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ABSTRACT

The process of characterizing human exposure to particulate matter requires information on both particle concentrations in microenvironments and the time-specific activity budgets of individuals among these microenvironments. Because the average amount of time spent indoors by individuals in the US is estimated to be greater than 75%, accurate characterization of particle concentrations indoors is critical to exposure assessments for the US population. In addition, it is estimated that indoor particle concentrations depend strongly on outdoor concentrations. The spatial and temporal variations of indoor particle concentrations as well as the factors that affect these variations are important to health scientists. For them, knowledge of the factors that control the relationship of indoor particle concentrations to outdoor levels is particularly important. In this report, we identify and evaluate sources of data for those factors that affect the transport to and concentration of outdoor particles in the indoor environment. Concentrations of particles indoors depend upon the fraction of outdoor particles that penetrate through the building shell or are transported via the air handling (HVAC) system, the generation of particles by indoor sources, and the loss mechanisms that occur indoors, such as deposition. To address these issues, we (i) identify and assemble relevant information including the behavior of particles during air leakage, HVAC operations, and particle filtration; (ii) review and evaluate the assembled information to distinguish data that are directly relevant to specific estimates of particle transport from those that are only indirectly useful and (iii) provide a synthesis of the currently available information on building air-leakage parameters and their effect on indoor particle matter concentrations.

KEYWORDS: Exposure assessment, indoor environment, mass-balance model, particles, air infiltration

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EXECUTIVE SUMMARY

Characterizing human exposure to particulate matter requires information on both particle concentrations in microenvironments and the time-specific activity budgets of individuals who move among these microenvironments. Because the US population is estimated to spend on average more than 75% of their time indoors, accurate characterization of concentrations of particles of outdoor origin in the indoor environment is critical to exposure assessments. In this report we summarize, compile, and evaluate sources of data for factors that affect the concentration of outdoor particles indoors (COPI). COPI depends upon the fraction of particles that penetrate through the building shell or are transported via the HVAC system and on the loss mechanisms that occur indoors, such as deposition. To address these issues, this project had three specific tasks: (i) to identify and assemble the relevant information on air leakage and on HVAC operations, including particle filtration; (ii) to review and evaluate the assembled information to distinguish data that are directly relevant to specific estimates of particle transport from those that are only indirectly useful and (iii) provide a synthesis of the currently available information on building parameters and their effect on particle transport.

In addressing these tasks, we found that a thorough understanding of the processes affecting the concentration of outdoor particle indoors is essential for improving assessments of human exposure to particles of outdoor origin. This is particularly important for assessors who need to consider the spatial and temporal variation of indoor exposures to outdoor particles. We also found that simple indoor/outdoor ratios are insufficient for understanding and predicting indoor concentrations. A dynamic mass balance approach is necessary in order to account for all of the critical parameters affecting the indoor/outdoor relationship. However, the appropriate input values for these critical parameters are currently not well understood. These parameters are identified and summarized in the following paragraphs.

Particle deposition is an important factor affecting indoor particle concentrations in all types of buildings. However, deposition loss rates appear to be highly sensitive to environmental conditions and particle characteristics, leading to significant variations in experimentally determined deposition rates. Given the wide range of deposition values obtained experimentally, it is difficult to determine which of the deposition models predicts indoor deposition most accurately and which model parameters most accurately reflect real building conditions.

Another critical factor is the fraction of outdoor particles that remain in infiltrating air and enter the building interior, typically referred to as the Penetration Factor, P. In some published articles, the term penetration factor has been given other

definitions, such as either the indoor/outdoor ratio of all particles or of particles of outdoor origin. However, these definitions confuse the factors affecting indoor concentrations by combining the influence of infiltration, deposition, and even generation into a single term. There is insufficient data to determine a likely average or minimum P for either residences or commercial buildings.

Understanding the basic building characteristics is also critical to determining indoor particle concentrations. In contrast to COPI factors that are needed to carry out mass balances on particles, the quantity and quality of data on basic building characteristics for both residential and commercial buildings is quite high. However, there are still significant gaps in the dataset, such as assessment of infiltration rates into commercial buildings and the prevalence of local exhaust use in residential buildings.

Information of the efficiency of various types of filters is fairly high, both in quality and quantity. However, data on air flow rates in central forced-air residential heating and cooling systems are very sparse, leading to large uncertainties in particle filtration rates in residences. The operation times of commercial building HVAC systems and flow rates through air filters will vary with climate, building design, internal heat loads, type of HVAC system, type of HVAC control system, and user behaviors. Rough estimates of typical flow rates and operation times are provided based on anecdotal reports and limited data from publications; however, the range, geographic variability, and uncertainty in these estimates are unknown and could be potentially important due to the significant particle concentration reductions that can be achieved through filtration.

Data quality, quantity, and representativeness were evaluated for key factors such as HVAC design and operation, infiltration and leakage area, deposition, penetration factors, and natural ventilation. We found that none of the critical factors affecting the indoor/outdoor particle relationship are yet well enough characterized to provide reliable inputs to exposure models.

In reviewing data needs for improving the ability to link indoor concentration of particles to outdoor concentrations, we have determined that the most critical missing information includes the following:

measured particle penetration factors;
measured particle deposition rates in commercial and institutional buildings;
infiltration rates in commercial buildings;
the types of filters used in all buildings (except large offices);
window opening behaviors; and
rates of indoor resuspension of particles transferred indoors from outdoors.

1.0 Introduction

The process of characterizing human exposure to particles requires information on both particle concentrations in microenvironments and the time-specific activity budgets of individuals among these microenvironments. Because the US population is estimated to spend on average more than 75% of their time indoors, accurate characterization of particle concentrations indoors is critical to exposure assessments. In most cases, concentrations of ambient particles indoors depend primarily upon the quantity of particulate matter that penetrates through the building shell or is transported via the heating, ventilation, and air conditioning (HVAC) system. In addition, the concentration of particles indoors is affected by several other factors such as filtration, ventilation, deposition, re-emission, and indoor sources. In order to evaluate and model human exposures to particles, information is required on these characteristics. We refer to such factors as Concentration-of-Outdoor-Particles-Indoors (COPI) factors. Most COPI factors vary from one type of building to another. Thus, COPI factors cannot be represented by a single value. Instead the variation in these factors needs to be explored and recorded. And how this variation relates to building design and operation needs to be evaluated. In this report, we identify the COPI factors that are most needed for assessing human exposure to outdoor particles and then compile and evaluate information sources for these COPI factors.

1.1 Approach

In most buildings, concentrations of ambient particles indoors depend primarily upon the transport of particles from outside the building through the building shell (through intentional and unintentional openings) or via the HVAC system and the loss mechanisms that occur indoors, such as deposition. To characterize human exposure indoors to particles originating from the outdoor environment, we prepared this report based on the following specific aims:

Identify the relevant information on air leakage and on HVAC operations, including particle filtration;

Review and evaluate the identified information to distinguish data that are most relevant to assessments that quantify exposures indoors to particles of outdoor origin; and

Provide a synthesis and evaluation of the currently available information on COPI factors for residential and commercial buildings.

Considerable previous work has been expended to understand and measure building leakage and other air flow characteristics as they affect air infiltration and ventilation, however the connection between these air-flow pathways and particle entry into buildings remains poorly understood. To address this issue, this report provides an examination of experiments and modeling to better characterize the transport of ambient particles from outdoor air to the indoor environment. Specifically, we examine the available information about features of buildings that affect indoor concentrations of ambient particles originating outdoors.

1.2 Characterizing Exposures to Particles

The process of characterizing particle exposures requires information on particle concentrations, the time-specific locations of population cohorts relative to these concentrations, and the variations of these concentrations and time budgets.

1.2.1 Components of an Exposure Assessment

A review of the current literature reveals that *exposure* is defined in terms of the contact of an agent of concern with the visible exterior of the person including the skin and openings into the body, such as mouth and nostrils, over a specified period of time (McKone and Daniels, 1991; NAS, 1991a; NAS, 1991b; USEPA, 1992; Lioy and Pellizzari, 1996; Zartarian et al., 1997). In earlier studies, exposure assessments often relied implicitly on the assumption that exposure to air pollutants indoors could be linked by simple parameters to ambient concentrations in outdoor air. Later studies showed that this assumption is rarely correct. More recent exposure studies based on total exposure assessments that include time and activity patterns and micro-environmental data reveal that an exposure assessment is most valuable when it provides a comprehensive view of exposure pathways and identifies major sources of variability and uncertainty.

1.2.2 The Basic Exposure Model

An exposure model predicts cumulative exposures to particles that people encounter during activities that bring them in contact with particle concentrations in various microenvironments. To construct an exposure model one must link an individual or a population cohort with both a series of time-specific activities and with the geographic locations and microenvironments associated with those activities. In addition, it is necessary, through a combination of detection and monitoring data and process models, to define particle concentrations in each combination of time period, location, and microenvironment. An exposure model must be able to represent peak exposure concentration, the number of times the concentration exceeds specified concentration levels, the average exposure concentration exceeding a specified level, or the cumulative intake or uptake during a series of exposure events.

Predictive modeling can take various forms. One commonly used modeling approach is to estimate the average exposure experienced in each location (for an individual or group) using the time budget and the measures of concentration in each microenvironment. The most general way to define exposure is in terms of a concentration in a specified medium and the time that the receptor has contact with that concentration. To address exposure in such situations the standard approach is to use the model equations proposed by Duan (1982) and utilized by others (Ott, 1984; Ott et al., 1988; Ott et al., 1992; Klepeis, 1994; Lurmann and Korc, 1994; MacIntosh et al., 1995).

$$\xi_i = \frac{1}{T}\sum_{j=1}^{J} z_j t_{ij} \tag{1.1}$$

$$T = \sum_{j=1}^{J} t_{ij} \tag{1.2}$$

where ξ_i *i*s the average exposure of person *i* over averaging time *T*, while z_j is the concentration that person *i* encounters in micro environment *j* and t_{ij} is the time spent by person *i* in micro environment *j* , *J* is the total number of micro environments visited over time *T*. The discrete times t_{ij} that person *i* spends in various micro environments is referred to as the person’s “activity pattern.” Exposure assessment is a key step in the analysis of the link between various contaminant sources and human health risks and, ultimately, to effective risk management strategies.

1.2.3 The Importance of Indoor/Outdoor Relationships

The exposure characterization process requires knowledge of what data is needed as well as a compilation and evaluation of the sources for the data. Exposure information includes monitoring, time-activity, and other available data (e.g., from questionnaires and diaries, including past and current exposures and exposure factors).

1.3 The Information Evaluated in this Report

We consider four categories of COPI-factors information in our analysis. First is the nature of building shell leaks and what influence they have on air flow and particle transport. Second is the role of HVAC systems in supplying air to the building interior, typically through filter media of varying types and filtration efficiency. Third is information obtained from experiments in which indoor/outdoor particle concentrations are measured and particularly whether there is ancillary information about the building and/or its leakage characteristics. Fourth is information from papers and reports in which particle penetration is estimated and discussed. We address these issues through three tasks that are summarized in the following paragraphs.

In the first task, we identify the relevant information, data bases, etc. needed to assess how transport of particles from outdoor to indoor air is impacted by leaks, HVAC systems, particle mass-balance data, and penetration data. Members of the LBNL Indoor Environment Department staff have broad familiarity with all of the major data bases and most of the literature on air leakage, HVAC operations, and particle filtration. This familiarity facilitated this first task. In addition, through efforts with the ongoing San Joaquin Valley project and other indoor particle research, LBNL staff have kept abreast of the literature on indoor-outdoor particle measurements, and on direct measures and model estimates of particle penetration factors (of which there is very little).

In the second task, we review and evaluate the identified information to determine which resources provide relevant COPI factors. In this task, we used three criteria by which we evaluated the available information. First was the quantity of information available. For example, is the information derived from a large survey or from a couple of test houses? Second was the quality of the information. For example, the reliability of the methods used—direct measurement, modeling, replication, quality control, etc. Third was the representativeness of the available information. For example were both residential and commercial buildings represented, and were the samples stratified so as to properly capture variability. We used the review and evaluation of currently available information identify data needs, current resources, and data gaps for COPI factors.

Our third task provides a synthesis of the currently available information on COPI factors and their effect on particle concentration indoors. We used this effort to identify areas for which there are important gaps or weaknesses in the information, particularly in linking air leakage information and particle transport and fate.

1.4 Overview of the Report

The remainder of this report consists of three sections. In section 2, we provide background on the issues that affect the transfer of particle matter from the outdoor to the indoor environment and how this relates to the reliability of exposure assessments. Here we consider factors that affect the transport, distribution, and loss of particulate matter drawn from outdoor air to the indoor environment. Then we consider the mass balance that links indoor particulate matter concentrations to outdoor levels, giving specific attention to air flow in buildings and the configuration of HVAC and filtration systems. Based on how they affect particle entry and removal, we assign relative significance to COPI factors. In Section 3, we identify and evaluate the types of data available on COPI factors. In Section 4, we provide an evaluation of the available data sets and information resources for COPI factors.

2.0 Defining a Set of Relevant COPI Factors

In this section, we identify those factors that affect the concentration of outdoor particulate matter indoors. We begin by defining (i) what is meant a "relevant factor", (ii) the balance model that is used to evaluate the relevance of COPI factors; and (iii) air flow in buildings and the configuration of HVAC and filtration systems. We consider both residential and commercial buildings. We conclude this section by listing and ranking relevant building characteristics based on their importance for assessing COPI.

2.1 What are The Relevant Factors Impacting Indoor Concentrations of Outdoor Particles?

Concentrations of ambient particles indoors depend upon the balance among input and loss processes. Inputs include the fraction of particles that penetrate through the building shell (through intentional and unintentional openings) or are transported via the HVAC system. The loss mechanisms that occur indoors include deposition, transformation, filtration, and ventilation. The purpose of this section is to identify those factors that impact the indoor/outdoor particle ratio. This is done in the context of a indoor/outdoor particle mass balance. Important to this mass balance in commercial buildings and many residences is the configuration and operation of HVAC systems.

2.2 Mass Balance Framework

Airborne particles in the indoor environment are derived from sources outdoors (both natural and anthropogenic) and sources indoors (smoking, wood stoves, cooking, resuspended particles from floors, vacuuming, etc.). The concentration of outdoor particles in the indoor environment is a balance between the rates at which outdoor particles enter and leave the air within the building and the rates at which they are removed, transformed, and re-emitted in the indoor environment. In general, a mass balance equation representing the change in indoor concentration, C_i, within the volume, V, over time, t, can be written as follows:

$$\frac{dC_i V}{dt} = \text{[Entry of Outdoor Particle Mass]} - \text{[Exit of Indoor Particle Mass]} - \text{[Mass Removal Indoors: deposition, filtration, transformation]} + \text{[Mass Re-emission Indoors: resuspension, transformation]} \quad (2.1)$$

Descriptions of the mass balance mechanisms in the indoor environment are provided in the following sections.

2.2.1 Entry and Exit of Particle Mass

Air carrying particles can enter and leave the indoor environment through three processes: mechanical ventilation, natural ventilation, and infiltration. Mechanical ventilation refers to using fan systems to move air, typically through ductwork, and supply it to areas within a building. These systems often supply heating and/or cooling in addition to the ventilation air (outside air). Mechanical ventilation systems may be controlled to vary the amount of air supplied according to the heating or cooling load, time of day, or other factors. In commercial buildings, typically filters are installed which remove particles before they enter the building. The removal efficiency of these filters ranges from highly effective to fairly ineffective, with removal being very dependent on the particle size. In addition, incidental removal may occur due to deposition onto duct surfaces and within fans, coils, and other system components. Mechanical ventilation systems are common in large commercial buildings, but almost never used in residential buildings. Although, residential houses often use forced air systems for maintaining temperature control, it is unusual for these systems to intentionally supply outside air for the purpose of ventilation.

Natural ventilation refers to opening windows and doors to increase entry of outside air. The amount of outdoor air supplied depends on factors such as the total open area, orientation to the wind, indoor/outdoor pressure difference, and indoor/outdoor temperature difference. Due to the large size of the openings, particles are not removed from air entering buildings through natural ventilation. Natural ventilation can move large volumes of air and, when used, will often be the dominant air entry route, particularly in buildings without mechanical ventilation.

The third entry route is infiltration. Infiltration refers to the entry of air through small cracks and gaps in the building shell. Although the size, shape, and location of infiltration entry points is fixed for a given building, the amount of air which enters through infiltration will vary with the pressure differences across the exterior building surfaces. These pressure differences will vary with the wind speed/direction, indoor/outdoor temperature difference, and the operation of the HVAC system (this occurs when, for various reasons, the supply and return systems are not balanced). Unless the building is effectively pressurized or depressurized using a mechanical ventilation system, a building will have some walls under a positive pressure where the air is forced out and others under a negative pressure where air is drawn in. For small cracks, deposition onto crack surfaces may decrease the particle concentration as the air moves through the building shell. For larger gaps, particle removal during infiltration is unlikely.

2.2.2 Removal and Re-emission of Particle Mass in the Indoor Environment

Inside a building, particle concentrations can be altered through both incidental and intentional processes. Incidental losses occur as a result of particle deposition, particle transformation, and resuspension. Transformation can increase or decrease particle concentration within a specified particle size range. Resuspension increases particle concentrations during periods of occupancy and indoor activities. The most common intentional removal process is filtration, which can occur either within the HVAC system or in stand alone units.

2.2.2.1 Incidental processes

The largest incidental losses occur as a result of particle deposition to surfaces. Due to the relatively large surface-to-volume ratio indoors, deposition has a much larger effect on reducing concentrations indoors than it does outdoors. The magnitude of the deposition loss rate within a building is influenced by many factors including particle size, shape, and density; surface area and orientation; surface roughness; surface-to-air temperature difference; surface-particle charge difference; and air speed.

Transformation processes can either increase or decrease the particle mass. The processes of the most potential importance include vapor deposition (water, semi-volatile organics), gas-to-particle conversion (ammonia-nitrate), and coagulation (in the presence of indoor sources such as tobacco smoke). Transformation processes can also change the size of existing particles and shift the overall size distribution. These processes can be promoted due to the differences between indoor and outdoor temperature, relative humidity, gas concentrations, and particle concentrations caused by indoor heating and cooling, particle penetration, and deposition of gases and particles to surfaces.

Resuspension can significantly increase the concentration of airborne particles within a building. Under typical conditions, only particles larger than 1 micrometer undergo significant resuspension. However, even moderate indoor activity, such as walking, can lead to large increases in super-micrometer particle concentrations. The portion of resuspended particles that are derived from deposited particles of outdoor origin, as opposed to deposited indoor sources and tracked materials, is not currently known. The Figure 2.2.2 shows some of the most important transport and transformation mechanisms in the indoor environment.

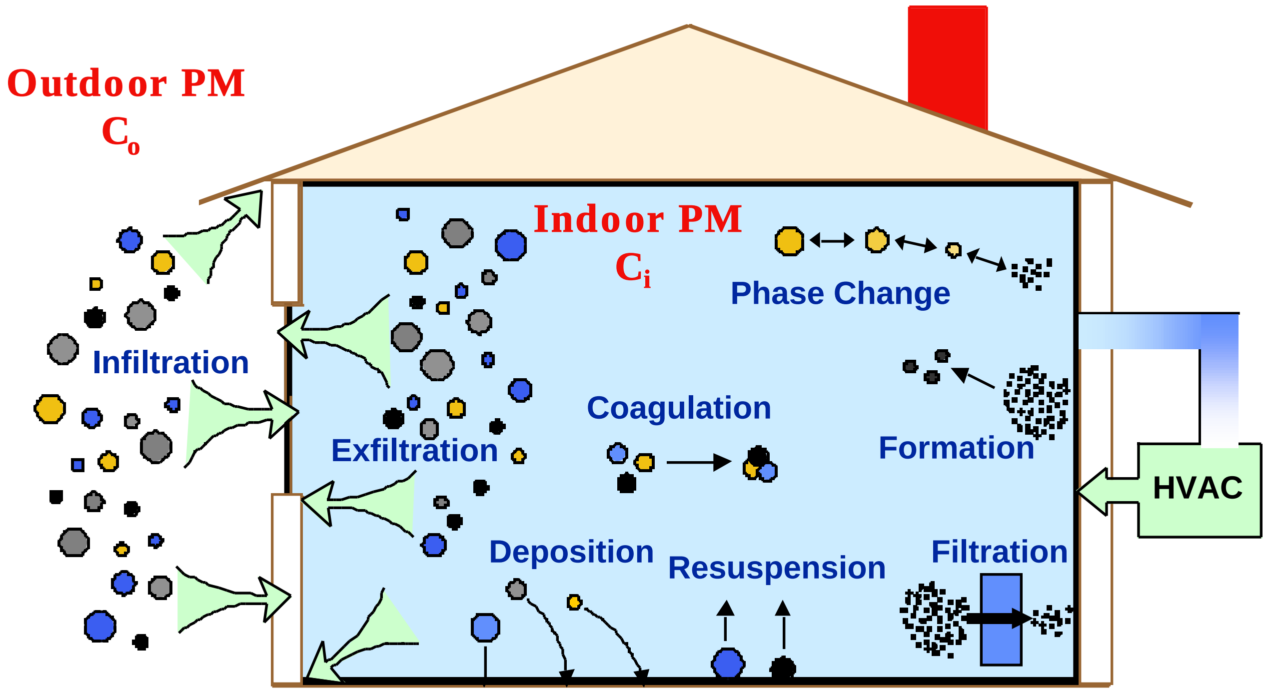

Figure 2.2.2. Transport and transformation mechanisms that define particulate matter concentrations in the indoor environment.

2.2.2.1 Dependence of entry and removal processes on particle size

Particle removal processes are highly dependant on particle size. For particles larger than about 1 µm, momentum and gravitational settling have a dominant influence on particle motion. For smaller particles, diffusion tends to have a more significant effect. As a consequence, the impact of intentional filtration, deposition to surfaces, and resuspension on indoor concentrations varies significantly depending on the particle size of concern. For super-micrometer particles, deposition losses, filtration efficiency, and resuspension all increase with particles size. For deposition and filtration, there is a minimum effect for particles around 0.3 µm, with removal rates increasing as particle size is further reduced and the diffusivity of the particle increases. Resuspension rates do not exhibit this minimum and are typically unimportant for sub-micrometer particles.

Chemical composition will also vary with particle size. For example, soil particles tend to exist predominantly in the super-micrometer size range while soot particles are more commonly found in the sub-micrometer size range. As a consequence, chemical transformation processes may occur preferentially for certain size particles based on the composition of particles within that size range.

2.2.2.2 Intentional removal--air cleaning processes

The most common intentional removal process is filtration. In buildings with forced air heating and / or cooling systems, there are typically one or more filters within the supply or return ducts. The effectiveness of these filters varies considerably. The least expensive residential filters are essentially "see-through", with large openings that do little or nothing to capture particles smaller than 5 micrometers in diameter. However, there are higher quality residential filters on the market that are much more efficient. Commercial grade filters have a wide range of efficiencies. Factors affecting particle-removal efficiency and efficiency rating methods are discussed in Section 3.3.1.1. Air by-pass (i.e. leakage) around the filter will decrease the effective efficiency, since by-pass air is unfiltered. In residences with susceptible populations, occupants may install in-room cleaning devices. These portable air cleaners can have very high efficiencies. However, in some cases the air-flow rates are fairly low, thereby reducing the effectiveness of the devices for reducing the indoor particle concentrations.

2.2.3 Mass Balance Model

In the most general form, the indoor concentration of a specific size and composition particle can be represented mathematically by the following mass balance equation.

$$\frac{\partial C_I}{\partial t} = (C_O P - C_I)\lambda_v + C_O P_H \lambda_H - C_I P_F \lambda_F - C_I P_{AF} \lambda_{AF} - C_I \beta + G + S + F + K + H + R \qquad (2.2)$$

Where:

C_I = indoor particle concentration at time t (# cm^{-3}),

t = time (h^{-1}),

C_O = outdoor particle concentration at time t (# cm^{-3}),

P = penetration factor,

P_H = penetration factor through HVAC supply,

P_F = penetration factor through HVAC recirculation that accounts for particle removal by filters and deposition in the duct system (no units),

P_{AF} = penetration factor (1-efficiency) for auxiliary filter (no units),

λ_v = air exchange rate due to infiltration (h^{-1}),

λ_H = air exchange rate through HVAC system supply air (h^{-1}),

λ_F = normalized air flow rate through HVAC recirculation or other filtration systems (h^{-1}),

λ_{AF} = normalized air flow rate auxiliary (portable) air filters (h^{-1}),

β = deposition loss rate (h^{-1}),

G = generation of particles indoors from sources such as cooking or smoking (# cm^{-3} t^{-1}),

S = particle formation through gas/particle conversion (# cm^{-3} t^{-1}),

F = particle formation due to reaction (# cm^{-3} t^{-1}),

K = particle size change through coagulation(# cm^{-3} t^{-1}),

H = particle size change through hygroscopic growth (# cm^{-3} t^{-1}), and

R = generation of particles indoors from resuspension (# cm^{-3} t^{-1}).

In the above equation, the terms *t* and λ are independent of particle size and composition. However, all of the other terms in this equation are likely to be functions of particle size, particle composition, or both.

2.3 Air Flow in Buildings

Air flow between a building and the outside, or between rooms, is driven by ventilation and/or recirculation. Ventilation brings outside air indoors. Recirculation draws air from a building volume and moves it through an HVAC system (potentially including filters and air treatment) and then back into the building volume, often into a new location within the interior of the building.

The overall mass flow induced by pressure differences is often described using some form of an orifice flow, where the size of the orifice is the effective leakage area of the opening. For example, net flow through a relatively large opening (such as a small open window) opening is often described as flow through a necking pipe and modeled using the classic orifice equation:

$$Q = C_D \; A \sqrt{2\Delta P / \rho} \qquad (2.3)$$

Where: Q is the volumetric flow rate, C_D is the orifice discharge coefficient, ΔP is the pressure difference across the orifice, ρ is density, and A is the area of the orifice.

However, flow through small openings (cracks around closed windows and doors) is often described by the crack equation:

$$Q = C\ \Delta P^n \tag{2.4}$$

The coefficient *C* and exponent *n* are typically determined through pressurization tests. The exponent *n* varys between 0.5 and 1, with a typical value between 0.6 and 0.65. By combining equations (2.3) and (2.4) one can arrive at the effective leakage area, ELA_e, which is given by equation (2.5). For this derivation, the discharge coefficient (C_D) is assumed to be unity. Some data sets assume other values, such as 0.6.

$$ELA_e = C\ \sqrt{\rho/2}\ \Delta P_e^{(n-1/2)} \tag{2.5}$$

Complex two-way flows may exist through large vertical openings (open doors and windows) when there is a temperature difference across the opening. The temperature difference imposes a buoyancy driven flow, causing flow into the bottom half and out-of the top (or vice-a-versa) (Reynolds et al., 1988).

The three driving forces that impose pressure differences within the building are 1) mechanical systems (HVAC and exhaust systems), 2) wind on the exterior, and 3) temperature differences both within the building and between the building and outside. When present, mechanical systems usually dominate.

The overall flow into and within a building is predicted by balancing the network of pressure – flow relations so that air flow mass is conserved. Feustel and Rayner-Hooson (1990) and Klote and Milke (1992) provide comprehensive descriptions for solving the system of pressure – flow equations to estimate air flow infiltration and inter-room flow and transport.

However, considerable uncertainty remains in estimating the descriptive input parameters for the pressure – flow relations. For example, in Equation 2.3, the effective size of the opening and the influence of necking on the free-stream airflow each dramatically influence the predicted air flow. While a limited number of estimates are available in the literature, these parameters are often building- or event-specific in nature. For example, when air flows quickly through a small window opening, the effects of necking are likely to be high ($C_d \sim 0.6$), whereas when the flow is very slow, the effects are minimal (e.g., $C_d \sim 0.9$). The degree to which flow conditions vary in the building must dictate the appropriate value selected. Both the literature and the practitioner typically use some form of ELA or the crack equation directly.

Uncertainties are also present in relating how environmental (e.g., wind and temperature) and mechanical (e.g., HVAC) systems affect air flow, and ultimately particle penetration. For example, wind velocity imposes a dynamic pressure gradient on a building wall according to Bernoulli's law (see e.g., Feustel and Rayner-Hooson, 1990). A positive pressure is presented on the windward side and a negative pressure is imposed on the leeward side of the building. However, relating the wind speed to the pressure gradient observed on the wall surface is both uncertain and variable. The surface roughness of the building wall caused by wall protrusions, e.g., shingle siding, open window shutters, and window and door trim, will affect the resulting wind pressure induced spatially on the wall and temporally as wind conditions change. Another and potentially larger order affect is upstream obstructions e.g. trees, nearby buildings, etc. Similar difficulties arise in estimating the effects of buoyancy induced pressure gradients. The spatial and temporal variations of temperature in and around a building can influence the rate of air infiltration in a manner which is difficult to predict.

2.4 Configuration of Building HVAC and Filtration Systems

Residential and commercial buildings typically have heating, ventilating, and air conditioning (HVAC) systems for space heating and or cooling. This section provides a general description of these HVAC systems and discusses the mechanisms by which these systems may affect indoor concentrations of outdoor particles. The major data sets of HVAC characteristics are identified and discussed in Section 3.

2.4.1 Residences

There are several principle types of HVAC systems used in residences. The type of system employed will have a significant influence on air flow patterns within the home and can have a significant impact on the overall ventilation rate. The most common residential systems are discussed below.

2.4.1.1 Ducted forced–air residential HVAC systems

Most US residences have “forced-air” HVAC systems that provide space heating and/or cooling using fans to direct (force) airflow over a heat exchanger located within a furnace, heat pump, or air conditioner. In “ducted” forced air HVAC systems, a fan system draws “return air” from the building interior through a return duct or return plenum system to the furnace or air conditioner, where heat is added or removed. The fan system forces the heated or cooled “supply air” through a system of ductwork delivering supply air to various rooms through supply registers. Most residential HVAC systems contain no provisions for outside air ventilation. A particle filter is incorporated within most furnaces, heat pumps, and air conditioners and additional particle filters or electronic air cleaners are sometimes installed in the duct systems.

There are multiple mechanisms through which ducted residential forced-air HVAC systems may affect indoor concentrations of outdoor particles. The most obvious mechanism is the intentional filtration of the air passing through these systems to remove particles. These systems usually contain a panel-type furnace filter, 2.5 cm or less in thickness, upstream of the heat exchanger (or sometimes located at the return-air grille). The rate of particle removal depends on the product of the air flow rate through the filter and the particle removal efficiency. The flow rates for whole-house forced air system is typically a few indoor volumes per hour, but the system operation is discontinuous. When there is no heating or cooling, these systems do not operate and no filtration occurs. During periods of particularly cold or warm weather, HVAC systems system may operate 50% of the time or more and provide filtration whenever they are operation.

Some forced-air residential HVAC systems have supplemental air cleaners for removing particles. Typically, the supplemental air cleaner is an electrostatic precipitator or other electronic air cleaner installed in the return air duct at a location upstream of the furnace or air conditioner. In the last few years, non-electronic higher efficiency filtration systems with pleated filters have been also marketed for residences. No data were identified on the extent to which these supplemental air cleaners are installed or used.

Particles can also be removed from the air flowing through HVAC systems by deposition on the surfaces of ducts and on heating and cooling coils. Relatively few studies or predictions of the particle loss rates have been reported (e.g., Wallin, 1993; Siegel and Carey, 2001; Muyshondt et al., 1998). For submicrometer-size particles, predicted and measured particle removal rates through deposition on ducts and coils are only a few percent of the particle flow rate. However, particle deposition on these duct surfaces and components increases with particle size. Wallin (1993) predicted that ~7% of 10 μm particles would deposit on new clean surfaces of a duct system and that the depositional losses would increase to near 100% over a period of 10 years as the duct surfaces become rough due to accumulation of particles. Predictions and experiments by Siegel and Carey (2001) indicate that approximately 20% of 10 μm particles will deposit on a cooling coil as the air passes through the coil. However, if sufficiently-efficient filters were deployed upstream, many of these particles will be removed before they reach coils and supply air ductwork.

Forced air HVAC systems increase the indoor air motion, i.e., velocities and turbulence. Based on theory and limited empirical data (discussed subsequently), rates of particle removal from the indoor air due to deposition on surfaces will increase with increased air movement.

Due to air leakage, ducted residential HVAC systems unintentionally modify rates of outside air ventilation and the entry pathways of outside air containing particles. In-turn, the ventilation rate affects rates of particle entry and removal. The following paragraphs describe the mechanisms by which ventilation rates are modified.

- Portions of the HVAC system are often located in an unconditioned, highly ventilated attic, crawlspace, or garage. Air leakage in these systems tends to pressurize or depressurize the house and drive air infiltration or exfiltration (Modera, 1993; Cummins and Tooley, 1989; Walker and Modera, 1998). For example, an HVAC system with air leakage from pressurized supply ducts located in a ventilated attic might draw 4 indoor volumes of air per hour (4 h^{-1}) from the house but deliver only 3.6 h^{-1} back to the house (10% leakage). The actual increase in the ventilation rate, above the rate caused by wind and indoor-outdoor temperature differences, will normally be less than the amount of air leakage. The final total ventilation rate is sometimes estimated as the square root of the sum of the squares of the natural and fan-forced rates (Modera and Peterson 1985, Sherman and Matson 1997). Thus, in the prior example, if the house had a ventilation rate of 0.5 h^{-1} without leakage from the ducts and 0.4 h^{-1} of air leaks from the supply ducts, the estimated final ventilation rate is 0.64, i.e., $(0.5^2 + 0.4^2)^{0.5}$.

- Air leakage in residential HVAC systems modifies the pathways through which air containing particles enters houses. For example, if leaky return air ducts are located in a crawlspace, air with particles will be drawn into these ducts and supplied to the house after passing through the HVAC system, its air filter, and supply ductwork. Particle depositional losses in this pathway may differ from the particle losses as air leaks through cracks in the building envelope.

- Residential HVAC systems unintentionally increase outside air ventilation rates because they tend to pressurize some rooms and depressurize other rooms unless the doors between rooms are open (Modera, 1993; Cummins and Tooley, 1989). Pressures generated in rooms are on the order of 5-10 Pa.

- Residential furnaces that combust fuels (e.g., natural gas) have an exhaust duct that carries combustion products to outdoors. If a furnace is located in the conditioned space, the furnace exhaust stack system is essentially an open duct from the building interior to the exterior. This stack increases the ventilation rate of the residence, sometimes markedly (Walker, 1989; Wilson and Walker, 1992; Walker and Wilson, 1990, 1998). Modern more energy efficient furnaces with a forced-air combustion system may increase ventilation rates by a smaller amount than systems without forced-air combustion, because they have a smaller exhaust duct and a more restrictive airflow pathway.

2.4.1.2 Forced-air residential HVAC system without ducts

Some residences have forced-air furnaces and air conditioners installed through walls or windows. A window air conditioner is a very common example. These systems may incorporate filters for removal of large particles and particles may also be removed by deposition of other surfaces, such as the cooling coil of an air conditioner. The filter is often a thin, easily-cleaned pad or mesh. Air leakage in these systems can lead to increased ventilation rates and to the pressurization or depressurization of rooms. Some window air conditioners have intentional provisions for supply of outside air or exhaust of indoor air to outdoors; thus, these systems will bring outdoor particles into houses.

2.4.1.3 Gravity furnaces

Some residences have “gravity” furnaces without fans. The airflow through the furnace is driven by natural convection. Often these systems have no ducts and the furnace is installed in a crawlspace with a grille in the floor above the crawlspace. Gravity furnaces do not contain air filters. Air leakage in the gravity furnace system can modify building ventilation rates. Also, houses with gravity furnaces will tend to have a high degree of vertical air temperature stratification, which affects the locations and rates of air and particle infiltration and exfiltration.

2.4.1.4 Other residential HVAC configurations

Some residential HVAC systems have no ducts, exhaust stacks, or fans. Examples include baseboard electric resistance heating systems without ducts and systems that have heated and/or cooled floors. On average, we expect lower ventilation rates in houses with these HVAC systems compared to forced-air HVAC systems.

2.4.1.5 Evaporative (swamp) coolers

In hot dry climates, many residences have an evaporative cooling system in place of an air conditioner. These systems are usually mounted on the roof or in windows and have no ducts. Evaporative coolers pass warm-dry outside air over a wetted surface, often a wetted fibrous mat, and supply this air to the house. Air exits the house through leakage pathways and sometimes through partially open windows. Evaporative air conditioners supply outside air containing particles at high air flow rates, thus, the resulting building ventilation rates are high, e.g., $> 10\ h^{-1}$. To a certain degree, the wetted surfaces, e.g., fibrous mats, will filter out particles from the incoming outside air. But we found no data on the particle removal efficiency of swamp coolers.

2.4.1.6 Residential exhaust fans

Many residences have intermittently-operated exhaust fans in kitchens and bathrooms. When operated, these fans depressurize the house and draw outside air containing particles into leakage areas in the building envelope.

2.4.1.7 Operable windows

Virtually all residences in the U.S. have operable windows. When windows (or doors) are substantially open, ventilation rates can be very high; thus the rates of entry of particles will be correspondingly high and indoor concentrations of outdoor particles may approach the outdoor concentrations. Windows are more often open during mild or warm weather. Consequently, the extent and timing of window opening will be an important determinate of indoor concentrations of outdoor particles. Data on window opening behavior, discussed subsequently, is quite limited.

2.4.1.8 Intentional mechanical ventilation systems in residences

Residential forced-air HVAC systems rarely have a ventilation air stream -- the air in these systems is usually 100% recirculated indoor air. When ventilation air is incorporated into the HVAC system, the ventilation air is usually drawn into the return air plenum of the HVAC system through a duct to outdoors. In some systems, the duct is continuously open while in others it contains a shut-off damper. Systems may contain a timer that turns the HVAC system fan on and off so that ventilation occurs only when there is no need for heating or cooling.

A few residences have mechanical ventilation systems that are independent of the systems that provide heat and cooling. The two most common systems are continuously or periodically operating exhaust fans and heat-recovery ventilators (HRVs). HRVs have supply and exhaust airstreams and a heat exchanger designed to recover energy. Some HRV systems incorporate air filters for removing particles.

Currently two states have residential ventilation standards—Washington and Minnesota. There is a proposed standard in the ASHRAE system 62.2P. These standards allow for various methods of achieving adequate ventilation. They include localized exhaust, whole house exhaust, and whole house supply systems.

2.4.1.9 Auxiliary Air Cleaners

In addition to particle filtration associated with either residential or commercial building HVAC systems, portable or auxiliary particle air cleaners are sometimes used to control particle concentrations in indoor environments. These may supplement air cleaning provided by filters in the HVAC system or used as a primary means of control. In many residential forced air heating/cooling systems, the “furnace filter” provides only coarse filtration of very large particles, usually to keep the motor and/or air mover from loading with household dust or ‘lint’. These filters provide negligible removal of particles smaller than a few micrometers in diameter (except possibly when loaded, see Hanley et al., 1994)

There are several types of portable filtration units; these range from simple panel filters and various extended media filters (HEPA or ‘HEPA-type’) to electrostatic precipitators and ionizers. These devices also cover a wide range of performance, both in terms of overall particle removal rates and particle removal efficiencies that depend on particle size. Offermann et al (1985) examined the operation of several different types of air cleaners that were then commercially available. Their data showed filtration efficiencies for cigarette smoke that ranged from nearly zero for a foam panel filter unit designed so that most of the air by-passed the filter to essentially 100% for units employing ‘HEPA-type’ (high efficiency particle absolute) filters. However, as noted by these authors, filter efficiency is not, by itself, an appropriate metric for gauging the overall effectiveness of a filter system.

In order for a particle air cleaner to be effective, it should have overall removal rates – either overall or for the sizes of particles of interest – that are at least comparable to removal rates from other processes, such as ventilation. Even a highly efficient filter changes the indoor concentration very little if the flow rate through the filter is low. This can be seen from the mass balance equation 2.2. If the indoor concentrations are assumed to be at steady state (i.e., dC / dt = 0), then equation 2.2 becomes:

$$C_I = \frac{C_O P\lambda_v + C_O P_H \lambda_H + G + S + F + K + H + R}{\lambda_v + P_F\lambda_F + P_{AF}\lambda_{AF} + \beta} \qquad (2.6)$$

While the assumption of steady-state is unrealistic in most real world applications where dynamic processes (such as changes in outdoor concentration and infiltration rates) are important, the equation can be used to simply illustrate the balance of processes affecting indoor aerosol concentrations.

Equation 2.6 shows that, if the auxiliary filtration plus other filtration rates, $P_F\lambda_F + P_{AF}\lambda_{AF}$, are the same size as the sum of the ventilation rates, this will lead to, at most, a two-fold reduction in particle concentrations. When particle deposition losses become more important, as they are for larger particles (> 2-3 micrometers), then filtration removal rates need to be even higher to yield proportional reductions in steady-state aerosol concentrations.

In practice, this means that the air flow through a mechanically-driven air cleaner (almost all air cleaners –except ionizers – are fan-powered) needs to be at least 50 cfm or larger, depending upon the overall filtration efficiency, the size of the room or rooms to be cleaned, etc. In their examination of portable filtration units, Offermann et al. (1985) used the concept of an “effective cleaning rate” (ECR) as a metric for air cleaner performance. The ECR is the volumetric flow of ‘clean’ (particle free) air delivered by the device. This metric has the advantage that these flows can be compared directly with ventilation flows, for example. This term – now referred to as the ‘clean air delivery rate’ or CADR - has since been adopted and used the Association of Home Appliance Manufacturers (AHAM), which provides an air cleaner testing and rating service for voluntary use by air cleaner manufacturers (ANSI, 1988). These tests – very similar to those conducted by Offermann et al., (1985) - are based on measuring the reduction in particle concentrations as a function of time in a test chamber after an initial injection of particles from a source. The tests are conducted both with and without the operation of the air cleaner being tested, to take into account other particle loss mechanisms in the chamber (deposition, exfiltration). Often the several tests are performed using different particle sources – environmental tobacco smoke (ETS), dust and pollen – which provide some indication of the effectiveness of the air cleaner against different particle sizes.

In addition to the CADR rating, AHAM also provides a recommendation for the largest room size (in area) that corresponds to the CADR for ETS. This recommendation is based on AHAM's criterion of 80% reduction in particle concentrations, a room air exchange rate of 1 h^{-1} and a deposition loss rate of 0.1 h^{-1}. The most recent compilation of testing and certification results for approximately 160 units– given by manufacturer and by model number – show CADR's (in units of ft^3 / min) ranging from ~40 to 400 and corresponding room areas from 55 to 615 ft^2 (AHAM 2001)

A recent review of air cleaning notes that while CADR is a metric that can be applied to the air cleaner, the overall benefit of using an air cleaner is better described by its effectiveness (Nazaroff, 2000). In a steady-state model, this is parameterized as the ratio of the CADR to all of the removal processes, (i.e., CADR plus the other particle removal terms - typically ventilation rate and losses due to deposition). An effectiveness of 0.5 occurs when the magnitude of the CADR is equal to that of these other processes. More effective (and thus more desirable) air cleaning requires effectiveness values approaching one.

Much of the above discussion also applies to particle-size specific concerns – although the overall particle removal rate is typically the only consideration. In a few of the CADR ratings in the AHAM list, there are significant differences in the CADR values for ETS, dust, and pollen, so the particle type under consideration for control will dictate the specific type of control used.

2.4.2 Commercial and Institutional Buildings

Relative to residences, commercial buildings more frequently have forced-air HVAC systems with ducts. Large commercial buildings tend to have the most complex HVAC system with sophisticated control systems. Smaller commercial and institutional buildings frequently have one or more packaged roof-top air handling systems or packaged terminal air conditioning systems.

Many of the previous comments on residential HVAC systems and their influence on indoor particles apply to commercial HVAC systems. Consequently, this section will only describe features of commercial HVAC systems that are distinct from residential system that may substantially affect indoor concentrations of outdoor particles. These features are: 1) intentional supply of outside air, often with an economizer system; 2) use of more efficient air filters; 3) continuous re-circulation of air through filters; 4) presence of duct systems within the conditioned space, 5) smaller air infiltration rates; and 6) sealed windows.

2.4.2.1 Outside air supply

Commercial building HVAC systems normally draw in outside air, mix it outside air with re-circulated indoor air, and then filter and thermally-condition the mixture before it is supplied to the building. Many of these HVAC systems, particularly larger systems, have an outside-air economizer that modulates the outside air supply rate. A minimum quantity of outside air, ideally consistent with code requirements, is supplied except during mild weather conditions, when larger quantities of outside air are more economical from an energy perspective. Thus, with an economizer system the rate of supply of outside air containing particles varies widely with changes in weather, which, in turn, varies geographically and with time. Modeling of economizer system operation cycles will be critical to the prediction of indoor particle concentrations in buildings with economizers.

2.4.2.2 Periods of fan operation and air recirculation

In larger commercial buildings, the HVAC fans are operated continuously during occupancy; thus, air is continuously recirculated through filters that remove particles. Air recirculation rates depend on the building’s heating and cooling loads and on supply air temperatures. Many buildings have variable air volume (VAV) systems where air recirculation rates are modulated over time in order to maintain the desired indoor air temperatures. In general, air recirculation rates are on the order of three to five building volumes per hour.

Smaller roof-top or packaged terminal air conditioning systems often have fans that operate only during periods of heating or cooling, much like a residential furnace or air conditioner; however, some of these systems provide for either continuous or discontinuous fan operation.

2.4.2.3 Filter efficiencies

HVAC systems in large commercial buildings tend to have more efficient air filters (for small particles) than residential systems. Filter efficiency, characterized by ASHRAE test methods (ASHRAE, 1992,1999a), varies over a very wide range. Fisk et al. (2001) and Riley et al. (2001) provide predictions of the influence of filter efficiency on indoor concentrations of outdoor particles.

2.4.2.4 Duct system locations

In large commercial buildings, duct systems are usually located within the conditioned space. Consequently, air leakage from these ducts will not drive air infiltration as it does in many residences with ducts located in attics or crawl spaces.

Commercial buildings with roof-top air handling units may have ducts on the roof and within the plenum above a suspended ceiling. In some of these buildings, the plenum is ventilated like a residential attic. Air leakage from these types of duct systems can drive air infiltration that, in turn, affects indoor concentrations of outdoor particles.

2.4.2.5 Air infiltration rates

Compared to residences, large commercial buildings have a smaller ratio of exterior envelope surface area to indoor volume. Consequently, these buildings may have a lower rate of air infiltration than residences. However, infiltration rates in commercial buildings are still significant and air infiltration can be an important source of outdoor particle entry. This is especially true when high efficiency filters are used to remove particles from air delivered through the mechanical ventilation system, leaving infiltration as the dominant pathway for entry of particles into the indoor environment.

2.4.2.6 Sealed windows

Many large commercial buildings have sealed windows. The sealing of windows eliminates periods with very high rates of entry of outdoor particles through windows.

2.5 The Significance of Variability and Uncertainty in COPI Factors

The concentration of outdoor particles in the indoor environment is a balance between several competing processes: particle entry, particle removal, and particle re-emission. Of these three processes, the least is known about particle re-emission. As a consequence re-emission rates introduce a high degree of uncertainty for predicted particle concentrations in occupied spaces.

Particle entry rates are influenced by the overall ventilation rate, the route of entry (e.g., through filters, cracks, windows), and particle penetration efficiencies. While considerable work has been expended on defining the factors affecting ventilation rates, there is still significant uncertainty concerning the route of entry in several areas (such as crack size distributions or infiltration rates in large commercial buildings) and even more uncertainty in the area of particle penetration efficiency.

Removal mechanisms and rates (e.g., deposition, filtration, and exfiltration) are probably the best understood of the mass balance components, with experimental data and well formulated theoretical models for at least some of the components. However, variability is very high between buildings and the causes for this variability are poorly understood. Chemical transformation in the indoor environment is only just beginning to be investigated and may prove to be an important loss factor for some particle types.

3.0 Evaluation of Available Data on COPI Factors

This section identifies ranges of available data, data quality concerns, and data gaps. When appropriate, the dependence on particle size is discussed. Examples or summaries of data are provided, but the report does not attempt to compile/include all data.

3.1 Overview of the Currently Available Sources of Data on Building Characteristics

Building characteristics have a significant impact on concentrations of outdoor particles in the indoor environment. This section discusses the most important sources for information regarding both residential and commercial buildings.

3.1.1 Residential-building Data

Residential Energy Consumption Survey. The Energy Information Administration of the Department of Energy has conducted an ongoing survey of energy use in residential houses since 1978 called the Residential Energy Consumption Survey (RECS). It is a national statistical survey, sampling approximately 5,900 housing units in the 1997 survey alone. The surveys are based on either 30-minute personal interviews, telephone interviews, or mailed questionnaires. The resulting data describes energy use and many characteristics of the United States housing stock (U.S. DOE, 2000) including the size of housing units, types of heating and cooling systems installed, and numbers of household members present. The survey is also a detailed source of information for quantifying the status and types of residential buildings geographically. The survey has not, however, conducted any field examinations that enable estimates of air infiltration, the types of cracks in building envelopes, or the types of filters used in residential HVAC systems.

American Housing Survey. Via interviews, the US Department of Commerce (1999) also conducts surveys of housing characteristics. The 1997 survey of 56,000 housing units in 46 metropolitan areas collected data on single-family homes, apartments, and mobile homes. The most relevant data from this survey appear to be basic housing characteristics such as age, fuel use, heating and air conditioning equipment, and number of occupants. The survey does include questions about large cracks and holes in the structure, but the information obtained likely has questionable value for predictions of ventilation or particle infiltration rates due to the lack of differential pressure values and precise hold sizes and shapes.

3.1.2 Commercial-building Data

Commercial Building Energy Consumption Survey. The Energy Information Administration of the Department of Energy conducts a periodic survey of energy use in commercial buildings called the Commercial Building Energy Consumption Survey (CBECS). This survey leads to two major reports, the first on energy consumption (U.S. Department of Energy, 1998) and the second on commercial building characteristics (US Department of Energy, 1997). CBECS is a national statistical survey comparable to the RECS in its completeness and characterization of energy consumption in commercial buildings. Relevant information in the CBECS survey includes data on types, numbers, and sizes of buildings, HVAC system characteristics, and presence or absence of operable windows.

EPA BASE Study. The EPA Building Assessment Survey and Evaluation (BASE) study (USEPA, 1994; Womble, 1994, 1995) was conducted by the USEPA to obtain baseline information on indoor air quality, health symptom prevalences, and relevant building characteristics in US office buildings. One hundred office buildings in the period 1996 to 1998 were studied. Relevant data from the BASE study include: measured indoor and outdoor PM2.5 and PM10 concentrations, temperatures, and humidity levels; descriptions of the building envelope; descriptions of interior finish materials (which may affect particle deposition); a detailed description of the buildings' HVAC systems, including information of the types of particle filters (manufacturer, model, and usually an efficiency rating); and rated and measured air flow rates in HVAC systems. These data apply to a test space within each building, which is often smaller than the entire building. The BASE Study emphasizes large office buildings with mechanical ventilation and air conditioning.

3.2 COPI Factors Affecting Rates and Routes of Particle Entry

The construction of a building and the operation of building HVAC and other systems will affect the overall ventilation rate, as well as the routes through which air enters a building. The following sections discuss important building characteristics and their effect on particle entry rates into buildings.

3.2.1 Measured and Predicted Ventilation Rates

A significant body of data has been collected describing ventilation rates in buildings. This data has been used to formulate predictive models which take into account the most important physical factors affecting air entry into buildings. The most significant of these references are discussed below.

3.2.1.1 Measured ventilation rates—residences

A primary source of information on residential ventilation rates is measurements made using a convenient tracer gas measurement procedure with diffusion-based tracer gas emitters and diffusive sampling on solid sorbents. A set of 2844 of these measurements of residential ventilation rates in U.S. houses compiled from 66 studies were analyzed by Murry and Burmaster (1995). [A prior analysis of the same data was reported by Pandian et al. (1993).] The measured data from these 66 studies are not from a representative sample of residences; however, this analysis is still probably the best available information on the distribution of ventilation rates in U.S. houses. To the best of our knowledge, there is no publicly-accessible data base containing the results of these measurements; however, summary information is provided in these two papers. Based on all climate zones and seasons, the arithmetic and geometric mean ventilation rates were 0.76 h^{-1} and 0.53 h^{-1} with a geometric standard deviation of 2.3. There are large variations in ventilation rates with season and climate zone. The winter and summer arithmetic means, for all climate zones, are 0.55 and 1.50 h^{-1}. Approximately one third of the measured ventilation rates in the winter season are less than the 0.35 h^{-1}, the minimum rate in the 1999 ASHRAE ventilation standard. In the coldest climate zone, approximately 55% of the measured ventilation rates, from all seasons, are less than 0.35 h^{-1}. Many other papers provide the results of measurements of ventilation rates in a few residences; however, these data do not add substantially to that analyzed by Murry and Burmaster (1995).

Approximately 20% of U.S. housing units are apartments. Published information on the rates of ventilation in multi-family apartment buildings are extremely sparse. Based on case studies in a small number of buildings, Diamond et al (1999) reports that ventilation rates are 0.5 to 1.5 h^{-1} for low rise apartments with a frame or brick construction and 0.2 to 1.0 h^{-1} for high rise apartments with a more air-tight concrete construction. We can expect ventilation rates to vary a great deal with both time of day, with season of the year, between apartment buildings, and among apartments within a building.

3.2.1.2 Measured ventilation rates – commercial and institutional buildings

Commercial and institutional buildings may be ventilated mechanically with an HVAC system, via air infiltration, and through the operable windows present in 40% of the commercial floor space. The ventilation provided through each of these mechanisms varies over time. As mentioned in the previous discussion of economizer systems (Section 2.4.2), the mechanical supply of outside air is often minimized when the outside air exceeds approximately 20 to 24 °C, hence, the building may be operated with a minimum ventilation rate for much of the cooling season. Minimum ventilation is also provided during cold weather when the outside air temperature falls below a set point that varies among buildings.

Ventilation rate data from U.S. commercial and institutional buildings are very limited and come primarily from modest-size research projects and from samples taken at buildings geographically convenient to the researchers. Consequently, only rough estimates can be provided on the distribution of ventilation rates in U.S. commercial buildings. Table 3-2 provides summary information from the largest data sets. All of these measurements were performed using a tracer gas procedure that measures the total ventilation rate, i.e., both the outside air supply from the air handling system and air infiltration. The data from Persily (1989) are based on long periods (weeks or months) of monitoring, while the other data are snapshots representing ventilation rates over a several hour period. The measured ventilation rates vary over a large range, from 0.3 to 2.9 h^{-1}. Most data are from office buildings, with geometric means of 1.3, 1.2 and 0.8 h^{-1} from the three largest surveys. The available data suggest that schools tend to have a higher air exchange rate than offices (although lower ventilation rates per occupant), which is expected due to the higher occupant density in schools. Some of the original references provide descriptive information on the buildings, e.g., size, year of construction, and type of ventilation system; however, the quantity of data is probably too limited for meaningful assessments of ventilation rates in subcategories of buildings.

In addition to the data within Table 3-2, many publications report measured ventilation rates in one or a few buildings from studies of indoor air quality or building-related complaints. It is beyond the scope of this report to identify all of these publications. Some of these references are provided in reviews by Berkeley Solar Group (1992) and Daisey and Angell (1998).

Table 3-2. Summary information from the three largest surveys of ventilation rates in U.S. commercial and institutional buildings.

Study	No. of Buildings	Type of Buildings	Operating Condition*	Reported Ventilation Rates				
				Mean (GM)	St. Dev. (GSD)	Min	Max	Units
Turk et al., 1989	24	Offices	As found	1.6 (1.3)	0.9 (1.9)	0.3	2.7	h^{-1}
	3	Libraries	As found	0.6	0.4	0.3	1.0	h^{-1}
	5	Multi use	As found	1.4	0.5	0.6	1.9	h^{-1}
	6	Schools	As found	1.9	0.7	0.8	3.0	h^{-1}
Lagus Applied Tech., 1995	17	Small Office	Min. Vent.	1.3 (1.2)	0.7 (1.8)	0.3	2.7	h^{-1}
	5	Large Office	Min. Vent.	0.8	0.6	0.7	2.7	h^{-1}
	13	Retail	Min. Vent.	2.2 (2.2)	1.6 (1.6)	0.5	7.0	h^{-1}
	14	Schools	Min. Vent.	2.4 (2.1)	1.6 (1.8)	1.2	2.9	h^{-1}
Persily, 1989	14	Offices	Yearly avg.	0.9 (0.8)	0.3 (1.5)	0.3	1.7	h^{-1}

*With the ventilation system providing the minimum rate of supply of outside air, a normal condition during cold weather and also when outside temperatures exceed the indoor temperature.

Very few data are available on the rates of air leakage (infiltration) into commercial buildings through ventilation; however, the existing data suggests that infiltration is appreciable, particularly in smaller buildings (Persily and Norford, 1987; Persily, 1999; Lagus Applied Technologies, 1995). In the survey of ventilation within California buildings by Lagus Applied Technologies (1995) the ratio of measured infiltration rate to total ventilation rates averaged 0.3 for small office buildings, 0.2 for large office buildings, 0.6 for retail buildings, and 0.2 for schools. These infiltration rates have typically been measured when the building's air handling system was not operating. Because air-handling systems modify indoor pressures, with the usual design intent being pressurization of the building, infiltration rates during periods of air handler operation may differ from those reported in the measurements.

In the EPA BASE study, the data collected from a survey of 100 U.S. office spaces included measurements of ventilation rates. When possible, the rate of outside air intake into air handling units was determined from multipoint velocity measurements in the outside air duct. In other buildings, the percentage of outside air in the supply air stream, based on multi-point measurements of CO_2 concentrations, was multiplied by the measured rate of air supply to the occupied space by the air handling unit. With both of these procedures, substantial measurement errors are common and the measurement does not include the outside air infiltration into the building. The data from these measurements are being further analyzed by Dr. Andy Persily at the National Institute for Standards and Testing (NIST) and will be summarized in a future NIST report.

3.2.1.3 Information for ventilation rate predictions

A source of information for predictions of ventilation rates in U.S. residences is measurements of the air-tightness of building envelopes with windows and doors closed. Ventilation rates can be predicted with semi-empirical models, using measured values of building air tightness combined with climate data and indicators of building's shielding from wind as model inputs. When annual-average ventilation rates are desired, the predictions may also include terms to account for natural ventilation via windows; however, the current knowledge of window use and effects on ventilation is cursory.

Based on air tightness and climate data for approximately 12000 houses, Sherman and Matson (1997) estimate that the arithmetic average effective ventilation rate of houses in the U.S. is 1.1 h^{-1}. This average reflects ventilation rates when windows are closed and also the higher ventilation rates that occur with open windows during mild weather. Air tightness normalized by house size is highly variable (Sherman and Dickerhoff, 1994), with a standard deviation that is approximately 50% of the mean. The mean of the air tightness data from individual states varies among the states by more than a factor of three. In the available data, there is no trend in air tightness with severity of climate. The available data indicated that houses constructed after 1980 are more air tight (by ~ 50%) than older houses (Sherman and Dickerhoff, 1994); however, there was no trend evident in air tightness with age for houses constructed after 1980.

The Indoor Environment Department at LBNL (i.e., Sherman and Matson) is updating their data base on air tightness of U.S. residences and will analyze these data to develop new predictions of residential ventilation rates. At present, the data base contains approximately 13,000 measurements of the air tightness of building envelopes and approximately 10,000 measurements of the air tightness of duct systems. The data are from 27 states. Approximately one third of the data are associated with energy efficiency programs. A first report based on these data should available within the next year.

3.2.2 Window Opening

Natural ventilation (airflow through open windows or other large openings) is common in commercial buildings, particularly in smaller and older buildings. The Commercial Building Energy Consumption Survey (CBECS) (DOE-EIA 1995, 1997) reports 40% of commercial building space has operable windows. It also reports that of the 40%, half is in buildings with floor areas smaller than 4650 m^2 (50,0000 ft^2). However, natural ventilation is poorly understood. Windows are often placed in commercial and residential buildings more for aesthetic reasons, such as to provide an even distribution of windows on a facade, than to manage building ventilation. Thus, the amount of air flowing through windows and the affect of this flow on indoor air motion is often ignored in the design of the building. Moreover, research in this area may decrease as fewer new buildings incorporate operable windows in their construction. There is reluctance by main-stream architectural and engineering communities in the US to use windows in ventilating a building for several anecdotal reasons: (1) it is difficult to control HVAC systems with varying window conditions; (2) smoke containment is difficult to design; and (3) occupants are not shielded from outdoor noises.

3.2.3 Prevalence of Mechanical Ventilation

Ventilation air delivered through a forced air fan system will have different particle concentrations than air entering through other routes. The primary factors affecting the installation of mechanical ventilation systems are discussed below.

3.2.3.1 Residences

Beyond localized exhaust fans (for example kitchen and toilet fans) very few residential systems have intentional mechanical ventilation. These exhaust fans often rely on leakage of air through the building envelope for make up air. This results in a depressurized building.

Currently Minnesota and Washington are the only states with code-required ventilation standards for residences. Washington State Ventilation and Indoor Air Quality Code (VIAQ) has required the installation of whole house ventilation systems in new homes since July 1991. ASHRAE has a proposed standard 62.2 Residential Ventilation Standard which sets performance levels and would increase the use of mechanical ventilation.

No data were identified that quantifies the extent to which these mechanical ventilation systems are deployed or operated in U.S. residences; however, we believe that they are present is a very small fraction of existing houses.

3.2.3.2 Commercial buildings

ASHRAE standard 62-1999 prescribes minimum quantities of ventilation air on a per-person basis as a function of building usage. Building codes typically use the ASHAE standard-62 rates. Most large commercial buildings make an attempt at satisfying Standard 62 through explicit design of the system. Light-commercial buildings often do not explicitly meet Standard 62.

3.2.3.3 Air filters in outside air entry pathway

Filters directly in the outside air entry pathways are often known as pre-filters. At best the filters are high quality and provide a high degree of filtration, more typically the filters are of low quality and just remove the largest of particles, and at worst the pre-filters are little more than screening for the largest of debris (birds, leaves, etc.).

3.2.4 Air Leakage in Ducts

It is widely known that the ductwork used in residential and light-commercial buildings is not airtight. For residential buildings, Walker (1998) suggests that the average leakage rate is 17% of the system airflow. The current California Title 24 energy standard assumes average leakage rates of 28% for older homes and 22% for new homes. As discussed in Section 3.2.1.3, the Indoor Air Department at LBNL is updating a database on air leakage in residences. At present the database contains approximately 10,000 measurements of the tightness of duct systems. This data set has not yet been analyzed, but represents the largest known collection of data on leakage area of ducts. Air leakage rates from ducts in light-commercial buildings are of the same order as residential buildings (~24%) (Delp, et al., 1998). Much less is known about large buildings, but the limited data available suggests that leakage areas are similar to those in light-commercial buildings (Fisk, et al., 1999). Actual leakage rates vary widely between buildings of a similar type. The standard deviation of the leakage data of a particular building type is nearly the same as the average value.

Air leakage in ducts influences outdoor particle entry in three ways. Firstly, if the ducts are located outside the central building envelope (e.g., crawlspaces and attics), as is common in residential construction, return-air leaks draw outside air into the building. Secondly, if the filter is located at a grill, the return-air leaks are unfiltered. Finally, the imbalance in supply and return leads to pressure differentials across the building shell and changes the rate of infiltration in a house, often tripling the rate of air entry (Cummings and Tooley, 1989; Modera, 1989).

3.2.5 Pathways for Air and Particle Leakage into Buildings

As discussed above, air enters buildings through many pathways. The entry of outdoor particles is affected not only by window and duct leakage (discussed above in Sections 3.2.2 and 3.2.4, respectively), but also by the nature and abundance of small openings such as cracks in the building shell. The path followed by infiltrating air may be fairly straight (such as leaking around a door or window) or tortuous (for instance, entering through an exterior wall at an outdoor light fixture, traveling down a wall, and leaking in at an electrical outlet), resulting in different particle loss rates In addition to the multitude of small cracks found in all buildings, many also have larger openings such as poorly sealed doors, leaky fireplace dampers, or unsealed plumbing penetrations.

The construction methods used affect not only the volume of infiltrating air, but also the nature of the infiltration pathways. For instance, residences with the substructure directly on the ground will have less infiltration than those with raised flooring and crawl-spaces. The use of energy efficient construction practices, such as installing vapor barriers, caulking along sill plates and around penetrations, and energy efficient windows, also reduce infiltration of particles.

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers completed a project (**ASHRAE Research Project RP-438**: Colliver et al., 1993, 1994) that summarizes effective leakage areas for individual components in residential and commercial buildings. For example, the survey provides best estimates, and in some cases minimum and maximum values, for effective leakage areas for air flow through doors, ceiling cracks, windows, and, fireplaces. Much of the data, derived from published literature, are provided without details on how the estimates where derived. Furthermore, in estimating overall leakage area of buildings, for the propose of estimating ventilation rates or particle penetration, care must be used in estimating the number of individual building leakage components to derive overall leakage. Sohn et al. (2001) reviewed existing infiltration estimates and derived uncertainty ranges for whole wall leakage. However, their estimates are not based on experiments but computer model simulations and some component leakage summations. The number of leakage pathways not accounted for or inadequately understood may be significantly greater than the leakage pathways that are well understood.

3.2.6 Particle Penetration Efficiencies

Particles within infiltrating air may deposit onto surfaces as they pass through the building shell. The fraction of particles which pass through the building shell will depend on many factors including the size and length of the infiltration pathways, the pressure differential across the building shell, and the size of the particles. **The fraction of outdoor particles that remain in infiltrating air and enter the building interior is typically referred to as the Penetration Factor, P. In some published articles, the term penetration factor has been given other definitions, such as either the indoor/outdoor ratio of all particles or of particles of outdoor origin. However, these definitions confuse the factors affecting indoor concentrations by combining the influence of infiltration, deposition, and even generation into a single term.**

Previous experiments on penetration factors have found a large variation in values. Thatcher and Layton (1995) measured P for particles sizes larger than 1 μm and found that P was near 1 for the single residence studied, meaning that the building shell essentially provides no filtration. Wallace (1996) also calculated penetration factors very close to 1 for PM 2.5 and PM 10, based on the data of the EPA PTEAM study of a large number of households in the Los Angles area. Cristy and Chester (1981) generated large quantities of 2 µm spores outside a trailer home, which are often not well-sealed, and measured the indoor concentration response. They calculated that penetration losses did not have a significant effect on indoor concentrations (i.e., P was near to unity). Vette, et al (2001) reported penetration factors for a single house between 0.4 and 0.9 for ambient particles with diameters between 0.01 and 2.5 µm. However, they did not measure air exchange rates during the period when the penetration rates were calculated, but assumed that the daytime and night-time air exchange rates were equal and not subject to temporal or diurnal variation. Thatcher and Layton (1995), Wallace (1996), and Vette (2001) all based their calculations on measurements of ambient particles, which may undergo reaction and/or transformation in the indoor environment. Roed and Cannell (1987) reported P = 1 for 2 radioactive isotopes (^{131}I and ^{7}Be) and P = 0.53 for a third (^{137}Cs), based on measurements in a single home. Koutrakis, et al (1992) measured PM 2.5 in 394 homes and estimated penetration factors between 0.58 and 1.04 for 8 elements primarily of outdoor origin. Their calculations assumed that all 8 elements had an average deposition velocity of 0.18 m h^{-1}, instead of determining size- (or element-) specific deposition rates. Since the main factors affecting the particle size dependence of penetration factors (diffusion rate, inertia, electrostatics, gravitational settling velocity, etc.) are also the main factors affecting deposition velocity, it seems unreasonable to assume apriori that one factor is responsible for the total observed difference. Chao and Tung (2001) report P = 0.85 for PM 2.5 in five homes. Their analysis assumed that indoor deposition losses (β) were negligible, which will lead to errors in the value of P since the effects β and P on indoor concentrations are similar. Tung, et al. (1999) measured concentrations of PM10 in an interior conference room and corridor of an office building and calculated penetration factors ranging from 0.69 to 0.86. However, their data show that a large increase in the particle concentration in the corridor did not cause any response in the conference room concentration. They attribute this to the low air exchange rate (0.29 h^{-1}) between the corridor and room, despite the fact that a transient model using their parameters indicates that the room concentration should have showed a substantial response. A possible explanation for this discrepancy is that some other pathway (such as the unused ductwork or ceiling area) was the main source of infiltrating air for the conference room, not the corridor.

McMurray, et al. (1985) measured indoor/outdoor (I/O) ratios in a well-sealed residence and found no correspondence between these ratios and particle diameter for particles between 0.1 and 1 µm. However, their I/O ratios assumed that the indoor and outdoor concentrations were at steady state, despite the low air exchange rates and correspondingly long particle residence times. The most striking effect of this assumption can be seen during the rainfall episode where the I/O ratios rise drastically for all size ranges during the rainfall and drop back down quickly once the rain ends.

This indicates that when the outdoor concentration dropped during rainfall there was significantly less reduction in indoor concentration, leading to an increase in the I/O ratio.

In addition to the whole house studies listed above, several studies have looked at penetration through manufactured cracks in experimental chambers. Lewis (1995) reported penetration factors between 0.97 and 0.29 for particles between 1 and 6 µm passing through a Perspex (plastic) slit 0.1 mm high and 40 mm wide with a pressure differential of 10 Pa across the slit. Mosely, et al. (2001) passed monodispersed particles through manufactured aluminum slits 0.508 mm high and 10 cm wide. They found penetration factors between 0.02 and 0.9 for 2 µm particles and 0.001 and 0.09 for 5 µm particles, with a strong dependence on the pressure differential across the crack.

In general, chamber studies have reported lower penetration rates than whole house studies. The reason for this is not entirely clear. However, it is reasonable that the penetration factor should be highly influenced by the size and geometry of the infiltration route, which has not been systematically investigated for a wide variety of houses. Older homes, and other homes which are not tightly sealed, may have a significant portion of their infiltrating air entering through relatively large openings around pipes and electrical outlets, poorly sealed windows and doors. The ASHRAE Fundamentals Handbook (1997) reports that a large fraction of air infiltrating into a residence can come from large openings such as around fireplace dampers (0 to 30%) or in the heating system (3 to 28%). When these pathways are prominent, penetration factors would be expected to be higher. In a tightly sealed home, where most of the air enters through very small cracks, the observed penetration rates may approach those found in chamber studies.

3.2.7 Stairwells and Buoyancy Induced Flow

In multi-floor and tall residential houses and commercial buildings, buoyancy induced flow can often dominate indoor air motion depending on the temperature difference between the inside and outside of a building or at different locations within a building. For example, differential heating can be induced by the sun shining on an improperly insulated building, a stove operating in a kitchen, or an HVAC system providing unequal indoor air temperatures. A temperature gradient, even as small as 2 degrees Celsius, can induce a draft that may draw considerable outside air into the building. This effect is magnified as the height of the building increases. Klote and Milke (1992) describe the fundamental governing equations characterizing temperature gradient induced flow. Notable experimental systems describing these flow conditions include Zohrabian et al. (1989; 1990), who studied bi-directional flow in a stairwell model as a function of temperature differences at the top and bottom of the stairwell, and Diamond et al. (1996) who estimated flow rates in a multi-story apartment building as a function of indoor temperature gradients as well as indoor–outdoor temperature differences. The estimates where compared to model simulations to demonstrate that flow through the building can be dominated by the stairwell configuration. Other important studies on stairwell flow include Achakji and Tamura (1988), Brown (1962), Ergin-Ozkan et al. (1993), and Reynolds et al. (1988).

Fire engineers have made efforts to address similar issues of buoyancy induced flow when responding to exposure to smoke in the event of an interior fire. For example, Tamura and Shaw (1976a, 1976b) and Klote and Milke (1992) summarize empirical and quantitative methods for estimating and managing smoke transport in large buildings, estimating effective leakage areas for walls and doors, and quantifying smoke transport in shafts. While significant, these efforts are often based on the assumed transport of large volumes of smoke resulting from high temperature gradients. Their assumed flow rates are so great that only large flow pathways in a building are studied in detail. Other possible transport routes and leakage paths that may be important under more normal building operating conditions are not considered. Hence, care must be taken in relating infiltration pathways and rates used for predicting smoke transport to particle transport under normal operating conditions.

3.3 COPI Factors Affecting Particle Removal Rates

Particle removal in buildings may be due to intentional removal mechanisms (such as filtration with the HVAC system) or inherent removal mechanisms (such as particle deposition to surfaces). In this section, we discuss both types of removal mechanisms and the factors influencing their effects on indoor concentrations.

3.3.1 Filtration in Residential and Commercial HVAC systems

Particle removal by filtration is influenced by the removal efficiency of the filters used and by the design of the filtration or HVAC system. The methods for determining and reporting filter efficiency, as well as the types of systems typically encountered, are discussed below.

3.3.1.1 Filter efficiencies

The two filter standards currently in use are ASHRAE 52.1 and 52.2. Standard 52.1 is an old standard that measures arrestance, dust spot efficiency, dust holding capacity, and pressure drop. The arrestance values in ASHRAE 52.1 only provide information on filtration of the largest particles and therefore are not relevant to this report. The duct spot efficiency is more useful because it can approximated by a curve that relates particle removal efficiency with size. See for example the work of Hanley et al., (1994). The newer standard (52.2) adds a true particle size efficiency measurement (PSE) and summarizes the results with a Minimum Efficiency Reporting Value (MERV). MERV values range from 1 to 16, with the higher values indicating a more efficient filter. MERV rated consumer grade filters are starting to appear on the market.

Several different types of filters are in common usage. “Cut-to-fit” and washable open cell foam filters have a low efficiency for particles smaller than several micrometers, and are often found in window air conditioners and motel style units. Washable metal filters, which have a frame holding a loosely bundled matrix of randomly wound aluminum wire, are similar in design to kitchen grease filters. In most residential air handling systems, inexpensive one-inch thick fiberglass panel-type furnace filters are used. These units are only effective at removing very large particles.

The size-dependent particle removal efficiency of the panel-type furnace filters used in most residential HVAC systems has not been widely reported and existing data vary considerably. Data from Hanley et al. (1994) indicate that the efficiency is 10% or less for particles between 0.05 and 1 μm and approximately 50% at 2 μm. Fisk et al. (2001) predict the effects of these filters on indoor concentrations of outdoor fine-mode particles.

Unpublished data from the Research Triangle Institute distributed at an ASHRAE tutorial on air cleaning indicate that a furnace filter has a peak efficiency of approximately 20% in the 1 to 2 μm particle size range and an efficiency between 0 and 10% for smaller and larger particles. These efficiencies are for clean (unused) filters. As filters are used they accumulate particles and dust and their efficiency increases, sometimes markedly (Hanley 1994). Within the last few years, more efficient filters with a pleated media and a thickness in the direction of airflow of approximately 2.5 cm have been marketed for direct replacement of the panel-type filters in residential HVAC systems. The manufacturers of these filters claim particle removal efficiencies on the order of 98%, but this has not been confirmed. Some of these products have electrically-charged fibers within the filter media to enhance filtration efficiency. No data were identified on the extent to which these pleated filters are used, but they are now widely available in building supply stores.

Several investigators have worked to develop characteristic representations of filter efficiencies across a range of particle sizes. Hanley et al. (1994) measured the removal efficiency of several filters for particles with diameters between 0.01 to 2.4 μm. This study included both commercial and residential filters. Riley et al. (2001) used the bed filtration theory of Hinds (1999) to augment these results for particles smaller than 0.01 μm and larger than 2.4 μm. They applied this method to a loaded home furnace filter and two commonly used commercial filters: the 40% and 85% ASHRAE filters (ASHRAE, 1993a). This theory integrates the single fiber particle scavenging efficiency (by gravitational settling, impaction, interception, and Brownian diffusion) to generate an overall bed efficiency. A best fit was generated to the Hanley et al. (1994) dataset by minimizing the log-squared difference between theoretical and measured removal efficiencies. Bed solidity and fiber diameter were used as fitting parameters. Different fits were generated for particles with diameters less than 0.01 μm and greater than 2.4 μm for each filter (Figure 3.3.1). Linear interpolation between data points was used for particles with diameters between 0.01 and 2.4 μm.

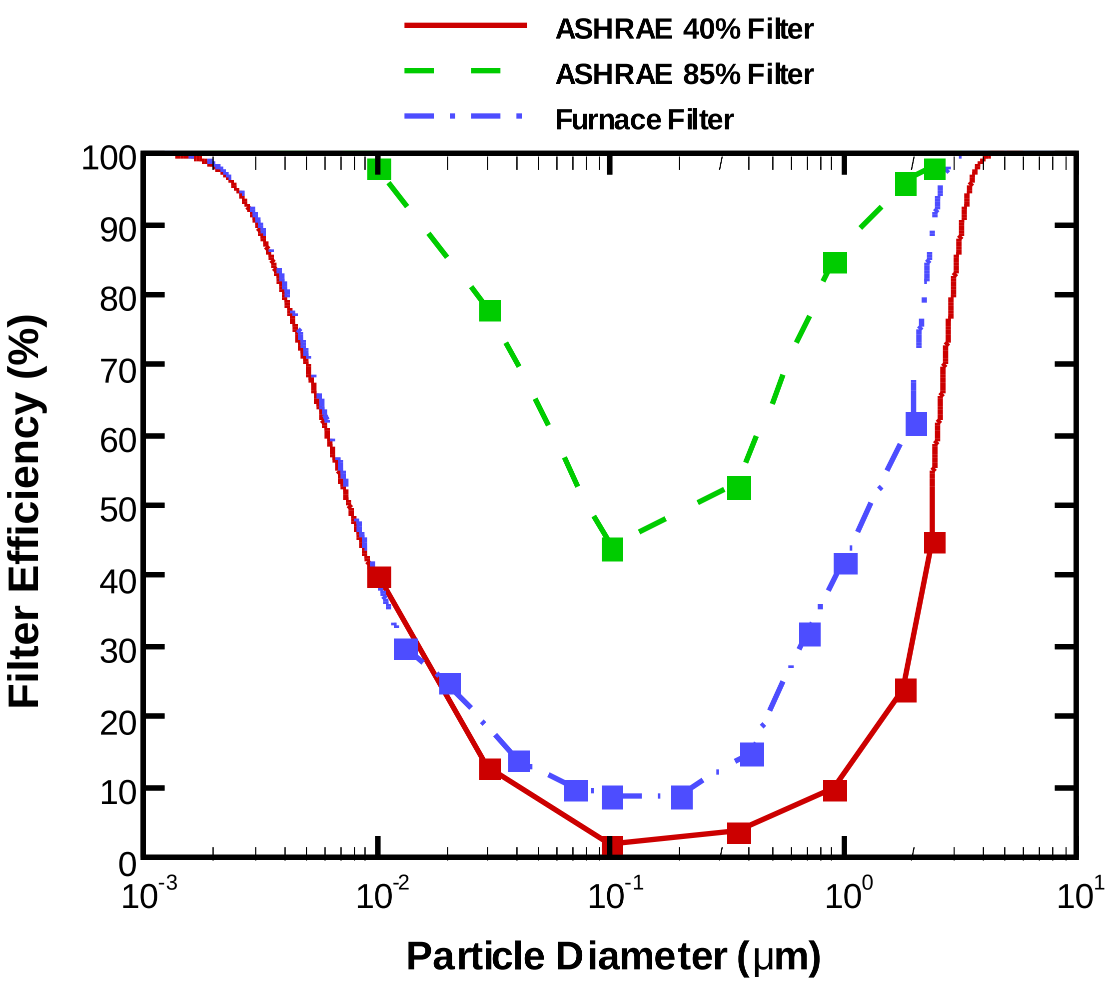

Figure 3.3.1 Filter efficiency data from Hanley et al. (1994) along with best fit lines from Riley et al. (2001).

3.3.1.2 Rates and times of air flow through filters

When assessing the impact of particle removal by filters within HVAC systems, it is important to remember that these filters are effective only when the system fan is operating and air flows through the filters. This is especially relevant for residential buildings, where HVAC systems typically are controlled using an on/off dead-band thermostat. The HVAC system turns on when the temperature reaches a set-point and turns off when it reaches another set-point, thereby keeping the temperature within a preset range. The type of residential heating and/or cooling system employed will affect the time of HVAC operation and corresponding time with air flow through filters. In the United States, 65% of all households have forced air central heating, 47% have central cooling, and 26% use window or wall air conditioners (U.S. DOE 2000). Residential central heating systems are designed to operate about 35 minutes every hour at design heating load—defined as the 88th coldest hour on an annual basis (ASHRAE, 1993b). More typically, loads will be lower than the design load and the fraction of time when the HVAC system operates will be less than 35 minutes out of a typical hour; however, no significant data sets with relevant data on operation times for residential central heating or air condition systems were identified. For window mount air conditioner systems, the amount of time of operation will depend on the system's heating or cooling capacity versus the heating or cooling load. Often, these type of units are sized to cool a single room, but doors are maintained open, which leads to near continuous operation when the units are turned on. For both heating and cooling, systems are typically operated on a seasonal basis, with the heating and cooling season varying with climate. When HVAC systems are not operated during mild weather, windows will more often be open. Also, user behaviors have a large impact on operation time, e.g., systems may be turned off during the night or when the residence is vacant.

Data on air flow rates in central forced-air residential heating and cooling systems are also sparse. No relevant data bases were identified, however, several published papers from measurements in only a few states (Davis et al., 1998, Jump et al., 1996; Olson et al., 1993; Walker et al., 1996, 1998, 1999) provide both measured flow rates and the floor area or volume of the residence. The average flow rate per unit floor area in the 84 HVAC systems within these papers is 0.3 L s^{-1} m^{-2} (0.7 cfm ft^{-2}). The same normalized flow rate is used as a default value for cooling systems in California's Title 24 Energy Efficiency Standard (California Energy Commission, 1998). Assuming a ceiling height of 2.6 m (8.5 ft), the flow rate per unit volume is 5 h^{-1}.

Many small commercial buildings utilize HVAC systems and control strategies similar to those in residential buildings. Of the approximately 60% of all commercial building floor space which is conditioned, more than half of this space is conditioned with package rooftop or residential-style HVAC units (U.S. Department of Energy, 1997). Flow rates per unit indoor air volume and operation times as a percentage of total time will be similar to those in residences. However, these systems may be operated only during work hours. Relevant data for small samples of buildings are available in research reports (e.g., Delp et al., 1997, 1998), but no data bases were identified.

In many large commercial buildings, HVAC system fans are operated continuously during building occupancy. In severe climates, the system may also be operated with different temperature setpoints even when the building is unoccupied. In milder climates, HVAC systems may be turned off during most unoccupied periods, and turned on one or two hours prior to occupancy to establish comfortable conditions at the start of occupancy. While the period of operation (nearly all occupied periods) is more certain for large commercial buildings than for residential or small commercial buildings, data on system flow rates are again sparse. Actual flow rates will depend on heating and cooling loads which vary with climate and many building factors. Anecdotally, peak HVAC system flow rates are typically about 4 to 5 L s^{-1} m^{-2} of floor area (0.8 to 1.0 cfm per ft^2) in offices and schools and about 4 to 9 L s^{-1} m^{-2} of floor area (0.8 to 1.8 cfm per ft^2) in retail buildings. These numbers can be converted to flow rates per unit air volume if the total height between floor and ceiling is known, including the height of the plenum above the suspended ceilings present in many large commercial buildings. Anecdotally, a typical floor to ceiling height is 4 m (14 ft). Flow rate data from studies in small numbers of buildings are available in research reports (e.g., Fisk et al., 1999); however, the largest and most useful data set is from the EPA-BASE study (USEPA, 1994). For air handlers serving the study spaces in 100 office buildings, the BASE study recorded the design supply air flow rate, a measured supply air flow rate, and the floor area served by the air handler. These data have not been fully analyzed.

In summarizing this section, we observe that the operation times of HVAC systems and flow rates through air filters will vary with climate, building design, internal heat loads, type of HVAC system, type of HVAC control system, and user behaviors. Except for data from the EPA-BASE study for large commercial buildings, no large data bases with relevant information were identified. Rough estimates of typical flow rates and operation times are provided in the EPA-BASE data set, but the data are based on anecdotal reports and limited data from publications. As a result, the range, the geographic variability, and uncertainty in these central estimates are unknown. Because filtration can have a large impact on indoor particle concentrations, better information is highly desirable. Options for reducing uncertainty in these parameters include: analyses of the existing EPA-BASE data; compilation of the data provided for small numbers of buildings in large numbers of publications; modeling based on climate, building, and HVAC data; and implementation of large surveys. The effort required to accurately measure flow rates in HVAC systems is a barrier to large surveys.

3.3.2 Particle Removal by Auxiliary Air Cleaners

No large data sets were identified with information on the presence or usage of auxiliary particle air cleaners in commercial or residential buildings.

3.3.3 Measured particle deposition rates in buildings

Particle deposition to indoor surfaces will reduce indoor airborne particle concentrations of particles. For this reason, understanding deposition loss rates under typical indoor conditions is important for assessing human health impacts from exposure to particles in the indoor environment. Many experiments have been performed to study particle deposition in the indoor environment (Offermann et al., 1985; Xu et al., 1994; Byrne et. al., 1995; Thatcher and Layton, 1995; Fogh et al., 1997; Vette et al., 2001; Mosley et al., 2001, and Thatcher, et al., 2001). The results of these eight studies show a wide degree of variability in deposition rate for any given particle size. This variability is due, at least in part, to variations in the conditions under which deposition rates were measured. Factors such as airflow conditions, furnishings, surface-to-air temperature differences, surface roughness, electrostatic charges, particle type and measurement methods may all be expected to influence the measured deposition rate.

Figure 3.3.3 shows a comparison of results from the eight studies, described below, which were conducted under a variety of conditions. Xu et al. (1994) used an unfurnished, full-scale room with a volume of 36.5 m^3 to measure deposition loss rates of environmental tobacco smoke under both still and actively mixed airflow conditions. Byrne et al. (1995) measured deposition loss rates for monodispersed porous silica and indium acetylacetonate in a 8 m^3 smooth walled aluminum chamber mixed with a small fan. Fogh et al. (1997) performed experiments to determine deposition loss rates for monodispersed porous silica particles in four houses, with and without furnishings. Mosley et al. (2001) determined deposition loss rates in an unfurnished 19 m^3 room using oil droplets created using a monodispersed-aerosol generator. Vette et al. (2001) performed their deposition decay experiment in a furnished residential building using ambient particles. Abt et al (2000) measured deposition loss rates after cooking events (oven cooking, toasting, and sautéing) in several homes. Thatcher and Layton (1995) measured deposition loss rates for resuspended particles within a single residence. Thatcher et al. (2001) measured deposition losses for oil droplets in a single room and they found that both furnishing level and mean air speed significantly affected deposition rates for the particle diameters studied (0.5 to 10 μm).

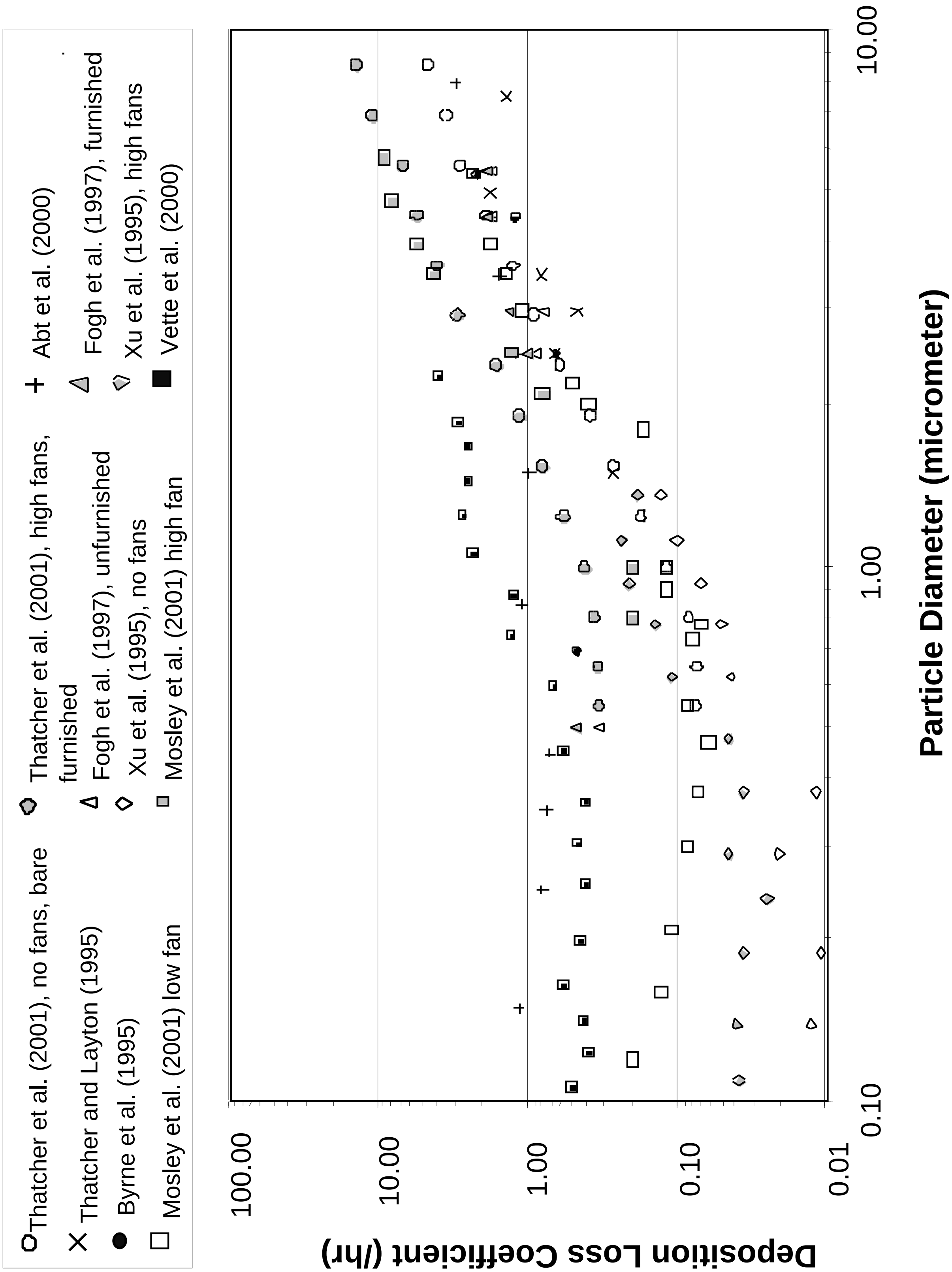

Figure 3.3.3: Published deposition loss rates for full-scale rooms and residences.

For a given particle size, the ensemble of results vary over a large range. This is not surprising, given the significant influence that furnishings and air flow have on deposition rates and the variety of particle types (from ambient aerosols to oil droplets), environmental conditions, and study locations (from controlled chambers to residences) investigated in these experiments. In some locations, thermal effects likely caused natural convection flow and thermophoresis to have significant effects on measured deposition rates. In addition, electrostatic effects may be important under some circumstances. All of these factors will influence observed deposition rates and increase variability. Significant experimental and modeling work is needed to quantify these effects. Wallace (1996) measured indoor particles for a large number of homes and reported an average deposition loss rate for ambient particles of $0.39 \pm 0.16\ h^{-1}$ for PM2.5 and $1.01 \pm 0.43\ h^{-1}$ for PM10. Although these particle measurements are not highly size specific, the results are consistent with those of more the highly size resolved studies discussed above and are possibly more representative since they were collected from a larger number of sample homes.

3.3.4 Modeled Particle Deposition Rates in Buildings

The first model for predicting particle deposition in an enclosure with turbulent airflow was presented by Corner and Pendlebury (1951). Since then, significant modifications and enhancements have been made by a number of researchers. Table 3.3.4, taken from Lai and Nazaroff (2000), summarizes these efforts.

Lai and Nazaroff (2000) developed a model for particle deposition to a smooth surface which includes the effects of Brownian and turbulent diffusion and gravitational settling. This paper presents results for horizontal, vertical, and spherical surfaces. Riley et al. (2001) developed a model for predicting indoor particle concentrations which incorporated size-dependent removal mechanisms. The deposition portion of the model incorporates results from the experimental studies described in section 3.3.3. Since there are no published experimental data for particles with diameters less than 0.06 μm, they applied the smooth indoor surface particle

deposition theory of Lai and Nazaroff (2000) to estimate deposition for these ultrafine particles. **Given the wide range of deposition values obtained experimentally, it is difficult to determine which of the deposition models predicts indoor deposition most accurately and which model parameters most accurately reflect real building conditions.**

Table 3.3.4: Summary of model developments for particle deposition from turbulent flow in enclosures (Lai and Nazaroff, 2000)

Investigators	Expressions	Comments
Corner and Pendlebury (1951)	$\varepsilon_p = K_e y^2$ $K_e = \kappa^2 \frac{dU}{dy}$	The first published analytical work. Velocity gradient, dU/dy, evaluated based on drag-force balance for a flat plate.
Crump and Seinfeld (1981)	$\varepsilon_p = K_e y^n$ $K_e = 0.4 \frac{dU}{dy}$	Exponent n is arbitrary. Analyzed overall depositional loss for vessel of arbitrary shape. Velocity gradient dU/dy, evaluated based on energy dissipation rate (Okuyama *et al.*, 1977).
McMurry and Rader (1985)	$\varepsilon_p = K_e y^2$	Extension of Crump and Seinfeld (1981) theory to include electrostatic attraction. Turbulence intensity parameter, K_e, was treated as an empirical parameter obtained by fitting experimental results.
Nazaroff and Cass (1989)	$\varepsilon_p = K_e y^2$ $K_e = \kappa^2 \frac{dU}{dy}$	Follows work of Corner and Pendlebury, incorporating the effects of thermophoresis.
Shimada et al. (1989)	$\varepsilon_p = K_e y^{2.7}$ $K_e = 7.5\sqrt{\frac{2\varepsilon}{15\upsilon}}$	Incorporates the effect of particle inertia.
Benes and Holub (1996)	$\varepsilon_p = K_e \delta^2 \left(\frac{y}{\delta}\right)^n$ $\delta = \frac{L}{\sqrt{\mathrm{Re}}}$ $K_e = \kappa^2 \frac{dU}{dy}$	Eliminates dimensional problems associated with non-integer value of n. Expression for δ based on theory for laminar boundary layer; Re based on the velocity at tip of stirrer blade. Velocity gradient, dU/dy, evaluated based on work of Okuyama *et al.*(1986).

3.4 Resuspension

A potentially important source of aerosols in indoor environments is resuspension of solid materials deposited on various indoor surfaces, as indicated schematically in Figure 2.2.2. These materials may originate out-of-doors, either as aerosols that are transported indoors as aerosols and then deposit on indoor surfaces or as materials tracked or otherwise carried into buildings ‘mechanically’. Examples of the latter include soil materials attached to shoes or other items in contact with the ground (e.g. wheels). Resuspendable materials may also be generated indoors, such as from deposited indoor aerosols or solid residues remaining on surfaces after a liquid evaporates.

Analyses of lead data for a residential neighborhood in The Netherlands, near a secondary lead smelter, indicates that resuspension accounted for approximately 60% by weight of suspended lead particles in indoor air (Diemel, et al., 1981). Another study has shown that house dust and tracked-in soils are sources of soil-derived contaminants from atmospheric deposition, such as polycyclic aromatic hydrocarbons (Chuang et al., 1995). A number of studies have investigated the sources and speciation of trace elements in street and house dust. These have shown that soil is a major component of both dusts, but there is enrichment in some of the elemental concentrations due to production indoors (Fergusson and Kim, 1991).

While it is apparent that resuspension provides a source of indoor aerosols, the magnitude of the effect is not well known. Only limited data are available on the rates with which particles on floors are suspended into air (expressed as a fraction of particulate loading on floor surfaces suspended per unit time) by human activities. Early work on resuspension indoors focused on the movement of radionuclides from floors to air. Healy (1971) developed a time-weighted-average resuspension rate of 5×10^{-4} h^{-1} for a house. This is comparable to the value of 10^{-4} h^{-1} selected by Murphy and Yocom (1986). These average values don't provide any detailed understanding, especially regarding the effects of particle size and resuspension mechanisms.

Measurements of particles in indoor air using optical particle counters demonstrate that resuspension is a function of human activities as well as particle size. Kamens, et al. (1991), for example, showed that the increase in suspended particles over the course of a day in a house corresponded to the activities of the residents. Thatcher and Layton (1995) found that the apparent resuspension threshold of particles from floor surfaces is about 2 µm. Resuspension was found to be particularly effective for particles greater than about 2.5 µm in diameter but essentially negligible for submicrometer particles, at least under conditions commonly found in residences. The study of Clayton, et al. (1993) supports this relationship. They found that the concentrations of fine particulate matter (i.e., particles under 2.5 µm in diameter) in the main living area of a sample of houses were highly correlated with the outdoor levels recorded at fixed monitors, however, PM10 concentrations had a correlation coefficient of only 0.37 with fixed-site monitors. This suggests that a significant portion of the PM10 particles collected were suspendable particles over 2 µm in diameter generated from human activities or other indoor sources. The resuspension rates increase significantly with aerosols larger than ~2 µm, as illustrated in Figure 3.4.

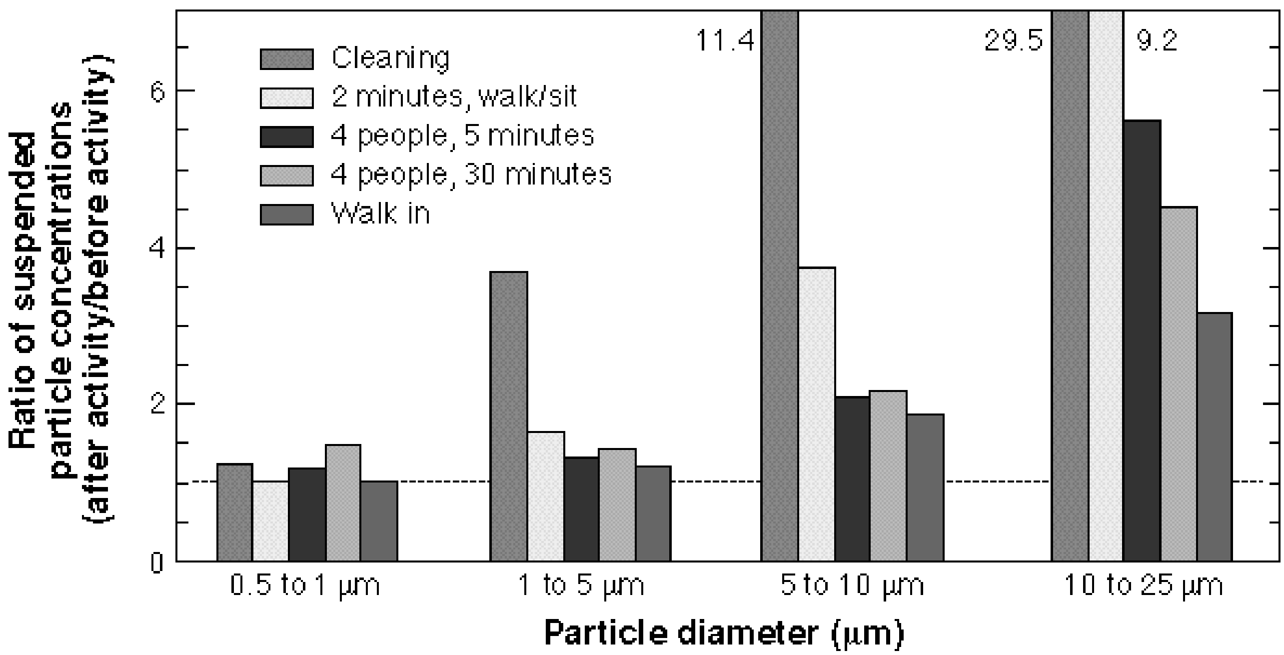

Figure 3.4 Ratios of suspended particle concentrations after human activities to concentrations before activity in a single-family residence (from Thatcher and Layton (1995)).

These limited studies pose as many questions as they provide answers. Our understanding of the actual mechanisms involved in resuspension of materials from indoor surfaces is poor. There appear to be many parameters affecting resuspension, including the types of surfaces involved (including HVAC ducts), the materials themselves, and the resuspension processes involved, including intermediate activities, such as mechanically grinding or processing larger solid materials into resuspendable sizes.

Moreover, and probably of most significance here, there is little understanding and few supporting data about how various chemicals or other species partition among the different materials or particle sizes. In addition, the proportion of resuspended particles which originate from outdoor aerosol and the factors affecting this proportion are unknown. Thus we know very little about which combination of source materials, indoor surfaces, and resuspension activities lead to significant health effects due to the inhalation of the aerosols produced.

4.0 Discussion and Conclusions

Accurate characterization of human exposures indoors to particles transferred there from the outdoor environment is a fundamental challenge in assessing and managing the health risks of airborne particles. A key step for improving exposure models is to determine how buildings transfer and alter outdoor particles brought to the indoor environment.

Concentrations of ambient particles indoors depend upon the balance among source and loss processes. Defining out this balance requires knowledge of basic building characteristics—size, number of floors, window openings, HVAC features; configuration, envelope leakage areas, etc. Sources of outdoor aerosol to the indoor environment include the particles that penetrate through the building shell (through intentional and unintentional openings) and those that are transported indoors via the HVAC system, which often includes particle filters. In the indoor environment, the loss mechanisms for these inputs include deposition, transformation, filtration, and ventilation. Each of these three classes of factors have been addressed here in terms of their impact on the concentration of outdoor particles indoors (COPI). The three classes of COPI factors are (i) basic building characteristics, (ii) those factors that impact the source (entry rate), and (iii) factors that impact losses. Some COPI factors affect both the particle source and loss rates, such as commercial building filters that remove particles from both the incoming outside air and re-circulated indoor air.

The information we assembled here improves the understanding of the processes that impact outdoor/indoor particle transport. For the COPI factors summarized below, we discuss their importance with regard to exposure, and assess the quantity, quality, and representativeness of available data used to quantify values for each COPI factor. We also discuss what additional data would increase the reliability with which particle entry and removal rates can be quantified.

4.1 Basic Building Characteristics

Basic building characteristics are parameters that describe the size, location, layout, heating/ventilation system, and leakage areas of buildings. Basic building characteristics that are important for exposure assessment include the size of a building, the number of floors, the type of HVAC system, operability of windows (do they open?), building leakage area, and duct leakage.

4.1.1 Importance of Basic Building Characteristics

Many basic building characteristics are important for exposure assessments. The size and dimensions of a building are needed to carry out a mass-balance assessment for particles entering a building. The number of floors is needed for evaluating the thermal forces driving infiltration and distributions through ventilation systems. The type of HVAC system determines whether, when, and how air is mechanically transported from outdoors to indoors and within the building volume. Whether windows open or closed determines the potential for penetration through the building envelope. Also important for determining particle transport into the building envelope are the effective leakage area of the building envelope and the leakage area of building duct work.

4.1.2 Quantity, Quality, and Representativeness of the Available Data

In contrast to COPI factors that are needed to carry out mass balances on particles, the quantity and quality of data on basic building characteristics is quite high for both residential and commercial buildings.

4.1.2.1 Residential buildings

As a result of the Department of Energy Residential Energy Consumption Survey (RECS), and the American Housing Survey, residential buildings have been well characterized in terms of the size of housing units, number of floors, types of heating and cooling systems installed, and availability of operable windows. For residential buildings, the basic building characteristics data available from RECS is expected to be highly representative of the US housing stock. This survey includes on the order of 5,000 to 6,000 units sampled in a given year. The survey has been conducted since 1978. The variation in building characteristics among residential units is not large relative to the size of the sample collected. As a result, we expect the data available from this survey to be highly representative of the US housing stock. Virtually all residences in the U.S. have windows that open, but data on residential window opening behavior are very limited. The quantity and representativeness of these data are high. However, the quality of the data is diminished and uncertain because data obtained from interviews and questionnaires have not been independently verified.

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) study on effective leakage areas for individual components in buildings provides a large quantity of data on effective leakage area in residential environments. Although the quantity of these data is high, the quality is uncertain because most of the values come from published literature with an absence of information on data collection procedures that would allow for determination data quality. Leakage estimates are limited to common components. Thus, estimating overall infiltration rates from summing individual leakage components is not practical in most instances since the number and type of components in a building are not well known or necessarily well represented. Also, the physical dimensions of many leaks in building envelopes, which strongly affects the rates of particle loss, is unknown.

A database under development by the Indoor Environment Department at LBNL currently has about 13,000 measurements of the effective leakage area of building envelopes. The data are from 27 states, but are not a rigorously representative sample (one third of these data are associated with energy efficiency programs). Accuracy of leakage area measurements, typically within 20%, is acceptable. These leakage areas can be used in models to predict ventilation rates; but the major limiting factors are the lack of available information on occupant behaviors, such as window opening or periods of HVAC operation, which strongly affect ventilation rates.

The database under development by the Indoor Environment Department also currently has about 10,000 measurements of the effective leakage area of building duct systems—making the quantity of available data high. Unfortunately, information on the location of leaks in ducts, which determines how these leaks affect particle entry rates, is largely unavailable, and limits the quality and representativeness of the data.

4.1.2.2 Commercial buildings

As a result of the DOE Commercial Building Energy Consumption Survey (CBECS), the quantity and representativeness of data available on commercial buildings is quite high in the areas of size, number of floors, HVAC technologies, operable windows, etc. But data quality is uncertain, because the survey responses have not been verified via inspections or independent measurements.

The ASHRAE study on effective leakage areas for individual components in buildings provides a lesser quantity of data for commercial buildings then for residential buildings. As was the case for residential buildings, the results of this study are limited by the derivation of most values from published literature in a way that excludes information on data collection procedures. Because leakage estimates are limited to common components, estimating overall infiltration rates from summing individual leakage components is not practical when the number and type of components in a building are not well known.

The available data on effective leakage areas of ducts in commercial buildings is far less than the available data for residences, and no significant data bases were identified. In small commercial buildings, which have many of the ducts located outdoors, the leakage area of ducts may significantly affect indoor concentrations of outdoor particles. The leakage area of ducts located within buildings, which includes most of the ducts in large commercial buildings, will have a relatively smaller impact on indoor concentrations of outdoor particles.

4.2 Factors that Impact Sources of Particles to the Indoor Environment

Outdoor particles enter the indoor environment by passing through windows; through unintentional leaks in the building envelope; through unintentional leaks in duct work located outdoors, in ventilated crawl spaces or in attics; and through the ventilation systems in mechanically ventilated buildings.

4.2.1 Types and Importance of Source Factors

Understanding the movement of ambient particles from outdoor air to the indoor environment is key to assessing the concentration of indoor particles attributable to outdoor concentrations. This movement of particles occurs through intentional processes, such as open windows or through ventilation systems that draw in outside air. It also takes place largely through non-intended processes such as leakage through the building envelope. The quantity of particles entering the indoor environment is governed by the outdoor concentration, the flow rate of air entering the building, and the fraction of particles in the entering air that reach the indoor environment. Infiltration, natural ventilation, mechanical ventilation, particle penetration factors, and filter efficiencies are thus key parameters for characterizing the particle source term. Outdoor particles may also deposit on surfaces and then be resuspended by occupant activities. However, resuspension processes are poorly understood. Currently, the significance of resuspension as a mechanism to enhance indoor exposure to particles of outdoor origin cannot be quantified reliably.

4.2.2 Penetration through the Building Envelope

4.2.2.1 Residential buildings

There have been a small number of experiments on penetration of particles though the envelope of residential buildings. The fraction of particles that pass through the building shell depends on many factors including the size and length of the infiltration pathways, the pressure differential across the building shell, the size of the particles. Because of the limited number of measurements of penetration through the building envelope, the quality and representativeness of this parameter for residential buildings is very low. Penetration factors for poorly sealed residences and buildings with open windows will likely be near unity. However, there is insufficient data to determine a likely average or minimum penetration value for residences.

4.2.2.2 Commercial buildings

No measurements of penetration of particles across the envelope of commercial buildings were identified. As a result nothing definitive can be said about the quality and representativeness of this parameter for commercial buildings. However, to first order, penetration factors measured for residences should apply for commercial buildings.

4.2.3 Infiltration and Natural Ventilation

4.2.3.1 Residential buildings

Ventilation in residences is derived mainly from infiltration and natural ventilation. Residential ventilation rates have been measured using tracer gas experiments, or derived from estimates of building component leakage areas. Because they can be highly variable, currently available measurements of residential ventilation rates have limited value for exposure assessments. The Murray and Burmaster (1995) compilation of 2,844 measurements from 66 research projects provides a sample of ventilation rates typical in residences. Although this data set is useful for assessing the median range of ventilation values, it is not sufficient to describe the extent to which variations in ventilation measurements are linked to factors such as indoor and outdoor climate condition, building age, and building size. In addition, the degree that these measurements represent typical rates among houses in the U.S. has not yet been determined.

Ventilation rates derived from component leakage areas are widely available. Sherman and Matson's (1997) compilation of 12,000 houses selected from many U.S. regions provides satisfactory representativeness of derived ventilation rates. Nevertheless, it should be recognized that few studies have quantitatively compared predicted and measured ventilation rates across a range of building types and conditions. Further studies are needed to examine the quality of the derived estimates.

4.2.3.1 Commercial buildings

Very few commercial buildings have been measured for ventilation. Most of the currently available measurements were gathered from convenience samples of buildings and modest-size research projects. Rough estimates of ventilation rates are provided in Table 3-2. However these estimates are not sufficient to evaluate the likely variability in ventilation attributable to variations in air handler operation, climate, and building size. How these factors link to variation in building ventilation remains poorly understood.

Infiltration rates in commercial buildings derived from component air leakage values are limited by a lack of component leakage area information. Available information on leakage area (primarily the ASHRAE study on effective leakage areas for individual components in buildings) does not yet provide information that is highly representative of commercial buildings. Moreover, few studies have quantitatively compared predicted and measured ventilation rates for an adequate range of building types and conditions. Thus, additional studies are needed to examine the quality of the derived estimates.

4.2.4 Mechanical Ventilation

Mechanical ventilation systems may increase airflow leakage pathways across the building envelope. The data available for assessing mechanical ventilation range from almost no measurements for residential buildings to measurements that provide very low quantity, quality and representativeness for commercial buildings.

4.2.4.1 Residential buildings

With the exception of localized exhaust fans, very few residential systems have intentional mechanical ventilation. However, because of a dearth of measurements and surveys, we cannot determine the extent to which exhaust fans depressurize a building, increase envelope leakage, and affect the size of particles penetrating the building.

4.2.4.2 Commercial buildings

In commercial buildings, infiltration and outside air supply are largely dictated by the ASHRAE 62-1999 standard. However, there are only a limited number of measurements of flow rates available to confirm the extent to which the commercial building stock complies with or deviates from the ASHRAE standard. Ventilation rate data from the EPA-BASE study of 100 office buildings, which has not yet been analyzed, promises to add substantially to existing data. However, the BASE data are representative only of large office buildings. No one has yet determined the degree to which the BASE data are representative of buildings across the U.S.

4.3 Factors that Impact Removal of Particles from the Indoor Environment

Once indoors, airborne particles are removed by deposition to surfaces, filtration, transformation, and transfer to the outdoors with ventilated or exfiltrated air. Predicting particle losses due to ventilation and exfiltration is similar to predicting infiltration and mechanical ventilation, issues that are discussed above. Deposition, filtration, and transformation are discussed below.

4.3.1 Types and Importance of Removal-Rate Parameters

Deposition, filtration, and transformation are all potentially significant mechanisms for removing particles from either indoor air or from a parcel of air entering a building through ventilation or infiltration. Deposition losses are certainly a key removal mechanism for indoor particles in all building types. Due to high surface-to-volume ratios in buildings, deposition losses can exceed all other loss mechanisms for larger particle sizes, particularly in residences where the occupants are unlikely to use effective filtration systems. Air filtration can occur in several locations: incoming outside air filters, re-circulated air filters, and stand-alone systems. The importance of filtration as a loss mechanism depends largely on the rate at which air flows through the filter system and the removal efficiency of the filters. Particle transformation, such as particle-to-gas conversion or evaporation of volatile species, is a poorly quantified process. However, transformations may be important in regions where volatile particles, such as ammonium nitrate, form a significant portion of the outdoor aerosol concentration.

4.3.2 Deposition

4.3.2.1 Residential buildings

There have been a number of studies applied to whole houses and room scale systems to assess both the magnitude of indoor deposition rates and the factors influencing deposition rates. However, each study has included, at most, a small sample of the range of homes needed to represent the US housing stock. To date, there are no comprehensive studies that investigate deposition rates for a wide range of housing stock, locations, or seasons. As a consequence, the representativeness of the current data set is unknown. The data that do exist indicate that deposition loss rates are highly influenced by particle size, air flow conditions, and (to a lesser degree) furnishing level. Factors such as electrostatics, surface-to-air temperature difference (or its surrogate indoor-outdoor temperature difference), and surface roughness may also be important, but there are not a sufficient number of studies to determine the effects of these various factors on the magnitude of deposition rates in residences.

4.3.2.2 Commercial buildings

There are few measurements of deposition of particles in commercial buildings. As a result, nothing definitive can be said about the quality and representativeness of deposition rate measurements for commercial buildings. However, to first order, deposition factors measured for residences should apply for commercial buildings, if adjustments are made for the differences in surface-to-volume ratios and airflow conditions.

4.3.3 Filtration

The impact of filtration on particles requires information on filter efficiency and information on the flow of air through the filter. The quantity and quality of data on filter efficiency is moderate. On the subjects of filter use and the amount of air flow through filters, the available information is relatively high in quantity, quality and representativeness for office buildings (i.e. the EPA BASE data) but mostly unavailable for other commercial buildings, institution buildings, and for residential buildings.

4.3.3.1 Filter efficiency

The quality of data on filter efficiency is high although the current information does not have either a large set of measurements or a fully representative set of filter types. Nevertheless, both commercial and residential filters have been measured for efficiency and a range of particle sizes have been considered. What is missing are studies of how the actual use (or misuse) of filters alters efficiency relative to laboratory measurements. The measurements of Hanley (1994) with modeled extensions to larger and smaller particle sizes by Riley et al. (2001) provide relatively accurate estimates of the variation of filter efficiency for particles ranging from 0.01 to 10 μm. The Riley et al. (2001) estimates have been applied to a loaded home furnace filter and two commonly used commercial filters: the 40% and 85% ASHRAE filters (ASHRAE, 1993).

4.3.3.2 Filter use in residential buildings

Data on air flow rates in central forced-air residential heating and cooling systems are very sparse. We have not identified any data bases for residential buildings, but have located published papers with measurements from a few states. These studies provide both measured flow rates and the floor area or volume of the residence.

4.3.3.3 Filter use in commercial buildings

The operation times of HVAC systems and flow rates through air filters will vary with climate, building design, internal heat loads, type of HVAC system, type of HVAC control system, and user behaviors. Except for data from the EPA-BASE study for large office buildings, no data bases with relevant information were identified. Rough estimates of typical flow rates and operation times are provided based on anecdotal reports and limited data from publications; however, the range, geographic variability, and uncertainty in these estimates are unknown. Because filtration can have a large impact on indoor particle concentrations, better information is highly desirable. Options for reducing uncertainty in these parameters include: analyses of the existing EPA-BASE data; compilation of the data provided for small numbers of buildings in large numbers of publications; modeling based on climate, building, and

HVAC data; and implementation of large surveys. The effort required to accurately measure flow rates in HVAC systems is a barrier to large surveys.

4.3.4 Transformation

The importance of transformation processes on indoor particle concentration is only now being investigated. To date, no published data is available on this topic. However, over some size ranges and chemical compositions of particles, transformation processes could be a significant mechanism of particle losses in the indoor environment. Transformation can also result in changes in the composition and size distribution of indoor particles of outdoor origin.

4.4 Concluding Remarks

A thorough understanding of the processes affecting the concentration of outdoor particle indoors is essential for improving assessments of human exposure to particles of outdoor origin. This is particularly important for assessors who need to consider the spatial and temporal variation of indoor exposures to outdoor particles. We have found that simple indoor/outdoor ratios are insufficient for understanding and predicting indoor concentrations. A dynamic mass balance approach is necessary in order to account for all of the critical parameters affecting the indoor/outdoor relationship. Data quality, quantity, and representativeness were evaluated for key factors such as HVAC design and operation, infiltration and leakage area, deposition, penetration factors, and natural ventilation. None of these critical factors affecting the indoor/outdoor particle relationship are yet well enough characterized to provide reliable inputs to exposure models.

In reviewing data needs for improving the ability to link indoor concentration of particles to outdoor concentrations, we have determined that the most critical missing information includes the following:

measured particle penetration factors;
measured particle deposition rates in commercial and institutional buildings;
infiltration rates in commercial buildings;
the types of filters used in all buildings (except large offices);
window opening behaviors; and
rates of indoor resuspension of particles transferred indoors from outdoors.

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