_Closed_Window_AER = -0.821;
    GeoSD_Closed_Window_AER = 0.713;

    % Calculation of a Closed Window AER based on a lognormal
    % distribution
    AER_Closed_Windows(j) =
logninv(rand(1),Geomean_Closed_Window_AER,GeoSD_Closed_Window_AER);

    % Calculation of an Open Window AER associated
    AER_Open_Windows(j) = AER_Closed_Windows(j)*(1 -
f_mild*f_Open_Windows_Mild) +
f_mild*f_Open_Windows_Mild*(p_open_windows_high*m_open_windows_high*AER
_Closed_Windows(j) +
p_open_windows_low*m_open_windows_low*AER_Closed_Windows(j));




    % Calculation of Closed Window deposition values based on a
deposition
    % values matrix
    random_variable = randi(9999,1,1);
    k_dep_Closed_Windows(:,j) = k_dep_complete(:,random_variable);


    % Get natural Penetration values in this house
    random_variable_bis = randi(9999,1,1);
    P_Closed_Windows(:,j) = P_complete(:,rd4);


    % Geomean and GeoSD for the HVAC Runtime
    Geomean_f_HVAC = -1.478;
    GeoSD_f_HVAC = 0.495;

    % Calculation of a random HVAC runtime based on a lognormal
distribution
    f_HVAC(j) = logninv(rand(1),Geomean_f_HVAC,GeoSD_f_HVAC);
```

```
    % Geomean and GeoSD for the HVAC Recirculation Rate
    Geomean_Recirculation_Rate_HVAC = 1.740;
    GeoSD_Recirculation_Rate_HVAC = 0.288;

    % Calculation of a random HVAC Recirculation Rate based on a
lognormal distribution
    Recirculation_Rate_HVAC(j) =
logninv(rand(1),Geomean_Recirculation_Rate_HVAC,GeoSD_Recirculation_Rat
e_HVAC);

    % Stores the parameters for each simulation
    Summary_Table(1,j) = f_mild;
    Summary_Table(2,j) = f_Open_Windows_Mild;
    Summary_Table(3,j) = AER_Closed_Windows(j);
    Summary_Table(4,j) = AER_Open_Windows(j);
    Summary_Table(5,j) = f_HVAC(j);
    Summary_Table(6,j) = Recirculation_Rate_HVAC(j);

    % Stores the Filter categoty for each simulation

    if (j <= N_MERV5_Simulations)
     Summary_Table(7,j) = 5;
    elseif (j <= n_merv6)
     Summary_Table(7,j) = 6;
    elseif (j <= N_MERV8_Simulations)
     Summary_Table(7,j) = 8;
    elseif (j <= N_MERV12_Simutions)
     Summary_Table(7,j) = 16;
    elseif (j <= N_Simulations)
     Summary_Table(7,j) = 0;
            end

     %Size-resolved calculaltions

     for  i = 1 : N_particle_diameters

     % Calculation of Size-resolved Open Window Deposition Rates
     k_dep_Open_Windows(i,j) = k_dep_Closed_Windows(i,j)*(1 -
f_mild*f_Open_Windows_Mild) +
f_Open_Windows_Mild*f_mild*k_dep_Closed_Windows(i,j)*(p_open_windows_hi
gh*Beta + p_open_windows_low*Alpha);


     % Calculation of Size-resolved Open Window Penetration Rates
     Penetration_total(i,j) = P_Closed_Windows(i,j)*(1 -
f_mild*f_Open_Windows_Mild) +
f_mild*f_Open_Windows_Mild*(1*p_open_windows_high +
(0.5*P_Closed_Windows(i,j)+0.5*1)*p_open_windows_low);

     %Stores size-resolved parameters for each simulation
     Summary_Table(i+8,j) = k_dep_Closed_Windows(i,j);
```

```
      Summary_Table(i+110,j) = k_dep_Open_Windows(i,j);

      Summary_Table(i+212,j) = P_Closed_Windows(i,j);

      Summary_Table(i+314,j) = Penetration_total(i,j);

    end

end

% Infiltration factors' calculations for houses with a MERV 5 filter

    for j = 1: N_MERV5_Simulations

      for i = 1: N_particle_diameters

        % Assigns filter efficiency

        Efficiency(i) = Filter_Eff_5(i);

        % Infiltration factors' calculations

        F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j) +
Recirculation_Rate_HVAC(j)*Efficiency(i)*f_HVAC(j));

      end

    end

    % Infiltration factors' calculations for houses with a MERV 6
filter

    for j = N_MERV5_Simulations + 1: n_merv6

      for i = 1: N_particle_diameters

        % Assigns filter efficiency

        Efficiency(i) = Filter_Eff_6(i);

        % Infiltration factors' calculations

        F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j) +
Recirculation_Rate_HVAC(j)*Efficiency(i)*f_HVAC(j));
```

```
      end

    end

    % Infiltration factors' calculations for houses with a MERV 8
filter

     for j = n_merv6 + 1: N_MERV8_Simulations

       for i = 1: N_particle_diameters

         % Assigns filter efficiency

          Efficiency(i) = Filter_Eff_8(i);

         % Infiltration factors' calculations

          F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j) +
Recirculation_Rate_HVAC(j)*Efficiency(i)*f_HVAC(j));

       end


     end


        % Infiltration factors' calculations for houses with a MERV 12
filter

        for j = N_MERV8_Simulations + 1: N_MERV12_Simulations

         for i = 1: N_particle_diameters

         % Assigns filter efficiency

          Efficiency(i) = Filter_Eff_12(i);

         % Infiltration factors' calculations

          F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j) +
Recirculation_Rate_HVAC(j)*Efficiency(i)*f_HVAC(j));

         end

        end
```

```
        % Infiltration factors' calculations for houses with a MERV 16
filter

         for j = N_MERV12_Simulations + 1: N_MERV16_Simulations

           for i = 1: N_particle_diameters

               % Assigns filter efficiency

                Efficiency(i) = Filter_Eff_16(i);

               % Infiltration factors' calculations

                F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j) +
Recirculation_Rate_HVAC(j)*Efficiency(i)*f_HVAC(j));

           end


         end


         % Infiltration factors' calculations for houses with NO filter

         for j = N_MERV16_Simulations + 1: N_Simulations

           for i = 1: N_particle_diameters

               % No Filter



               % Infiltration factors' calculations


               F_inf(i,j) =
(Penetration_total(i,j)*AER_Open_Windows(j))/(AER_Open_Windows(j) +
k_dep_Open_Windows(i,j));

           end


         end


        for j = 1: N_Simulations

            for i = 1 : N_particle_diameters

                Summary_Table(i+416,j) = F_inf(i,j);
```

```
    if (isnan(Summary_Table(i,j)))
            Summary_Table(i,j)=0;

    end

    end

end
```

APPENDIX A

Multilinear regression analysis tables

Table 7. Regression outputs for each particle size for all homes

Geometric mean diameter (μm)	AER Closed windows $\lambda_{closedwindows}$		Open windows fraction $f_{openwindows}$		HVAC system Runtime f_{HVAC}		Recirculation rate λ_{HVAC}		Filter efficiency $\eta_{i,HVAC}$		Deposition rate Closed windows $k_{i,dep,closedwindows}$		Penetration factor Closed windows $P_{i,closedwindows}$		Model Constant	
	β_i	SRC	β_i	SRC	β_i	SRC	β_i	SRC	β_i	SRC	β_i	SRC	β_i	SRC	β_i	Model R^2
0.0014	0.01	0.19	0.02	0.33	0.00	-0.02	0.00	-0.02	0.00	-0.09	0.00	-0.41	0.00		0.01	0.32
0.0024	0.01	0.23	0.03	0.32	0.00	-0.03	0.00	-0.02	-0.01	-0.11	0.00	-0.46	0.11	0.03	0.01	0.38
0.0035	0.01	0.26	0.03	0.29	-0.01	-0.03	0.00	-0.02	-0.01	-0.12	0.00	-0.49	0.12	0.06	0.02	0.42
0.0045	0.02	0.28	0.03	0.27	-0.01	-0.04	0.00	-0.03	-0.01	-0.12	0.00	-0.52	0.13	0.09	0.02	0.44
0.0055	0.02	0.30	0.03	0.25	-0.01	-0.04	0.00	-0.03	-0.01	-0.13	0.00	-0.53	0.14	0.11	0.02	0.47
0.0065	0.02	0.31	0.03	0.23	-0.01	-0.04	0.00	-0.03	-0.01	-0.13	-0.01	-0.54	0.15	0.12	0.03	0.49
0.0075	0.03	0.33	0.04	0.22	-0.01	-0.04	0.00	-0.03	-0.02	-0.14	-0.01	-0.55	0.15	0.14	0.03	0.50
0.0085	0.03	0.34	0.04	0.20	-0.01	-0.04	0.00	-0.03	-0.02	-0.14	-0.01	-0.56	0.16	0.15	0.03	0.51
0.0095	0.04	0.35	0.04	0.17	-0.02	-0.04	0.00	-0.03	-0.02	-0.14	-0.01	-0.57	0.16	0.17	0.04	0.53
0.0105	0.04	0.35	0.04	0.17	-0.02	-0.04	0.00	-0.03	-0.03	-0.14	-0.01	-0.57	0.17	0.18	0.04	0.54
0.012	0.06	0.37	0.04	0.14	-0.02	-0.05	0.00	-0.03	-0.04	-0.15	-0.02	-0.58	0.18	0.21	0.06	0.56
0.015	0.08	0.38	0.04	0.11	-0.03	-0.05	0.00	-0.03	-0.05	-0.15	-0.03	-0.59	0.19	0.23	0.08	0.58
0.018	0.09	0.39	0.04	0.10	-0.04	-0.05	0.00	-0.03	-0.06	-0.15	-0.04	-0.59	0.20	0.25	0.09	0.60
0.021	0.11	0.40	0.05	0.09	-0.05	-0.05	0.00	-0.03	-0.07	-0.16	-0.05	-0.59	0.22	0.26	0.10	0.62
0.024	0.12	0.40	0.05	0.08	-0.05	-0.05	0.00	-0.03	-0.08	-0.16	-0.05	-0.59	0.22	0.27	0.11	0.63
0.027	0.13	0.41	0.05	0.08	-0.05	-0.05	0.00	-0.03	-0.09	-0.16	-0.06	-0.60	0.23	0.28	0.11	0.64
0.03	0.13	0.42	0.05	0.08	-0.06	-0.05	0.00	-0.03	-0.10	-0.16	-0.07	-0.60	0.24	0.29	0.12	0.65
0.033	0.14	0.42	0.05	0.08	-0.06	-0.05	0.00	-0.03	-0.11	-0.17	-0.07	-0.60	0.25	0.30	0.12	0.66
0.036	0.15	0.42	0.05	0.08	-0.06	-0.05	0.00	-0.03	-0.11	-0.17	-0.08	-0.60	0.26	0.30	0.12	0.67
0.039	0.15	0.43	0.05	0.08	-0.06	-0.05	0.00	-0.03	-0.12	-0.17	-0.09	-0.60	0.27	0.31	0.13	0.68
0.042	0.16	0.43	0.05	0.08	-0.06	-0.05	0.00	-0.03	-0.12	-0.17	-0.09	-0.60	0.27	0.31	0.13	0.68
0.045	0.16	0.44	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.13	-0.17	-0.10	-0.60	0.28	0.32	0.13	0.69
0.048	0.16	0.44	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.14	-0.18	-0.11	-0.60	0.29	0.32	0.13	0.69
0.051	0.17	0.44	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.14	-0.18	-0.11	-0.60	0.29	0.33	0.13	0.70
0.054	0.17	0.44	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.15	-0.18	-0.12	-0.60	0.30	0.33	0.14	0.71

0.057	0.17	0.45	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.15	-0.18	-0.13	-0.60	0.30	0.33	0.14	0.71
0.06	0.17	0.45	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.15	-0.18	-0.13	-0.60	0.31	0.34	0.14	0.71
0.063	0.18	0.45	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.16	-0.19	-0.14	-0.60	0.32	0.34	0.14	0.72
0.066	0.18	0.45	0.06	0.08	-0.07	-0.05	0.00	-0.03	-0.16	-0.19	-0.14	-0.59	0.32	0.35	0.14	0.72
0.069	0.18	0.45	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.17	-0.19	-0.15	-0.59	0.33	0.35	0.14	0.73
0.072	0.18	0.45	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.17	-0.19	-0.15	-0.59	0.33	0.35	0.14	0.73
0.075	0.18	0.45	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.17	-0.19	-0.16	-0.59	0.34	0.36	0.14	0.73
0.078	0.18	0.46	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.18	-0.19	-0.16	-0.59	0.34	0.36	0.14	0.73
0.081	0.19	0.46	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.18	-0.20	-0.17	-0.59	0.34	0.36	0.14	0.74
0.084	0.19	0.46	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.18	-0.20	-0.18	-0.59	0.35	0.37	0.14	0.74
0.087	0.19	0.46	0.06	0.08	-0.08	-0.06	0.00	-0.03	-0.19	-0.20	-0.18	-0.59	0.35	0.37	0.14	0.74
0.09	0.19	0.46	0.07	0.08	-0.08	-0.06	0.00	-0.03	-0.19	-0.20	-0.19	-0.59	0.36	0.37	0.14	0.74
0.093	0.19	0.46	0.07	0.08	-0.08	-0.06	0.00	-0.03	-0.19	-0.20	-0.19	-0.59	0.36	0.37	0.14	0.75
0.096	0.19	0.46	0.07	0.08	-0.08	-0.06	0.00	-0.03	-0.20	-0.20	-0.20	-0.58	0.36	0.38	0.14	0.75
0.099	0.19	0.46	0.07	0.08	-0.08	-0.06	0.00	-0.03	-0.20	-0.21	-0.20	-0.58	0.37	0.38	0.14	0.75
0.105	0.19	0.46	0.07	0.08	-0.08	-0.06	0.00	-0.03	-0.21	-0.21	-0.22	-0.58	0.38	0.39	0.14	0.75
0.115	0.20	0.46	0.07	0.08	-0.09	-0.06	0.00	-0.03	-0.22	-0.22	-0.23	-0.57	0.39	0.40	0.14	0.76
0.125	0.20	0.46	0.07	0.08	-0.09	-0.06	0.00	-0.03	-0.22	-0.22	-0.24	-0.57	0.40	0.40	0.15	0.76
0.145	0.20	0.46	0.07	0.09	-0.09	-0.06	0.00	-0.04	-0.24	-0.23	-0.27	-0.56	0.42	0.42	0.15	0.77
0.175	0.20	0.46	0.07	0.09	-0.09	-0.06	0.00	-0.04	-0.25	-0.24	-0.29	-0.55	0.43	0.43	0.15	0.77
0.205	0.20	0.46	0.07	0.09	-0.10	-0.06	0.00	-0.04	-0.26	-0.25	-0.30	-0.54	0.44	0.43	0.15	0.77
0.235	0.20	0.46	0.07	0.09	-0.10	-0.07	0.00	-0.04	-0.27	-0.26	-0.31	-0.54	0.44	0.43	0.15	0.77
0.265	0.20	0.46	0.07	0.08	-0.10	-0.07	0.00	-0.04	-0.27	-0.27	-0.31	-0.54	0.44	0.43	0.15	0.77
0.295	0.21	0.46	0.07	0.08	-0.11	-0.07	0.00	-0.04	-0.27	-0.27	-0.31	-0.54	0.44	0.42	0.16	0.77
0.325	0.21	0.47	0.07	0.08	-0.11	-0.07	0.00	-0.04	-0.27	-0.28	-0.31	-0.54	0.43	0.42	0.16	0.77
0.355	0.21	0.47	0.07	0.08	-0.11	-0.07	0.00	-0.04	-0.27	-0.28	-0.30	-0.54	0.43	0.41	0.16	0.77
0.385	0.21	0.47	0.07	0.08	-0.11	-0.07	0.00	-0.04	-0.27	-0.28	-0.29	-0.54	0.42	0.41	0.16	0.77
0.415	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.27	-0.28	-0.29	-0.54	0.42	0.40	0.16	0.77
0.445	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.26	-0.28	-0.28	-0.54	0.41	0.40	0.16	0.76
0.475	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.26	-0.28	-0.27	-0.54	0.41	0.39	0.16	0.76
0.505	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.25	-0.28	-0.26	-0.54	0.40	0.38	0.16	0.76
0.535	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.25	-0.28	-0.26	-0.55	0.39	0.38	0.17	0.76
0.565	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.25	-0.28	-0.25	-0.55	0.39	0.37	0.17	0.75

0.590	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.24	-0.28	-0.24	-0.55	0.38	0.36	0.17	0.75
0.615	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.24	-0.28	-0.23	-0.55	0.38	0.36	0.17	0.75
0.655	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.24	-0.28	-0.23	-0.55	0.37	0.35	0.17	0.75
0.685	0.21	0.47	0.07	0.08	-0.11	-0.07	-0.01	-0.04	-0.23	-0.28	-0.22	-0.56	0.37	0.35	0.17	0.75
0.715	0.21	0.47	0.06	0.08	-0.11	-0.07	-0.01	-0.04	-0.23	-0.28	-0.22	-0.56	0.36	0.34	0.17	0.74
0.745	0.21	0.47	0.06	0.07	-0.11	-0.07	0.00	-0.04	-0.22	-0.28	-0.21	-0.56	0.36	0.34	0.17	0.74
0.775	0.21	0.47	0.06	0.07	-0.11	-0.07	0.00	-0.04	-0.22	-0.27	-0.20	-0.56	0.35	0.34	0.17	0.74
0.805	0.21	0.47	0.06	0.07	-0.11	-0.07	0.00	-0.04	-0.21	-0.27	-0.20	-0.56	0.35	0.33	0.17	0.74
0.835	0.21	0.47	0.06	0.07	-0.11	-0.07	0.00	-0.04	-0.21	-0.27	-0.19	-0.56	0.34	0.33	0.17	0.73
0.865	0.21	0.47	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.21	-0.27	-0.19	-0.56	0.34	0.33	0.17	0.73
0.895	0.21	0.47	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.20	-0.27	-0.18	-0.56	0.34	0.32	0.17	0.73
0.925	0.20	0.47	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.20	-0.27	-0.18	-0.57	0.33	0.32	0.17	0.73
0.955	0.20	0.46	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.20	-0.27	-0.17	-0.57	0.33	0.32	0.17	0.72
0.985	0.20	0.46	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.19	-0.26	-0.17	-0.57	0.32	0.32	0.17	0.72
1.14	0.19	0.46	0.06	0.07	-0.10	-0.07	0.00	-0.04	-0.17	-0.25	-0.14	-0.57	0.29	0.30	0.16	0.70
1.44	0.19	0.45	0.05	0.07	-0.09	-0.06	0.00	-0.04	-0.15	-0.24	-0.12	-0.58	0.27	0.28	0.16	0.68
1.74	0.18	0.44	0.05	0.07	-0.09	-0.06	0.00	-0.04	-0.14	-0.23	-0.10	-0.58	0.26	0.27	0.16	0.67
2.05	0.17	0.43	0.05	0.07	-0.08	-0.06	0.00	-0.04	-0.12	-0.22	-0.09	-0.58	0.24	0.27	0.15	0.65
2.35	0.16	0.43	0.05	0.06	-0.08	-0.06	0.00	-0.04	-0.12	-0.22	-0.08	-0.58	0.23	0.26	0.15	0.64
2.65	0.16	0.42	0.05	0.06	-0.08	-0.06	0.00	-0.04	-0.11	-0.21	-0.07	-0.57	0.22	0.26	0.15	0.63
2.95	0.15	0.41	0.05	0.06	-0.07	-0.06	0.00	-0.04	-0.10	-0.21	-0.06	-0.57	0.22	0.25	0.14	0.62
3.25	0.15	0.41	0.04	0.06	-0.07	-0.06	0.00	-0.04	-0.10	-0.20	-0.06	-0.57	0.21	0.25	0.14	0.61
3.55	0.14	0.40	0.04	0.06	-0.07	-0.06	0.00	-0.04	-0.09	-0.20	-0.06	-0.57	0.20	0.25	0.14	0.60
3.85	0.14	0.40	0.04	0.06	-0.07	-0.06	0.00	-0.04	-0.09	-0.20	-0.05	-0.57	0.20	0.25	0.13	0.59
4.15	0.13	0.39	0.04	0.06	-0.07	-0.06	0.00	-0.04	-0.08	-0.19	-0.05	-0.57	0.19	0.24	0.13	0.59
4.45	0.13	0.39	0.04	0.06	-0.06	-0.06	0.00	-0.04	-0.08	-0.19	-0.04	-0.57	0.19	0.24	0.13	0.58
4.75	0.12	0.39	0.04	0.06	-0.06	-0.06	0.00	-0.04	-0.08	-0.19	-0.04	-0.56	0.18	0.24	0.12	0.57
5.05	0.12	0.38	0.04	0.07	-0.06	-0.06	0.00	-0.03	-0.07	-0.19	-0.04	-0.56	0.18	0.24	0.12	0.57
5.35	0.12	0.38	0.04	0.07	-0.06	-0.05	0.00	-0.03	-0.07	-0.19	-0.04	-0.56	0.18	0.24	0.12	0.56
5.65	0.11	0.38	0.04	0.07	-0.06	-0.05	0.00	-0.03	-0.07	-0.18	-0.04	-0.56	0.18	0.23	0.12	0.56
5.95	0.11	0.37	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.07	-0.18	-0.03	-0.56	0.17	0.23	0.11	0.55
6.25	0.11	0.37	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.07	-0.18	-0.03	-0.56	0.17	0.23	0.11	0.55
6.55	0.10	0.37	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.03	-0.56	0.17	0.23	0.11	0.54

6.85	0.10	0.37	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.03	-0.56	0.17	0.22	0.11	0.54
7.15	0.10	0.36	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.03	-0.56	0.16	0.22	0.11	0.53
7.45	0.10	0.36	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.03	-0.56	0.16	0.22	0.10	0.53
7.75	0.09	0.36	0.04	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.03	-0.55	0.16	0.22	0.10	0.53
8.05	0.09	0.36	0.03	0.07	-0.05	-0.05	0.00	-0.03	-0.06	-0.18	-0.02	-0.55	0.16	0.22	0.10	0.52
8.35	0.09	0.36	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.06	-0.18	-0.02	-0.55	0.16	0.21	0.10	0.52
8.65	0.09	0.35	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.05	-0.18	-0.02	-0.55	0.15	0.21	0.10	0.52
8.95	0.09	0.35	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.05	-0.17	-0.02	-0.55	0.15	0.21	0.10	0.51
9.25	0.09	0.35	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.05	-0.17	-0.02	-0.55	0.15	0.21	0.10	0.51
9.55	0.08	0.35	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.05	-0.17	-0.02	-0.55	0.15	0.21	0.10	0.51
9.85	0.08	0.35	0.03	0.07	-0.04	-0.05	0.00	-0.03	-0.05	-0.17	-0.02	-0.55	0.15	0.21	0.09	0.51
Mean	**0.15**	**0.42**	**0.05**	**0.09**	**-0.07**	**-0.06**	**0.00**	**-0.04**	**-0.14**	**-0.21**	**-0.13**	**-0.56**	**0.28**	**0.30**	**0.13**	**0.65**
SD	**0.06**	**0.06**	**0.01**	**0.05**	**0.03**	**0.01**	**0.00**	**0.00**	**0.08**	**0.05**	**0.10**	**0.03**	**0.10**	**0.09**	**0.04**	**0.11**

Table 8. Regression outputs for each particle size for homes without HVAC systems

Geometric mean	**AER Closed windows** $\lambda_{closedwindows}$		**Open windows fraction** $f_{openwindows}$		**Deposition rate Closed windows** $k_{i,dep,closedwindows}$		**Penetration factor Closed windows** $P_{i,closedwindows}$		**Model Constant**	
diameter (μm)	β_i	**SRC**	β_i	**SRC**	β_i	**SRC**	β_i	**SRC**	β_i	**Model R^2**
0.0014	0.01	0.13	0.03	0.32	0.00	-0.44	0.00		0.01	0.31
0.0024	0.01	0.16	0.03	0.30	0.00	-0.50	0.11	0.02	0.02	0.37
0.0035	0.01	0.18	0.04	0.27	0.00	-0.54	0.14	0.05	0.02	0.40
0.0045	0.02	0.20	0.04	0.25	-0.01	-0.57	0.15	0.08	0.02	0.43
0.0055	0.02	0.22	0.04	0.23	-0.01	-0.58	0.16	0.10	0.03	0.45
0.0065	0.02	0.23	0.04	0.21	-0.01	-0.60	0.17	0.11	0.03	0.47
0.0075	0.03	0.24	0.04	0.20	-0.01	-0.61	0.18	0.13	0.04	0.48
0.0085	0.03	0.25	0.04	0.18	-0.01	-0.62	0.19	0.14	0.04	0.50
0.0095	0.04	0.26	0.04	0.16	-0.02	-0.63	0.19	0.16	0.05	0.51
0.0105	0.04	0.27	0.04	0.15	-0.02	-0.63	0.20	0.17	0.05	0.52
0.012	0.06	0.28	0.05	0.12	-0.03	-0.64	0.21	0.20	0.06	0.54
0.015	0.07	0.30	0.05	0.10	-0.04	-0.65	0.23	0.22	0.08	0.56
0.018	0.09	0.31	0.05	0.08	-0.05	-0.65	0.24	0.24	0.10	0.58
0.021	0.10	0.32	0.05	0.07	-0.06	-0.65	0.25	0.25	0.11	0.60

0.024	0.11	0.33	0.05	0.07	-0.07	-0.66	0.26	0.26	0.11	0.61
0.027	0.12	0.33	0.05	0.07	-0.08	-0.66	0.27	0.27	0.12	0.62
0.03	0.13	0.34	0.05	0.07	-0.09	-0.66	0.28	0.28	0.12	0.63
0.033	0.14	0.35	0.05	0.07	-0.10	-0.66	0.29	0.29	0.12	0.64
0.036	0.14	0.35	0.05	0.07	-0.11	-0.66	0.29	0.29	0.12	0.65
0.039	0.15	0.36	0.05	0.07	-0.11	-0.66	0.30	0.30	0.12	0.66
0.042	0.15	0.36	0.06	0.07	-0.12	-0.66	0.31	0.31	0.13	0.67
0.045	0.15	0.37	0.06	0.07	-0.13	-0.66	0.32	0.31	0.13	0.68
0.048	0.16	0.37	0.06	0.07	-0.14	-0.66	0.32	0.32	0.13	0.68
0.051	0.16	0.37	0.06	0.07	-0.14	-0.66	0.33	0.32	0.13	0.69
0.054	0.16	0.38	0.06	0.07	-0.15	-0.66	0.34	0.33	0.13	0.70
0.057	0.17	0.38	0.06	0.07	-0.16	-0.66	0.34	0.33	0.13	0.70
0.06	0.17	0.38	0.06	0.07	-0.17	-0.66	0.35	0.34	0.13	0.71
0.063	0.17	0.39	0.06	0.07	-0.17	-0.66	0.35	0.34	0.13	0.71
0.066	0.17	0.39	0.06	0.07	-0.18	-0.66	0.36	0.34	0.13	0.72
0.069	0.17	0.39	0.06	0.07	-0.19	-0.66	0.36	0.35	0.13	0.72
0.072	0.17	0.39	0.06	0.07	-0.19	-0.66	0.37	0.35	0.13	0.72
0.075	0.18	0.40	0.06	0.07	-0.20	-0.66	0.37	0.36	0.13	0.73
0.078	0.18	0.40	0.06	0.07	-0.21	-0.66	0.38	0.36	0.13	0.73
0.081	0.18	0.40	0.06	0.07	-0.21	-0.66	0.38	0.36	0.13	0.73
0.084	0.18	0.40	0.06	0.07	-0.22	-0.66	0.39	0.37	0.13	0.74
0.087	0.18	0.40	0.06	0.07	-0.22	-0.66	0.39	0.37	0.13	0.74
0.09	0.18	0.40	0.06	0.07	-0.23	-0.66	0.40	0.37	0.13	0.74
0.093	0.18	0.40	0.07	0.07	-0.24	-0.66	0.40	0.38	0.13	0.74
0.096	0.18	0.41	0.07	0.07	-0.24	-0.66	0.41	0.38	0.13	0.75
0.099	0.18	0.41	0.07	0.07	-0.25	-0.66	0.41	0.38	0.13	0.75
0.105	0.19	0.41	0.07	0.08	-0.26	-0.65	0.42	0.39	0.13	0.76
0.115	0.19	0.41	0.07	0.08	-0.28	-0.65	0.43	0.40	0.12	0.76
0.125	0.19	0.41	0.07	0.08	-0.29	-0.65	0.44	0.41	0.12	0.77
0.145	0.19	0.42	0.07	0.08	-0.33	-0.64	0.46	0.43	0.12	0.77
0.175	0.19	0.42	0.07	0.08	-0.35	-0.63	0.48	0.45	0.12	0.78
0.205	0.19	0.42	0.07	0.08	-0.37	-0.63	0.49	0.46	0.12	0.78
0.235	0.19	0.42	0.07	0.08	-0.38	-0.63	0.49	0.46	0.12	0.79

0.265	0.19	0.42	0.07	0.08	-0.39	-0.63	0.49	0.45	0.12	0.79
0.295	0.20	0.42	0.07	0.08	-0.39	-0.63	0.49	0.45	0.12	0.79
0.325	0.20	0.42	0.07	0.08	-0.39	-0.64	0.49	0.45	0.12	0.78
0.355	0.20	0.42	0.07	0.08	-0.38	-0.64	0.48	0.44	0.12	0.78
0.385	0.20	0.42	0.07	0.08	-0.37	-0.64	0.48	0.43	0.12	0.78
0.415	0.20	0.42	0.07	0.08	-0.36	-0.64	0.47	0.43	0.13	0.78
0.445	0.20	0.42	0.07	0.07	-0.36	-0.65	0.47	0.42	0.13	0.78
0.475	0.20	0.42	0.07	0.07	-0.35	-0.65	0.46	0.41	0.13	0.77
0.505	0.20	0.42	0.07	0.07	-0.34	-0.65	0.46	0.41	0.13	0.77
0.535	0.20	0.42	0.07	0.07	-0.33	-0.65	0.45	0.40	0.13	0.77
0.565	0.20	0.42	0.07	0.07	-0.32	-0.66	0.45	0.39	0.13	0.77
0.590	0.20	0.42	0.07	0.07	-0.31	-0.66	0.44	0.39	0.13	0.76
0.615	0.20	0.42	0.07	0.07	-0.31	-0.66	0.43	0.38	0.13	0.76
0.655	0.20	0.42	0.07	0.07	-0.30	-0.66	0.43	0.37	0.14	0.76
0.685	0.20	0.42	0.06	0.07	-0.29	-0.67	0.42	0.37	0.14	0.76
0.715	0.20	0.42	0.06	0.07	-0.28	-0.67	0.42	0.36	0.14	0.75
0.745	0.20	0.42	0.06	0.07	-0.28	-0.67	0.41	0.36	0.14	0.75
0.775	0.20	0.41	0.06	0.07	-0.27	-0.67	0.41	0.35	0.14	0.75
0.805	0.20	0.41	0.06	0.07	-0.26	-0.67	0.40	0.35	0.14	0.75
0.835	0.20	0.41	0.06	0.07	-0.26	-0.67	0.40	0.35	0.14	0.74
0.865	0.20	0.41	0.06	0.07	-0.25	-0.67	0.40	0.34	0.14	0.74
0.895	0.20	0.41	0.06	0.06	-0.24	-0.67	0.39	0.34	0.14	0.74
0.925	0.20	0.41	0.06	0.06	-0.24	-0.67	0.39	0.34	0.14	0.74
0.955	0.20	0.41	0.06	0.06	-0.23	-0.67	0.38	0.33	0.14	0.73
0.985	0.20	0.40	0.06	0.06	-0.23	-0.67	0.38	0.33	0.14	0.73
1.14	0.19	0.39	0.06	0.06	-0.19	-0.68	0.35	0.30	0.14	0.71
1.44	0.18	0.38	0.05	0.06	-0.16	-0.68	0.32	0.29	0.15	0.69
1.74	0.17	0.37	0.05	0.06	-0.14	-0.67	0.31	0.27	0.15	0.67
2.05	0.17	0.36	0.05	0.05	-0.12	-0.67	0.29	0.27	0.15	0.65
2.35	0.16	0.35	0.05	0.05	-0.11	-0.67	0.28	0.26	0.15	0.64
2.65	0.15	0.34	0.05	0.05	-0.10	-0.67	0.27	0.25	0.14	0.62
2.95	0.15	0.33	0.05	0.05	-0.09	-0.66	0.26	0.25	0.14	0.61
3.25	0.14	0.32	0.04	0.05	-0.09	-0.66	0.25	0.24	0.14	0.60

3.55	0.14	0.32	0.04	0.05	-0.08	-0.66	0.25	0.24	0.14	0.59
3.85	0.13	0.31	0.04	0.05	-0.07	-0.65	0.24	0.24	0.14	0.58
4.15	0.13	0.31	0.04	0.05	-0.07	-0.65	0.24	0.24	0.14	0.58
4.45	0.12	0.30	0.04	0.05	-0.07	-0.65	0.23	0.23	0.13	0.57
4.75	0.12	0.30	0.04	0.05	-0.06	-0.65	0.23	0.23	0.13	0.56
5.05	0.12	0.29	0.04	0.05	-0.06	-0.65	0.22	0.23	0.13	0.56
5.35	0.11	0.29	0.04	0.05	-0.06	-0.64	0.22	0.23	0.13	0.55
5.65	0.11	0.29	0.04	0.05	-0.05	-0.64	0.22	0.22	0.13	0.55
5.95	0.11	0.28	0.04	0.05	-0.05	-0.64	0.21	0.22	0.12	0.54
6.25	0.10	0.28	0.04	0.05	-0.05	-0.64	0.21	0.22	0.12	0.54
6.55	0.10	0.28	0.04	0.05	-0.05	-0.64	0.21	0.22	0.12	0.53
6.85	0.10	0.27	0.04	0.06	-0.04	-0.64	0.21	0.21	0.12	0.53
7.15	0.10	0.27	0.04	0.06	-0.04	-0.63	0.20	0.21	0.12	0.52
7.45	0.09	0.27	0.04	0.06	-0.04	-0.63	0.20	0.21	0.12	0.52
7.75	0.09	0.27	0.04	0.06	-0.04	-0.63	0.20	0.21	0.11	0.52
8.05	0.09	0.26	0.04	0.06	-0.04	-0.63	0.20	0.20	0.11	0.51
8.35	0.09	0.26	0.04	0.06	-0.04	-0.63	0.20	0.20	0.11	0.51
8.65	0.09	0.26	0.04	0.06	-0.04	-0.63	0.20	0.20	0.11	0.51
8.95	0.08	0.26	0.04	0.06	-0.03	-0.63	0.19	0.20	0.11	0.51
9.25	0.08	0.26	0.04	0.06	-0.03	-0.63	0.19	0.20	0.11	0.50
9.55	0.08	0.25	0.04	0.06	-0.03	-0.63	0.19	0.20	0.11	0.50
9.85	0.08	0.25	0.04	0.06	-0.03	-0.63	0.19	0.19	0.11	0.50
Mean	**0.14**	**0.35**	**0.05**	**0.08**	**-0.16**	**-0.65**	**0.32**	**0.30**	**0.12**	**0.65**
SD	**0.06**	**0.07**	**0.01**	**0.05**	**0.12**	**0.03**	**0.11**	**0.10**	**0.03**	**0.11**

Table 9. Regression outputs for each particle size for homes with HVAC systems

Geometric mean diameter (μm)	**AER Closed windows $\lambda_{closedwindows}$**		**Open windows fraction $f_{openwindows}$**		**HVAC system Runtime f_{HVAC}**		**Recirculation rate λ_{HVAC}**		**Filter efficiency $\eta_{i,HVAC}$**		**Deposition rate Closed windows $k_{i,dep,closedwindows}$**		**Penetration factor Closed windows $P_{i,closedwindows}$**		**Model Constant**	
	β_i	**SRC**	**β_i**	**SRC**	**β_i**	**SRC**	**β_i**	**SRC**	**β_i**	**SRC**	**β_i**	**SRC**	**β_i**	**SRC**	**β_i**	**Model R^2**
0.0014	0.01	0.26	0.02	0.38	0.00	-0.05	0.00	-0.04	0.00	-0.06	0.00	-0.41	0.00		0.01	0.39
0.0024	0.01	0.32	0.02	0.36	-0.01	-0.06	0.00	-0.05	0.00	-0.07	0.00	-0.46	0.11	0.04	0.01	0.45
0.0035	0.01	0.35	0.03	0.34	-0.01	-0.07	0.00	-0.05	-0.01	-0.08	0.00	-0.49	0.11	0.07	0.01	0.50

0.0045	0.02	0.38	0.03	0.31	-0.01	-0.07	0.00	-0.05	-0.01	-0.08	0.00	-0.51	0.12	0.10	0.02	0.53
0.0055	0.02	0.40	0.03	0.29	-0.01	-0.08	0.00	-0.06	-0.01	-0.09	0.00	-0.53	0.12	0.12	0.02	0.56
0.0065	0.02	0.42	0.03	0.27	-0.02	-0.08	0.00	-0.06	-0.01	-0.09	0.00	-0.54	0.13	0.14	0.02	0.58
0.0075	0.03	0.43	0.03	0.25	-0.02	-0.08	0.00	-0.06	-0.01	-0.10	-0.01	-0.55	0.14	0.16	0.03	0.59
0.0085	0.03	0.44	0.03	0.23	-0.02	-0.09	0.00	-0.06	-0.01	-0.10	-0.01	-0.55	0.14	0.17	0.03	0.60
0.0095	0.04	0.45	0.03	0.20	-0.03	-0.09	0.00	-0.06	-0.02	-0.11	-0.01	-0.56	0.14	0.19	0.04	0.62
0.0105	0.04	0.45	0.04	0.19	-0.03	-0.09	0.00	-0.06	-0.02	-0.11	-0.01	-0.56	0.15	0.20	0.04	0.62
0.012	0.06	0.46	0.04	0.16	-0.04	-0.09	0.00	-0.06	-0.03	-0.12	-0.02	-0.57	0.16	0.23	0.05	0.64
0.015	0.08	0.47	0.04	0.13	-0.05	-0.09	0.00	-0.06	-0.04	-0.13	-0.02	-0.57	0.17	0.25	0.07	0.66
0.018	0.10	0.47	0.04	0.11	-0.06	-0.09	0.00	-0.06	-0.05	-0.14	-0.03	-0.57	0.19	0.27	0.08	0.67
0.021	0.11	0.48	0.05	0.10	-0.07	-0.09	0.00	-0.06	-0.06	-0.14	-0.04	-0.57	0.20	0.28	0.09	0.68
0.024	0.12	0.48	0.05	0.10	-0.08	-0.09	0.00	-0.06	-0.07	-0.15	-0.04	-0.57	0.21	0.29	0.10	0.69
0.027	0.13	0.48	0.05	0.09	-0.08	-0.09	0.00	-0.06	-0.07	-0.15	-0.05	-0.57	0.21	0.30	0.11	0.70
0.03	0.14	0.49	0.05	0.09	-0.09	-0.09	0.00	-0.06	-0.08	-0.16	-0.06	-0.57	0.22	0.31	0.11	0.70
0.033	0.14	0.49	0.05	0.09	-0.09	-0.09	0.00	-0.06	-0.09	-0.16	-0.06	-0.57	0.23	0.31	0.12	0.71
0.036	0.15	0.49	0.05	0.09	-0.10	-0.09	0.00	-0.06	-0.09	-0.17	-0.07	-0.57	0.24	0.32	0.12	0.72
0.039	0.15	0.49	0.05	0.09	-0.10	-0.09	0.00	-0.06	-0.10	-0.17	-0.07	-0.57	0.24	0.32	0.12	0.72
0.042	0.16	0.49	0.05	0.09	-0.10	-0.09	0.00	-0.06	-0.11	-0.17	-0.08	-0.57	0.25	0.32	0.13	0.72
0.045	0.16	0.50	0.06	0.09	-0.10	-0.09	0.00	-0.06	-0.11	-0.18	-0.09	-0.57	0.26	0.33	0.13	0.73
0.048	0.17	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.12	-0.18	-0.09	-0.57	0.26	0.33	0.13	0.73
0.051	0.17	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.12	-0.18	-0.10	-0.57	0.27	0.34	0.13	0.74
0.054	0.17	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.13	-0.19	-0.10	-0.57	0.28	0.34	0.14	0.74
0.057	0.18	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.13	-0.19	-0.11	-0.56	0.28	0.34	0.14	0.74
0.06	0.18	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.14	-0.19	-0.11	-0.56	0.29	0.35	0.14	0.75
0.063	0.18	0.50	0.06	0.09	-0.11	-0.09	-0.01	-0.06	-0.14	-0.19	-0.12	-0.56	0.29	0.35	0.14	0.75
0.066	0.18	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.14	-0.20	-0.12	-0.56	0.30	0.35	0.14	0.75
0.069	0.18	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.15	-0.20	-0.13	-0.56	0.30	0.36	0.14	0.75
0.072	0.18	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.15	-0.20	-0.13	-0.56	0.31	0.36	0.14	0.76
0.075	0.19	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.15	-0.20	-0.14	-0.56	0.31	0.36	0.14	0.76
0.078	0.19	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.16	-0.21	-0.14	-0.56	0.32	0.37	0.14	0.76
0.081	0.19	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.16	-0.21	-0.15	-0.55	0.32	0.37	0.15	0.76
0.084	0.19	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.16	-0.21	-0.15	-0.55	0.33	0.37	0.15	0.76
0.087	0.19	0.50	0.06	0.09	-0.12	-0.09	-0.01	-0.06	-0.17	-0.21	-0.16	-0.55	0.33	0.37	0.15	0.76

0.09	0.19	0.50	0.07	0.09	-0.12	-0.09	-0.01	-0.06	-0.17	-0.22	-0.16	-0.55	0.33	0.38	0.15	0.77
0.093	0.19	0.50	0.07	0.09	-0.13	-0.09	-0.01	-0.06	-0.17	-0.22	-0.17	-0.55	0.34	0.38	0.15	0.77
0.096	0.20	0.50	0.07	0.09	-0.13	-0.10	-0.01	-0.06	-0.18	-0.22	-0.17	-0.55	0.34	0.38	0.15	0.77
0.099	0.20	0.50	0.07	0.09	-0.13	-0.10	-0.01	-0.06	-0.18	-0.22	-0.18	-0.55	0.35	0.38	0.15	0.77
0.105	0.20	0.50	0.07	0.09	-0.13	-0.10	-0.01	-0.06	-0.19	-0.23	-0.19	-0.54	0.36	0.39	0.15	0.77
0.115	0.20	0.50	0.07	0.09	-0.13	-0.10	-0.01	-0.06	-0.20	-0.23	-0.20	-0.54	0.37	0.40	0.15	0.78
0.125	0.20	0.50	0.07	0.09	-0.13	-0.10	-0.01	-0.06	-0.20	-0.24	-0.21	-0.53	0.37	0.40	0.15	0.78
0.145	0.20	0.50	0.07	0.09	-0.14	-0.10	-0.01	-0.06	-0.22	-0.26	-0.24	-0.52	0.39	0.42	0.16	0.78
0.175	0.21	0.50	0.07	0.09	-0.14	-0.10	-0.01	-0.06	-0.23	-0.27	-0.25	-0.51	0.40	0.43	0.16	0.78
0.205	0.21	0.50	0.07	0.09	-0.15	-0.11	-0.01	-0.06	-0.24	-0.28	-0.26	-0.50	0.41	0.43	0.16	0.79
0.235	0.21	0.50	0.07	0.09	-0.15	-0.11	-0.01	-0.06	-0.24	-0.29	-0.27	-0.49	0.41	0.43	0.16	0.79
0.265	0.21	0.50	0.07	0.09	-0.16	-0.11	-0.01	-0.07	-0.25	-0.29	-0.27	-0.49	0.41	0.42	0.17	0.78
0.295	0.21	0.50	0.07	0.09	-0.16	-0.11	-0.01	-0.07	-0.25	-0.30	-0.27	-0.49	0.41	0.42	0.17	0.78
0.325	0.21	0.51	0.07	0.09	-0.16	-0.11	-0.01	-0.07	-0.25	-0.30	-0.26	-0.49	0.40	0.41	0.17	0.78
0.355	0.21	0.51	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.25	-0.30	-0.26	-0.49	0.40	0.41	0.17	0.78
0.385	0.21	0.51	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.25	-0.30	-0.25	-0.49	0.39	0.40	0.17	0.78
0.415	0.21	0.51	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.24	-0.30	-0.24	-0.49	0.39	0.40	0.18	0.78
0.445	0.21	0.51	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.24	-0.30	-0.24	-0.49	0.38	0.39	0.18	0.78
0.475	0.21	0.51	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.24	-0.30	-0.23	-0.49	0.37	0.39	0.18	0.78
0.505	0.21	0.52	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.23	-0.30	-0.22	-0.49	0.37	0.38	0.18	0.77
0.535	0.22	0.52	0.07	0.09	-0.17	-0.12	-0.01	-0.07	-0.23	-0.30	-0.21	-0.49	0.36	0.38	0.18	0.77
0.565	0.22	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.22	-0.30	-0.21	-0.50	0.36	0.37	0.18	0.77
0.590	0.22	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.22	-0.30	-0.20	-0.50	0.35	0.36	0.18	0.77
0.615	0.22	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.22	-0.30	-0.20	-0.50	0.34	0.36	0.18	0.77
0.655	0.22	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.21	-0.30	-0.19	-0.50	0.34	0.35	0.18	0.77
0.685	0.21	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.21	-0.29	-0.18	-0.50	0.33	0.35	0.18	0.76
0.715	0.21	0.52	0.07	0.08	-0.17	-0.12	-0.01	-0.07	-0.21	-0.29	-0.18	-0.51	0.33	0.35	0.18	0.76
0.745	0.21	0.52	0.06	0.08	-0.17	-0.12	-0.01	-0.07	-0.20	-0.29	-0.17	-0.51	0.33	0.34	0.18	0.76
0.775	0.21	0.52	0.06	0.08	-0.17	-0.12	-0.01	-0.07	-0.20	-0.29	-0.17	-0.51	0.32	0.34	0.18	0.76
0.805	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.19	-0.29	-0.16	-0.51	0.32	0.34	0.18	0.76
0.835	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.19	-0.29	-0.16	-0.51	0.31	0.33	0.18	0.76
0.865	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.19	-0.28	-0.15	-0.51	0.31	0.33	0.18	0.75
0.895	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.18	-0.28	-0.15	-0.51	0.30	0.33	0.18	0.75

0.925	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.18	-0.28	-0.15	-0.51	0.30	0.33	0.18	0.75
0.955	0.21	0.52	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.18	-0.28	-0.14	-0.52	0.30	0.32	0.17	0.75
0.985	0.20	0.53	0.06	0.08	-0.16	-0.12	-0.01	-0.07	-0.17	-0.27	-0.14	-0.52	0.29	0.32	0.17	0.75
1.14	0.20	0.52	0.06	0.08	-0.15	-0.12	-0.01	-0.07	-0.15	-0.26	-0.11	-0.52	0.27	0.31	0.17	0.74
1.44	0.19	0.52	0.05	0.08	-0.14	-0.12	-0.01	-0.07	-0.13	-0.24	-0.09	-0.53	0.24	0.29	0.16	0.73
1.74	0.18	0.52	0.05	0.08	-0.14	-0.12	-0.01	-0.07	-0.12	-0.23	-0.08	-0.53	0.23	0.29	0.16	0.72
2.05	0.17	0.52	0.05	0.08	-0.13	-0.12	-0.01	-0.07	-0.11	-0.22	-0.07	-0.54	0.22	0.28	0.15	0.71
2.35	0.16	0.51	0.05	0.08	-0.13	-0.11	-0.01	-0.07	-0.10	-0.21	-0.06	-0.54	0.21	0.28	0.14	0.70
2.65	0.16	0.51	0.05	0.08	-0.12	-0.11	-0.01	-0.07	-0.09	-0.20	-0.05	-0.54	0.20	0.28	0.14	0.70
2.95	0.15	0.51	0.05	0.08	-0.12	-0.11	-0.01	-0.07	-0.08	-0.19	-0.05	-0.54	0.19	0.27	0.13	0.69
3.25	0.15	0.51	0.04	0.08	-0.11	-0.11	-0.01	-0.07	-0.08	-0.18	-0.05	-0.54	0.18	0.27	0.13	0.69
3.55	0.14	0.51	0.04	0.08	-0.11	-0.11	-0.01	-0.07	-0.07	-0.18	-0.04	-0.54	0.18	0.27	0.13	0.68
3.85	0.14	0.51	0.04	0.08	-0.11	-0.11	-0.01	-0.07	-0.07	-0.17	-0.04	-0.54	0.17	0.27	0.12	0.68
4.15	0.13	0.51	0.04	0.08	-0.10	-0.11	0.00	-0.07	-0.07	-0.17	-0.04	-0.54	0.17	0.27	0.12	0.68
4.45	0.13	0.50	0.04	0.08	-0.10	-0.11	0.00	-0.07	-0.06	-0.16	-0.03	-0.54	0.16	0.27	0.11	0.67
4.75	0.12	0.50	0.04	0.08	-0.10	-0.11	0.00	-0.07	-0.06	-0.16	-0.03	-0.54	0.16	0.27	0.11	0.67
5.05	0.12	0.50	0.04	0.08	-0.09	-0.11	0.00	-0.07	-0.06	-0.15	-0.03	-0.54	0.16	0.27	0.11	0.67
5.35	0.12	0.50	0.04	0.09	-0.09	-0.11	0.00	-0.07	-0.05	-0.15	-0.03	-0.54	0.15	0.27	0.10	0.66
5.65	0.11	0.50	0.04	0.09	-0.09	-0.11	0.00	-0.07	-0.05	-0.14	-0.03	-0.54	0.15	0.26	0.10	0.66
5.95	0.11	0.50	0.04	0.09	-0.08	-0.11	0.00	-0.07	-0.05	-0.14	-0.02	-0.54	0.15	0.26	0.10	0.66
6.25	0.11	0.50	0.04	0.09	-0.08	-0.11	0.00	-0.07	-0.05	-0.14	-0.02	-0.54	0.15	0.26	0.10	0.66
6.55	0.10	0.50	0.04	0.09	-0.08	-0.11	0.00	-0.07	-0.04	-0.13	-0.02	-0.54	0.14	0.26	0.09	0.66
6.85	0.10	0.50	0.04	0.09	-0.08	-0.11	0.00	-0.07	-0.04	-0.13	-0.02	-0.54	0.14	0.26	0.09	0.65
7.15	0.10	0.50	0.04	0.09	-0.08	-0.11	0.00	-0.07	-0.04	-0.13	-0.02	-0.54	0.14	0.26	0.09	0.65
7.45	0.10	0.50	0.03	0.09	-0.07	-0.11	0.00	-0.07	-0.04	-0.12	-0.02	-0.54	0.14	0.25	0.09	0.65
7.75	0.09	0.50	0.03	0.09	-0.07	-0.11	0.00	-0.07	-0.04	-0.12	-0.02	-0.54	0.14	0.25	0.09	0.65
8.05	0.09	0.49	0.03	0.09	-0.07	-0.11	0.00	-0.07	-0.04	-0.12	-0.02	-0.54	0.13	0.25	0.08	0.65
8.35	0.09	0.49	0.03	0.09	-0.07	-0.11	0.00	-0.07	-0.04	-0.12	-0.02	-0.54	0.13	0.25	0.08	0.64
8.65	0.09	0.49	0.03	0.09	-0.07	-0.11	0.00	-0.07	-0.03	-0.11	-0.02	-0.54	0.13	0.25	0.08	0.64
8.95	0.09	0.49	0.03	0.10	-0.07	-0.11	0.00	-0.07	-0.03	-0.11	-0.02	-0.55	0.13	0.25	0.08	0.64
9.25	0.09	0.49	0.03	0.10	-0.07	-0.11	0.00	-0.07	-0.03	-0.11	-0.02	-0.55	0.13	0.25	0.08	0.64
9.55	0.08	0.49	0.03	0.10	-0.07	-0.11	0.00	-0.07	-0.03	-0.11	-0.02	-0.55	0.13	0.24	0.08	0.64
9.85	0.08	0.49	0.03	0.10	-0.06	-0.11	0.00	-0.07	-0.03	-0.11	-0.01	-0.55	0.13	0.24	0.08	0.64

Mean	**0.15**	**0.49**	**0.05**	**0.11**	**-0.11**	**-0.10**	**-0.01**	**-0.06**	**-0.12**	**-0.20**	**-0.11**	**-0.53**	**0.25**	**0.31**	**0.13**	**0.71**
SD	**0.06**	**0.04**	**0.01**	**0.06**	**0.05**	**0.01**	**0.00**	**0.01**	**0.08**	**0.07**	**0.08**	**0.03**	**0.10**	**0.08**	**0.05**	**0.07**

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